FEEDFORWARD CONTROL OF BINARY DISTILLATION

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I. INTRODUCTION

For several decades automatic control has been used in chemical plants to reduce cost, to increase product yield and quality, and to maintain a high level of safety. Traditionally, plants were designed on a steady state basis, without consideration for the dynamic behavior which is so vitally important in determining their performance under automatic control.

In the past, the traditional method to control process systems has been with feedback control. Feedback control has the advantage of often providing acceptable control despite little knowledge of the process transfer functions due to the flexibility of most controllers, the over design of equipment, and self-regulation usually present in most chemical process equipment. Today this is not satisfactory with industry requiring higher product purities, lower equipment investments, and operation of some processes inside the region of instability.

Perfect feedback control has the disadvantages of not providing perfect control due to the fact that input disturbances are only detected after their effects are felt on outputs. Large output disturbances or instability may occur in distributed parameter systems or systems with slow response speeds. Undesirable feedback controller interactions may also occur in multivariable systems with feedback control.

One approach to overcome these problems which has received much attention over the past few years has been feedforward control combined with feedback control. In feedforward control, the process manipulated variables are controlled in such a manner as to minimize or eliminate the effect of disturbances in the uncontrolled input variables on the process outputs. Feedforward control is limited to measured input disturbances to the system since it has no knowledge of the actual process output.

Feedforward control also requires knowledge of the dynamic character of the process. Empirical transient response data or mathematical models must be available to design a feedforward controller for the process. Most systems where economic incentives would justify feedforward control are in general nonlinear, multivariable, distributed parameter systems. Much work over the past few years has been devoted to the development of simpler models of these complex systems due to the difficulty involved in solving the actual nonlinear equations even on the best computing equipment available today. One very popular technique which has received much attention in the literature since it considerably reduces the computational difficulties involved has been the linearization of these nonlinear equations.

In this study the experimental open loop transfer functions for a binary distillation column were determined and these transfer functions were compared with the transfer functions resulting from assuming a linear model of the system. The feedforward control transfer functions were also calculated based upon both the experimental data and the linear model data and compared.

II. LITERATURE REVIEW

The following is a general summary of the present methods used by control engineers for design. This should not be considered a reference on such work but only as a guide to the general knowledge required of a control engineer. Many books have been published covering this material in detail (3, 7, 11, 15, 16, 50). Johnson (30) has published a review article on the essential concepts of process control with regard to the chemical engineer working in the process industry. A reivew of the current literature on distillation column dynamics and feedforward control is also included.

Basic Principles of Process Control

Since World War II electrical engineers have developed methods of servomechanism analysis which are of interest to the chemical engineer involved in process control.

These methods can be used to predict the open loop response of a system to a given input or they can be used to predict the performance and stability of a system with control. Transient response and frequency response are generally used to answer these questions about process performance.

Transient Response. Curves of the transient response can be obtained for any postulated system by solving the differential equations of the system using the step function as the forcing function or input to the system in order to obtain the variation of the output variable as a function of time.

When considering an operation which is a simple lumped-parameter system, the resulting set of equations can be solved by the Laplace transform or other operations methods to obtain an analytical solution for the output. When the number of equations becomes large or the operation becomes a distributed-parameter system, this method generally does not allow one to determine the system transfer functions and requires trial and error to determine the optimum control scheme. Its advantage lies in the fact that the solution to the problem can be seen as a function of time and thus the system stability can be determined directly.

Frequency Response. Frequency response methods are based on the response of a system when a sine function disturbance is applied as the input rather than a step function. The frequency response of a system is readily determined by making the input oscillate as a sine wave with a fixed amplitude. If the system is linear, the output will be a sine wave of the same frequency but changed in amplitude and phase. The results are reported as a gain or magnitude ratio and as a phase shift for each frequency tested; such information completely characterizes the system. Two methods are generally used to evaluate such open-loop frequency response data. These two methods are graphical in nature and are called the Nyquist and Bode methods.

Nyquist Method. The Nyquist method involves plotting the magnitude ratio as the radius vector and phase shift in degrees on a polar diagram. The phase shift is plotted clockwise from the positive X-axis (zero degrees). The Nyquist method is generally used for control system design when the process transfer functions are known.

Bode Method. The Bode method consists of two graphs. One graph contains a plot of magnitude ratio in decibels on the ordinate versus the log of the frequency. The other graph consists of a plot of the phase angle in degrees, between the output and input signals, versus the log of the frequency.

The real advantage of the frequency response procedures and the Bode method of plotting the data are the ease with which series-connected components may be combined, and the ability to determine an estimate of the predominant process transfer functions for very complex systems.

When the Bode plot of the system is used, an estimate of the feedback control system required may be obtained by adding various amounts of proportional, derivative and integral control to the open loop response of the system. Normally the best control system is one which allows the highest proportional gain and which at the same time provides both the derivative action needed to speed up the process and the integral action needed to eliminate steady-state offset. Other methods of different complexity are available for control system synthesis; one example is the Black-Nichols chart (3, 7, 11) which is also based upon frequency response techniques.

Experimental Analysis

Both sinusoidal and transient testing, which have already been considered, have certain disadvantages from an experimental standpoint. Generally today some form of nonperiodic forcing functions are used in that they minimize the total process disturbance while providing the needed frequency information.

The sinusoidal testing method, which is the basis of the frequency response theory, has been used in the past for testing mainly in the electronics industry. Its main disadvantage for the chemical engineer is in order to cover the frequency range of interest, it is necessary to test at a series of discrete frequencies which requires a large amount of process time. It does have the advantage of good noise rejection and allows direct conversion to frequency response. Caldwell, Coon and Zoss (7) discuss sinusoidal testing in detail.

Nonperiodic Testing. In the chemical industry some form of nonperiodic forcing function is generally employed to determine the process frequency response (26). Clements and Schnelle (9) discuss the amount of frequency information in various pulse forms and the problems involved in the conversion of pulse response data to frequency response.

The main advantage of nonperiodic testing is that generally only one test signal or transient need be imposed on the system compared to the series of tests needed with the sinusoidal testing procedure since a continuous frequency spectrum is present in the nonperiodic test signal as determined by a Fourier analysis. Therefore the nonperiodic test procedure is a very convenient experimental technique.

The main disadvantage of nonperiodic testing involves data reduction. The frequency response of the system must be obtained by a Fourier series transform from the experimental input-output pulse response data. Several authors have discussed this technique and the numerical reduction on a digital computer (13, 18, 26, 42). Another problem faced with nonperiodic testing is noise rejection. Hennig (23, 24, 25) has discussed the problem of testing in the presence of noise and nonlinearity.

Distillation Column Dynamics and Control

Two review articles, one titled ''Process Control in Distillation'' by Gould (19) and the other by Rosenbrock (46) titled ''Transient Behavior of Distillation Columns and Heat Exchangers,'' review some of the current work in this field. I and EC review articles on Mathematics (51, 52) and Process Control (58, 59, 60) also critique the current publications of interest to the chemical engineer in these fields.

Distillation Dynamics. Gilliland and Mohr (17) have developed a general correlation for predicting the dynamic characteristics of a distillation column for changes in feed composition. Mohr (41) has also studied the effect of the equilibrium relationship on the dynamics of distillation columns. These types of correlations have promise for reducing the amount of work required to design an adequate control system.

Experimental transient response studies on a two-foot diameter, ten tray distillation column for step changes in the reflux, feed rate, feed composition and vapor rate have been studied by various investigators at the University of Delaware (2, 32, 37, 49, 54). They have shown that a linear model is adequate to describe the initial transient response of the column. Fogle (13) has studied the dynamics of a two-inch diameter Oldershaw sieve tray column for feed composition changes.

Huckaba and co-workers have proposed a nonlinear model for a distillation column and have reported very good experimental confirmation of their predictive model (27, 28). Johnson and Lupfer have also proposed a distillation column model which they have used for predictive control and optimization studies. Their expressions are based upon empirical methods and do reduce the amount of hardware required for analog simulation (38).

Deland and Wolf (10) have developed a method for multicomponent distillation simulation which is very general and includes a nonlinear free energy function which is used to describe the chemical equilibrium. Their model can include external sources or sinks of mass and energy.

Renfroe has investigated experimentally multicomponent distillation dynamics for feed composition changes in a two-foot diameter, ten tray distillation column (42). He has predicted the column dynamics with a nonlinear model with good agreement.

Distillation Column Control. Most of the past work on distillation column control has involved relatively simple models. Williams, Rose, and Harnett (56,57) have reported studies they have conducted on distillation column control. In their studies, an ideal, five tray column was simulated on an analog computer and varying amounts and types of feedback control were added. They reported their results as charts of controller settings versus stability of the column. More recent results for a larger column were reported by Moczek (40), and associates using a digital computer to study the system dynamics and control. This study points out some of the nonlinear problems one is faced with when trying to control a column producing very pure products. Haden (21) and this author (29) have considered a similar problem for a stripping column and have proposed a simple feedback-feedforward control scheme which has been tested by Haden on the A.I.Ch.E. column at the University of Delaware.

Grover and Peiser (20) have reported a study of the control of reboiler composition with large delay times in the corrective action.

They have been mainly concerned with reboiler stability and have developed a very detailed model of the reboiler system.

The case of feedback control of a distillation column with sidestream drawoff has been reviewed and ten schemes of control have been proposed (34).

Feedforward Control. Feedforward control in general has been discussed by Calvert and Coulman (8) and by Dobson (12) and applications of feedforward control to several process systems have been published.

Bollinger and Lamb (4) discuss multivariable linear systems in general and describe by the use of matrix methods the synthesis of feedback-feedforward controllers. In a later article the case of imperfect knowledge of the process dynamics is considered and a feedforward-feedback controller is designed which minimizes a penalty function (5). This same problem was extended by Verneuil (54) for the case of sampled-data feedforward control.

Rippin and Lamb (43) were the first to apply a frequency-domain solution for feedforward controller synthesis to a linear model of a distillation column. They determined the transfer functions of the column and used matrix methods to solve for the feedforward controller transfer functions. The feedforward controller model was tested by simulating the linear model of the column with controller on an analog computer.

Luyben (33) has experimentally applied feedforward control to the A.I.Ch.E. distillation column at the University of Delaware and has found satisfactory column performance without including the dynamic terms of the controller model. The effectiveness of a feedforward controller on a 40-tray column was also investigated by analog simulation during this same investigation. Anderson (1) has also used a linear model to characterize the dynamics of a distillation column and has designed and tested a feedforward controller by analog simulation. The dependence of feedforward steady-state gains on feed composition in binary distillation has also been investigated by Luyben (35).

Bollinger and Lamb's work has been extended by Cadman and Carr (6) to the multicomponent distillation case. They have used the linear model as a basis for calculating the feedforward controller model.

Two articles discussing the industrial use of analog computers on commerical columns for feedforward controllers have appeared (38,39). Both papers report improvement in column operability and corresponding reduced operating costs.

Several other articles which apply feedforward control to chemical reactors have appeared in the literature and which may be of interest to the reader (22, 36, 53).

III. MATHEMATICAL DEVELOPMENT

This section includes an outline of the mathematical procedure used to calculate the experimental frequency response, experimental feedforward controller, and the feedforward controller based on the linear model.

Pulse Data Conversion

The conversion of pulse response data to frequency response is based on Fourier transforms of the input and output functions. The Fourier transform for an arbitrary function of time, f(t), is defined as:

$$F(f(t)) = \int_{-\infty}^{\infty} f(t)* \exp(-i\omega t)* dt \qquad (1)$$

where

$F(f(t))$ = Fourier transform

i = $\sqrt{-1}$

ω = frequency, radians/time

t = time.

Making a trigonometric substitution for exp $(-i\omega t)$, equation (1) can be reduced to the following form:

$$F(f(t)) = \int_{-\infty}^{\infty} f(t)* \cos(\omega t)* dt - i\int_{-\infty}^{\infty} f(t)* \sin(\omega t)* dt . \qquad (2)$$

Note: Fortran notation has been followed with * being multiplication and ** being exponential.

If analytic functions are available for the function, f(t), then equation (2) can be evaluated directly. If sampled data is available for the function or if it is impossible to obtain a closed form for the integrals then equation (2) must be evaluated approximately.

The application of the trapezoidal rule to each of the terms on the right side of equation (2) results in the following approximations:

$$\int_0^\infty f(t)^* \cos(\omega t)^* \, dt = \Delta t \sum_{k=1/2}^{k=n-1/2} f(k\,\Delta t)^* \cos(\omega k\,\Delta t) \qquad (3)$$

and

$$\int_0^\infty f(t)^* \sin(\omega t)^* \, dt = \Delta t \sum_{k=1/2}^{k=n-1/2} f(k\,\Delta t)^* \sin(\omega k\,\Delta t) \qquad (4)$$

Substituting equations (3) and (4) into equation (2) results in the equation used for the numerical integration of equation (1) based upon the trapezoidal rule. From this equation it can be seen that the Fourier transformation of the pulse data results in a complex number which is a function of the frequency, (ω).

$$F(f(t)) = P(\omega) = A(\omega) - iB(\omega) \qquad (5)$$

where:

$P(\omega)$ = Fourier transform of the pulse evaluated for frequency, (ω)

$A(\omega)$ = real part of the transform

$B(\omega)$ = imaginary part of the transform.

For a more complete discussion of the numerical integration of equation (2) see (14, 19).

The process transfer function is obtained by taking the ratio of the output pulse to the input pulse in the following manner:

$$G(\omega) = P_{out}(\omega)/P_{in}(\omega) = \frac{A(\omega) - iB(\omega)}{C(\omega) - iD(\omega)} \qquad (6)$$

where:

$G(\omega)$ = process transfer function

$P_{out}(\omega)$ = transform of the output pulse

$P_{in}(\omega)$ = transform of the input pulse

$A(\omega)$ = real part of the output pulse transform

$B(\omega)$ = imaginary part of the output pulse transform

$C(\omega)$ = real part of the input pulse transform

$D(\omega)$ = imaginary part of the input pulse transform.

Equation (6) can be further reduced by complex rationization to the following form:

$$G(\omega) = TR(\omega) + iTI(\omega) \qquad (7)$$

where:

$$TR(\omega) = (A*C + B*D)/(C**2 + D**2) \qquad (8)$$

$$TI(\omega) = (A*D - B*C)/(C**2 + D**2) \qquad (9)$$

The system gain and phase angle can now be obtained for a given frequency, (ω), from the following expressions

$$\text{Gain}(\omega) = 10*\log_{10}\ (TR(\omega)**2 + TI(\omega)**2) \tag{10}$$

$$\text{Phase}(\omega) = 57.29578*\text{Arctan}\ (TI(\omega)/TR(\omega)) \tag{11}$$

where:

$\text{Gain}(\omega)$ = system gain, decibels

$\text{Phase}(\omega)$ = system phase angle or lag, degrees.

A complete program to carry out these calculations for evenly spaced data points appears in the Appendix, page 242.

Experimental Feedforward Controller

The experimental feedforward controller is obtained from the experimental pulse data transfer functions. The process transfer functions obtained between the distillate and bottoms compositions and the vapor rate, reflux rate and the feed composition at the same steady-state operating condition can be used to form the following expressions

$$X_d = P(1,1)*Z - P(1,2)*V + P(1,3)*R \tag{12}$$

$$X_b = P(2,1)*Z - P(2,2)*V + P(2,3)*R \tag{13}$$

where:

X_d = change in distillate composition

X_b = change in bottoms composition

Z = change in feed composition

V = change in vapor rate

R = change in reflux rate

P(1,1) = distillate composition/feed composition transfer function

P(1,2) = distillate composition/vapor rate transfer function

P(1,3) = distillate composition/reflux rate transfer function

P(2,1) = bottoms composition/feed composition transfer function

P(2,2) = bottoms composition/vapor rate transfer function

P(2,3) = bottoms composition/reflux rate transfer function.

The feedforward control criteria are that the changes in bottoms and distillate compositions shall be maintained equal to zero, (X_d=X_b=0). Then equations (12) and (13) can be set equal to zero and used to solve for the feedforward controller transfer functions, (R/Z) and (V/Z). Carrying out this operation results in the following equations

R/Z = -(P(2,2)*P(1,1) - P(1,2)*P(2,1))/PP (14)

V/Z = -(P(2,3)*P(1,1) - P(1,3)*P(2,1)/PP (15)

PP = (P(2,2)*P(1,3) - P(1,2)*P(2,3))

Since the transfer functions are complex numbers which are functions of frequency, (w), these calculations must be carried out in complex mathematics for the same values of frequency as the transfer functions were calculated and then reduced to the controller gain and phase angle by equations (10) and (11). A computer program has been written to carry out these calculations and is discussed in the Appendix, page 250.

Linear Model for Distillation Columns

A distillation column is basically a distributed parameter, nonlinear, multivariable system which in theory at least can be described mathematically. Due to our inability to solve these nonlinear, distributed parameter equations for cases of interest, much work in the past has been devoted to simplifying these models in order to be able to solve the equations on present day computing equipment.

For this study, the set of ordinary, nonlinear difference differential equations describing the column were linearized by the methods of Lamb and Pigford (31). This procedure has been applied to the Delaware experimental distillation column by several researchers (32, 37). Their work shows the ability of this technique to describe the dynamics of that distillation column during its initial transient period. These linearized equations will be described in the following section.

Linearized Equations. Use of the perturbation technique to linearize the set of nonlinear unsteady-state differential equations results in a set of linear differential equations with coefficients which are functions of the steady-state compositions, flow rates and equilibrium curve slope values. Average values of these steady state coefficients must be used which limits the precision of the equations to small excursions from the steady-state. Other than for the top tray which was divided into two sections, an energy section and a mass transfer section, each tray in the column was described by a simple mass transfer equation, a hydraulic equation and an equilibrium relationship. The energy equations were not required except on the top tray due to the assumption of equal molar overflow. The feed tray was not divided since in the course of this study changes in the feed rate were not considered. For a detailed statement of the assumptions applied and the derivation of the equations see Lamb and Pigford's paper (31).

Transfer Functions. In order to apply the theory of feedforward control to the linear system, the transfer functions which relate the input variables to the output variables must be developed.

The development of the equations for the experimental column consisting of reboiler, condenser, seventeen trays in the stripping and rectifying sections, feed tray and first order lags for vapor reflux rate changes and dead time delay for feed composition changes results in 42 linear differential equations made up of:

1 - energy equation
19 - mass transfer equations
19 - hydraulic equations
2 - first order lags
1 - dead time.

Laplace transforming of these equations results in forty-two algebraic equations. Solving this many simultaneous equations analytically for the required transfer functions becomes next to impossible for the distributed parameter problem.

Using Lamb and Rippin's (43) method of stepping up the column applying the principle of superposition, one is able to obtain the following matrix equation:

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_r \\ R \\ Y_t \end{bmatrix} = \begin{bmatrix} G(1,1) & G(1,2) & G(1,3) & G(1,4) \\ G(2,1) & G(2,2) & G(2,3) & G(2,4) \\ G(3,1) & G(3,2) & G(3,3) & G(3,4) \end{bmatrix} \begin{bmatrix} V \\ Z \\ L_n \\ X_b \end{bmatrix} \quad (16)$$

where the G(i,j) terms represent the transfer functions between variables.

To illustrate the method employed for these calculations consider a column containing a section of trays without reboiler and lag terms. The reboiler and lag terms were included in all calculations performed during this investigation but are not included here to simplify the development. Each tray is described by the following set of linearized, Laplace transformed equations:

$$X(n-1) = (\bar{V}/\bar{L})*(Y(n) - Y(n+1)) + C_1(n)*(v - l(n-1)) + (1 + s(\bar{H}/\bar{L}))*X(n) \quad (17)$$

$$l(n-1) = (1 + s*\beta)*l(n) \quad (18)$$

$$Y(n) = Eff(n)*Slope(n)*X(n) + (1 - Eff(n))*Y(n+1) \quad (19)$$

where:

X = change in liquid composition, mole fraction

Y = change in vapor composition, mole fraction

V = vapor rate in moles/time

L = liquid rate in moles/time

$C_1(n)$ = $(\bar{X}(n-1) - \bar{X}(n))$

H = tray holdup in moles

G = transfer function between variables

β = change in tray holdup with liquid rate

Slope = equilibrium curve slope evaluated at steady-state X(n)

Eff = tray efficiency

v = $V/\bar{V}$
n = tray number, decreasing up the column
l = $L/\bar{L}$
s = Laplace variable
bar terms are steady-state quantities.

Now assuming values for the variables, (l(m), v, Z, X(m)), on the first tray such that one is equal to unity and the other three equal to zero. Assuming the following:

X(m) = 1
v = 0
Z = 0
l(m) = 0

First solving equation (19) for Y(n) and then solving equation (17) for X(n-1) results in the following:

$$X(n-2) = a + sb \qquad (20)$$

Solving equation (19) for Y(n-1) and equation (17) for X(n-2) results in the following:

$$X(n-2) = bs^2 + cs + d \qquad (21)$$

This procedure could be continued to the top tray where a relation is obtained for the top tray composition and reflux flow rate. It turns out that this procedure develops very complex terms as one continues up the column.

This stepping procedure is greatly simplified if one goes into the frequency domain by substituting ($i\omega$) in the equations for the Laplace variable (s). Repeating the solution for $X(n-1)$ for a given frequency, (ω), results in a complex number.

$$X(n-1) = a + ib \tag{22}$$

Carrying out the same procedure for tray ($n-2$) results in a complex number which is a function of the frequency.

$$X(n-2) = c + id \tag{23}$$

Continuing the calculations to the top tray results in solutions for $X(1)$, the reflux, R, and the distillate flow, D, which are the $P(1,3)$, $P(2,3)$, and $P(3,3)$ terms of the matrix equation (16) for the given value of frequency.

$$\begin{aligned} X(1)(\omega) &= q + iy = P(1,3) \\ R(\omega) &= m + iu = P(2,3) \\ D(\omega) &= n + it = P(3,3) \end{aligned} \tag{24}$$

This procedure is now repeated for the same values of frequency assuming another value at the bottom of the column equal to unity and the remaining three variables equal to zero. This is repeated until all the matrix terms are calculated for the given value of frequency after which a new value of frequency is assumed and the procedure is repeated.

Following this procedure the required transfer functions between variables can be developed. Partitioning matrix equation (16)

$$\begin{bmatrix} 1 & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} X_r \\ Y_t \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} R = \begin{bmatrix} G(1,1) & G(1,2) & G(1,3) \\ G(2,1) & G(2,2) & G(2,3) \\ G(3,1) & G(3,2) & G(3,3) \end{bmatrix} \begin{bmatrix} Z \\ V \\ L_n \end{bmatrix} \qquad (25)$$

$$+ \begin{bmatrix} G(1,4) \\ G(2,4) \\ G(3,4) \end{bmatrix} X_b$$

Rearranging equation (25)

$$\begin{bmatrix} 1 & 0 & -G_{14} \\ 0 & 0 & -G_{24} \\ 0 & 1 & -G_{34} \end{bmatrix} \begin{bmatrix} X_r \\ Y_t \\ X_b \end{bmatrix} = \begin{bmatrix} G(1,1) & G(1,2) & G(1,3) & 0 \\ G(2,1) & G(2,2) & G(2,3) & -1 \\ G(3,1) & G(3,2) & G(3,3) & 0 \end{bmatrix} \begin{vmatrix} Z \\ V \\ L_n \\ R \end{vmatrix} \qquad (26)$$

using the second of these equations to obtain a relation between L_n and R since all the terms in this equation except G(2,3) are zero.

$$L_n = (1/G(2,3))\,R \qquad (27)$$

Disregarding the output variable Y_t and substituting equation (27) into equation (26) results in the following equation:

$$\begin{bmatrix} 1 & -G_{14} \\ 0 & -G_{34} \end{bmatrix} \begin{bmatrix} X_r \\ X_b \end{bmatrix} = \begin{bmatrix} G_{11} & G_{12} & G_{13}/G_{23} \\ G_{31} & G_{32} & G_{33}/G_{23} \end{bmatrix} \begin{bmatrix} Z \\ V \\ R \end{bmatrix} \qquad (28)$$

Equation (28) can now be solved either for the column open loop response or for the feedforward controller transfer functions.

Setting the left side of equation (28) to zero, eliminating the reflux, R, and solving simultaneously the two resulting equations for the feedforward controller transfer functions one obtains the following equations:

$$\frac{V}{Z} = (P_{33} P_{11} - P_{13} P_{31})/(P_{13} P_{32} - P_{33} P_{12}) \qquad (29)$$

$$\frac{R}{Z} = - P_{23} (P_{32} P_{11} - P_{12} P_{31})/(P_{13} P_{32} - P_{33} P_{12}). \qquad (30)$$

IV. EXPERIMENTAL

The following section includes a statement of the purpose of this investigation, the plan of investigation, the plan of experimentation, a list of major apparatus and materials, and an outline of the procedure followed in the operation of the system, the data collection and reduction of experimental data.

Purpose of the Investigation

The purpose of this investigation was to experimentally determine the system open-loop transfer functions for changes in feed composition, vapor rate and reflux rate from which to formulate the experimental feedforward controller transfer functions and compare these transfer functions with the transfer functions as predicted by the linear model assumption.

Plan of Investigation

The plan of investigation followed in this research consisted of the following: Modification of equipment, experimental tests, experimental data reduction, and calculation of the feedforward controller based upon a linear model assumption.

Modification of Equipment. Before the experimental investigation for this study was undertaken, several major design changes were undertaken. Major modifications were made to the reboiler, column trays, insulation and control instrumentation on the eight-inch diameter column located in the V.P.I. Chemical Engineering Department Unit Operations Laboratory. These changes will be discussed separately.

A feed preheater and bottoms and distillate coolers were constructed from 1/4-inch copper tubing and installed in the process lines. A heating tape was installed on the reflux line to maintain an elevated reflux temperature in the stream returning to the column.

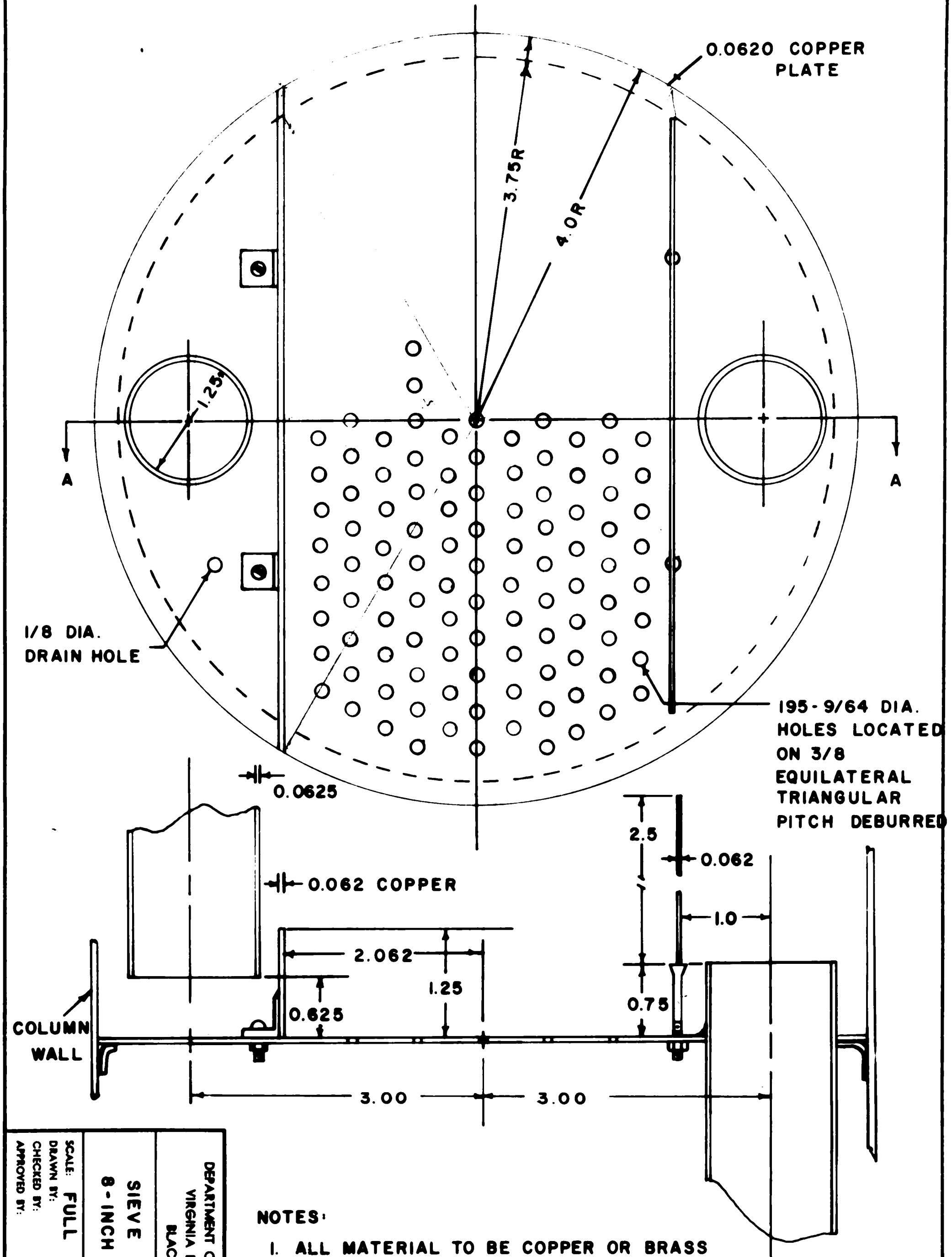
A vapor-liquid disengagement tank was located between the vapor discharge from the column and the condenser. This unit consisted of a 3-ft length, 6-inch diameter copper pipe with the vapor entering the center and discharging from the side at the top. This unit was required due to the short vapor-liquid disengagement space available on the top tray before neckdown to the 1-1/2 - inch diameter copper vapor line.

Reboiler. The kettle type reboiler with a holdup of approximately 50 gallons was replaced with a thermosiphon reboiler consisting of 21-3/4 - inch O.D., No. 17 BWG, copper tubes 65-inches long. This reboiler has an average operating holdup of 4 gallons. Complete drawings are on file in the V.P.I. Chemical Engineering Department equipment files.

Column Trays. The column was originally equipped with copper bubble cap trays consisting of two-inch diameter caps located on a reverse flow tray with an outlet weir height of two inches. Tray spacing was 6-inches.

These trays were replaced with copper sieve trays containing 195-9/~~1~~64- inch diameter holes located on a 3/8-inch equilateral triangular pitch. The tray thickness was 0.0620 inches. This tray was equipped with an inlet weir 1.25-inches high and an 3/4-inch high outlet weir made from 1-1/4 - inch diameter copper tubing. A 2.5 inches high vapor-liquid disengagement baffle was located 1/4-inch before the outlet weir and 3/4-inch above the tray floor. The tray spacing was increased from 6-inches to 12-inches. The column now consists of 18 trays and a reboiler. Figure 1, page 28, is the sieve tray design used in this unit.

Sample taps were installed on all trays except tray 10 since at this point the column passes through the flooring and it was impossible to install the tap. The sample taps draw liquid samples from behind the tray inlet weir and therefore the sample represents the liquid concentration leaving the tray above. For this reason it is impossible to sample the liquid leaving the bottom tray in the reboiler. The sample taps consist of approximately 8-inches of 1/8-inch diameter stainless steel tubing up to the valve located on the outside of the column. A small water cooler is located past the valve for cooling the sample.



DEPARTMENT OF CHEMICAL ENGINEERING
VIRGINIA POLYTECHNIC INSTITUTE
BLACKSBURG, VIRGINIA

SIEVE TRAY
8-INCH DIA. COLUMN

SCALE: FULL DATE: 6-9-65 CASE NO:
DRAWN BY: FILE NO:
CHECKED BY: FIGURE NO: 1
APPROVED BY: SHEET NO:

NOTES:

1. ALL MATERIAL TO BE COPPER OR BRASS
2. TRAYS AND WEIRS MUST NOT HAVE OVER 1/16" PITCH
3. TRAYS WILL BE SOLDERED INTO COLUMN
4. 20 REQUIRED

Insulation. The entire column was insulated to reduce heat losses from the copper column. The column was covered with a 1-inch layer of fiberglass insulating material between flanges. A 1/2-inch layer of fiberglass insulating material was then wrapped around the entire column on the outside of the flanges and this was then covered with corrugated aluminum sheeting.

Control Instrumentation. Initially the column was equipped with no control instrumentation and complete instrumentation was required for this investigation. Figure 2, page 30, shows the instrumentation diagram for the unit.

The four major process streams, feed, distillate, reflux, and bottoms, were equipped with Fischer-Porter indicating-transmitting rotameters. These instruments were connected to Foxboro controllers mounted on the main control panel. Orifice meters were installed in the steam line to the reboiler and cooling water line to the condenser. Foxboro Dp cells were used to transmit the orifice readings to the Foxboro controllers located on the main panel board. Foxboro Dp cells were also installed to transmit liquid-level readings from the reboiler and accumulator to the controllers. Two temperature transmitters were installed, one was located in the feed line after the feed preheater and was used for feed preheater temperature control and the other was located at the condenser discharge and was

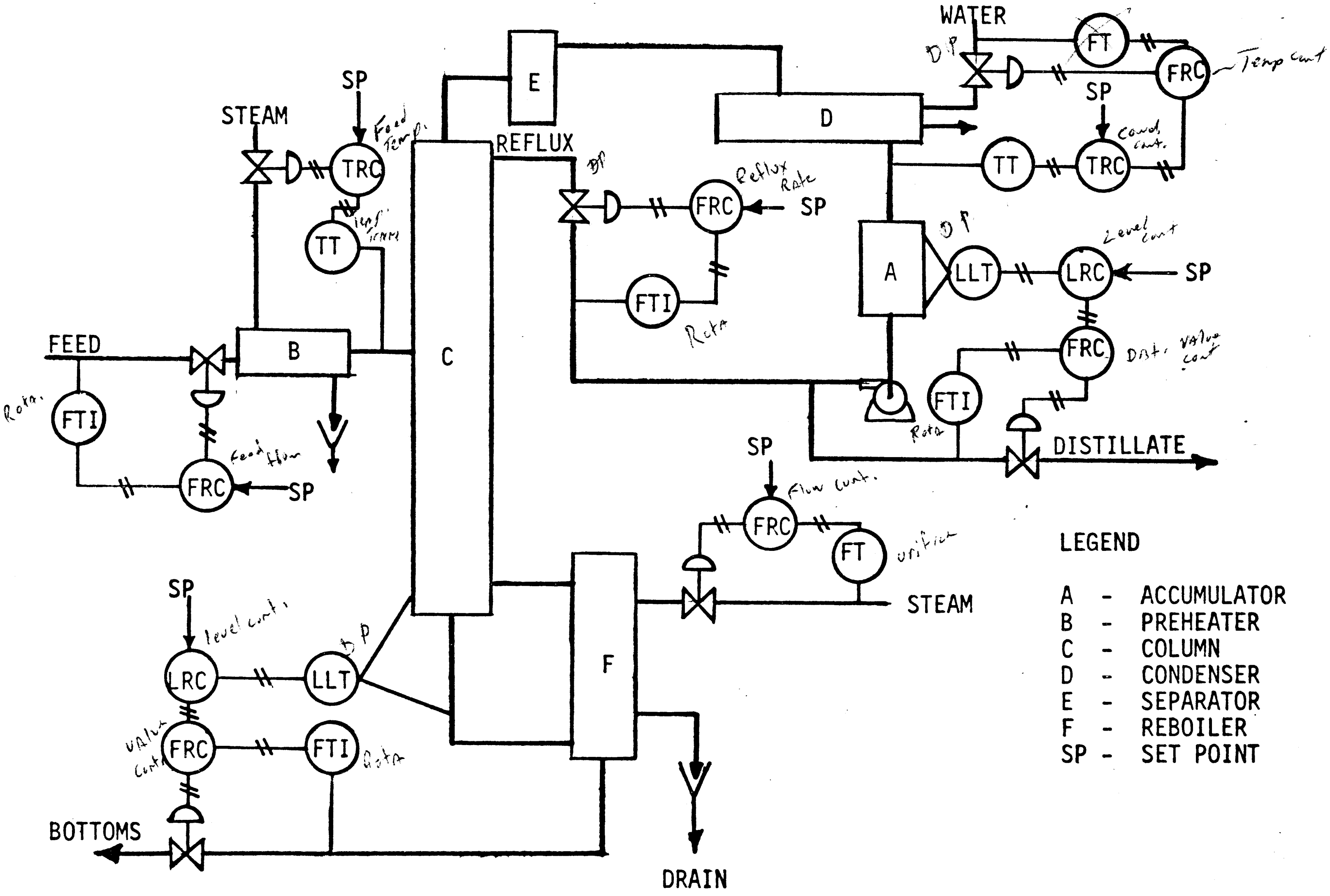


FIGURE 2. SCHEMATIC DIAGRAM OF DISTILLATION COLUMN CONTROL SYSTEM

used for distillate temperature control. Properly sized research control valves were installed in the process lines to complete the control loops.

In total, eight Foxboro recorder-controllers were panel mounted on the main panel board and were used to record and control all process streams. Six control valves were installed in total for control.

A Thermo-Electic temperature indicator with a 24 point selector switch was panel mounted and was used to monitor all tray, reboiler, overhead vapor, inlet and outlet water from the condenser and the steam side of the reboiler temperatures. A Foxboro differential pressure transmitter was installed to measure the pressure drop between trays two and seventeen.

Experimental Tests. Before the dynamic tests could be conducted a series of steady-state tests were performed during which all control loops were adjusted to give maximum response without instability and the performance of the system was reviewed to determine the range of satisfactory operation. These tests were the basis for the selected steady-state conditions around which the pulse tests were conducted. It was also necessary to calibrate all flow transmitters and recorders.

A series of eight pulse tests were conducted. Three tests involved changes in feed composition, three tests involved vapor rate changes and two tests were reflux rate changes. During each test continuous refractometers were used to monitor the distillate and bottoms compositions except during three tests when one refractometer was operating improperly and hand samples were taken of the bottoms composition at one minute intervals. The process refractometer outputs were recorded on a two channel Texas Instrument Recorder.

Feed pulses were obtained by injecting into the feed stream from a five gallon tank a monitored amount of pure component ahead of the feed pump and flow control system for a given period of time. Hand samples were taken of the feed during the feed pulse tests to determine the exact feed composition during these tests.

The reflux and vapor rate pulses were obtained by adjusting the setpoint on the appropriate controller and after a predetermined time the setpoint was shifted back to its original value.

At the beginning and end of each test composition samples were taken from each tray, reflux, feed, and distillate streams and the reboiler. All temperatures, recorder readings and steam rate were recorded at the start of each test.

Evaluation of Experimental Data. The steady-state performance of the column at the beginning of each test was evaluated by digital computer program SSDDR which can be found in the Appendix, page 205. This program performs a complete heat and material balance for the system. The program converts the refractive index readings for each stream and trays to the corresponding mole fraction, calculates the theoretical tray pressure based upon the temperature reading and tray composition, and evaluates the Murphree tray efficiency based on the vapor phase. This program also generates the required steady-state constants required for the calculation of the feedforward controller matrix based upon the linear model.

The refractive index readings from either the hand samples or the continuous process refractometer readings taken at a fixed time interval with the appropriate input pulse data were reduced by digital computer program PDCONV which may be found in the Appendix, page 232. This program converted the refractive index readings to mole fractions and also calculated the change from steady state for both the input and output pulses.

The system transfer functions were then calculated by a Fourier analysis of the pulse difference data by digital computer program PDTFR. This program appears in the Appendix, page 242. The experimental feedforward controller was then calculated from the system transfer functions determined from the pulse data. Six transfer functions are required to determine the controller functions, the distillate composition to the feed composition, reflux rate and vapor rate. These open loop transfer functions serve as the input data to digital computer program CEFFCM which calculates the feedforward controller transfer functions.

The feedforward controller transfer functions based upon the linear model are calculated by digital computer program FFCLM which appears in the Appendix, page 258. The appropriate data from the steady-state program, SSDDR, is used as input data for this program.

The feedforward controller transfer functions determined from the experimental data were then compared with the corresponding transfer functions based upon the linear model.

Materials

The following major materials were used during this investigation.

Air. Supplied at 80-90 lb/sq in., gage, filtered and reduced to 20 lb/sq in., gage. Obtained from Virginia Polytechnic Institute Power Plant. Used as supply for pneumatic control instruments.

Benzene. Pure grade, 99 mol per cent minimum. Obtained from Phillips Petroleum Company, Special Products Division, Bartlesville, Oklahoma. Used as one component of the binary mixture fractionated in the distillation column during this investigation.

N-Heptane. Pure grade, 99 mol per cent minimum. Obtained from Phillips Petroleum Company, Special Products Division, Bartlesville, Oklahoma. Used as one component of the binary mixture fractionated in the distillation column during this investigation.

Steam. Supplied at an average pressure of 80 lb/sq in., at 100 per cent quality. Obtained from the Virginia Polytechnic Institute Power Plant. Used as the heat supply for the column reboiler.

Water. Tap, approximately 68 °F, supplied at 80 lb/sq in., gage. Obtained from the water mains of the Unit Operations Laboratory, Department of Chemical Engineering, Virginia Polytechnic Institute.

Used for condensing the overhead vapor product and for cooling the product streams.

Apparatus

A list of the major apparatus used in this investigation is included in the following paragraphs.

Amplifier, D. C. Model 759-6. Manufactured by Magnetic Instruments Co., Inc., Thornwood, New York. Used to convert mv output of process refractometers to ma signal for recording on Texas Instrument recorder.

Column, Distillation. Eight-inch I. D. equipped with 18 sieve trays spaced every foot. Equipped with condenser. Manufactured by Vulcan Copper Works, Cincinnati, Ohio and modified by the Virginia Polytechnic Institute, Chemical Engineering Department Shop. Used as the distillation column for this investigation.

Controller. Pneumatic, model 58P4F, serial No 255927, three mode. Manufactured by the Foxboro Company, Foxboro, Massachusetts. Used to control the distillate temperature.

Controller. Penumatic, model 58P4, serial No 255903, proportional plus reset. Manufactured by the Foxboro Company, Foxboro, Massachusetts. Used to control the bottoms product flow rate.

Controller. Pneumatic, model 58P4F, serial No 255919, proportional plus reset. Manufactured by the Foxboro Company, Foxboro, Massachusetts. Used to control the feed flow rate.

Controller. Pneumatic, model 58P2, serial No 194539, proportional. Manufactured by the Foxboro Company, Foxboro, Massachusetts. Used to control reboiler level.

Controller. Pneumatic,model 58P4, serial No 255906, proportional plus reset. Manufactured by the Foxboro Company, Foxboro, Massachusetts. Used to control reboiler steam rate.

Controller. Pneumatic model 58P4F, serial No 255922, proportional plus reset. Manufactured by the Foxboro Company, Foxboro, Massachusetts. Used to control feed preheater temperature.

Controller. Pneumatic, model 58P4F, serial No 255920, proportional plus reset. Manufactured by the Foxboro Company, Foxboro, Massachusetts. Used to control the reflux flow rate.

Controller. Pneumatic, model 58P4F, serial No 255925, proportional plus reset. Manufactured by the Foxboro Company, Foxboro, Massachusetts. Used to control condenser water flow rate.

Controller. Pneumatic, model 58P4F, serial No 255926, proportional plus reset. Manufactured by the Foxboro Company, Foxboro, Massachusetts. Used to control distillate flow rate.

Controller. Pneumatic, model 58P2 serial No 195642, proportional. Manufactured by the Foxboro Company, Foxboro, Massachusetts. Used to control the accumulator level.

Derivative Unit. Inverse, Nullmatic model 59, serial No 353799. Manufactured by Moore Products Company, Philadelphia, Pennsylvania. Used in the reboiler level control loop.

Derivative Unit. Inverse, Nullmatic model 59 serial No 353789. Manufactured by the Moore Products Company, Philadelphia, Pennsylvania. Used in the condenser cooling water flow rate control loop.

Pump. Centrifugal, model B-F-34C, serial No C2D-1123. Manufactured by Eastern Industries, Hamden, Connecticut. Equipped with Master electric motor code F, Iden. No 616187-JL, 1/2 hp, 115/230 v, 60 cy, 3450 rpm. Manufactured by Master Electric Company, Dayton, Ohio. Pump used to pump the bottoms product.

Pump. Centrifugal, model 3F-340L, serial No C1C-1080. Manufactured by Eastern Industries, Hamden, Connecticut. Equipped with Master electric motor, style 337194, serial No HS-37529, 1/2 hp, 115/220 v, 60 cy, 3450 rpm. Manufactured by Master Electric Company, Dayton, Ohio. Pump used to pump the feed to the column.

Pump. Centrifugal, model TA-4, serial No 58148. Manufactured by the Eco Engineering Co., 12 New York Avenue, Newark, New Jersey. Equipped with Master electric motor, type PA, frame F660, 1/2 hp, 208-220/440 v, 60 cy, 3 phase 3450/2850 rpm. Manufactured by Master Electric Company, Dayton, Ohio. Pump used to pump the reflux and distillate streams.

Reboiler. Thermosiphon, type, contains 21-3/4 - inch O. D., No 17 BWG, copper tubes, 65-inches long. Manufactured by the Department of Chemical Engineering Shop, Virginia Polytechnic Institute, Blacksburg, Virginia. Used as column reboiler on the distillation column used for this investigation.

Recorder. Pneumatic, model 5403PS, serial No 547017, 1 pen. Manufactured by the Foxboro Company, Foxboro, Massachusetts. Used to record the reflux flow rate.

Recorder. Pneumatic model 5312PS, serial No 255755, 1 pen. Manufactured by the Foxboro Company, Foxboro, Massachusetts. Used to record the feed temperature.

Recorder. Pneumatic, model 5312PS, serial No 255770, 1 pen. Manufactured by the Foxboro Company, Foxboro, Massachusetts. Used to record the feed rate.

Recorder. Pneumatic model 5322PS, serial No 255777, 2 pen. Manufactured by the Foxboro Company, Foxboro, Massachusetts. Used to record the reboiler level and the bottoms flow rate.

Recorder. Pneumatic model 5322PS, serial No 255778, 2 pen. Manufactured by the Foxboro Company, Foxboro, Massachusetts. Used to record the reboiler steam rate and the condenser cooling water rate.

Recorder. Pneumatic model 5322PS, serial No 255782, 2 pen. Manufactured by the Foxboro Company, Foxboro, Massachusetts. Used to record the distillate flow rate.

Recorder. Pneumatic, model 5322PS, serial No 255779, 2 pen. Manufactured by the Foxboro Company, Foxboro, Massachusetts. Used to record the accumulator level and column pressure drop.

Recorder. Pneumatic, model 5312TS, serial No 170462, 1 pen. Manufactured by the Foxboro Company, Foxboro, Massachusetts. Used to record the distillate temperature leaving the condenser.

Recorder. Dual channel ''Recti/Riter'' recorder, Model PDR1M1M-A16T-L16, serial No PDR-1361, 0-1 ma range. Manufactured by Texas Instruments Inc., Houston, Texas. Used to record process refractometer outputs.

Refractometer. Laboratory, Cat. No 33-45-58, Serial No 9781 UB. Manufactured by Bausch and Lomb, Inc., Rochester, New York. Used to analyze liquid samples during this investigation.

Refractometer. Process, Model 660, serial No A/1003, C0113E-8. Manufactured by Nester/Faust Manufacturing Co., Inc., Newark, Delaware. Used to analyze process streams during pulse tests.

Refractometer. Process, Model 660, serial No A/1002, C0113E-2. Manufactured by Nester/Faust Manufacturing Co., Inc., Newark, Delaware. Used to analyze process streams during pulse tests.

Transmitter. Differential pressure, type 5A, serial No H93744. Manufactured by the Foxboro Company, Foxboro, Massachusetts. Used as the reboiler liquid level transmitter.

Transmitter. Differential pressure, type 5A, serial No 183442. Manufactured by the Foxboro Company, Foxboro, Massachusetts. Used as the cooling water flow rate transmitter.

Transmitter. Differential pressure, type 5A, serial No 285017. Manufactured by the Foxboro Company, Foxboro, Massachusetts. Used as the accumulator liquid level transmitter.

Transmitter. Differential pressure, type 5A, serial No 390046. Manufactured by the Foxboro Company, Foxboro, Massachusetts. Used as the reboiler steam rate transmitter.

Transmitter. Flow, model OK-1615, serial No 5706A1173B2, tube serial No 6504A479202. Manufactured by Fischer and Porter Company, Warminster, Pennsylvania. Used as the bottoms flow rate transmitter.

Transmitter. Flow, model OK-1615, series No 1, serial No W5-1149/1. Manufactured by Fischer and Porter Company, Warminster, Pennsylvania. Used as the feed flow rate transmitter.

Transmitter. Flow, model OKJ-1401KA41, serial No 5908A1290A1, tube serial No. 6504A4792C3. Manufactured by Fischer and Porter Company, Warminster, Pennsylvania. Used as the distillate flow rate transmitter.

Transmitter. Flow, model OK-1615, series No 1, serial No W5-1149/2. Manufactured by Fischer and Porter Company, Warminster, Pennsylvania. Used as the reflux flow rate transmitter.

Transmitter. Temperature, Model No 628N4C-Q, serial No 844846, primary element No 673D51A6-18-C5. Manufactured by Minneapolis Honeywell Regulator Company, Brown Instrument Division, Philadelphia, Pennsylvania. Used as top product condensate temperature transmitter.

Transmitter. Temperature, Nullmatic model 33E5072, serial No 14033-5072-51, Manufactured by Moore Products Company, Philadelphia, Pennsylvania. Used as the feed temperature transmitter.

Valve. Control, type 75, serial No 27878, trim C, action ATC. Manufactured by Research Control Valve Division, Precision Products and Controls, Inc., Tulsa, Oklahoma. Used to control the cooling water flow to the overhead condenser.

Valve. Control, type 75, serial No 27830, trim B, action ATO. Manufactured by Research Control Valve Division, Precision Products and Controls, Inc., Tulsa, Oklahoma. Used to control the steam flow to the feed preheater.

Valve. Control, type 78S, serial No 27874, trim D, action ATC. Manufactured by Research Control Valve Division, Precision Products and Controls, Inc., Tulsa, Oklahoma. Used to control the reflux flow rate.

Valve. Control, type 78S, serial No 27879, trim F, action ATO. Manufactured by Research Control Valve Division, Precision Products and Controls, Inc., Tulsa, Oklahoma. Used to control the bottoms flow rate.

Valve. Control, type 78S, serial No 27875, trim E, action ATC. Manufactured by Research Control Valve Division, Precision Products and Controls, Inc., Tulsa, Oklahoma. Used to control the distillate flow rate.

Valve. Control, type 75, serial No 27877, trim B, action ATO. Manufactured by Research Control Valve Division, Precision Products and Controls, Inc., Tulsa, Oklahoma. Used to control the steam flow rate to the reboiler.

Method of Procedure

This section contains an outline of the preliminary tests, the column startup procedure and operational procedure for the pulse response tests. A control schematic diagram for the unit is included, Figure 1, page 28.

Preliminary Tests. Before the dynamic test series of this investigation could be undertaken numerous tests were conducted. At the start of this investigation all flow transmitters were calibrated by adjusting the setpoint of the controller on the particular loop and after steady-state operation was obtained the flow was collected in a bucket for a given period of time and then weighed. These values were converted to weight per unit time and plotted versus recorder reading. The temperature transmitters were calibrated by inserting the probes in a heated oil bath and adjusting the temperature of the bath. After thermal equilibrium was obtained the temperature in the oil bath and the recorder readings were noted. This data was plotted for each transmitter as temperature versus per cent maximum recorder reading. The steam and level transmitters were not calibrated before column operation. Steam condensate readings were taken at the beginning and end of all tests by the bucket method. The Thermo-Electric temperature indicator was calibrated following the procedure outlined in the instruction manual.

A calibration curve for the mole fraction of benzene versus refractive index at 30 $^{\circ}$C was determined. Weighed samples of benzene n-heptane were made up and the refractive index of these samples was determined on the Bausch and Lomb refractometer. The Nester/Faust model 660 process refractometers were calibrated in the laboratory following the procedure outlined in their instruction manual as revised August 1966.

Numerous steady-state tests were conducted to adjust all controllers to give the maximum controller performance but still maintaining stable operation. These steady-state tests were also used to determine the proper liquid levels, feed, reflux, and steam rates to give smooth column performance without being near regions of column instability.

Startup Procedure. This startup procedure is the same regardless of the type of tests planned. Before startup all valves were set to give the proper process flow directions between the storage tanks and the column and return. The main electrical power was turned on and the controller charts started. The cooling water was turned on at the supply points to the condenser and to the product stream coolers. The water to the organic vapor condenser on the feed tank was opened to give maximum flow. The cooling water flow to the overhead condenser was adjusted to 50 per cent of maximum flow by switching the condenser temperature controller to the manual mode and adjusting its setpoint. The cooling water flow rate is recorded on the same recorder as the steam flow rate. Next the vent valve on top of the overhead condenser is opened. This prevents pressure buildup during startup and the steam should not be turned on before this valve is opened.

During startup procedure all controllers are assumed to be in the automatic mode except where noted. Now the column is ready for startup of the organic feed. The feed pump is started after which the feed rate controller, in the automatic mode, is adjusted to the required flow rate. Now the steam supply valve to the feed preheater is opened and the setpoint of the feed temperature controller, automatic mode, adjusted to the required feed temperature. After the organic level in the reboiler appears in the sight glass the high pressure steam supply valve is opened. The steam rate controller setpoint is adjusted to 30 per cent of maximum flow, controller should be in the automatic mode. After the controller is adjusted, the supply pressure regulator should be checked and adjusted to the required supply pressure. During this investigation 45 psig gave the best operation. Next the bottoms pump is started and the reboiler liquid level purge supply is started by adjusting the valve in the 3/8-inch copper tubing line connected to the bottoms pump and the reboiler level controller setpoint adjusted to the required value, 20 per cent during this investigation. The steam rate controller setpoint may be readjusted to the required value after reboiler level control has been obtained. High steam rates may not be possible until reflux flow has been obtained.

When the accumulator is half full the reflux pump should be started and the reflux controller setpoint adjusted to the required value and the heater on the reflux line started. During initial startup it is recommended that the hand valve in the distillate line after the flow transmitter be closed until after stable reflux flow is obtained. Distillate flow rate is controlled by accumulator level and during initial startup it is possible to get control loop interaction between reflux flow and distillate flow. The accumulator liquid level purge system should be started as soon as possible after the reflux pump is started. After stable reflux flow is obtained the accumulator liquid level controller setpoint should be adjusted to the required level, 40 per cent during this investigation, and the hand valve in the distillate line opened. The distillate liquid temperature leaving the overhead condenser controller may now be switched to the automatic mode and adjusted to the required temperature.

After column operation has been achieved the condenser vent valve can be closed and the column pressure adjusted by the use of nitrogen. The amount of inert gas bleed is adjusted through the vent rotameter. After the column pressure has stabilized, final adjustment of process variables should be made. After a proper line-out period the column should attain steady-state operation.

Dynamic Testing Procedure. After initial startup the column was allowed to operate four hours before dynamic testing was started. After this period liquid samples were taken from all trays, reboiler, and the reflux, and feed streams. When taking the liquid samples approximately 15 cc of sample was drawn off and discarded from each sample port before the actual samples were taken. This insures that the sample taken is a true tray sample. All stream and tray temperatures and recorder chart readings were recorded. The steam rate was also measured by the bucket method.

The reflux and vapor pulse tests were carried out by adjusting the setpoint of the appropriate controller and after a predetermined time interval the controller setpoint was adjusted back to its initial setting. The feed composition pulse tests were conducted by pumping into the feed stream, ahead of the feed pump and flow control loop, a metered amount of pure component material. The rate of injection was adjusted during the startup of the column, after which it was not changed. The following steps were followed during feed composition pulsing; 1) The five gallon storage tank was filled with pure component material depending on the direction of the required pulse, 2) The steady-state samples and readings were taken and recorded, 3) The feed pulse pump was started, 4) at time zero the solenoid valve in the feed pulse line was opened, 5) Feed stream samples were taken by hand at half minute intervals, 6) The solenoid valve was closed at the end of the pulse period.

At the start of each dynamic test, the process refractometers were adjusted to allow maximum pen travel during the test. The refractometer centerline value was recorded on the chart along with the chart speed being used during the pulse test. At the start of the test, time zero, the recorder charts were marked. During some tests the amount of composition change exceeded the recorder range and the process refractometer was readjusted and the recorder marked with the new centerline reading.

Shutdown Procedure. The first step was to shut off the steam supply to both the feedpreheater and reboiler. Next, the nitrogen pressure supply was shutdown and the condenser vent valve opened. After the temperature of the feed had decreased the feed pump was turned off. After the accumulator had emptied the reflux pump and heater were shut down. When the reboiler level had returned to the controlled level, the bottoms pump was turned off. Next, the cooling water to the distillate and bottoms coolers along with the water to the overhead condenser were turned off. A small water flow was allowed to flow at all times through the feed tank condenser. Lastly, the electrical power supply to the recorder charts was turned off.

Data and Results

The data obtained during the performance of the experimental test 11F on the distillation column and the feedforward controller results of this investigation are presented in this section. Test 11F is included in the data section and represents a typical data set. The test data from the remaining seven tests are included in the Appendix starting on page 138. Tables I and II on pages 54 and 55, are summaries of the various tests conducted during this investigation and should be referred to as a guide to the various experimental test numbers.

Steady-State Test Data. Table III, page 56, lists the steady-state conditions at the start of test 11F. This table has the complete overall material and component balances with the molar errors and percent errors for each balance. The internal molar flow rates based upon the reflux rate for the column are also reported in this table under the heading Column Internal Flow Rates. The q-values for both the feed and reflux are reported along with F-factors above and below the feed tray. Heat balance results and errors are included for the overall system, condenser and tower.

Tables XXV, XXXII, XXXVIII, XXXXVI, LIV, LX, and LXVIII, pages 140, 150, 158, 168, 178, 186, and 196, in the Appendix are similar tables stating the steady-state conditions at the beginning of each of the pulse tests. Similarly tables XXXXIV, LII, LVIII, LXIV, and LXXII, pages 166, 176, 184, 192, and 202, list the steady-state conditions at the completion of the respective tests.

Table IV, page 57, lists the liquid compositions of the trays and major streams along with the equilibrium curve slopes evaluated at the tray liquid compositions. The Murphree tray efficiencies based upon the vapor phase along with the tray temperatures and pressures are reported for test 11F. Included in Table IV are the average liquid holdups on the trays above and below the feed tray in moles. Tables XXVI, XXXIII, XXXIX, XXXXVII, LV, LXI, and LXIX, pages 141, 151, 159, 169, 179, 187, and 197 of the Appendix, report the similar data for the other seven pulse tests. Tables XXXXV, LIII, LIX, LXV, and LXXIII, pages 167, 177, 185, 193, and 203 report the conditions at the completion of the respective pulse tests.

Pulse Test Data. Table V, page 58, lists the experimental pulse data for the feed composition during pulse test 11F. Tables VI and IX, pages 59 and 63, report the composition time data during pulse test 11F for the distillate and bottoms streams.

Figure 11, page 86, shows a typical set of controller charts during an experimental pulse test. This set of controller charts are from test 9V.

Experimental Open Loop Transfer Functions. Open loop transfer functions for the distillate and bottoms compositions were calculated from the pulse data obtained during the experimental pulse testing. Digital computer program PDTFR was used to carry out the required Fourier analysis of the data. Tables VII and X, pages 60 and 64, report the results of this analysis for pulse test 11F. On Figures 3 and 4, pages 62 and 66, are plotted the results of these experimental open loop transfer functions. The experimental open loop transfer functions for the remaining seven pulse tests can be found in the Appendix starting on page 138.

Table XXIV, page 85 , lists a summary of the dead times in minutes and first order time constants determined for each of the pulse tests evaluated.

Figure 14, page 149 in the Appendix, shows for the bottoms composition/feed composition open loop transfer function, the comparison between the experimental data points obtained from the regression analysis of the experimental pulse data and subsequent analysis of data points calculated at 0.2 minute intervals from the regression equation. The regression model results are reported in Table XXXI, page 148 of the Appendix.

Linear Model Open Loop Transfer Functions. The steady-state data taken at the beginning of tests 6F and 11F were used to calculate the open loop transfer functions for the system applying the linear model assumptions to the system. These calculations were carried out as a function of frequency by digital computer program FFCLM. The results of these calculations for the distillate and bottoms compositions for changes in feed composition based on steady-state conditions for pulse test 11F are reported in Tables VIII and XI, pages 61 and 65 , and are plotted for comparison with experimental data on Figures 3 and 4, pages 62 and 66 . Similar results for comparison with the experimental transfer functions are located in the Appendix starting on page 138.

Experimental Feedforward Controller Transfer Functions. The experimental open loop transfer functions resulting from the pulse tests were used to calculate the experimental feedforward controller transfer functions. The feedforward controller transfer functions calculated were the reflux and vapor flow rate changes required to maintain constant distillate and bottoms product purity for changes in feed composition. Feedforward controllers were determined for both sets of basic steady-state conditions used during this investigation.

Table XII, page 67, is the reflux rate/feed composition experimental feedforward controller transfer function data determined as a function of frequency based on data sets 6F, 6V and 6S. Table XIV, page 70 , reports similar results for the vapor rate/feed composition controller function based upon the same data sets. These results are plotted in Figures 4 and 5, pages 66 and 69.

Five pulse tests were conducted at the second steady-state condition in order to determine the magnitude of the nonlinear effects. Therefore, two feedforward controllers were determined to evaluate the effect of pulse direction on feedforward controller transfer functions. Data sets 8R, 10V and 11F represents positive reflux pulse, positive vapor rate pulse and a decreasing benzene composition pulse. Data sets 8R, 9V and 12F involved ia positive reflux rate pulse, negative vapor rate and an increasing benzene composition pulse. Tables XVI and XX, pages 73 and 79, are the feedforward controller transfer function data based upon tests 8R, 10V and 11F and Tables XVII and XXI, pages 75 and 81, are the data based upon tests 8R, 9V and 12F.

The resulting feedforward controllers from this analysis are plotted on Figures 7, 8, 9, and 10, pages 74, 76, 80, and 84.

Linear Model Feedforward Controller Transfer Functions. The open loop transfer functions were used to calculate the required feedforward controller transfer functions which correspond to the experimental feedforward controller functions. Steady-state data sets 6F and 11F were used as the conditions around which these calculations were performed. Tables XIII and XV report the results for the case of experimental data set 6F. This data is plotted for comparison with the corresponding experimental feedforward controller functions on Figures 5 and 6, pages 69 and 72. Table XVIII and XXII report the results of these calculations for experimental data 11F. Since, in the linear model calculations, the direction of the pulse has no effect on the calculated results, these data points are plotted for comparison purposes on Figures 7, 8, 9 and 10, pages 74, 76, 80, and 84.

Feedforward controller transfer function data are also reported in Tables XIX and XXIII, pages 78 and 83, based on steady-state conditions for test 9V for comparison with the results determined at steady-state conditions for test 11F.

Frequency Response Program Testing. Computer Program PDTFR was tested by calculating the response of a first order system to a pulse as a function of time and using this data as input data to the frequency response program. The results of this program testing procedure are reported in Table LXXIV, page 204, as the frequency response of a first order system. The data point time interval was 0.2 minutes for this analysis.

TABLE I

Summary of Experimental Pulse Tests

Test No	Stream Pulsed	Pulsed Stream Flow Rates[a]				Pulse Interval Minutes
		Initial	Pulse	Final		
6F	Feed	0.0611	0.0611	0.0611	+	10
6S	Reflux	0.0705	0.1075	0.0705	+	6
6V	Vapor	0.11433	0.12576	0.1233	+	5
8R	Reflux	0.0688	0.0854	0.0688	+	15
9V	Vapor	0.1277	0.1197	0.1228	-	15
10V	Vapor	0.1234	0.1271	0.1227	+	20
11F	Feed[b]	0.0630	0.0630	0.0623	+	8
12F	Feed	0.0623	0.0623	0.0626	-	6

[a] Lb Moles per Minute

[b] See TABLE 5 page 58 for feed composition change.

TABLE II

Summary of Steady-State Test Data Tables

Test No	Description
6F	Steady-State Column Conditions at Start of Pulse Test 6F
6S	Steady-State Column Conditions at Start of Pulse Test 6S
6V	Steady-State Column Conditions at Start of Pulse Test 6V
6VA	Steady-State Column Conditions at Completion of Pulse Test 6V
9V	Steady-State Column Conditions at Start of Pulse Test 9V
9VA	Steady-State Column Conditions at Completion of Pulse Test 9V
10V	Steady-State Column Conditions at Start of Pulse Test 10V
10VA	Steady-State Column Conditions at Completion of Pulse Test 10V
11F	Steady-State Column Conditions at Start of Pulse Test 11F
12F	Steady-State Column Conditions at Start of Pulse Test 12F
12FA	Steady-State Column Conditions at Completion of Pulse Test 12F

TABLE III

BINARY DISTILLATION STEADY-STATE TEST DATA
HEAT AND MATERIAL BALANCES
EXPERIMENTAL DATA SET 11F

STREAM	MOLES/MINUTE		MOLES BENZENE/MINUTE
FEED	0.0630		0.0421
BOTTOMS	0.0205		0.0042
OVERHEAD	0.0439		0.0384
REFLUX	0.0689		0.0602
TOTAL MASS ERROR	-0.0015	PERCENT	2.4260
BENZENE ERROR	-.0005	PERCENT	1.1769
COLUMN INTERNAL FLOW RATES			
TOP VAPOR	0.117379		
TOP LIQUID	0.073437	L/V TOP	0.625639
BOTTOM VAPOR	0.120522		
BOTTOM LIQUID	0.139536	L/V BOTT	1.157765

Q-VALUE FEED = 1.0499 REFLUX = 1.0661

F-FACTOR TOP = 1.0309 BOTTOM = 1.1607

FEED TRAY = 9

HEAT BALANCE DATA

	INPUT BTU/MIN	OUTPUT BTU/MIN	ERROR BTU/MIN	PERCENT ERROR
OVERALL	2802.4	2123.8	678.6	24.21
CONDENSER	2934.8	2528.8	406.1	13.84
TOWER	3601.4	3328.9	272.5	7.57

TABLE IV

BINARY DISTILLATION STEADY-STATE TEST DATA
TRAY TO TRAY CALCULATION RESULTS
EXPERIMENTAL DATA SET 11F

FEED TRAY = 9

TRAY	LIQUID MOLE FRACT	TEMPERATURE DEGREES F	EQUILIBRIUM CURVE SLOPE	EFFICIENCY MURPHERE	PRESSURE MM HG
FEED	0.6683	181.00			
REFLUX	0.8736	168.00			
1	0.8373	192.50	0.7024	0.8893	927.2
2	0.8089	193.00	0.6942	0.7572	922.7
3	0.7796	193.50	0.6877	0.8506	917.7
4	0.7645	194.00	0.6852	0.4567	918.7
5	0.7444	194.80	0.6829	0.6457	921.9
6	0.7219	195.20	0.6817	0.7722	918.0
7	0.7051	196.00	0.6819	0.6102	922.5
8	0.6802	196.20	0.6839	0.9819	914.4
9	0.6680	197.50	0.6857	0.4726	928.8
10	0.6572	198.00	0.6877	0.4726	930.9
11	0.6438	198.50	0.6909	0.4726	932.2
12	0.6223	199.00	0.6975	0.5849	929.8
13	0.5812	200.00	0.7154	0.7758	925.5
14	0.5372	201.20	0.7432	0.6349	922.5
15	0.4798	203.00	0.7939	0.6477	921.3
16	0.3849	205.00	0.9185	0.8342	903.3
17	0.3156	207.20	1.0455	0.5568	899.6
18	0.2532	212.00	1.1890	0.6424	935.9
REBOILER	0.2037	216.50	1.3241	0.6424	975.0

TRAY HOLDUP TOP = 0.00912 MOLES BOTTOM = 0.00830 MOLES

TIME CONSTANT, TRAY HOLDUP/LIQUID RATE = 0.05949 MINUTES

TABLE V

EXPERIMENTAL PULSE TEST RESULTS

FEED SAMPLES TEST DATA SET 11F FEED PULSE

TIME MINUTES	REFRACTIVE INDEX	MOLE FRACTION BENZENE	DIFFERENCE MOLE FRACTION
0.00	1.44160	0.6726	-0.0000
0.50	1.40830	0.3344	0.3382
1.00	1.40540	0.3002	0.3724
1.50	1.40490	0.2943	0.3783
2.00	1.40500	0.2955	0.3771
2.50	1.40500	0.2955	0.3771
3.00	1.40500	0.2955	0.3771
3.50	1.40490	0.2943	0.3783
4.00	1.40510	0.2967	0.3759
4.50	1.40500	0.2955	0.3771
5.00	1.40540	0.3002	0.3724
5.50	1.40540	0.3002	0.3724
6.00	1.40540	0.3002	0.3724
6.50	1.40520	0.2978	0.3747
7.00	1.40500	0.2955	0.3771
7.50	1.40520	0.2978	0.3747
8.00	1.40540	0.3002	0.3724
8.50	1.42990	0.5658	0.1068
9.00	1.44080	0.6657	0.0069
9.50	1.44110	0.6683	0.0043
10.00	1.44140	0.6709	0.0017
10.50	1.44140	0.6709	0.0017
11.00	1.44140	0.6709	0.0017

TABLE VI

EXPERIMENTAL PULSE TEST RESULTS

BOTTOMS SAMPLES   TEST DATA SET 11F   FEED PULSE

TIME MINUTES	REFRACTIVE INDEX	MOLE FRACTION BENZENE	DIFFERENCE MOLE FRACTION
0.00	1.39790	0.2087	-0.0000
0.25	1.39800	0.2099	-0.0012
0.50	1.39800	0.2099	-0.0012
0.75	1.39790	0.2087	-0.0000
1.00	1.39780	0.2074	0.0013
1.25	1.39770	0.2062	0.0025
1.50	1.39760	0.2049	0.0038
1.75	1.39780	0.2074	0.0013
2.00	1.39790	0.2087	-0.0000
2.25	1.39790	0.2087	-0.0000
2.50	1.39780	0.2074	0.0013
2.75	1.39750	0.2037	0.0050
3.00	1.39720	0.1999	0.0088
3.25	1.39690	0.1961	0.0125
3.50	1.39670	0.1936	0.0151
3.75	1.39650	0.1911	0.0176
4.00	1.39640	0.1898	0.0189
4.25	1.39630	0.1885	0.0201
4.50	1.39610	0.1860	0.0226
4.75	1.39590	0.1835	0.0252
5.00	1.39570	0.1810	0.0277
5.25	1.39540	0.1772	0.0315
5.50	1.39500	0.1721	0.0366
5.75	1.39470	0.1682	0.0404
6.00	1.39420	0.1619	0.0468
6.25	1.39370	0.1554	0.0532
6.50	1.39320	0.1490	0.0596
6.75	1.39280	0.1439	0.0648
7.00	1.39230	0.1374	0.0713
7.25	1.39190	0.1322	0.0764
7.50	1.39150	0.1270	0.0816
7.75	1.39120	0.1231	0.0855
8.00	1.39080	0.1179	0.0907
8.25	1.39050	0.1140	0.0947
8.50	1.39090	0.1192	0.0894
8.75	1.39050	0.1140	0.0947
9.00	1.39010	0.1088	0.0999
9.25	1.38970	0.1035	0.1051
9.50	1.38930	0.0983	0.1104
9.75	1.38890	0.0930	0.1157
10.00	1.38850	0.0877	0.1209
10.25	1.38810	0.0824	0.1262
10.50	1.38780	0.0784	0.1302
10.75	1.38750	0.0745	0.1342
11.00	1.38720	0.0705	0.1382
11.25	1.38690	0.0665	0.1422
11.50	1.38660	0.0625	0.1462
11.75	1.38640	0.0598	0.1489
12.00	1.38640	0.0598	0.1489
12.25	1.38630	0.0585	0.1502
12.50	1.38620	0.0571	0.1515
12.75	1.38610	0.0558	0.1529
13.00	1.38610	0.0558	0.1529
13.25	1.38610	0.0558	0.1529
13.50	1.38620	0.0571	0.1515
13.75	1.38620	0.0571	0.1515
14.00	1.38630	0.0585	0.1502
14.25	1.38640	0.0598	0.1489
14.50	1.38660	0.0625	0.1462
14.75	1.38670	0.0638	0.1449
15.00	1.38680	0.0651	0.1435
15.25	1.38700	0.0678	0.1409
15.50	1.38710	0.0691	0.1395
15.75	1.38730	0.0718	0.1369
16.00	1.38750	0.0745	0.1342
16.25	1.38770	0.0771	0.1315
16.50	1.38790	0.0798	0.1289
16.75	1.38800	0.0811	0.1276
17.00	1.38820	0.0837	0.1249
17.25	1.38840	0.0864	0.1223
17.50	1.38850	0.0877	0.1209
17.75	1.38860	0.0890	0.1196
18.00	1.38880	0.0917	0.1170
18.25	1.38900	0.0943	0.1143
18.50	1.38920	0.0970	0.1117
18.75	1.38940	0.0996	0.1091
19.00	1.38950	0.1009	0.1078
19.25	1.38970	0.1035	0.1051
19.50	1.39000	0.1075	0.1012
19.75	1.39030	0.1114	0.0973
20.00	1.39040	0.1127	0.0960
20.25	1.39050	0.1140	0.0947
20.50	1.39060	0.1153	0.0934
20.75	1.09370	-4.7725	4.9811
21.00	1.39080	0.1179	0.0907
21.25	1.39090	0.1192	0.0894
21.50	1.39110	0.1218	0.0868
21.75	1.39120	0.1231	0.0855
22.00	1.39140	0.1257	0.0829
22.25	1.39150	0.1270	0.0816
22.50	1.39160	0.1283	0.0803
22.75	1.39170	0.1296	0.0790
23.00	1.39190	0.1322	0.0764
23.25	1.39200	0.1335	0.0751
23.50	1.39220	0.1361	0.0725
23.75	1.39220	0.1361	0.0725
24.00	1.39220	0.1361	0.0725
24.25	1.39220	0.1361	0.0725
24.50	1.39220	0.1361	0.0725
24.75	1.39230	0.1374	0.0713
25.00	1.39240	0.1387	0.0700
25.25	1.39250	0.1400	0.0687
25.50	1.39240	0.1387	0.0700
25.75	1.39240	0.1387	0.0700
26.00	1.39240	0.1387	0.0700
26.25	1.39250	0.1400	0.0687
26.50	1.39270	0.1426	0.0661
26.75	1.39290	0.1452	0.0635
27.00	1.39300	0.1464	0.0622
27.25	1.39300	0.1464	0.0622
27.50	1.39300	0.1464	0.0622
27.75	1.39300	0.1464	0.0622
28.00	1.39300	0.1464	0.0622
28.25	1.39300	0.1464	0.0622
28.50	1.39310	0.1477	0.0609
28.75	1.39320	0.1490	0.0596
29.00	1.39320	0.1490	0.0596
29.25	1.39330	0.1503	0.0584
29.50	1.39340	0.1516	0.0571
29.75	1.39340	0.1516	0.0571
30.00	1.39350	0.1529	0.0558
30.25	1.39350	0.1529	0.0558
30.50	1.39360	0.1542	0.0545
30.75	1.39360	0.1542	0.0545
31.00	1.39370	0.1554	0.0532
31.25	1.39380	0.1567	0.0519
31.50	1.39380	0.1567	0.0519
31.75	1.39380	0.1567	0.0519
32.00	1.39390	0.1580	0.0507
32.25	1.39400	0.1593	0.0494
32.50	1.39400	0.1593	0.0494
32.75	1.39390	0.1580	0.0507
33.00	1.39390	0.1580	0.0507
33.25	1.39390	0.1580	0.0507
33.50	1.39400	0.1593	0.0494
33.75	1.39410	0.1606	0.0481
34.00	1.39420	0.1619	0.0468
34.25	1.39430	0.1631	0.0455
34.50	1.39440	0.1644	0.0443
34.75	1.39440	0.1644	0.0443
35.00	1.39440	0.1644	0.0443
35.25	1.39450	0.1657	0.0430
35.50	1.39450	0.1657	0.0430
35.75	1.39450	0.1657	0.0430
36.00	1.39450	0.1657	0.0430
36.25	1.39460	0.1670	0.0417
36.50	1.39440	0.1644	0.0443
36.75	1.39440	0.1644	0.0443
37.00	1.39450	0.1657	0.0430
37.25	1.39450	0.1657	0.0430
37.50	1.39460	0.1670	0.0417
37.75	1.39460	0.1670	0.0417
38.00	1.39460	0.1670	0.0417
38.25	1.39460	0.1670	0.0417
38.50	1.39470	0.1682	0.0404
38.75	1.39470	0.1682	0.0404
39.00	1.39460	0.1670	0.0417
39.25	1.39460	0.1670	0.0417
39.50	1.39470	0.1682	0.0404
39.75	1.39480	0.1695	0.0391
40.00	1.39480	0.1695	0.0391
40.25	1.39480	0.1695	0.0391
40.50	1.39470	0.1682	0.0404
40.75	1.39460	0.1670	0.0417
41.00	1.39450	0.1657	0.0430
41.25	1.39450	0.1657	0.0430
41.50	1.39450	0.1657	0.0430
41.75	1.39450	0.1657	0.0430
42.00	1.39450	0.1657	0.0430
42.25	1.39450	0.1657	0.0430
42.50	1.39460	0.1670	0.0417
42.75	1.39460	0.1670	0.0417
43.00	1.39470	0.1682	0.0404
43.25	1.39480	0.1695	0.0391
43.50	1.39490	0.1708	0.0379
43.75	1.39490	0.1708	0.0379
44.00	1.39490	0.1708	0.0379
44.25	1.39490	0.1708	0.0379
44.50	1.39490	0.1708	0.0379
44.75	1.39490	0.1708	0.0379
45.00	1.39490	0.1708	0.0379
45.25	1.39500	0.1721	0.0366
45.50	1.39500	0.1721	0.0366
45.75	1.39490	0.1708	0.0379
46.00	1.39490	0.1708	0.0379
46.25	1.39500	0.1721	0.0366
46.50	1.39500	0.1721	0.0366
46.75	1.39510	0.1733	0.0353
47.00	1.39510	0.1733	0.0353
47.25	1.39520	0.1746	0.0341
47.50	1.39520	0.1746	0.0341
47.75	1.39520	0.1746	0.0341
48.00	1.39520	0.1746	0.0341
48.25	1.39520	0.1746	0.0341
48.50	1.39530	0.1759	0.0328
48.75	1.39520	0.1746	0.0341
49.00	1.39520	0.1746	0.0341
49.25	1.39510	0.1733	0.0353
49.50	1.39510	0.1733	0.0353
49.75	1.39510	0.1733	0.0353
50.00	1.39520	0.1746	0.0341
50.25	1.39520	0.1746	0.0341
50.50	1.39520	0.1746	0.0341
50.75	1.39520	0.1746	0.0341
51.00	1.39510	0.1733	0.0353
51.25	1.39510	0.1733	0.0353
51.50	1.39500	0.1721	0.0366
51.75	1.39500	0.1721	0.0366
52.00	1.39510	0.1733	0.0353
52.25	1.39520	0.1746	0.0341
52.50	1.39540	0.1772	0.0315
52.75	1.39550	0.1784	0.0302
53.00	1.39550	0.1784	0.0302
53.25	1.39540	0.1772	0.0315
53.50	1.39540	0.1772	0.0315
53.75	1.39540	0.1772	0.0315
54.00	1.39530	0.1759	0.0328
54.25	1.39520	0.1746	0.0341
54.50	1.39520	0.1746	0.0341
54.75	1.39520	0.1746	0.0341
55.00	1.39520	0.1746	0.0341
55.25	1.39530	0.1759	0.0328

TABLE VII

BOTTOMS COMPOSITION/FEED COMPOSITION EXPERIMENTAL FREQUENCY RESPONSE RESULTS FOR PULSE TEST 11F

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
1.4475	0.0000	3.2125

MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1.0000	-0.00	-0.0000	0.0000
1.0000	-0.10	-0.0000	0.0001
1.0000	-0.52	-0.0001	0.0005
0.9999	-1.04	-0.0004	0.0010
0.9987	-5.18	-0.0112	0.0050
0.9975	-7.25	-0.0220	0.0070
0.9948	-10.36	-0.0449	0.0100
0.9884	-15.52	-0.1012	0.0150
0.9794	-20.68	-0.1805	0.0200
0.9679	-25.80	-0.2832	0.0250
0.9539	-30.90	-0.4096	0.0300
0.9188	-40.96	-0.7354	0.0400
0.8750	-50.75	-1.1602	0.0500
0.8239	-60.14	-1.6824	0.0600
0.7679	-68.97	-2.2939	0.0700
0.7099	-77.07	-2.9756	0.0800
0.6535	-84.29	-3.6948	0.0900
0.6022	-90.56	-4.4046	0.1000
0.5141	-102.96	-5.7799	0.1250
0.4852	-115.55	-6.2814	0.1500
0.4792	-133.43	-6.3901	0.1750
0.4575	-156.76	-6.7924	0.2000
0.3405	-211.27	-9.3589	0.2500
0.2406	-265.30	-12.3749	0.3000
0.2688	37.96	-11.4117	0.3500
0.3847	-23.37	-8.2979	0.4000
0.4942	-77.68	-6.1216	0.4500
0.6122	-120.27	-4.2617	0.5000
0.8764	-162.39	-1.1456	0.5500
1.2765	-212.94	2.1201	0.6000

TABLE VIII

BOTTOMS COMPOSITION/FEED COMPOSITION OPEN LOOP TRANSFER FUNCTION BASED ON LINEAR MODEL FOR EXPERIMENTAL DATA SET 11F

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
2.2024	0.00	6.8577

	MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1	1.0000	-0.00	-0.0000	0.0000
2	1.0000	-0.08	-0.0000	0.0001
3	1.0000	-0.39	-0.0001	0.0005
4	0.9999	-0.77	-0.0006	0.0010
5	0.9983	-3.86	-0.0149	0.0050
6	0.9967	-5.40	-0.0291	0.0070
7	0.9932	-7.70	-0.0593	0.0100
8	0.9849	-11.50	-0.1323	0.0150
9	0.9736	-15.23	-0.2325	0.0200
10	0.9596	-18.87	-0.3580	0.0250
11	0.9433	-22.43	-0.5068	0.0300
12	0.9053	-29.19	-0.8643	0.0400
13	0.8625	-35.47	-1.2851	0.0500
14	0.8175	-41.25	-1.7503	0.0600
15	0.7724	-46.53	-2.2437	0.0700
16	0.7284	-51.35	-2.7522	0.0800
17	0.6866	-55.76	-3.2660	0.0900
18	0.6473	-59.79	-3.7779	0.1000
19	0.5610	-68.52	-5.0210	0.1250
20	0.4906	-75.78	-6.1857	0.1500
21	0.4333	-81.99	-7.2633	0.1750
22	0.3865	-87.43	-8.2580	0.2000
23	0.3151	-96.75	-10.0319	0.2500
24	0.2638	-104.73	-11.5750	0.3000
25	0.2254	-111.85	-12.9424	0.3500
26	0.1956	-118.37	-14.1741	0.4000
27	0.1718	-124.47	-15.2990	0.4500
28	0.1524	-130.23	-16.3378	0.5000
29	0.1364	-135.73	-17.3062	0.5500
30	0.1228	-141.01	-18.2156	0.6000

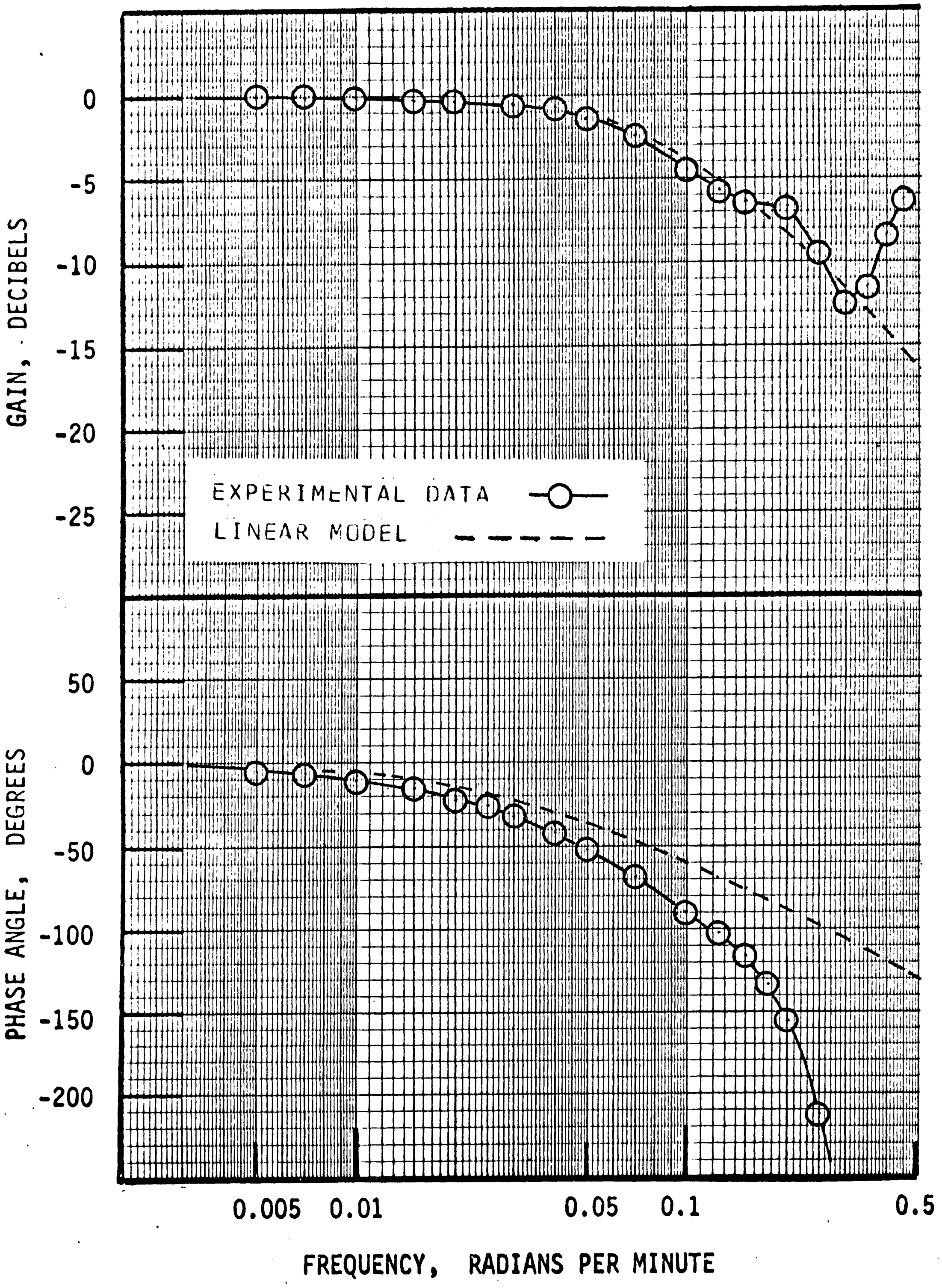


Figure 3. Bottoms Composition/Feed Composition Open Loop Transfer Functions based on Experimental and Linear Model Results For Test 11F

TABLE IX

EXPERIMENTAL PULSE TEST RESULTS

DISTILLATE SAMPLES   TEST DATA SET 11F   FEED PULSE

TIME MINUTES	REFRACTIVE INDEX	MOLE FRACTION BENZENE	DIFFERENCE MOLE FRACTION
0.00	1.47000	0.8709	-0.0000
0.25	1.47000	0.8709	-0.0000
0.50	1.47001	0.8710	-0.0001
0.75	1.47002	0.8710	-0.0001
1.00	1.47002	0.8710	-0.0001
1.25	1.47003	0.8711	-0.0002
1.50	1.47003	0.8711	-0.0002
1.75	1.47003	0.8711	-0.0002
2.00	1.47005	0.8712	-0.0003
2.25	1.47008	0.8713	-0.0004
2.50	1.47006	0.8712	-0.0003
2.75	1.47004	0.8711	-0.0002
3.00	1.47002	0.8710	-0.0001
3.25	1.47002	0.8710	-0.0001
3.50	1.46998	0.8708	0.0001
3.75	1.46995	0.8706	0.0003
4.00	1.46993	0.8705	0.0004
4.25	1.46990	0.8704	0.0005
4.50	1.46987	0.8702	0.0007
4.75	1.46983	0.8700	0.0009
5.00	1.46980	0.8698	0.0011
5.25	1.46976	0.8696	0.0013
5.50	1.46970	0.8693	0.0016
5.75	1.46965	0.8690	0.0019
6.00	1.46958	0.8686	0.0023
6.25	1.46948	0.8681	0.0028
6.50	1.46940	0.8677	0.0032
6.75	1.46928	0.8670	0.0039
7.00	1.46912	0.8661	0.0048
7.25	1.46900	0.8655	0.0054
7.50	1.46882	0.8645	0.0064
7.75	1.46863	0.8635	0.0074
8.00	1.46838	0.8621	0.0088
8.25	1.46815	0.8608	0.0101
8.50	1.46791	0.8595	0.0114
8.75	1.46770	0.8583	0.0126
9.00	1.46748	0.8570	0.0139
9.25	1.46720	0.8555	0.0154
9.50	1.46698	0.8542	0.0167
9.75	1.46675	0.8529	0.0180
10.00	1.46650	0.8515	0.0194
10.25	1.46628	0.8502	0.0207
10.50	1.46608	0.8490	0.0219
10.75	1.46585	0.8477	0.0232
11.00	1.46563	0.8464	0.0245
11.25	1.46530	0.8444	0.0265
11.50	1.46507	0.8431	0.0278
11.75	1.46485	0.8418	0.0291
12.00	1.46462	0.8404	0.0305
12.25	1.46440	0.8391	0.0318
12.50	1.46420	0.8379	0.0330
12.75	1.46398	0.8365	0.0344
13.00	1.46378	0.8353	0.0356
13.25	1.46362	0.8344	0.0365
13.50	1.46348	0.8335	0.0374
13.75	1.46337	0.8328	0.0381
14.00	1.46330	0.8324	0.0385
14.25	1.46328	0.8323	0.0386
14.50	1.46330	0.8324	0.0385
14.75	1.46338	0.8329	0.0380
15.00	1.46345	0.8333	0.0376
15.25	1.46350	0.8336	0.0373
15.50	1.46360	0.8342	0.0367
15.75	1.46365	0.8345	0.0364
16.00	1.46375	0.8351	0.0358
16.25	1.46385	0.8358	0.0351
16.50	1.46400	0.8367	0.0342
16.75	1.46415	0.8376	0.0333
17.00	1.46432	0.8386	0.0323
17.25	1.46448	0.8396	0.0313
17.50	1.46462	0.8404	0.0305
17.75	1.46478	0.8414	0.0295
18.00	1.46497	0.8425	0.0284
18.25	1.46513	0.8434	0.0275
18.50	1.46530	0.8444	0.0265
18.75	1.46545	0.8453	0.0256
19.00	1.46560	0.8462	0.0247
19.25	1.46573	0.8470	0.0239
19.50	1.46584	0.8476	0.0233
19.75	1.46597	0.8484	0.0225
20.00	1.46608	0.8490	0.0219
20.25	1.46618	0.8496	0.0213
20.50	1.46630	0.8503	0.0206
20.75	1.46640	0.8509	0.0200
21.00	1.46650	0.8515	0.0194
21.25	1.46620	0.8497	0.0212
21.50	1.46673	0.8528	0.0181
21.75	1.46687	0.8536	0.0173
22.00	1.46698	0.8542	0.0167
22.25	1.46710	0.8549	0.0160
22.50	1.46720	0.8555	0.0154
22.75	1.46730	0.8560	0.0149
23.00	1.46737	0.8564	0.0145
23.25	1.46744	0.8568	0.0141
23.50	1.46750	0.8572	0.0137
23.75	1.46760	0.8577	0.0132
24.00	1.46763	0.8579	0.0130
24.25	1.46770	0.8583	0.0126
24.50	1.46778	0.8587	0.0122
24.75	1.46778	0.8587	0.0122
25.00	1.46796	0.8597	0.0112
25.25	1.46802	0.8601	0.0108
25.50	1.46810	0.8605	0.0104
25.75	1.46817	0.8609	0.0100
26.00	1.46820	0.8611	0.0098
26.25	1.46825	0.8614	0.0095
26.50	1.46830	0.8616	0.0093
26.75	1.46832	0.8617	0.0092
27.00	1.46837	0.8620	0.0089
27.25	1.46840	0.8622	0.0087
27.50	1.46842	0.8623	0.0086
27.75	1.46846	0.8625	0.0084
28.00	1.46848	0.8626	0.0083
28.25	1.46850	0.8627	0.0082
28.50	1.46852	0.8629	0.0080
28.75	1.46855	0.8630	0.0079
29.00	1.46858	0.8632	0.0077
29.25	1.46861	0.8633	0.0075
29.50	1.46867	0.8637	0.0072
29.75	1.46870	0.8638	0.0071
30.00	1.46876	0.8642	0.0067
30.25	1.46880	0.8644	0.0065
30.50	1.46880	0.8644	0.0065
30.75	1.46882	0.8645	0.0064
31.00	1.46885	0.8647	0.0062
31.25	1.46888	0.8648	0.0061
31.50	1.46890	0.8649	0.0060
31.75	1.46890	0.8649	0.0060
32.00	1.46892	0.8651	0.0058
32.25	1.46893	0.8651	0.0058
32.50	1.46897	0.8653	0.0056
32.75	1.46900	0.8655	0.0054
33.00	1.46903	0.8657	0.0052
33.25	1.46907	0.8659	0.0050
33.50	1.46909	0.8660	0.0049
33.75	1.46911	0.8661	0.0048
34.00	1.46914	0.8663	0.0046
34.25	1.46914	0.8663	0.0046
34.50	1.46915	0.8663	0.0046
34.75	1.46917	0.8664	0.0045
35.00	1.46918	0.8665	0.0044
35.25	1.46918	0.8665	0.0044
35.50	1.46919	0.8665	0.0044
35.75	1.46920	0.8666	0.0043
36.00	1.46920	0.8666	0.0043
36.25	1.46922	0.8667	0.0042
36.50	1.46923	0.8667	0.0042
36.75	1.46927	0.8670	0.0039
37.00	1.46930	0.8671	0.0038
37.25	1.46930	0.8671	0.0038
37.50	1.46931	0.8672	0.0037
37.75	1.46932	0.8672	0.0037
38.00	1.46933	0.8673	0.0036
38.25	1.46937	0.8675	0.0034
38.50	1.46938	0.8676	0.0033
38.75	1.46939	0.8676	0.0033
39.00	1.46940	0.8677	0.0032
39.25	1.46940	0.8677	0.0032
39.50	1.46941	0.8677	0.0032
39.75	1.46942	0.8678	0.0031
40.00	1.46943	0.8678	0.0031
40.25	1.46943	0.8678	0.0031
40.50	1.46943	0.8678	0.0031
40.75	1.46944	0.8679	0.0030
41.00	1.46945	0.8679	0.0030
41.25	1.46946	0.8680	0.0029
41.50	1.46947	0.8680	0.0029
41.75	1.46948	0.8681	0.0028
42.00	1.46949	0.8682	0.0027
42.25	1.46950	0.8682	0.0027
42.50	1.46950	0.8682	0.0027
42.75	1.46951	0.8683	0.0026
43.00	1.46952	0.8683	0.0026
43.25	1.46953	0.8684	0.0025
43.50	1.46952	0.8683	0.0026
43.75	1.46951	0.8683	0.0026
44.00	1.46951	0.8683	0.0026
44.25	1.46951	0.8683	0.0026
44.50	1.46952	0.8683	0.0026
44.75	1.46953	0.8684	0.0025
45.00	1.46953	0.8684	0.0025
45.25	1.46955	0.8685	0.0024
45.50	1.46957	0.8686	0.0023
45.75	1.46958	0.8686	0.0023
46.00	1.46959	0.8687	0.0022
46.25	1.46960	0.8687	0.0022
46.50	1.46960	0.8687	0.0022
46.75	1.46960	0.8687	0.0022
47.00	1.46960	0.8687	0.0022
47.25	1.46960	0.8687	0.0022
47.50	1.46960	0.8687	0.0022
47.75	1.46960	0.8687	0.0022
48.00	1.46961	0.8688	0.0021
48.25	1.46962	0.8689	0.0020
48.50	1.46962	0.8689	0.0020
48.75	1.46962	0.8689	0.0020
49.00	1.46963	0.8689	0.0020
49.25	1.46963	0.8689	0.0020
49.50	1.46963	0.8689	0.0020
49.75	1.46963	0.8689	0.0020
50.00	1.46964	0.8690	0.0019
50.25	1.46963	0.8689	0.0020
50.50	1.46962	0.8689	0.0020
50.75	1.46963	0.8689	0.0020
51.00	1.46964	0.8690	0.0019
51.25	1.46966	0.8691	0.0018
51.50	1.46968	0.8692	0.0017
51.75	1.46968	0.8692	0.0017
52.00	1.46969	0.8692	0.0017
52.25	1.46970	0.8693	0.0016
52.50	1.46970	0.8693	0.0016
52.75	1.46967	0.8691	0.0018
53.00	1.46964	0.8690	0.0019

TABLE X

DISTILLATE COMPOSITION/FEED COMPOSITION EXPERIMENTAL FREQUENCY RESPONSE RESULTS FOR PULSE TEST 11F

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
0.1764	0.0000	-15.0711

MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1.0000	-0.00	0.0000	0.0000
1.0000	-0.09	-0.0000	0.0001
1.0000	-0.43	-0.0001	0.0005
1.0000	-0.85	-0.0003	0.0010
0.9992	-4.26	-0.0068	0.0050
0.9985	-5.96	-0.0133	0.0070
0.9969	-8.51	-0.0271	0.0100
0.9930	-12.76	-0.0611	0.0150
0.9875	-16.99	-0.1090	0.0200
0.9805	-21.22	-0.1709	0.0250
0.9719	-25.42	-0.2472	0.0300
0.9502	-33.76	-0.4437	0.0400
0.9226	-41.95	-0.7000	0.0500
0.8896	-49.91	-1.0156	0.0600
0.8524	-57.57	-1.3869	0.0700
0.8123	-64.85	-1.8057	0.0800
0.7710	-71.66	-2.2585	0.0900
0.7306	-77.95	-2.7270	0.1000
0.6439	-91.56	-3.8236	0.1250
0.5880	-103.44	-4.6123	0.1500
0.5552	-115.85	-5.1111	0.1750
0.5256	-129.78	-5.5875	0.2000
0.4344	-158.08	-7.2415	0.2500
0.3548	-179.20	-8.9999	0.3000
0.3261	-201.97	-9.7320	0.3500
0.2741	-229.60	-11.2407	0.4000
0.2180	-248.85	-13.2312	0.4500
0.2103	-268.48	-13.5415	0.5000
0.1879	62.09	-14.5234	0.5500
0.1540	44.12	-16.2496	0.6000

TABLE XI

REFLUX COMPOSITION/FEED COMPOSITION OPEN LOOP TRANSFER FUNCTION BASED ON LINEAR MODEL FOR EXPERIMENTAL DATA SET 11F

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
0.0389	0.00	-28.1971

	MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1	1.0000	-0.00	0.0000	0.0000
2	1.0000	-0.03	-0.0000	0.0001
3	1.0000	-0.16	-0.0001	0.0005
4	1.0000	-0.32	-0.0002	0.0010
5	0.9993	-1.59	-0.0061	0.0050
6	0.9986	-2.22	-0.0119	0.0070
7	0.9972	-3.16	-0.0241	0.0100
8	0.9939	-4.71	-0.0536	0.0150
9	0.9893	-6.23	-0.0935	0.0200
10	0.9837	-7.70	-0.1428	0.0250
11	0.9772	-9.13	-0.2002	0.0300
12	0.9623	-11.82	-0.3335	0.0400
13	0.9460	-14.28	-0.4822	0.0500
14	0.9293	-16.53	-0.6368	0.0600
15	0.9131	-18.59	-0.7900	0.0700
16	0.8977	-20.49	-0.9370	0.0800
17	0.8836	-22.26	-1.0750	0.0900
18	0.8707	-23.94	-1.2028	0.1000
19	0.8436	-27.86	-1.4777	0.1250
20	0.8224	-31.58	-1.6985	0.1500
21	0.8054	-35.24	-1.8799	0.1750
22	0.7912	-38.88	-2.0346	0.2000
23	0.7675	-46.23	-2.2988	0.2500
24	0.7467	-53.66	-2.5369	0.3000
25	0.7269	-61.13	-2.7707	0.3500
26	0.7071	-68.60	-3.0102	0.4000
27	0.6871	-76.04	-3.2602	0.4500
28	0.6666	-83.44	-3.5224	0.5000
29	0.6459	-90.76	-3.7972	0.5500
30	0.6249	-98.00	-4.0842	0.6000

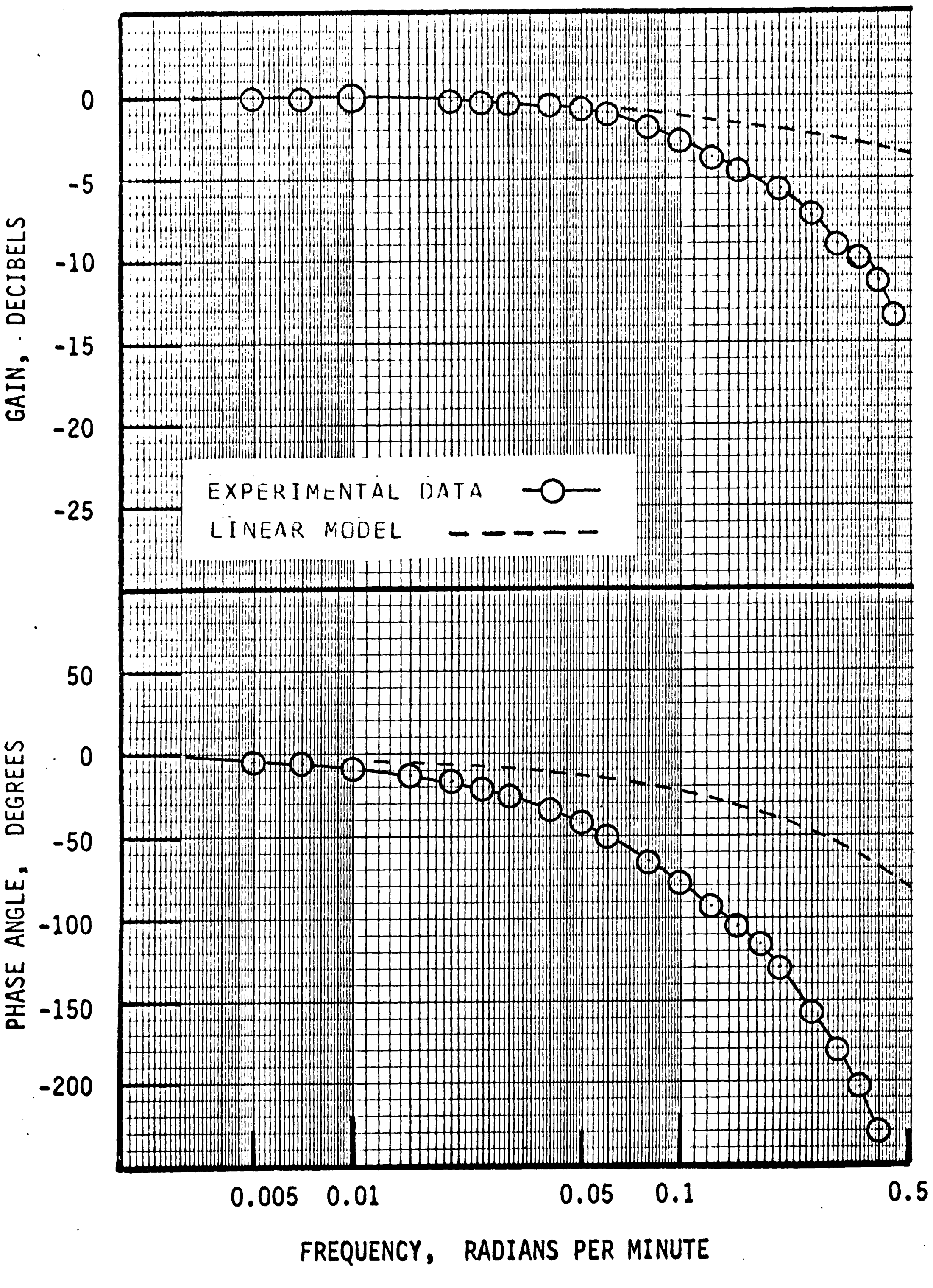


Figure 4. Distillate Composition/Feed Composition Open Loop Transfer Function based on Experimental and Linear Model Results For Test 11F

TABLE XII

EXPERIMENTAL FEEDFORWARD CONTROLLER
REFLUX/FEED COMPOSITION CONTROLLER FUNCTION
BASED ON DATA SETS 6F, 6V, 6S

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
0.2021	0.0000	-13.8895

	MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1	1.0000	0.00	0.0000	0.0000
2	1.0000	-0.17	-0.0000	0.0001
3	0.9999	-0.84	-0.0006	0.0005
4	0.9997	-1.67	-0.0024	0.0010
5	0.9976	-5.01	-0.0207	0.0030
6	0.9933	-8.33	-0.0581	0.0050
7	0.9871	-11.63	-0.1130	0.0070
8	0.9788	-14.92	-0.1863	0.0090
9	0.9741	-16.54	-0.2283	0.0100
10	0.9434	-24.55	-0.5059	0.0150
11	0.9036	-32.27	-0.8804	0.0200
12	0.8570	-39.65	-1.3408	0.0250
13	0.8057	-46.66	-1.8763	0.0300
14	0.7519	-53.29	-2.4773	0.0350
15	0.6970	-59.54	-3.1349	0.0400
16	0.6423	-65.44	-3.8447	0.0450
17	0.5887	-70.98	-4.6020	0.0500
18	0.5367	-76.21	-5.4054	0.0550
19	0.4866	-81.11	-6.2568	0.0600
20	0.3930	269.98	-8.1117	0.0700
21	0.3086	262.34	-10.2126	0.0800
22	0.2330	256.25	-12.6520	0.0900
23	0.1661	252.61	-15.5928	0.1000
24	0.0527	-71.36	-25.5586	0.1250
25	0.1127	-16.07	-18.9592	0.1500
26	0.1966	-29.74	-14.1287	0.1750
27	0.2521	-58.68	-11.9678	0.2000
28	0.1540	208.57	-16.2524	0.2500
29	0.0614	59.48	-24.2369	0.3000
30	0.1017	-27.57	-19.8568	0.3500

TABLE XIII

REFLUX RATE/FEED COMPOSITION FEEDFORWARD CONTROLLER TRANSFER FUNCTION BASED ON LINEAR MODEL FOR EXPERIMENTAL DATA SET 6F

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
0.6095	0.00	-4.3005

	MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1	1.0000	0.00	0.0000	0.0000
2	1.0000	0.00	-0.0001	0.0001
3	1.0000	0.00	0.0000	0.0005
4	1.0000	0.00	-0.0000	0.0010
5	1.0000	0.02	0.0000	0.0050
6	1.0000	0.02	0.0001	0.0070
7	1.0000	0.03	0.0003	0.0100
8	1.0001	0.05	0.0007	0.0150
9	1.0001	0.07	0.0011	0.0200
10	1.0002	0.08	0.0018	0.0250
11	1.0003	0.10	0.0025	0.0300
12	1.0005	0.13	0.0045	0.0400
13	1.0008	0.16	0.0071	0.0500
14	1.0012	0.19	0.0102	0.0600
15	1.0016	0.22	0.0138	0.0700
16	1.0021	0.25	0.0180	0.0800
17	1.0026	0.28	0.0228	0.0900
18	1.0032	0.31	0.0281	0.1000
19	1.0051	0.38	0.0438	0.1250
20	1.0073	0.44	0.0628	0.1500
21	1.0098	0.49	0.0850	0.1750
22	1.0128	0.53	0.1102	0.2000
23	1.0197	0.58	0.1696	0.2500
24	1.0280	0.58	0.2396	0.3000
25	1.0374	0.53	0.3189	0.3500
26	1.0479	0.41	0.4063	0.4000
27	1.0593	0.22	0.5002	0.4500
28	1.0714	-0.03	0.5992	0.5000
29	1.0842	-0.35	0.7019	0.5500
30	1.0974	-0.74	0.8070	0.6000

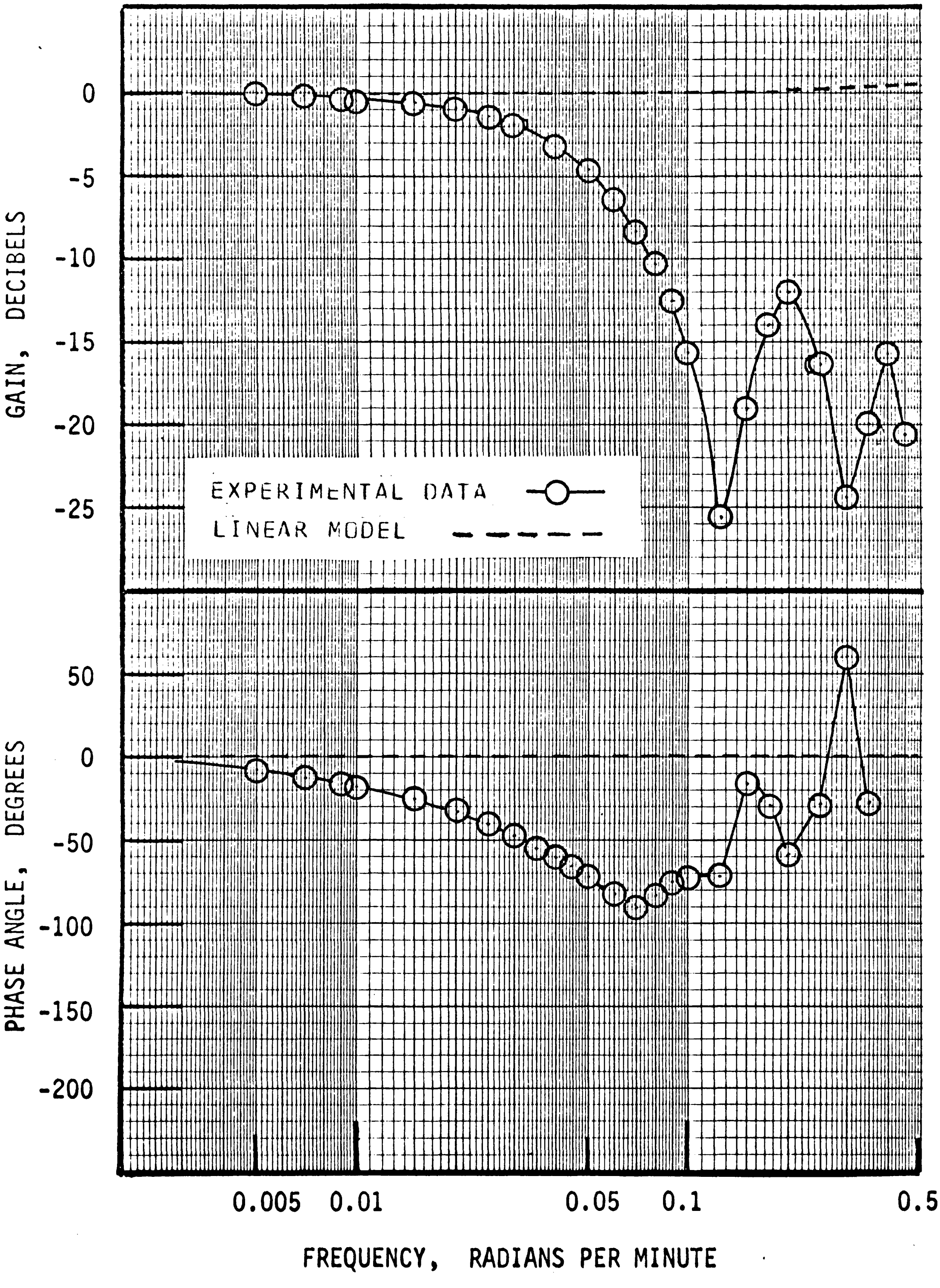


Figure 5. Comparison of Experimental and Linear Model Reflux Rate/ Feed Composition Feedforward Controller Transfer Functions based on Data Sets 6F, 6V, and 6S

TABLE XIV

EXPERIMENTAL FEEDFORWARD CONTROLLER
VAPOR/FEED COMPOSITION CONTROLLER FUNCTION
BASED ON DATA SETS 6F, 6V, 6S

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
0.4931	0.0000	-6.1407

	MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1	1.0000	0.00	0.0000	0.0000
2	1.0000	-0.15	-0.0000	0.0001
3	0.9999	-0.76	-0.0006	0.0005
4	0.9997	-1.52	-0.0025	0.0010
5	0.9974	-4.56	-0.0222	0.0030
6	0.9929	-7.58	-0.0621	0.0050
7	0.9862	-10.59	-0.1210	0.0070
8	0.9773	-13.57	-0.1994	0.0090
9	0.9722	-15.05	-0.2449	0.0100
10	0.9394	-22.28	-0.5431	0.0150
11	0.8967	-29.21	-0.9467	0.0200
12	0.8468	-35.75	-1.4447	0.0250
13	0.7919	-41.88	-2.0268	0.0300
14	0.7342	-47.58	-2.6833	0.0350
15	0.6756	-52.82	-3.4065	0.0400
16	0.6172	-57.62	-4.1918	0.0450
17	0.5601	-61.96	-5.0354	0.0500
18	0.5048	-65.84	-5.9373	0.0550
19	0.4519	-69.24	-6.8997	0.0600
20	0.3540	-74.43	-9.0197	0.0700
21	0.2678	-76.86	-11.4441	0.0800
22	0.1946	-74.95	-14.2166	0.0900
23	0.1383	-65.24	-17.1832	0.1000
24	0.1257	-10.40	-18.0148	0.1250
25	0.2164	0.73	-13.2931	0.1500
26	0.2970	-9.26	-10.5461	0.1750
27	0.3319	-27.50	-9.5793	0.2000
28	0.1564	-50.39	-16.1133	0.2500
29	0.2155	-9.29	-13.3292	0.3000
30	0.3016	-34.59	-10.4127	0.3500

TABLE XV

VAPOR RATE/FEED COMPOSITION FEEDFORWARD CONTROLLER TRANSFER FUNCTION BASED ON LINEAR MODEL FOR EXPERIMENTAL DATA SET 6F

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
0.4444	0.00	-7.0453

	MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1	1.0000	0.00	0.0000	0.0000
2	1.0000	0.00	0.0000	0.0001
3	1.0000	0.02	-0.0000	0.0005
4	1.0000	0.05	0.0001	0.0010
5	1.0001	0.25	0.0005	0.0050
6	1.0001	0.35	0.0009	0.0070
7	1.0002	0.50	0.0017	0.0100
8	1.0004	0.75	0.0039	0.0150
9	1.0008	1.00	0.0070	0.0200
10	1.0013	1.24	0.0109	0.0250
11	1.0018	1.49	0.0157	0.0300
12	1.0032	1.98	0.0278	0.0400
13	1.0050	2.47	0.0434	0.0500
14	1.0072	2.96	0.0623	0.0600
15	1.0098	3.44	0.0846	0.0700
16	1.0128	3.91	0.1102	0.0800
17	1.0161	4.38	0.1389	0.0900
18	1.0199	4.84	0.1709	0.1000
19	1.0309	5.94	0.2642	0.1250
20	1.0442	6.99	0.3755	0.1500
21	1.0597	7.96	0.5036	0.1750
22	1.0773	8.85	0.6469	0.2000
23	1.1185	10.38	0.9725	0.2500
24	1.1668	11.54	1.3403	0.3000
25	1.2216	12.33	1.7384	0.3500
26	1.2819	12.76	2.1568	0.4000
27	1.3470	12.84	2.5871	0.4500
28	1.4162	12.61	3.0226	0.5000
29	1.4891	12.10	3.4583	0.5500
30	1.5650	11.32	3.8904	0.6000

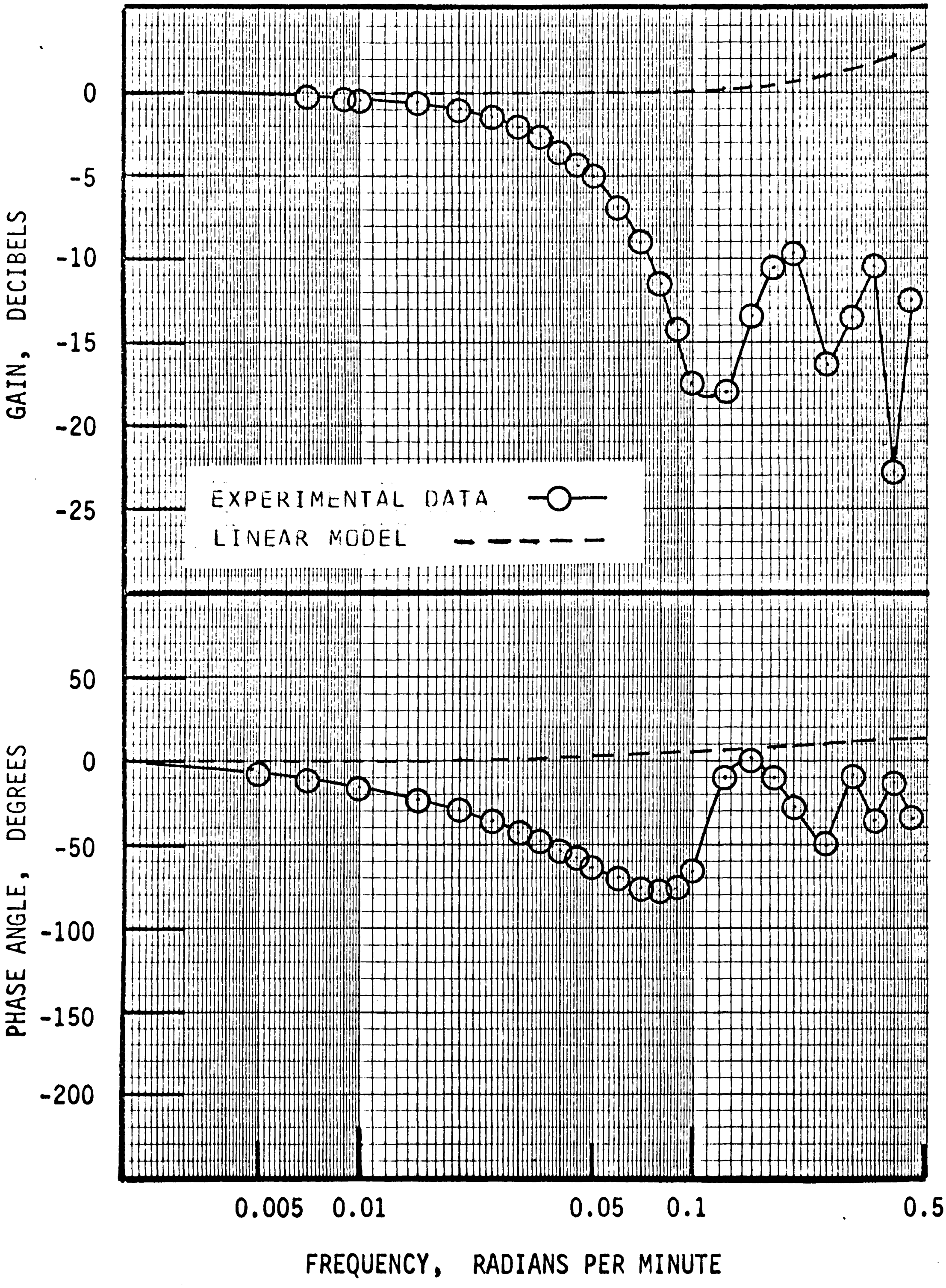


Figure 6. Comparison of Experimental and Linear Model Vapor Rate/ Feed Composition Feedforward Controller Transfer Functions Based on Data Sets 6F, 6V, and 6S

TABLE XVI

EXPERIMENTAL FEEDFORWARD CONTROLLER
REFLUX/FEED COMPOSITION CONTROLLER FUNCTION
BASED ON DATA SETS 8R, 10V, 11F

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
0.2588	0.0000	-11.7407

	MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1	1.0000	0.00	0.0000	0.0000
2	1.0000	-0.02	-0.0000	0.0001
3	1.0000	-0.12	-0.0003	0.0005
4	1.0000	-0.24	-0.0003	0.0010
5	1.0001	-0.71	0.0008	0.0030
6	1.0004	-1.18	0.0036	0.0050
7	1.0008	-1.66	0.0066	0.0070
8	1.0012	-2.14	0.0106	0.0090
9	1.0015	-2.39	0.0132	0.0100
10	1.0035	-3.62	0.0299	0.0150
11	1.0061	-4.91	0.0524	0.0200
12	1.0093	-6.26	0.0808	0.0250
13	1.0131	-7.72	0.1133	0.0300
14	1.0172	-9.30	0.1480	0.0350
15	1.0212	-11.05	0.1821	0.0400
16	1.0246	-12.98	0.2109	0.0450
17	1.0266	-15.13	0.2280	0.0500
18	1.0260	-17.55	0.2226	0.0550
19	1.0211	-20.22	0.1817	0.0600
20	0.9912	-26.30	-0.0767	0.0700
21	0.9240	-32.65	-0.6868	0.0800
22	0.8228	-37.80	-1.6940	0.0900
23	0.7111	-40.31	-2.9614	0.1000
24	0.5106	-33.93	-5.8376	0.1250
25	0.4587	-18.70	-6.7691	0.1500
26	0.5084	-7.77	-5.8754	0.1750
27	0.5948	-5.39	-4.5122	0.2000
28	0.7784	-12.77	-2.1764	0.2500
29	0.6651	-52.93	-3.5424	0.3000
30	0.6191	-21.42	-4.1643	0.3500

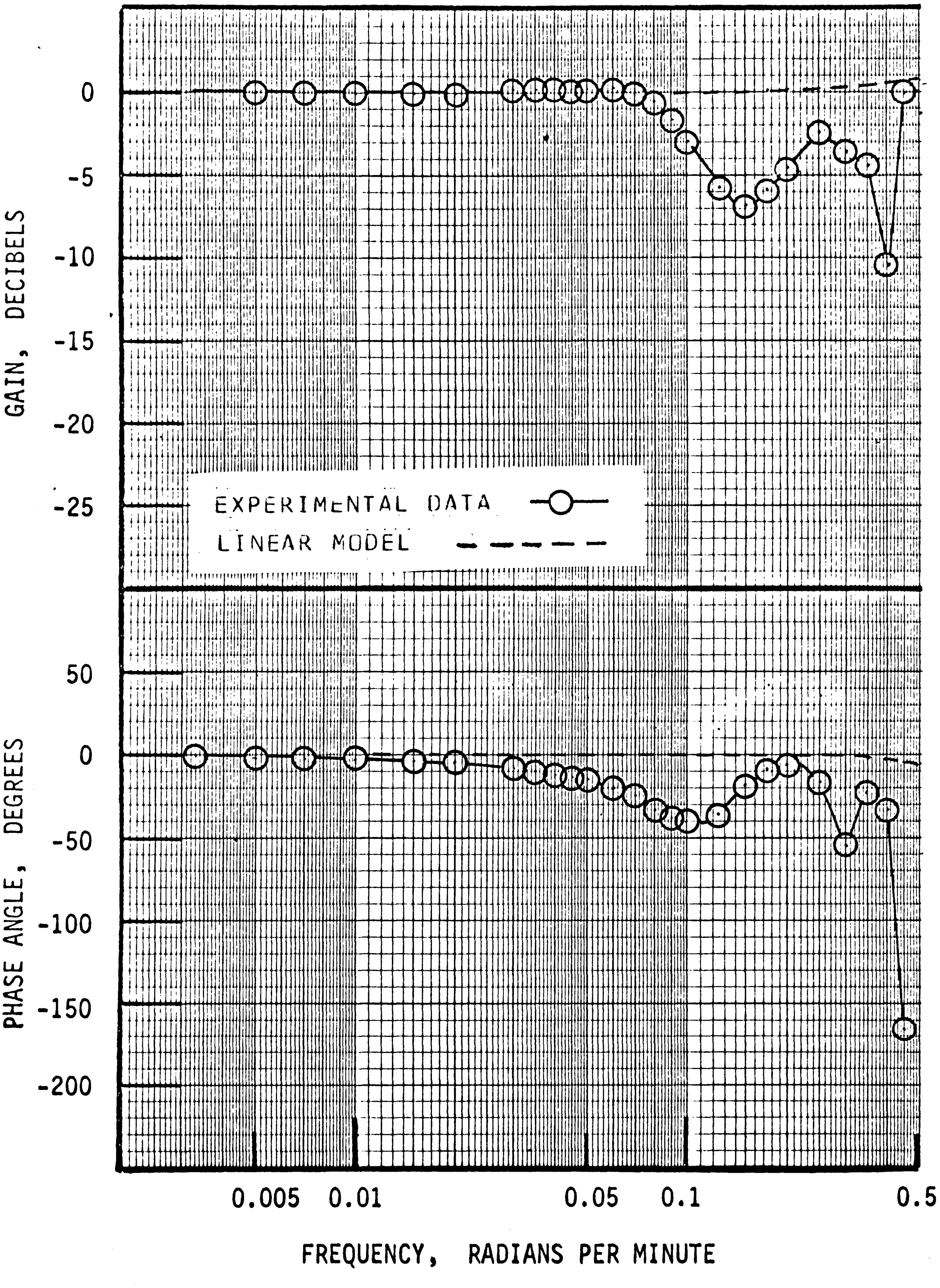


Figure 7. Comparison of Experimental and Linear Model Reflux Rate/ Feed Composition Feedforward Controller Transfer Function Based on Data 8R, 10V, and 11F

TABLE XVII

EXPERIMENTAL FEEDFORWARD CONTROLLER
REFLUX/FEED COMPOSITION CONTROLLER FUNCTION
BASED ON DATA SETS 8R, 9V, 12F

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
0.3859	0.0000	-8.2702

	MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1	1.0000	0.00	0.0000	0.0000
2	1.0000	-0.04	0.0000	0.0001
3	1.0000	-0.20	0.0002	0.0005
4	1.0000	-0.41	0.0001	0.0010
5	0.9998	-1.24	-0.0020	0.0030
6	0.9993	-2.06	-0.0057	0.0050
7	0.9987	-2.88	-0.0116	0.0070
8	0.9978	-3.70	-0.0191	0.0090
9	0.9973	-4.12	-0.0237	0.0100
10	0.9938	-6.18	-0.0539	0.0150
11	0.9889	-8.26	-0.0971	0.0200
12	0.9825	-10.35	-0.1535	0.0250
13	0.9745	-12.46	-0.2244	0.0300
14	0.9649	-14.59	-0.3104	0.0350
15	0.9535	-16.73	-0.4138	0.0400
16	0.9402	-18.89	-0.5358	0.0450
17	0.9249	-21.07	-0.6784	0.0500
18	0.9074	-23.25	-0.8437	0.0550
19	0.8878	-25.44	-1.0342	0.0600
20	0.8413	-29.76	-1.5007	0.0700
21	0.7856	-33.86	-2.0964	0.0800
22	0.7217	-37.50	-2.8334	0.0900
23	0.6524	-40.35	-3.7096	0.1000
24	0.4841	-41.92	-6.3009	0.1250
25	0.3661	-33.64	-8.7288	0.1500
26	0.3244	-16.56	-9.7773	0.1750
27	0.3752	-2.95	-8.5139	0.2000
28	0.5108	-11.20	-5.8354	0.2500
29	0.4256	-27.53	-7.4195	0.3000
30	0.2083	-6.59	-13.6272	0.3500

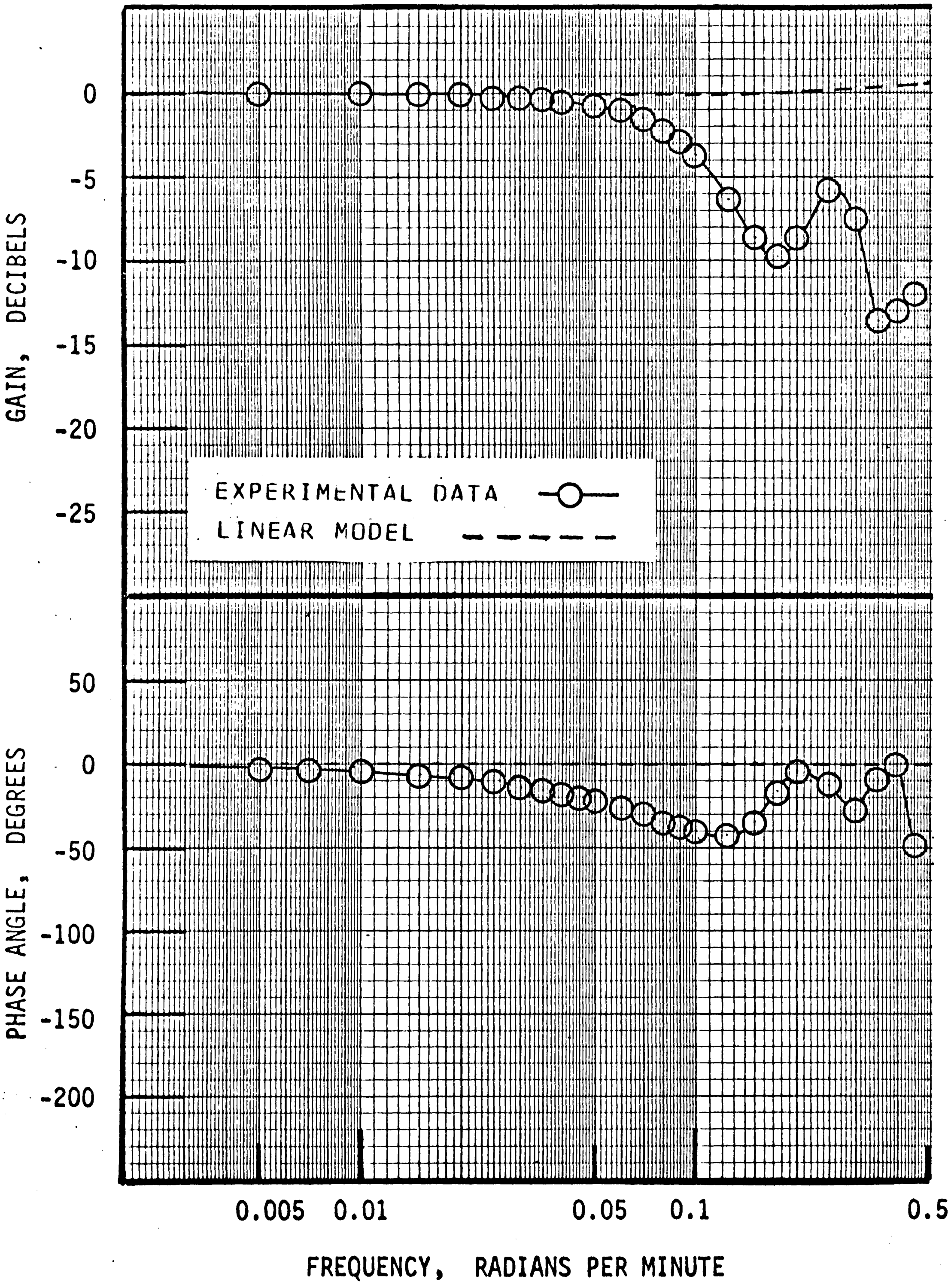


Figure 8. Comparison of Experimental and Linear Model Reflux Rate/ Feed Composition Feedforward Controller Transfer Function Based on Data 8R, 9V, and 12F

TABLE XVIII

REFLUX RATE/FEED COMPOSITION FEEDFORWARD CONTROLLER TRANSFER FUNCTION BASED ON LINEAR MODEL FOR EXPERIMENTAL DATA SET 11F

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
1.9017	0.00	5.5830

	MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1	1.0000	0.00	-0.0000	0.0000
2	1.0000	-0.00	-0.0000	0.0001
3	1.0000	-0.00	-0.0001	0.0005
4	1.0000	-0.00	-0.0001	0.0010
5	1.0000	-0.00	0.0000	0.0050
6	1.0000	-0.01	0.0002	0.0070
7	1.0000	-0.01	0.0004	0.0100
8	1.0001	-0.01	0.0008	0.0150
9	1.0002	-0.02	0.0014	0.0200
10	1.0002	-0.02	0.0021	0.0250
11	1.0004	-0.03	0.0032	0.0300
12	1.0007	-0.04	0.0057	0.0400
13	1.0010	-0.05	0.0088	0.0500
14	1.0015	-0.06	0.0129	0.0600
15	1.0020	-0.07	0.0176	0.0700
16	1.0026	-0.08	0.0229	0.0800
17	1.0033	-0.10	0.0290	0.0900
18	1.0041	-0.11	0.0357	0.1000
19	1.0064	-0.15	0.0557	0.1250
20	1.0093	-0.20	0.0800	0.1500
21	1.0125	-0.25	0.1083	0.1750
22	1.0163	-0.32	0.1408	0.2000
23	1.0253	-0.50	0.2170	0.2500
24	1.0361	-0.73	0.3078	0.3000
25	1.0485	-1.03	0.4116	0.3500
26	1.0626	-1.41	0.5270	0.4000
27	1.0780	-1.86	0.6525	0.4500
28	1.0948	-2.40	0.7864	0.5000
29	1.1127	-3.02	0.9274	0.5500
30	1.1316	-3.72	1.0739	0.6000

TABLE XIX

REFLUX RATE/FEED COMPOSITION FEEDFORWARD CONTROLLER TRANSFER FUNCTION BASED ON LINEAR MODEL FOR EXPERIMENTAL DATA SET 9V

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
2.2718	0.00	7.1273

	MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1	1.0000	0.00	-0.0000	0.0000
2	1.0000	-0.00	-0.0001	0.0001
3	1.0000	-0.00	-0.0001	0.0005
4	1.0000	-0.00	0.0000	0.0010
5	1.0000	-0.00	0.0000	0.0050
6	1.0000	-0.00	0.0001	0.0070
7	1.0000	-0.00	0.0002	0.0100
8	1.0001	-0.01	0.0007	0.0150
9	1.0002	-0.01	0.0014	0.0200
10	1.0002	-0.01	0.0020	0.0250
11	1.0004	-0.01	0.0033	0.0300
12	1.0007	-0.02	0.0057	0.0400
13	1.0010	-0.03	0.0090	0.0500
14	1.0015	-0.03	0.0130	0.0600
15	1.0020	-0.04	0.0176	0.0700
16	1.0027	-0.05	0.0231	0.0800
17	1.0034	-0.05	0.0293	0.0900
18	1.0042	-0.06	0.0361	0.1000
19	1.0065	-0.09	0.0563	0.1250
20	1.0093	-0.13	0.0807	0.1500
21	1.0127	-0.17	0.1097	0.1750
22	1.0165	-0.23	0.1424	0.2000
23	1.0256	-0.39	0.2198	0.2500
24	1.0365	-0.60	0.3117	0.3000
25	1.0492	-0.88	0.4169	0.3500
26	1.0634	-1.23	0.5339	0.4000
27	1.0791	-1.67	0.6613	0.4500
28	1.0961	-2.18	0.7972	0.5000
29	1.1144	-2.78	0.9404	0.5500
30	1.1336	-3.47	1.0893	0.6000

TABLE XX

EXPERIMENTAL FEEDFORWARD CONTROLLER
VAPOR/FEED COMPOSITION CONTROLLER FUNCTION
BASED ON DATA SETS 8R, 10V, 11F

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
0.0522	0.0000	-25.6437

	MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1	1.0000	0.00	0.0000	0.0000
2	1.0000	-0.05	-0.0000	0.0001
3	0.9999	-0.27	-0.0005	0.0005
4	1.0000	-0.54	-0.0004	0.0010
5	1.0003	-1.61	0.0025	0.0030
6	1.0011	-2.68	0.0095	0.0050
7	1.0021	-3.76	0.0179	0.0070
8	1.0033	-4.85	0.0288	0.0090
9	1.0041	-5.40	0.0358	0.0100
10	1.0094	-8.20	0.0811	0.0150
11	1.0166	-11.11	0.1427	0.0200
12	1.0257	-14.19	0.2205	0.0250
13	1.0365	-17.48	0.3116	0.0300
14	1.0486	-21.03	0.4124	0.0350
15	1.0615	-24.92	0.5187	0.0400
16	1.0743	-29.20	0.6227	0.0450
17	1.0858	-33.93	0.7153	0.0500
18	1.0941	-39.19	0.7810	0.0550
19	1.0966	-45.03	0.8012	0.0600
20	1.0726	-58.46	0.6089	0.0700
21	0.9923	-73.75	-0.0670	0.0800
22	0.8562	-89.60	-1.3485	0.0900
23	0.6941	255.25	-3.1720	0.1000
24	0.3534	218.09	-9.0341	0.1250
25	0.2189	156.04	-13.1959	0.1500
26	0.3480	97.91	-9.1673	0.1750
27	0.6072	67.74	-4.3335	0.2000
28	1.3129	15.37	2.3647	0.2500
29	0.7760	-66.78	-2.2027	0.3000
30	1.8666	-13.10	5.4208	0.3500

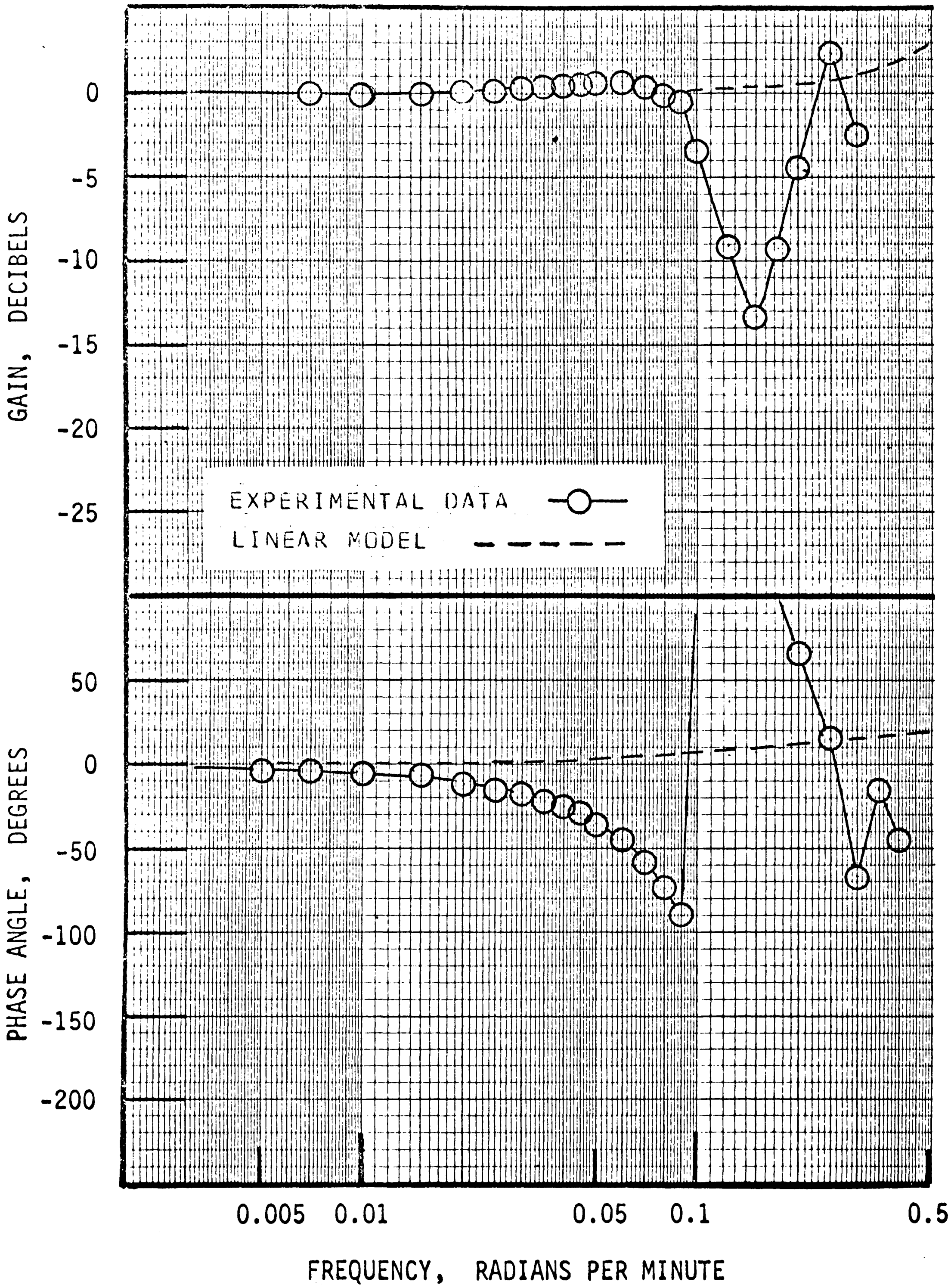


Figure 9. Comparison of Experimental and Linear Model Vapor Rate/ Feed Composition Feedforward Controller Transfer Function Based on Data 8R, 10V, 11F

TABLE XXI

EXPERIMENTAL FEEDFORWARD CONTROLLER
VAPOR/FEED COMPOSITION CONTROLLER FUNCTION
BASED ON DATA SETS 8R, 9V, 12F

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
0.0718	0.0000	-22.8750

	MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1	1.0000	0.00	0.0000	0.0000
2	1.0000	-0.07	0.0000	0.0001
3	1.0000	-0.35	0.0003	0.0005
4	1.0000	-0.69	0.0002	0.0010
5	0.9998	-2.08	-0.0019	0.0030
6	0.9993	-3.46	-0.0057	0.0050
7	0.9987	-4.85	-0.0116	0.0070
8	0.9978	-6.23	-0.0191	0.0090
9	0.9973	-6.93	-0.0236	0.0100
10	0.9938	-10.41	-0.0540	0.0150
11	0.9888	-13.90	-0.0977	0.0200
12	0.9823	-17.42	-0.1548	0.0250
13	0.9742	-20.96	-0.2268	0.0300
14	0.9645	-24.53	-0.3144	0.0350
15	0.9528	-28.13	-0.4204	0.0400
16	0.9391	-31.76	-0.5461	0.0450
17	0.9232	-35.41	-0.6938	0.0500
18	0.9051	-39.10	-0.8659	0.0550
19	0.8846	-42.79	-1.0650	0.0600
20	0.8361	-50.15	-1.5553	0.0700
21	0.7778	-57.29	-2.1831	0.0800
22	0.7117	-63.93	-2.9544	0.0900
23	0.6420	-69.68	-3.8490	0.1000
24	0.4941	-78.87	-6.1245	0.1250
25	0.4150	-87.43	-7.6386	0.1500
26	0.3231	255.82	-9.8130	0.1750
27	0.1844	235.12	-14.6855	0.2000
28	0.1014	28.40	-19.8827	0.2500
29	0.3742	-1.25	-8.5389	0.3000
30	0.1159	237.29	-18.7165	0.3500

TABLE XXII

VAPOR RATE/FEED COMPOSITION FEEDFORWARD CONTROLLER TRANSFER FUNCTION BASED ON LINEAR MODEL FOR EXPERIMENTAL DATA SET 11F

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
0.3815	0.00	-8.3712

	MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1	1.0000	0.00	0.0000	0.0000
2	1.0000	0.01	-0.0000	0.0001
3	1.0000	0.03	-0.0004	0.0005
4	1.0000	0.06	-0.0003	0.0010
5	1.0000	0.30	0.0002	0.0050
6	1.0001	0.42	0.0009	0.0070
7	1.0002	0.60	0.0018	0.0100
8	1.0004	0.89	0.0036	0.0150
9	1.0007	1.19	0.0065	0.0200
10	1.0011	1.49	0.0099	0.0250
11	1.0017	1.78	0.0147	0.0300
12	1.0030	2.37	0.0262	0.0400
13	1.0047	2.96	0.0405	0.0500
14	1.0068	3.54	0.0586	0.0600
15	1.0092	4.12	0.0797	0.0700
16	1.0120	4.69	0.1037	0.0800
17	1.0152	5.26	0.1308	0.0900
18	1.0187	5.81	0.1608	0.1000
19	1.0290	7.17	0.2485	0.1250
20	1.0415	8.46	0.3533	0.1500
21	1.0560	9.68	0.4733	0.1750
22	1.0724	10.82	0.6074	0.2000
23	1.1106	12.85	0.9108	0.2500
24	1.1550	14.52	1.2519	0.3000
25	1.2048	15.63	1.6185	0.3500
26	1.2591	16.79	2.0011	0.4000
27	1.3169	17.42	2.3913	0.4500
28	1.3776	17.75	2.7822	0.5000
29	1.4403	17.80	3.1691	0.5500
30	1.5046	17.61	3.5484	0.6000

TABLE XXIII

VAPOR RATE/FEED COMPOSITION FEEDFORWARD CONTROLLER TRANSFER FUNCTION BASED ON LINEAR MODEL FOR EXPERIMENTAL DATA SET 9V

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
0.6361	0.00	-3.9289

	MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1	1.0000	0.00	0.0000	0.0000
2	1.0000	0.01	-0.0001	0.0001
3	1.0000	0.03	-0.0003	0.0005
4	1.0000	0.06	0.0000	0.0010
5	1.0000	0.29	0.0003	0.0050
6	1.0001	0.41	0.0007	0.0070
7	1.0002	0.59	0.0013	0.0100
8	1.0004	0.88	0.0035	0.0150
9	1.0008	1.17	0.0066	0.0200
10	1.0011	1.46	0.0099	0.0250
11	1.0017	1.75	0.0149	0.0300
12	1.0030	2.34	0.0263	0.0400
13	1.0048	2.91	0.0412	0.0500
14	1.0069	3.49	0.0594	0.0600
15	1.0093	4.05	0.0803	0.0700
16	1.0121	4.61	0.1049	0.0800
17	1.0154	5.17	0.1325	0.0900
18	1.0189	5.72	0.1630	0.1000
19	1.0294	7.04	0.2518	0.1250
20	1.0420	8.31	0.3577	0.1500
21	1.0568	9.50	0.4800	0.1750
22	1.0735	10.62	0.6159	0.2000
23	1.1123	12.60	0.9243	0.2500
24	1.1576	14.21	1.2710	0.3000
25	1.2085	15.46	1.6446	0.3500
26	1.2640	16.36	2.0349	0.4000
27	1.3234	16.93	2.4339	0.4500
28	1.3859	17.18	2.8345	0.5000
29	1.4508	17.16	3.2321	0.5500
30	1.5175	16.90	3.6226	0.6000

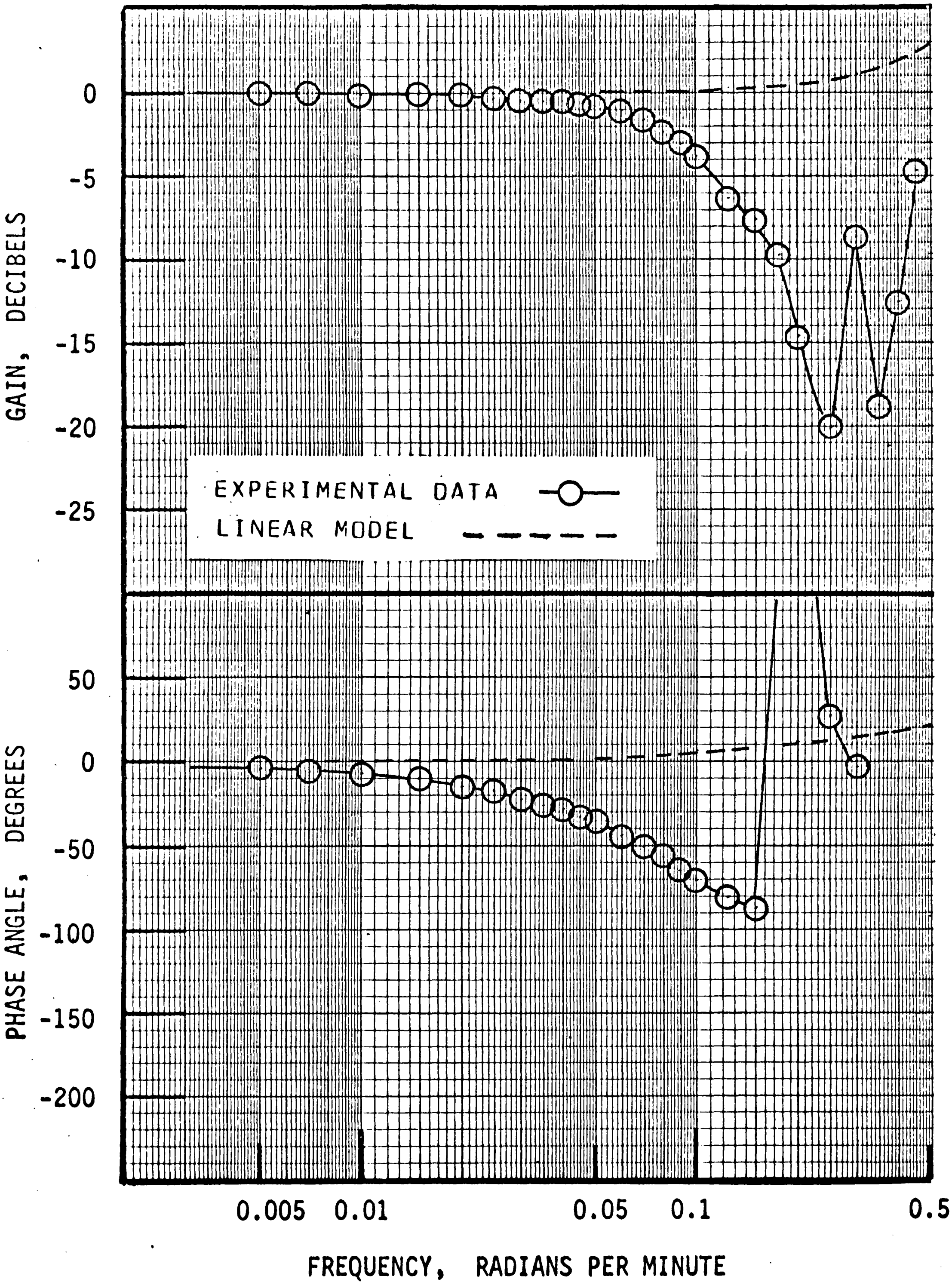


Figure 10. Comparison of Experimental and Linear Model Vapor Rate/ Feed Composition Feedforward Controller Transfer Function Based on Data 8R, 9V, and 12F

TABLE XXIV

Summary of Open Loop Distillation Column Dynamics

Test No	Stream	Dead time minutes	-3 db break frequency Radians/min	1st order time constant min
6F	Distillate	6.00	0.370	2.70
	Bottoms	3.00	0.050	17.88
6V	Distillate	2.00	0.185	5.41
	Bottoms	3.00	0.163	6.14
6S	Distillate	5.00	0.158	6.33
	Bottoms	2.00	0.122	8.20
8R	Distillate	2.25	0.215	4.65
	Bottoms	4.25	0.092	10.88
9V	Distillate	5.25	0.189	5.30
	Bottoms	2.00	0.087	11.50
10V	Distillate	4.25	0.250	4.00
	Bottoms	2.50	0.112	6.93
11F	Distillate	3.25	0.108	9.26
	Bottoms	2.25	0.080	12.50
12F	Distillate	5.00	0.098	10.20
	Bottoms	3.00	0.082	12.20

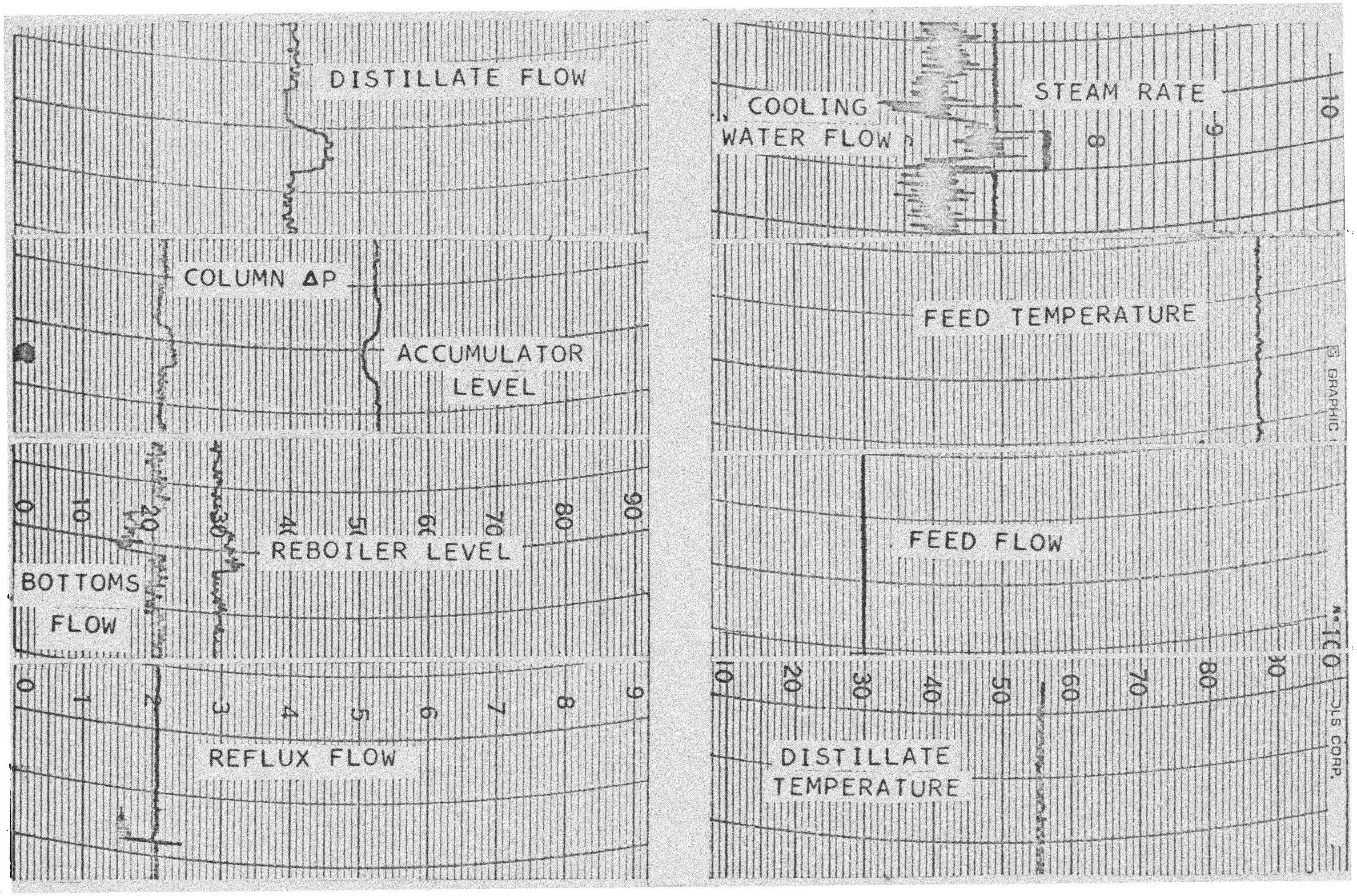


Figure 11. Experimental Controller Charts from Pulse Test 10V

V. DISCUSSION

The discussion of binary distillation column dynamics and feed-forward control has been divided into four major sections for the benefit of the reader. The first two sections are concerned with the experimental aspects of the investigation followed by a discussion of the data reduction and results of the investigation. Included in the discussion section are also the recommendations for future work and the limitations of this investigation.

Experimental Equipment

The experimental equipment used for the dynamic tests is discussed in the following section. Included in this section is also a discussion of the column control and pressure effects during operation.

Column Trays. The column was originally equipped with trays containing two bubble caps per tray. This tray had a reverse flow liquid pattern caused by a three-inch baffle located down the center of the tray. A two-inch bubble cap was located on each side of this baffle and the inlet and outlet weirs were located on opposite sides of the baffle next to the column wall. This design had in the past given very poor tray efficiencies based on operation by students during Unit Operations Laboratory. Normally the best tray efficiencies were in the order of 20 per cent. Part of the problem was considered to be caused by the six-inch tray spacing in this column. During the summer of 1965, while making modifications to the column reboiler, six trays were removed from the lower section increasing the tray spacing to one-foot for the lower six trays. During the column operation in the summer laboratory the tray efficiencies were again checked. Increasing the tray spacing had not improved the tray efficiencies a significant amount. This led to the conclusion that it was the tray design itself which was to blame.

A reverse flow tray is generally used for low liquid rates in industrial practice and in combination with close tray spacing the maximum vapor velocity is limited to very low values. This tower appeared to have been originally designed for a very high contact time. After tests proved that it was very difficult to establish a satisfactory operating range for the unit it was decided that the trays should be modified. It was impossible to make any reasonable modifications to the bubble cap trays themselves which would substantially improve their performance, therefore, it was decided to replace the bubble cap trays.

The standard industrial practice today generally favors sieve tray columns considering the number of columns installed. The old bubble cap trays were removed and replaced with the sieve trays designed by the procedure outlined in Smith's book (49). Further testing yielded only minor tray efficiency improvement resulting from the installation of sieve trays.

A three-tray section containing a glass section in the center, which had similar dimensions to the actual column, was fabricated. The system used in the test section was air-water. The sieve tray, as designed, was tested in order to establish the reasons for poor separation. It was discovered that the tray was actually unstable except in a very narrow region of vapor-liquid rates. This instability appeared to be caused by two factors. First, the tray had been designed without a downcomer baffle to block the vapor from the downcomer and therefore liquid and vapor were being carried directly into the pipe. In viewing the tray from the top during operation it was impossible to determine the actual downcomer location due to the froth coverage. Secondly, very slight variations in vapor or liquid rates would cause the liquid and froth on the tray to start oscillating across the tray. This oscillation would then be aggravated by the vapor shifting in the direction of lower pressure drop caused by the liquid shifting to one side of the tray. Next, the tray would dump on the high liquid side until the pressure drop became less at which time the vapor passing through the tray would switch sides. This oscillation would continue undamped unless the liquid or vapor rates were decreased to very low rates compared to those formed in column operation.

From this information it appeared that the dry pressure drop and the operating pressure drop on the tray needed to be balanced in order to decrease the effect of slight changes in liquid level on the tray.

The sieve tray was modified to decrease the tray instability by reducing the outlet weir height from 1.25 inches to 0.75 inches which served to reduce the operating tray pressure drop. In addition, ten per cent of the holes were closed up in the region around the downcomer. This modification in the tray holes had two effects; first, it increased the vapor velocity through the remaining holes increasing the dry tray pressure drop, and secondly it decreased the agitation in the region of the downcomer. These changes improved the dry tray to operating tray pressure drop ratio. Decreasing the number of holes surrounding the downcomer also provided a larger region for vapor-liquid disengagement before entrance into the downcomer. A baffle was also placed before the downcomer which caused the liquid to flow under the baffle to reach the downcomer. These modifications resulted in a major improvement in the vapor-liquid disengagement problem and functioned as a device for damping the oscillations.

The bubble cap tray was also tested with the air-water system and our previous convictions were verified. At moderate vapor rates the vapor would not contact the liquid but would travel up through the space between the cap and the tower wall because of their proximity. In addition, the liquid was being thrown over the low reverse flow baffle into the baffle and downcomer with very little vapor-liquid contact. This liquid had the effect of short-circuiting the tray.

Reboiler. As originally designed a large kettle was used for the reboiler which had a copper coil wrapped along the outside wall. This unit had a capacity of approximately 70 gallons and required nearly 40 gallons of liquid holdup to maintain the coil submerged below the liquid. This situation resulted in the reboiler having a liquid capacity about 80 times as great as a column tray. If dynamic tests were conducted in this unit, changes in the reboiler composition would be almost impossible to detect during pulse testing. A kettle type heater requires also a large heating area due to the poor heat transfer coefficients generally obtained with these units and therefore, this results in poor control because of the large thermal lag.

After much consideration of the matter, it was decided to fabricate and install a thermosiphon reboiler because these units are widely used in industry and have very low liquid holdups. Such units generally have moderately high heat transfer coefficients and are easier to control.

The thermosiphon reboiler was designed, fabricated, and installed on the unit in place of the kettle reboiler. The unit was equipped with steam flow control and inventory control, in the form of level control. The unit was equipped with steam flow control instead of pressure control to insure a more constant molar boilup rate. When steam flow is controlled, the reboiler steam pressure and temperature difference are allowed to adjust in order to maintain a constant heat flux. This constant heat flux is possible because the per cent error in the heat of condensation of steam with pressure variations over a small range is small. If pressure control had been used, the result would have been to maintain the steam side of the reboiler at a constant temperature, and as the composition varied in the reboiler the boiling temperature would change resulting in a heat flux that would be a function of the reboiler composition. Slight changes in the reboiler heat transfer coefficient also would have caused the heat flux to vary for steam pressure control. Small variations in the heat transfer coefficient in the case of steam flow control has very little real effect on the heat flux since the temperature difference automatically adjusts to correct for this change. If pressure control had been used during the dynamic tests the column vapor rate would have become a function of the reboiler composition and thus dependent on the pulsed variable.

Pressure control is widely used in industry for steam flow control. The reason stems from the fact that closed loop control is used with distillation columns to maintain uniform product stream compositions. Industrial practice simply takes advantage of the self-compensating aspects of pressure control.

Column. The column used for this investigation consisted of eighteen trays available for mass transfer. This unit was eight inches in diameter which was large enough so that industrial instrumentation could be applied to the unit successfully. The column performance was also considered to be similar to that expected from an industrial unit.

The major modifications to the column trays and reboiler have already been discussed previously. The only other changes made to this unit was first the installation of a vapor-liquid separator between the top tray and the condenser and secondly the insulation of the column.

Insulation of the column resulted in the reduction of the heat losses from a level of 40-50 per cent to a level of 10-20 per cent of the total column heat input. This was necessary so that the assumption of equal molal overflow would be reasonably valid for the unit. This assumption, although convenient for the linear model, is not necessary since the heat balance equation for each tray could have been included.

Insulating the column also greatly improved the column operation. With a large heat loss it is necessary to have high vapor rates in the lower section of the tower in order to have a moderate vapor velocity in the top section of the column. In a sieve tower this results in only a few trays giving satisfactory performance because of their generally narrow range of operational vapor rates.

Column Control. Figure 2, page 30, shows the schematic diagram of the column control system. These control systems are all secondary control systems in that they only control the column inventory and flow rates. No primary control was applied for composition control since open loop system response was required for this investigation. Good secondary control was required, however, in order to independently investigate the various manipulative and uncontrolled variables of the system. The feed composition and feed rate which under closed loop control are the uncontrolled variables, were controlled variables for this study.

The secondary control systems were installed for flow control of the reflux, distillate, bottoms, steam, and feed rates along with level control of the reboiler and accumulator. The distillate temperature leaving the overhead condenser and the feed temperature were also controlled. These secondary control systems allowed the major flow streams, feed, reflux, and vapor rates to be set independently, within physical limiations. The bottoms flow rate was controlled by the reboiler liquid level controller loop to maintain constant reboiler level. The distillate flow rate was set by the accumulator level control system to maintain constant liquid level in the accumulator.

Therefore, it was possible to establish within the limits of instrument sensitivity that the only variations within the system were those being intentionally varied. The control scheme was arranged so that there was no interaction between the major internal process streams because of controller action. The independent control of the vapor rate has already been discussed in the reboiler section of the discussion.

Figure 11, page 86, shows a typical set of controller charts recorded during an actual dynamic test. It can be seen that changes occurred in the accumulator and reboiler levels during this test. These variations are magnified on the controller charts in that the transmitter ranges were very narrow and these changes, in fact, represent less than a ten per cent change in unit inventory. It was not desirable to increase the control system response speed to eliminate this error because the flow streams being used for control would have become effectively on-off or bang-bang controlled. With on-off control it is difficult to measure the process flow rates even during steady-state operation. It is also desirable from a control standpoint not to have bang-bang control since the liquid level control loops were cascaded and this would have caused the loops to become unstable.

Pressure Effects. Pressure effects are of major importance during dynamic testing due to their effect on the equilibrium relationship. If major pressure changes occur during a dynamic test then the data is of questionable value. Not only does the pressure affect the equilibrium relationship but it also affects the heat content of the liquid and vapor steams in the column.

In this investigation an attempt was made to reduce the pressure effects during the pulse tests. Nitrogen gas from a cylinder was used to provide an inert gas blanket in the top of the condenser and to provide a constant column pressure supply. Therefore, there was a positive bleed of inert gas from the top of the condenser. The rate of bleed was controlled by a pressure flow controller so that as the pressure increased the rate of gas discharge increased. If the pressure decreased the rate of bleed would decrease and the pressure regulator on the nitrogen cylinder would adjust to maintain the pressure at the regulated value. Two pressure regulators were used on the nitrogen cylinder in order to obtain more precise control. The first regulator was used to reduce the cylinder pressure to 45 psig and the second was used to reduce the pressure from 45 psig to the column pressure.

During the initial periods of the pulse test the pressure gauge located on the second tray of the column was monitored. The pressure variation in any test was less than 0.2 psig. The pressure returned to the controlled value within two or three minutes after the initial disturbance. The change in column pressure drop was determined to be less than ten inches of water during the pulse tests. Based upon this information it was concluded that pressure effects should not have seriously influenced the dynamic test data during this investigation.

Experimental Testing Phase

In the following sections the actual experimental procedure will be discussed. First, the pulse testing will be discussed, followed by the sampling procedure used for both steady-state and dynamic test data collection. Included also in this section is a discussion of the operation of the process refractometer.

Pulse Testing. All pulse test forcing functions were obtained, except in the case of the feed composition pulse, by adjusting the appropriate controller set point to the required pulse amplitude value during the pulse interval and then back to the original value after the predetermined pulse interval. The amplitude and the time interval of each pulse were chosen small enough to minimize the column nonlinear effects while at the same time having enough energy so that changes could be detected in the process stream compositions.

Visual observation of a typical controller after a set-point change showed that the new value was obtained within a one-minute time interval after the set point change. Table XXIV, page 85, shows that there was a definite dead time present between the set point change and a detectable composition change in the process stream. Part of this dead time is actually due to delay in the response of the control system to change after the change occurred. This dead time must be accounted for in the process dynamics since these dead times will be present in the case of either feedback or feedforward control or any combination of the two. In the pulse data reduction it was assumed that the pulsed stream followed a ramp function over a one-minute period which was between the time of the actual set point change and the time required to reach the final value. This same ramp function was assumed to exist at the tail of the pulse as well.

Steady-State Sampling. Steady-state samples were taken before and after each test. When another test followed the test in question a separate set of steady-state samples were not taken for the completion of the first test. Instead the one set of samples were taken which served for both the final steady-state for the previous test and the start of the next planned test.

All steady-state samples were taken in the following manner: First a sample bottle of liquid was withdrawn from each sample tap and discarded; then a 20 cubic centimeter sample was withdrawn for analysis. This procedure was followed to insure that a representative sample of the tray liquid was actually collected. In every other tray approximately six to eight inches of 1/8-inch stainless steel tubing was required in order to withdraw a liquid sample from behind the inlet weir.

Dynamic Sampling. Samples were collected from the reflux and bottoms streams during dynamic tests 6F, 6S, and 6V. The sample taps were located next to the flow transmitters in these streams and the sample taps were adjusted to allow a flow rate of approximately 60 cubic centimeters of liquid per minute. The sample streams were allowed to flow throughout the entire test at this flow rate. The actual samples were collected at the start of each minute for a period of ten seconds. Therefore the samples obtained were samples averaged over a ten second period. The start and period of each sample was closely watched in order to have uniformly spaced samples. This procedure gave very uniform samples data for the pulse response analysis.

Sample Analysis. All liquid steady-state samples and samples taken during the dynamic tests were analyzed on a Bausch and Lomb laboratory refractometer for refractive index. The temperature of the refractometer prisms were maintained at 30 °C + 0.1 during these analyses. The reproducibility of these readings were checked by analyzing the same sample ten times and the range of variation was determined to be two units in the fourth place. Therefore the sample reproducibility was considered to be well within the precision of the instrument.

Process Refractometers. Two Nester/Faust Model 660 process refractometers were used for dynamic analysis of bottoms and distillate streams. The response time of these units was considered to be less than 15 seconds based upon laboratory experience and manufacturer information. The limiting factors in the response speed was the detector head volume, 75 cc, and the detector head temperature response. The response speed can be controlled to a large extent by the liquid flow rate through the head. During all tests except 6S, the flow rates were maintained at levels which did not adversely affect the response of the refractive index unit. In the case of test 6S the reflux pulse caused the distillate flow rate controller to decrease the flow rate to a very low value during the initial period of the test after which the flow rate returned to an acceptable level.

These units had automatic linear temperature correction built into them. This reduced any variation in output reading due to temperature changes. The response speed of the temperature correction circuit as originally obtained from the factory was of the order of five to ten minutes. The original thermistors were shielded to reduce their response speed. These thermistors were replaced with thermistors embedded only in an epoxy resin. After making this modification response speed of the units for temperature change was reduced to less than one minute. The process refractometer monitoring heads were located in the process streams after the bottoms and distillate coolers. These coolers had no temperature control on them but they removed any high frequency temperature variations from the system. These coolers did cause a temperature variation of several degrees to occur in the process stream. The frequency of this disturbance was of the order of three to five minutes and was dependent on the process flow rate variations. This disturbance was most noticeable in the bottoms stream refractometer where it was causing a cyclic variation of ± 2 per cent during steady-state operation.

The ability to detect changes in composition with these units was far better than the capability of determining the absolute value of the refractive index. The absolute refractive index of the streams could be read with a nominal error of ± 0.0001 refractive index units. The sensitivity of these units to detect relative changes in refractive index can be increased by amplifying the output signal. Noise becomes the limiting consideration in such cases.

During this investigation the output gain was adjusted by a factor of two on the distillate unit to give 0.00005 refractive index units per recorder division. The output gain for the bottoms unit was decreased by a factor of two to give 0.0002 refractive index units per recorder division. These changes were necessary due to the magnitude of the composition changes in the respective streams during the pulse tests. The ability to read the two channel recorders used with the refractometers was to within ± 0.25 division.

Data Reliability and Reduction

In the following sections the questions of data reliability and reduction will be discussed.

Flow Data and Material Balances. The unreduced flow data were taken from recorder charts for the process streams and the cooling water. The steam rate was measured by the bucket method. The flow recordings for the process streams could be read to within ± 1.0 per cent of full scale. The calibration plots for converting the process streams from chart units to pounds per minute could also be read to within ± 1.0 per cent of full scale.

The flow data for the process streams were corrected in the steady-state data reduction computer program for changes in density caused by both temperature and composition changes. All the flow transmitters were calibrated with pure benzene at 80 °F and this was the basis of the calibration curves for the meters.

This procedure has resulted in material balances with an error based upon total input of less than five per cent with the majority of the test results yielding errors of less than three per cent. The steady-state program also performed a calculation of the benzene material balance for each test. The error in the benzene balance was again on the order of less than five per cent based upon the total benzene input.

Temperature Data and Heat Balances. Thermocouples were located in all major process lines, all column trays, overhead condenser inlet and outlet water streams and the inlet vapor line to the condenser. The feed temperature was determined from the temperature recorder as was the temperature of the outlet liquid from the overhead condenser. The temperature indicator used to convert the thermocouple potential to temperature readings could be read to ± 0.5 °F. The process recorders could be read to within ± 1.0 per cent of full scale as could the calibration curves used to convert per cent full scale readings to temperature.

The thermodynamic properties of the hydrocarbon system were converted to equation form by regression analysis. The temperature and composition data were used to determine the enthalpy values of each process stream from the regression equations. The assumption of no heat of mixing was basic to these calculations. After the enthalpy values for each stream plus the corrected flow rates were calculated these results were used to formulate the required heat balances in the steady-state data reduction program. The heat input from steam condensation and the heat removed by the overhead condenser in BTU's per minute were part of the required input data for the program. These values were calculated by hand based upon the measured flow rates, temperatures and reboiler steam side pressure. Steam tables were used to evaluate the enthalpy values of the streams at their measured conditions.

The resulting heat balances show in general an error of 15 to 25 per cent in the overall balances based on total heat input. Heat balances were made on the tower without condenser and on the overhead condenser separately. The error in the tower heat balances accounted for less than half of the total heat balance error with heat losses ranging between 200 and 320 BTU per minute. This represents an error of less than ten per cent of the total heat input to the tower.

The two most critical values in these heat balance calculations are also the most difficult to measure. These two values are the total overhead vapor rate and the steam condensation rate. Before the installation of the vapor-liquid separator a large error was being introduced into the heat balance by liquid entrainment. The column overhead vapor rate is based upon the combined flow rates of the reflux and distillate streams. The installation of the separator has eliminated this error and now the tower heat balance agrees closely with estimated heat losses. The actual steam condensation rate was difficult to determine because of the fact that all the steam passing through the reboiler was not condensed. This resulted from the fact that a small amount of steam was being bypassed around the steam trap to reduce internal reboiler pressure effects from the steam trap opening and closing. Care was taken to only collect the steam condensate when making these weighings. This was also the reason for not using the steam flow chart recorder readings for determining the steam rates.

Composition Data. The refractive index of all samples taken at steady-state and during dynamic testing was converted to mole fraction benzene. A regression equation of the refractive index versus mole fraction benzene in normal heptane was determined for this purpose and was incorporated in the appropriate data reduction programs. The coefficient of determination for this regression equation was 0.9718.

A change of 0.0001 refractive index units resulted in a 0.0005 mole fraction change in the benzene composition at high concentrations of benzene and a 0.0012 mole fraction difference in benzene concentration at low benzene concentrations. It was noted in the sampling section that the refractive index could be determined in the laboratory with a confidence of plus or minus one unit in the fourth place. Therefore the maximum error between any two steady-state samples was less than half a mole per cent benzene.

In the section on Process Refractometers it was noted that 0.000025 refractive index unit changes could be accurately detected in the distillate stream. This corresponds to a composition change of 0.00015 mole fraction benzene. In the bottoms stream the process refractometer accurately detected changes of 0.0001 refractive index units which corresponds to a 0.00131 mole fraction change in the benzene composition.

This improvement in composition data reduction for the dynamic tests results mainly from the fact that only a change in composition is required and not the absolute value of the composition. The ability to determine the absolute value of refractive index on the process refractometers is the same as with the laboratory refractometer, but it is very difficult to calibrate these units to that precision.

Regression Analysis. Regression program, ''BMD03R - Multiple Regression with Case Combinations - Version of April 9, 1964'', available in the Virginia Polytechnic Institute Computing Center, Blacksburg, Virginia was used for regression analysis during this investigation. All physical property data for the hydrocarbon system benzene·n-heptane required for this investigation was converted to equation form by regression analysis. The coefficient of determination for these equations was 0.999. The coefficient of determination is a measure of the equation fit of the data; a coefficient of determination of unity means a perfectly fitting equation. These equations are listed in the Steady-State Program SSDDR, which may be found in the Appendix. Equations were developed, also, for the vapor-liquid equilibrium and refractive index versus mole fraction benzene data. The coefficient of determination for these two equations were 0.999 and 0.9718, respectively.

Regression analysis was also used to fit the bottoms composition pulse data for test 6F. This equation was used to calculate intermediate data points for the Fourier analysis to determine if the high frequency results being obtained in the frequency response plots were the results of data point spacing rather than column effects. This problem will be discussed in more detail in the section on pulse data reduction. The coefficient of determination for this equation was 0.9319.

Steady-State Distillation Calculations. The steady-state distillation calculations were carried out by digital computer program SSDDR which is located in the Appendix, page 205. This program converted the refractive index data to mole fraction benzene for each sample, and performed the steady-state heat and material balances. Each of these items ~~have~~ has already been considered separately. An important function of the steady-state program besides making the required heat and mass balances was the calculation of the steady-state constants for the linear model used to determine the theoretical frequency response of the system.

In addition this program calculates the Murphree vapor efficiency for each tray. These values are based upon the actual tray to tray calculations up the column knowing the liquid compositions on each tray except for trays 10 and 18 for which samples were not available. The tray efficiencies for trays 10 and 18 were calculated by assuming that the tray and the tray below it have the same efficiency. The reboiler is located below tray 18 and generally it is assumed that the reboiler is 100 per cent efficient. It turned out that assuming a reboiler efficiency of 100 per cent for this column is not a good selection since this results in the efficiency on tray 18 being very low in most cases and not being in agreement with the average values in the stripping section. Therefore, since some distribution of efficiency was required between these two trays, it was convenient to assume that the values were equal. This resulted in values of tray efficiency for tray 18 which was generally in agreement with the average values in the stripping section.

The tray efficiency values which were supplied for the linear model of the column were averaged to reduce the tray to tray variation which was present in the data. This had no effect on the dynamic characteristics of the column since these values only adjust the steady-state terms in the linear model simulation. This results from the assumption, which is generally included in the linear model assumptions, that the tray efficiencies are independent of the process variables around the steady-state condition of linearization. For this reason it was not necessary to obtain high precision in these efficiency values. However, more accurate values would be required if the steady-state gains for the system were calculated based upon these results. In the case of steady-state gains the dynamics would not have to be considered and only the steady-state equations would be solved for the new conditions and the required gains calculated from the resulting steady-state conditions for the given change. In that case considerable amount of work would be required to better define tray efficiency as a function of the process variables since the gains are generally nonlinear functions.

The steady-state tray efficiency problem may be difficult to define since there appears to be a large variation in tray efficiencies for a given tray from one test to another and also from tray to tray in any given section. There are several factors which may partially explain some of this variation. First of all, there is a physical variation in the installed trays in the column due to shop problems during installation. A tray pitch requirement was specified but on several trays it was impossible to meet this condition. There is also possible errors in the actual liquid samples being collected. The samples are withdrawn from behind the inlet weir on the tray below the actual tray of interest. Gas could have been entrained and carried down the downcomer and some liquid mixing may be occurring on the tray behind the inlet weir due to the small column size and the high turbulence. Both of these effects could cause variations in the liquid samples.

The steady-state program also carries out the calculations for the F-factors and tray liquid holdups above and below the feed tray. The F-factor is a measure of the column loading and is widely used in the chemical process industry. The tray holdup is calculated from the A.I.Ch.E. report on tray efficiencies. The time constant of the unit is the liquid tray holdup in the stripping section divided by the stripping section liquid rate. This time constant is generally called the dimensionless time and is used to generalize the calculations for changes in equipment size.

Pulse Data Reduction. The pulse data reduction program is a straightforward operation. This program converts the refractive index values for the streams at fixed time intervals to mole fraction benzene. Next the program subtracts away the steady-state value of composition at time zero from each data point which results in evenly spaced difference data for the frequency response analysis. The output data is supplied in the correct format for the frequency response program. Several types of data input may be used with this program which is considered in the Appendix.

The refractive index data was converted to mole fraction benzene using the regression equation that was employed in the steady-state program.

Frequency Response Program. The frequency response program employed in this study was very similar to programs used by Renfroe, Go and Fogle (42, 18, 13). The program accepted evenly spaced difference data for both the input and output pulse data. The use of this technique for determining system transfer functions has been discussed in detail by the above authors. The major modification to this program was the addition of a routine which subdivided the interval between data points which allowed a smaller time interval of integration.

This program was tested by calculating values of the output of a first order system as a function of time for a pulse disturbance. These values were then read into the program and the frequency response of the system calculated. The calculated value of frequency response was compared with the theoretical first order frequency response curve and was found to have good agreement out to frequencies greater than one radian per second. The first order time constant was so selected as to be of the order of the actual experimental system. The sample time interval was varied also to determine the effect on the calculated frequency response curve. It turned out as one would expect that as the interval became smaller the agreement also improved. Table LXXIV, page 204, contains the results of this test calculation with a data interval of 0.2 minutes. The interval used during tests 8 through 12 was 0.25 minutes. As noted, this program has built into it a data subdivision routine which will subdivide the interval between data points into X equal intervals assuming a linear relation between data points, where X is specified by the programmer. Dividing by two or four was found to improve the results but increasing the number of subdivisions still further had no effect except to increase the computation time. The computation time increases directly with X, the number of subdivisions.

Distillation Column Dynamics and Feedforward Control.

This aspect of the investigation represents the major results and conclusions of this investigation concerning the linear model technique as applied by previous authors. The discussion will consider open loop distillation column dynamics and feedforward control.

Column Open Loop Dynamics. The open loop dynamics of the distillation column were experimentally determined for disturbances in the feed composition, boil up rate and reflux rate. These are generally the streams which are of major importance in distillation column control. Commonly, disturbances are introduced into the system by means of the feed composition and then the vapor and reflux rates are varied to return the output compositions to the required values. Special situations can be proposed where this is not the problem of interest but in those cases the distillation column is being operated in a manner to meet the constraints being set by some other operation occurring in the process. From a control standpoint, it would be difficult to investigate generally all these special cases. But on the other hand, results obtained for this more general case should be applicable to special cases.

Open loop transfer functions were determined from eight pulse tests and are reported in this investigation. The dependent variables in all cases were the top and bottom compositions. This resulted in the calculation of sixteen open loop transfer functions. Three pulse tests involved changes in vapor rate while three tests involved changes in feed composition and the remaining two were reflux rate changes.

Figures 3 and 4, pages 62 and 66, are typical experimental open loop transfer functions. In all tests the bottoms composition transfer function is of higher order than the distillate transfer function and its response shows more or stronger nonlinear or higher order terms.

The linear model approximations are also included on each figure of the open loop transfer functions for comparison. It will be noted that for tests 6F, 6S, and 6V the corresponding linear models are all based on steady-state data from test 6F. At the second steady-state condition all the linear models are based on test 11F. This was done to reduce the total number of times that the linear model program had to be solved. It has no effect on the results since for each group of tests the steady-state conditions are approximately the same and the small variations between the tests in each group would have no effect on the column dynamics but would only slightly change the steady-state gains which are not considered accurate when determined in this manner.

In general the linear model fails to predict the high order and distributed parameter effects which occur at higher frequencies. This results from the removal of the nonlinear terms from the model. Even if the linear model fails to predict the high order and nonlinear effects which are present in the experimental data the linear model does predict the dynamics of the system to a first approximation. In most cases high frequency response data is not required for the system and the first order approximation is satisfactory. The actual error in the gain curves between the experimental tests and the linear model results are in general smaller than for the phase curves. This probably results from the fact that only approximate dead times were included in the model where on the other hand the actual equipment had dead time which could not be precisely estimated. Better estimates would have probably improved the phase angle curves since dead time has no effect on the gain curve.

To determine if the high order effects which appeared were actual system responses and not the effect of sampling or data spacing, a regression analysis was used to fix a power series to the pulse test data resulting from test 6F. This equation was used to calculate new data points at a smaller interval for use in the frequency response program. Terms were added to the regression equation until the coefficient of determination was increased to a value above 0.90. This was to insure a good fit of the experimental data. Figure 14, page 149, shows the comparison of the system frequency response based on the regression model and the points determined from only the experimental data are plotted for comparison. The regression model data agrees with the experimental data out to frequencies of 0.2 radians per second after which the model still predicts the same break points. The reduction in magnitude at the break points results probably from the smoothing of the actual data in the regression analysis. This result gives support to the validity experimental frequency response curves determined for the system during this investigation and rules out effects of data sampling on the response curves.

The open loop experimental transfer functions which were determined during this investigation definitely support the linear model assumption and the transient response data which has been used to justify the linear model assumption in the past. It does point out, however, that this is only a first order assumption and great care must be used when the absolute system response is required, or very close control must be obtained due to some process requirement. In these cases the actual nonlinear model should result in data that is in closer agreement with experimental results.

Another point which should be mentioned with regard to the results is the speed of the disturbances for which the linear model agrees, with the experimental data. If the curves agree out to 0.1 radians per minute, then one is considering disturbances which are occurring at a frequency of 1.6 cycles per minute. Generally, it would be better to design enough holdup capacity ahead of a unit to filter out disturbances which occur with such a high frequency. Generally, distillation column control schemes are only designed to remove disturbances which occur at very low frequencies compared to the response speed of the units.

Another point which can be observed from the experimental transfer functions is the nonlinear effects. Tests 9V and 10V are similar tests except for the direction of the pulse as were tests 11F and 12F. If the column behavior was truly linear then one would expect the transfer functions for the similar tests to be the same in both cases. It will be noted that to a first approximation the curves are the same but, at higher frequencies there is a general disagreement. This data supports the fact that generally the nonlinear effects will not be important except at high frequencies.

Feedforward Control. Three sets of feedforward controllers were calculated and compared with the predicted controllers based on the linear model assumption. One feedforward controller was calculated based on tests 6F, 6S, and 6V which were at the same steady-state conditions and two controllers were calculated based on the transfer functions determined at the second steady-state condition which encompassed the five remaining pulse tests.

A very suprising result occurred from the design of the feedforward controller. In all cases the linear model predicted only a proportional controller with, maybe, dead time added over the frequency range of interest. The experimental feedforward controllers did not always predict a proportional controller but they did predict a controller made up of only a first order lag followed by a first order lead which in effect is a proportional controller. This means that the feedforward controller is a very simple instrument for every case considered in this study. This result may help explain the good results that have been reported with feedforward controllers which were only simple functions and were designed by very approximate methods. If this result could be shown to be general, then the linear model assumption for the design of a feedforward controller would not be a critical assumption. This would reduce the work required to design feedforward controllers for existing columns. Only very simple tests would be required to determine the constants for an acceptable feedforward controller. More weight is given to this possibility by the fact that Foxboro is presently marketing a feedforward controller instrument which has a very simple function and they appear to obtain satisfactory operation in most cases reported. As far as can be determined there is no way of generally proving that this simple relationship will hold for distillation columns and at present each case must still be considered separately. At the same time there is no reason to believe that the feedforward controller should be a complex function over the range of frequencies of interest providing high frequency response is not required.

The feedforward programs have been checked in detail for errors and were compared with the programs used at the University of Delaware and found to be the same. The results have also been compared with the results reported by Luyben (33, 35). Luyben's feedforward controllers show dynamic terms but these functions appear at higher frequencies. These were actually investigated in this study and are above the range generally of interest.

Care should be used when reading the phase angle values for the feedforward controller transfer functions if they are large positive values. These values have had 180° added to them because of the way the phase angle was calculated and corrected for the steady-state gain value. The program was set up to accept positive real and imaginary numbers and in that case calculate a positive angle. This was done due to the possibility of the controllers containing leads. Therefore, when the program calculates an uncorrected angle greater than -270° it converts it to a positive angle and depending on the quadrant of the initial steady-state value it will add 180° to this value. Therefore, positive angles between 180° and 270° should have 180° subtracted from them to obtain the correct values.

Recommendations

In the course of this investigation several research areas have appeared which should add further insight into the dynamics and feedforward control of binary distillation columns. These recommendations are reported in the following sections.

Nonlinear Model. In this investigation it has been shown that the linear model is a good first order approximation of a binary distillation column. To further substantiate the applicability of a linear model it would be of interest to solve the nonlinear model and determine the per cent improvement one could expect by going to the more difficult model. This could afford some economic data on the per cent improvement versus increased computational time required due to the increased complexity.

Experimental Feedforward Control. Based upon the results of this investigation it appears that the feedforward controller should be a very simple function. There also appears to be a disagreement in the form of this function based upon the linear model and on the experimental data. Experimental testing of these feedforward controllers would establish the actual difference between these controllers. The controller based on a nonlinear model could also be included in the experimental work.

Feedforward Control. Due to the very simple feedforward controllers which were predicted during this investigation, it would be of interest to the industrial control engineer if some short cut method could be developed to estimate these controllers. It may be possible to correlate the physical aspects of the separation and equipment with the required feedforward controller functions and time constants. If it could be shown that in most separations a very simple controller will give some percentage of perfect feedforward control then this problem would reduce down to estimating the required time constants for the controller.

Analog Modeling. The analog computer would present another way of solving the set of nonlinear distributed parameter equations for the comparison with the experimental results. This method would have some advantages over a digital approach to this problem. The analog computer would allow one to estimate the required system dead times by comparing the response curves of the model with the experimental system.

Limitations

A list of the limitations imposed upon the operation of the distillation column used for this investigation along with the restrictions used in the linear model development are given in the following sections.

Distillation Column. The distillation column used was an 18 plate sieve tray tower, with an eight inch inside diameter. The primary material of construction was 1/8-inch copper sheet metal. The plates were spaced one foot apart. Each plate contained 195, 9/64-inch holes located on a 3/8-inch equilateral triangular pitch. The trays were equipped with 1-1/4 - inch inlet weirs and 3/4-inch outlet weirs. The heat for boilup was supplied by a thermosiphen reboiler consisting of 21, 3/4-inch diameter tubes containing an inside area of 18.75 square feet. The column was insulated with approximately 1-1/2 - inches of fiberglass insulation.

System Used. The binary mixture used in the distillation column consisted of a mixture of n-heptane and benzene. These materials had a minimum purity specification of 99 mole per cent.

Feed Flow Rates. The feed flow rates used during the dynamic tests were varied for the steady-state conditions between 0.0596 and

0.0635 moles per minute and benzene concentrations varied between 0.6186 and 0.6911 mole fraction benzene.

Reflux Rates. The steady-state reflux flow rates for tests 6F, 6S, and 6V varied between 0.0704 and 0.0705 moles per minute. The reflux flows for tests 8R, 9V, 10V, 11F, and 12F varied between 0.0686 and 0.0690 moles per minute. For reflux flow rate pulse test 6S the reflux rate was increased from 0.0705 to 0.1075 moles per minute and maintained at this value for a period of six minutes. The reflux flow rate for dynamic test 8R was increased from 0.0688 to 0.0854 for a period of fifteen minutes.

Vapor Rates. The reboiler steady-state vapor rates were maintained between 0.0274 and 0.0283 moles per minute for tests 6F, 6S and 6V. Likewise for tests 8R, 9V, 10V, 11F and 12F the vapor rate varied from test to test between 0.1205 and 0.1234 moles per minute. For pulse test 6V the vapor rate was increased from 0.1143 to 0.1258 moles per minute for a period of five minutes. For test 9V the vapor was decreased from 0.1277 to 0.1197 moles per minute for a fifteen minute period. Likewise for test 10V the vapor rate was increased from 0.1234 to 0.1271 for an interval of twenty minutes.

Bottoms Flow Rates. The steady-state bottoms flow rates during tests 6F, 6S, and 6V varied between 0.0274 and 0.0283 moles per minute. For tests 8R, 9V, 10V, 11F and 12F the steady-state bottoms flow rates varied between 0.0170 and 0.0205 moles per minute.

Distillate Flow Rates. The steady-state distillate flow rates for tests 6F, 6S, and 6V varied between 0.0340 and 0.0352 moles per minute. During tests 8R, 9V, 10V, 11F and 12F the flows varied between 0.0439 and 0.0464 moles per minute.

Feed Composition Pulses. Three feed composition pulses were used during this investigation. These pulses were rectangular waves to a first order approximation. For test 6F the feed composition was decreased from 0.64 to 0.44 mole fraction benzene for a period of ten minutes. In test 11F the feed composition decreased from 0.67 to 0.30 mole fraction benzene for an eight minute period. Likewise during test 12F the feed composition was increased from 0.64 to 0.83 mole fraction benzene for a period of six minutes.

F-factors. The F-factors for the first group of tests were approximately 0.94 above the feed tray and 1.04 in the section below the feed tray. During the second set of tests the F-factor was approximately 1.04 in the rectification section and 1.175 in the stripping section.

Column Pressure. The column absolute pressure for the first group of tests was controlled in the range of 950 to 1050 millimeters of Hg. For the second group of tests the pressure was in the range of 875 and 975 millimeters Hg absolute.

Sample Frequencies. During dynamic tests 6F, 6S, and 6V liquid samples were collected at one minute intervals. During dynamic tests 8R, 9V, 10V, 11F and 12F continuous refractive index data were recorded and values read off from the chart records for analysis at 0.25 minute intervals. The frequency responses of the dynamic data was considered to be accurate out to 0.6 radians per minute.

Linear Model Assumptions. The following assumptions were included in the linear model analysis:

1. Operational changes in all column variables are assumed small in relation to their steady-state values.
2. Compositions and flow rates are the primary variables from which fluctuations in temperatures and pressures are derived. Therefore, energy equations for the trays are not required.
3. The column operates adiabatically, and at steady-state and the molal flow rates of vapor and liquid streams are constant through the sections of the column above and below the feed tray.
4. The vapor holdup is negligible.
5. The liquid holdup on each tray is completely mixed so that the composition of liquid leaving is the same as that obtained by mixing all the holdup.
6. Fluctuations in column operation are caused by changes in feed flow rate, composition, reflux flow rate, and vapor boilup rates only.

VI. CONCLUSIONS

This study involved the determination of the open loop transfer functions for a binary distillation column and the comparison of these transfer functions with the predicted transfer functions based on the linear model assumption. The feedforward controller transfer functions required for changes in feed composition were developed based on both the linear model and experimental open loop transfer functions.

The pulse testing method was used to determine experimentally the system open loop transfer functions. Rectangular pulses were introduced into the feed composition, vapor boilup rates and the reflux flow rates for determining the open loop transfer functions. A total of eight pulse tests were conducted on the system; three feed composition pulses, three vapor boil-up rate pulses and two reflux rate pulses. The distillate and bottoms composition were sampled at one minute intervals for tests 6F, 6S, and 6V and were determined continuously for the remaining tests by the use of continuous process refractometers. The actual composition values were determined from the refractive index readings by the use of a regression equation developed for this purpose. The conclusions of this investigation are also subject to the limitations of the investigation. As a result of this investigation the following conclusions are drawn:

1. Distillation column open loop dynamics can be represented by a linear model as a first order approximation for frequencies out to 1.6 radians per dimensionless time. Where the dimensionless time is defined as the tray liquid holdup divided by the stripping section liquid rate.
2. Nonlinear and higher order effects do not affect distillation column dynamics below 1.6 radians per dimensionless time.
3. Simple feedforward controller functions should provide adequate control in the low frequency range generally of interest for distillation column control. Feedforward controllers consisting of proportional first order elements with dead time satisfy the requirements determined in this investigation.
4. Linear models fail to predict the higher order effects present at higher frequencies in distributed parameter systems.
5. Pulse techniques and numerical integration are adequate for the determination of system dynamics.
6. The use of linear models for the design of feedforward controllers results in controller transfer functions which are of lower order than predicted from experimental data.

VII. SUMMARY

This investigation involved the determination of the experimental open loop transfer functions for a binary distillation column and the comparison of these transfer functions to the transfer functions based on the solution of a set of linearized equations used to describe the system. The experimental transfer functions and the linear model transfer functions were then used to calculate the feed-forward controller transfer functions for changes in feed composition. Then a comparison of these independently developed transfer functions was made to estimate the effect of the linear model assumption on the system controller functions.

The experimental system consisted of an eight-inch diameter distillation column equipped with 18-sieve trays, a reboiler and a total condenser. The tray spacing was 12 inches. The tower was operated as an atmospheric column separating benzene from normal heptane.

The experimental tests consisted of pulse tests conducted at two separate steady-state conditions. At each of the steady-states conditions, the bottom and distillate composition responses were determined as functions of the feed composition, reflux rate and boilup rate. The pulse data was collected in the form of refractive index readings as a function of time. The refractive index data was converted to mole fraction benzene and then converted from pulse data to frequency response data and plotted as a Bode diagram. These plots give the transfer function relationship between the distillate and bottoms compositions and each of the forcing functions: feed composition, reflux rate and boilup rate.

For each steady-state condition, the open loop transfer functions for the distillate and bottoms compositions to disturbances in the feed composition, reflux rate and vapor or boilup rate were determined based on the linear model assumption. These calculations utilized the techniques developed by Lamb and Pigford for linearization and solution of the set of equations by stepping up the column in the frequency domain along with the required matrix inversion to obtain the required transfer functions.

The transfer functions based on the linear model were then compared to the experimental results to determine the effect or error resulting from the linear model assumption.

The open loop transfer functions determined from both the linear model and experimental pulse tests were then used to determine the required feedforward controller transfer functions. These transfer functions were also then compared.

Based upon this investigation it was concluded that the column transfer functions could be represented by the transfer functions based on the linear model to a first order approximation. The experimental and linear model transfer functions were in close agreement up to frequencies in the vicinity of 1.6 radians per dimensionless time, where the dimensionless time is defined as the tray holdup divided by the stripping section liquid rate. The nonlinear and higher order effects do not become important or appreciably effect the distillation column dynamics in the frequency range below 1.6 radians per dimensionless time. The linear model assumption does fail to predict the higher order and nonlinear effects present in the system at higher frequencies.

The results of this study indicate that very simple feedforward controller transfer functions should provide adequate control for distillation columns in the low frequency range. The feedforward controller transfer functions predicted by the linear model assumption were generally of lower order than predicted by the experimental data.

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XI. APPENDIX

The Appendix has been divided into two sections: Additional Data and Results Section and the Digital Computer Programs Section.

Additional Data and Results

Data and results which have been determined and discussed during this investigation has been included here for completeness and convenience to the reader. This data includes the steady-state conditions, experimental and linear model open loop transfer functions for pulse tests 6F, 6S, 6V, 8R, 9V, 10V, and 12F. For ease of comparison the experimental and linear model open loop transfer function data for each test have been plotted together.

Data Tables. For pulse tests 6F, 6S, 6V, 8R, 9V, 10V, and 12F the steady-state conditions at the start of each test are reported in Tables XXV, XXVI, XXXII, XXXIII, XXXVIII, XXXIX, XXXXVI, XXXXVII, LIV, LV, LX, LXI, LXVIII, and LXVIV, pages 140, 141, 150, 151, 158, 159, 168, 169, 178, 179, 186, 187, 196, and 197. The steady-state conditions at the completion of tests 6V, 8R, 9V, 10V, and 12F are reported in Tables XXXXIV, XXXXV, LII, LIII, LVIII, LIX, LXIV, LXV, LXXII, and LXXIII on pages 166, 167, 176, 177, 184, 185, 192, 193, 202, and 203.

The experimental frequency response open loop transfer function data for pulse tests 6F, 6S, 6V, 8R, 9V, 10V, and 12F are reported in Tables XXVII, XXIX, XXXIV, XXXVI, XXXX, XXXXII, XXXXVIII, L, LVI, LVII, LXII, LXIII, LXX, and LXXI, pages 142, 145, 155, 160, 163, 170, 173, 180, 182, 188, 190, 198, and 200. The corresponding open loop transfer functions based on the linear model assumptions are reported in Tables XXVIII, XXX, XXXV, XXXVIII, XXXXI, XXXXIII, IL, LI, LXVI, and LXVII on pages 143, 146, 153, 156, 161, 164, 171, 174, 194, and 195. The open loop transfer functions based on the linear model assumption used for comparison to experimental pulse test results for tests 6F, 6S, and 6V are based on steady-state data taken from test 6F. Likewise linear nodel transfer functions used for comparison to pulse test results for tests 8R, 9V, 10V, and 12F are based on steady-state data from pulse test 11F.

These transfer functions are plotted for ease of comparison in Figures 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, and 26,on pages 142, 147, 149, 154, 157, 162, 165, 172, 175, 181, 183, 189, 191, 199, and 201.

TABLE XXV

BINARY DISTILLATION STEADY-STATE TEST DATA
HEAT AND MATERIAL BALANCES
EXPERIMENTAL DATA SET 6F

STREAM	MOLES/MINUTE	MOLES BENZENE/MINUTE
FEED	0.0611	0.0388
BOTTOMS	0.0283	0.0085
OVERHEAD	0.0346	0.0305
REFLUX	0.0704	0.0621

TOTAL MASS ERROR -0.0018 PERCENT 3.0131

BENZENE ERROR -.0002 PERCENT 0.5775

COLUMN INTERNAL FLOW RATES

TOP VAPOR 0.111150

TOP LIQUID 0.076548 L/V TOP 0.688693

BOTTOM VAPOR 0.115479

BOTTOM LIQUID 0.141942 L/V BOTT 1.229157

Q-VALUE FEED = 1.0709 REFLUX = 1.0874

F-FACTOR TOP = 0.9389 BOTTOM = 1.0411

FEED TRAY = 11

HEAT BALANCE DATA

	INPUT BTU/MIN	OUTPUT BTU/MIN	ERROR BTU/MIN	PERCENT ERROR
OVERALL	2665.7	2227.1	438.5	16.45
CONDENSER	2739.3	2507.8	231.5	8.45
TOWER	3467.4	3260.3	207.1	5.97

TABLE XXVI

BINARY DISTILLATION STEADY-STATE TEST DATA
TRAY TO TRAY CALCULATION RESULTS
EXPERIMENTAL DATA SET 6F

FEED TRAY = 11

TRAY	LIQUID MOLE FRACT	TEMPERATURE DEGREES F	EQUILIBRIUM CURVE SLOPE	EFFICIENCY MURPHERE	PRESSURE MM HG
FEED	0.6349	180.00			
REFLUX	0.8824	164.00			
1	0.8644	196.50	0.7118	0.4839	1001.1
2	0.8433	197.00	0.7044	0.5785	999.6
3	0.8167	198.00	0.6962	0.7367	1003.6
4	0.8009	198.50	0.6922	0.4385	1004.4
5	0.7810	199.50	0.6879	0.5548	1011.2
6	0.7594	199.50	0.6845	0.6002	1001.1
7	0.7367	200.50	0.6823	0.6247	1006.5
8	0.7140	201.00	0.6817	0.6256	1003.6
9	0.6919	202.00	0.6827	0.6011	1009.0
10	0.6755	202.50	0.6845	0.4326	1009.0
11	0.6527	203.00	0.6887	0.4326	1005.9
12	0.6412	204.00	0.6916	0.5274	1016.2
13	0.6241	205.00	0.6969	0.5851	1023.7
14	0.6047	205.20	0.7042	0.5147	1017.2
15	0.5716	206.50	0.7207	0.6442	1021.1
16	0.5058	208.00	0.7688	0.8485	1010.8
17	0.4403	209.50	0.8393	0.6531	999.7
18	0.3787	213.00	0.9285	1.0532	1021.2
REBOILER	0.2990	217.50	1.0808	1.0532	1047.1

TRAY HOLDUP TOP = 0.00950 MOLES BOTTOM = 0.00876 MOLES

TIME CONSTANT, TRAY HOLDUP/LIQUID RATE = 0.06175 MINUTES

TABLE XXVII

REFLUX COMPOSITION/FEED COMPOSITION EXPERIMENTAL FREQUENCY RESPONSE RESULTS FOR PULSE TEST 6F

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
0.0392	-0.0000	-28.1313

MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1.0000	0.00	0.0000	0.0000
1.0000	-0.07	-0.0000	0.0001
1.0000	-0.33	-0.0001	0.0005
1.0000	-0.65	-0.0004	0.0010
0.9988	-3.25	-0.0101	0.0050
0.9977	-4.54	-0.0197	0.0070
0.9954	-6.48	-0.0400	0.0100
0.9898	-9.65	-0.0892	0.0150
0.9821	-12.77	-0.1566	0.0200
0.9727	-15.78	-0.2405	0.0250
0.9617	-18.69	-0.3390	0.0300
0.9367	-24.08	-0.5678	0.0400
0.9105	-28.82	-0.8141	0.0500
0.8872	-32.82	-1.0395	0.0600
0.8710	-36.15	-1.2001	0.0700
0.8654	-38.99	-1.2554	0.0800
0.8729	-41.64	-1.1810	0.0900
0.8935	-44.48	-0.9780	0.1000
0.9872	-54.05	-0.1123	0.1250
1.0912	-67.75	0.7581	0.1500
1.1507	-83.88	1.2194	0.1750
1.1422	-100.10	1.1552	0.2000
1.0028	-125.38	0.0243	0.2500
0.9297	-143.32	-0.6334	0.3000
0.7795	-164.18	-2.1642	0.3500
0.5588	-155.05	-5.0543	0.4000
1.0002	-151.82	0.0017	0.4500
1.3160	-186.63	2.3851	0.5000
0.9425	-213.52	-0.5139	0.5500
1.9102	-167.55	5.6218	0.6000

TABLE XXVIII

REFLUX COMPOSITION/FEED COMPOSITION OPEN LOOP TRANSFER FUNCTION BASED ON LINEAR MODEL FOR EXPERIMENTAL DATA SET 6F

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
0.0450	0.00	-26.9359

	MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1	1.0000	-0.00	0.0000	0.0000
2	1.0000	-0.03	-0.0000	0.0001
3	1.0000	-0.13	-0.0000	0.0005
4	1.0000	-0.25	-0.0001	0.0010
5	0.9997	-1.26	-0.0025	0.0050
6	0.9994	-1.76	-0.0048	0.0070
7	0.9989	-2.51	-0.0098	0.0100
8	0.9975	-3.75	-0.0218	0.0150
9	0.9956	-4.98	-0.0384	0.0200
10	0.9932	-6.21	-0.0591	0.0250
11	0.9904	-7.41	-0.0838	0.0300
12	0.9837	-9.76	-0.1432	0.0400
13	0.9758	-12.03	-0.2132	0.0500
14	0.9671	-14.21	-0.2904	0.0600
15	0.9581	-16.31	-0.3719	0.0700
16	0.9490	-18.33	-0.4550	0.0800
17	0.9399	-20.28	-0.5381	0.0900
18	0.9311	-22.16	-0.6197	0.1000
19	0.9107	-26.68	-0.8127	0.1250
20	0.8925	-31.00	-0.9877	0.1500
21	0.8763	-35.21	-1.1471	0.1750
22	0.8615	-39.37	-1.2951	0.2000
23	0.8344	-47.58	-1.5727	0.2500
24	0.8087	-55.73	-1.8445	0.3000
25	0.7831	-63.81	-2.1233	0.3500
26	0.7573	-71.80	-2.4151	0.4000
27	0.7310	-79.69	-2.7220	0.4500
28	0.7043	-87.46	-3.0445	0.5000
29	0.6775	-95.10	-3.3816	0.5500
30	0.6507	-102.61	-3.7321	0.6000

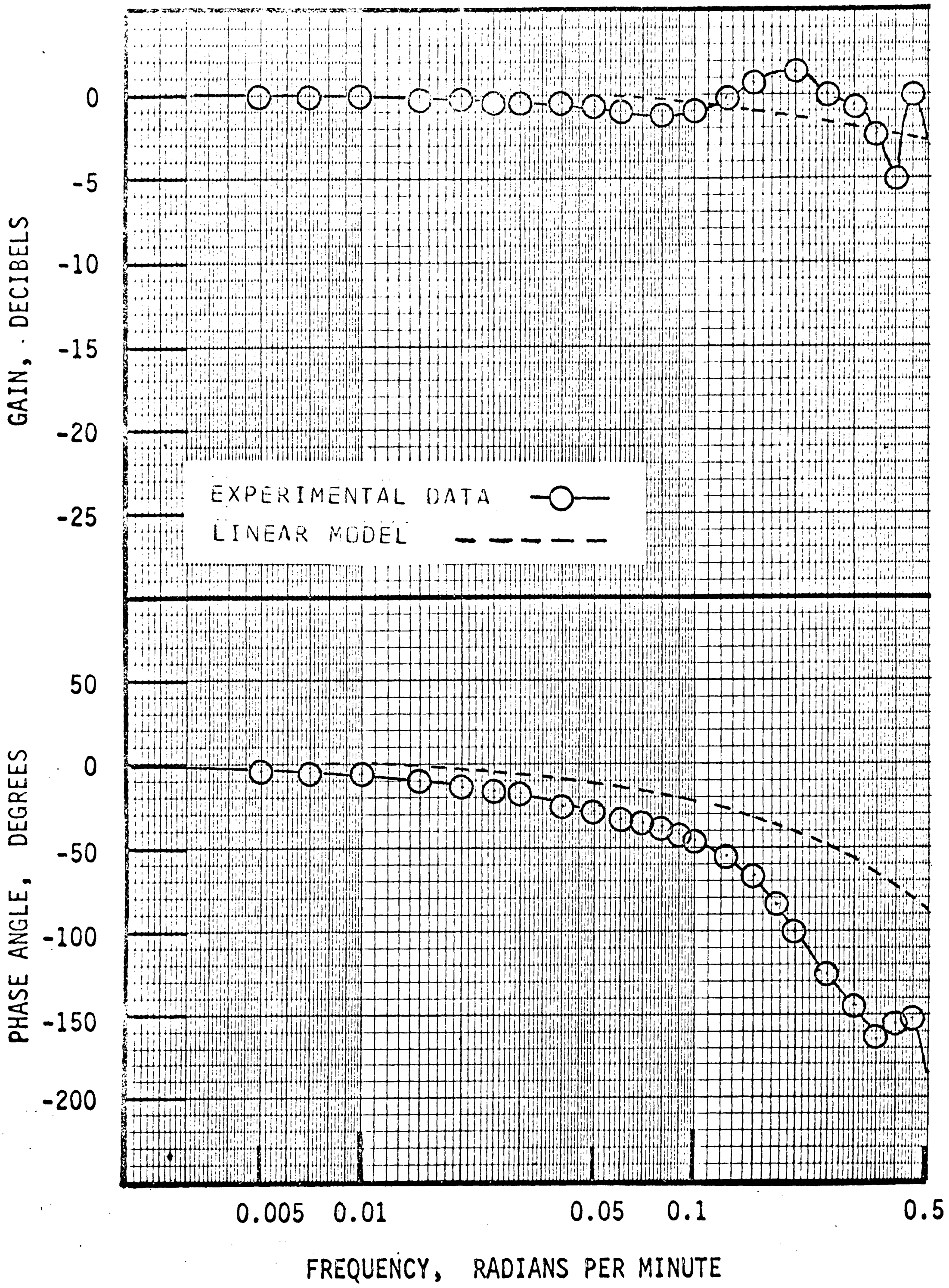

Figure 12. Reflux Composition/Feed Composition Open Loop Transfer Function based on Experimental and Linear Model Results for Test 6F

TABLE XXIX

BOTTOMS COMPOSITION/FEED COMPOSITION EXPERIMENTAL FREQUENCY RESPONSE RESULTS FOR PULSE TEST 6F

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
1.2911	-0.0000	2.2190

MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1.0000	0.00	-0.0000	0.0000
1.0000	-0.11	-0.0000	0.0001
1.0000	-0.56	-0.0002	0.0005
0.9999	-1.11	-0.0009	0.0010
0.9975	-5.57	-0.0216	0.0050
0.9951	-7.80	-0.0423	0.0070
0.9901	-11.13	-0.0864	0.0100
0.9778	-16.66	-0.1948	0.0150
0.9608	-22.16	-0.3474	0.0200
0.9392	-27.60	-0.5449	0.0250
0.9132	-32.97	-0.7884	0.0300
0.8493	-43.43	-1.4184	0.0400
0.7718	-53.35	-2.2502	0.0500
0.6840	-62.43	-3.2988	0.0600
0.5904	-70.23	-4.5778	0.0700
0.4963	-76.07	-6.0849	0.0800
0.4091	-78.89	-7.7630	0.0900
0.3386	-77.42	-9.4073	0.1000
0.2972	-60.55	-10.5399	0.1250
0.3830	-61.92	-8.3350	0.1500
0.4355	-79.85	-7.2207	0.1750
0.4062	-102.20	-7.8244	0.2000
0.1898	-127.84	-14.4337	0.2500
0.2168	-103.71	-13.2783	0.3000
0.2260	-148.31	-12.9173	0.3500
0.0450	-154.81	-26.9439	0.4000
0.1817	-119.07	-14.8120	0.4500
0.1445	-187.19	-16.8043	0.5000
0.1504	-69.21	-16.4529	0.5500
0.6911	-164.91	-3.2095	0.6000

TABLE XXX

BOTTOMS COMPOSITION/FEED COMPOSITION OPEN LOOP TRANSFER FUNCTION BASED ON LINEAR MODEL FOR EXPERIMENTAL DATA SET 6F

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
1.7522	0.00	4.8719

	MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1	1.0000	-0.00	-0.0000	0.0000
2	1.0000	-0.06	-0.0000	0.0001
3	1.0000	-0.30	-0.0001	0.0005
4	1.0000	-0.60	-0.0003	0.0010
5	0.9990	-2.98	-0.0085	0.0050
6	0.9981	-4.17	-0.0167	0.0070
7	0.9961	-5.94	-0.0340	0.0100
8	0.9913	-8.89	-0.0762	0.0150
9	0.9846	-11.81	-0.1346	0.0200
10	0.9763	-14.70	-0.2086	0.0250
11	0.9663	-17.53	-0.2973	0.0300
12	0.9424	-23.05	-0.5156	0.0400
13	0.9140	-28.32	-0.7813	0.0500
14	0.8825	-33.31	-1.0860	0.0600
15	0.8491	-38.02	-1.4213	0.0700
16	0.8148	-42.43	-1.7793	0.0800
17	0.7804	-46.57	-2.1533	0.0900
18	0.7467	-50.44	-2.5375	0.1000
19	0.6672	-59.06	-3.5147	0.1250
20	0.5970	-66.42	-4.4801	0.1500
21	0.5365	-72.79	-5.4092	0.1750
22	0.4846	-78.39	-6.2921	0.2000
23	0.4020	-87.91	-7.9144	0.2500
24	0.3403	-95.91	-9.3621	0.3000
25	0.2930	-102.89	-10.6638	0.3500
26	0.2557	-109.17	-11.8459	0.4000
27	0.2257	-114.92	-12.9295	0.4500
28	0.2011	-120.27	-13.9312	0.5000
29	0.1806	-125.30	-14.8638	0.5500
30	0.1634	-130.07	-15.7372	0.6000

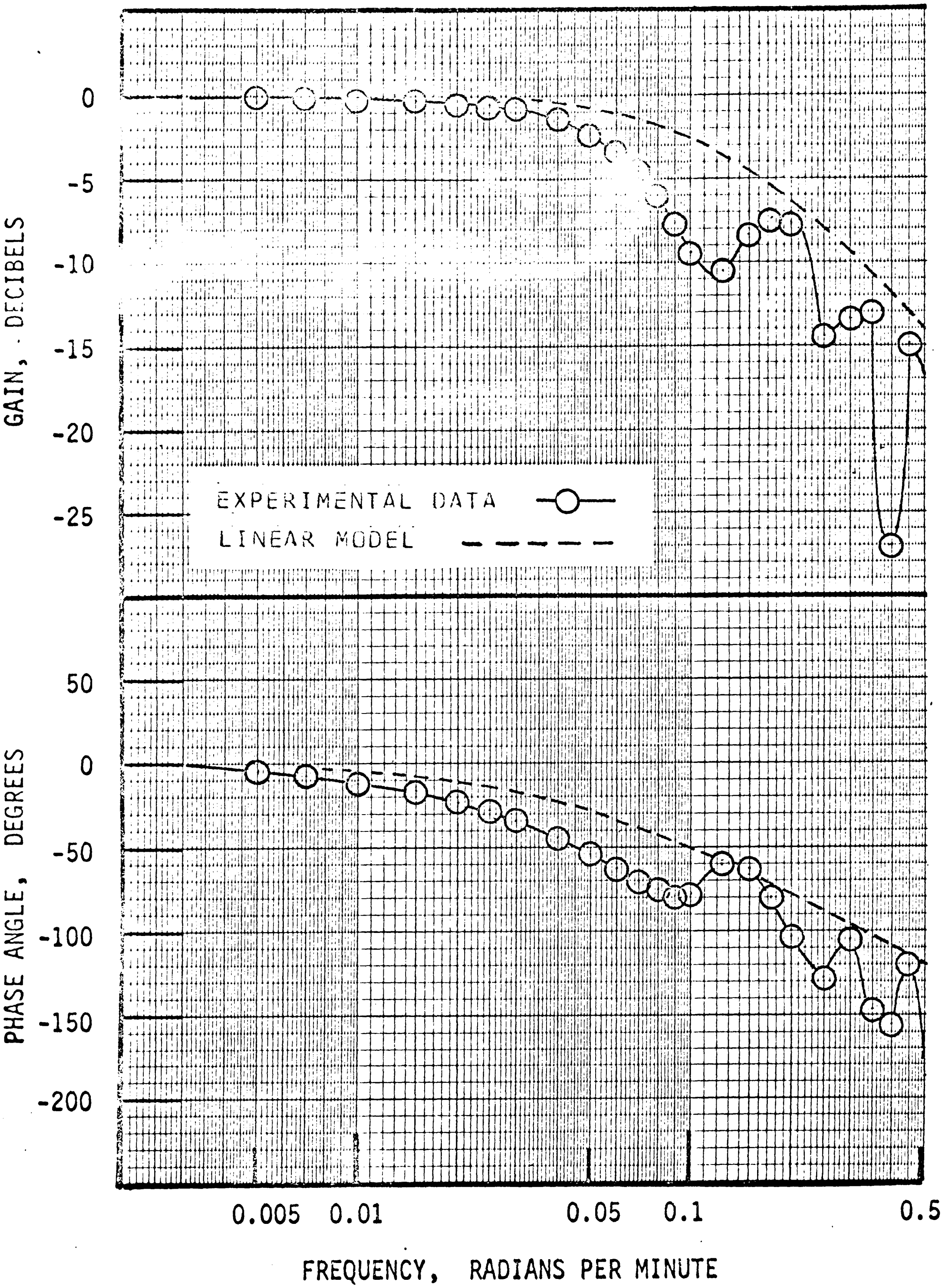

Figure 13. Bottoms Composition/Feed Composition Open Loop Transfer Function based on Experimental and Linear Model Results for Test 6F

TABLE XXXI

BOTTOMS COMPOSITION/FEED COMPOSITION EXPERIMENTAL FREQUENCY RESPONSE RESULTS FOR REGRESSION MODEL OF PULSE TEST 6F

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
1.2958	-0.0000	2.2510

MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1.0000	0.00	-0.0000	0.0000
1.0000	-0.11	-0.0000	0.0001
1.0000	-0.55	-0.0002	0.0005
0.9999	-1.11	-0.0009	0.0010
0.9975	-5.53	-0.0216	0.0050
0.9951	-7.74	-0.0423	0.0070
0.9901	-11.05	-0.0864	0.0100
0.9778	-16.55	-0.1949	0.0150
0.9608	-22.00	-0.3475	0.0200
0.9392	-27.41	-0.5450	0.0250
0.9132	-32.74	-0.7885	0.0300
0.8493	-43.13	-1.4183	0.0400
0.7718	-52.97	-2.2495	0.0500
0.6842	-61.98	-3.2970	0.0600
0.5906	-69.73	-4.5735	0.0700
0.4968	-75.53	-6.0763	0.0800
0.4099	-78.33	-7.7474	0.0900
0.3395	-76.90	-9.3838	0.1000
0.2972	-60.37	-10.5404	0.1250
0.3809	-61.96	-8.3848	0.1500
0.4314	-80.42	-7.3014	0.1750
0.4008	-104.17	-7.9410	0.2000
0.1660	-142.92	-15.5990	0.2500
0.1252	-89.80	-18.0463	0.3000
0.1223	-127.44	-18.2530	0.3500
0.0646	-55.14	-23.7899	0.4000
0.1516	-95.78	-16.3856	0.4500
0.0071	-35.89	-42.9470	0.5000
0.2961	-49.53	-10.5717	0.5500
0.3421	-134.02	-9.3170	0.6000

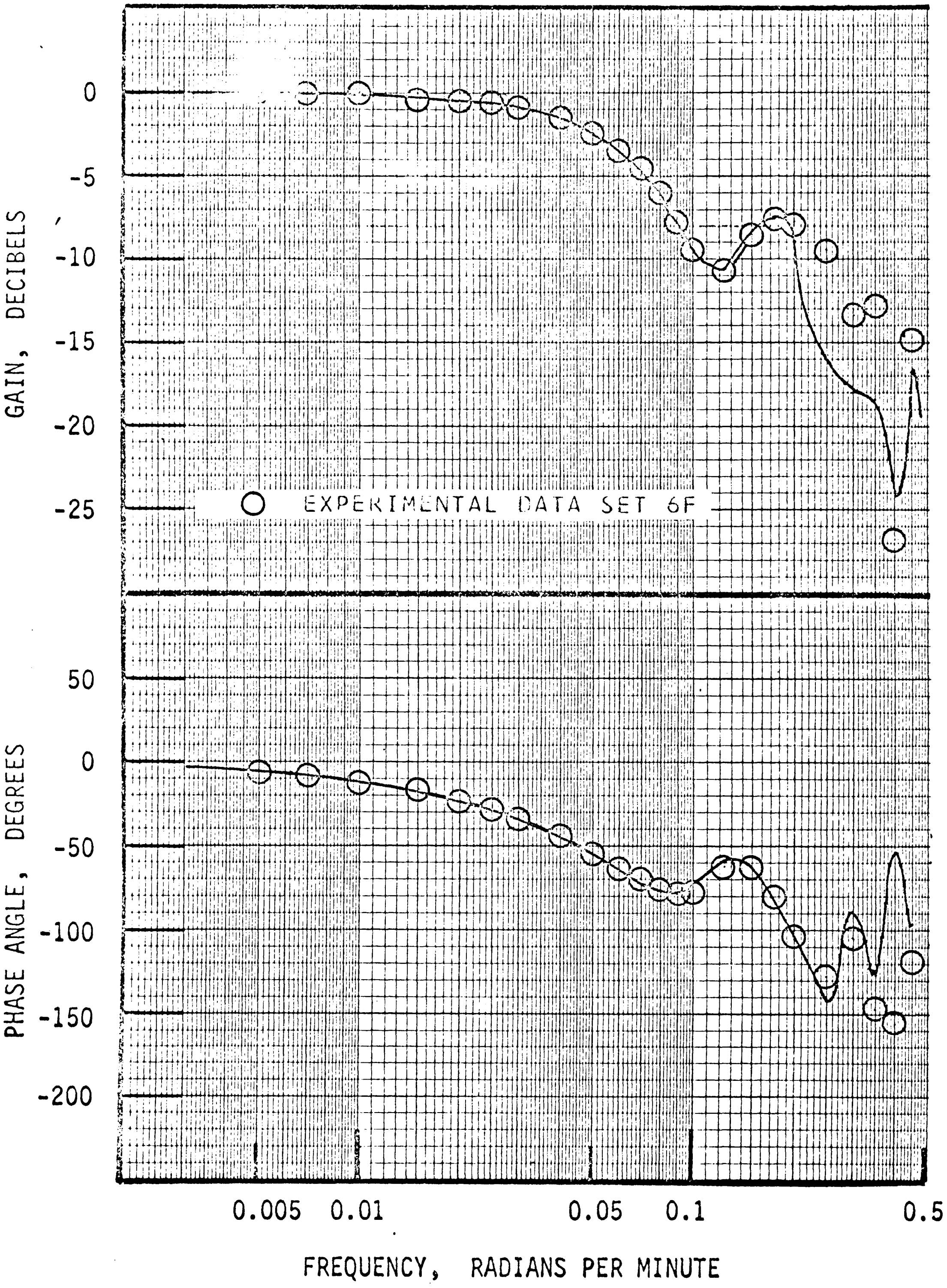

Figure 14. Bottoms Composition/Feed Composition Open Loop Transfer Function based on Data from Regression Model of Experimental Pulse Data 6F

TABLE XXXII

BINARY DISTILLATION STEADY-STATE TEST DATA
HEAT AND MATERIAL BALANCES
EXPERIMENTAL DATA SET 6S

```
STREAM          MOLES/MINUTE             MOLES BENZENE/MINUTE

FEED                 0.0612                     0.0392

BOTTOMS              0.0274                     0.0083

OVERHEAD             0.0352                     0.0312

REFLUX               0.0705                     0.0624

TOTAL MASS ERROR -0.0014         PERCENT   2.3248

BENZENE ERROR        -.0002       PERCENT   0.6253

COLUMN INTERNAL FLOW RATES
TOP VAPOR            0.112063

TOP LIQUID           0.076822     L/V TOP   0.685524

BOTTOM VAPOR         0.116578

BOTTOM LIQUID        0.142544     L/V BOTT 1.222737


Q-VALUE        FEED =   1.0738     REFLUX =   1.0899

F-FACTOR       TOP  =   0.9409     BOTTOM =   1.0426

                    FEED TRAY = 11


                    HEAT BALANCE DATA

              INPUT         OUTPUT         ERROR         PERCENT
             BTU/MIN       BTU/MIN        BTU/MIN         ERROR

OVERALL       2686.7        2192.7          494.0          18.39

CONDENSER     2758.5        2489.7          268.8           9.74

TOWER         3487.9        3262.6          225.2           6.46
```

TABLE XXXIII

BINARY DISTILLATION STEADY-STATE TEST DATA
TRAY TO TRAY CALCULATION RESULTS
EXPERIMENTAL DATA SET 6S

FEED TRAY = 11

TRAY	LIQUID MOLE FRACT	TEMPERATURE DEGREES F	EQUILIBRIUM CURVE SLOPE	EFFICIENCY MURPHERE	PRESSURE MM HG
FEED	0.6412	180.00			
REFLUX	0.8854	164.00			
1	0.8611	197.50	0.7106	0.6808	1015.7
2	0.8397	197.50	0.7032	0.6108	1006.0
3	0.8180	198.50	0.6966	0.6281	1012.2
4	0.8016	199.20	0.6923	0.4768	1015.9
5	0.7803	199.80	0.6878	0.6224	1015.7
6	0.7542	200.50	0.6838	0.7623	1014.7
7	0.7367	201.00	0.6823	0.5080	1014.5
8	0.7156	201.50	0.6817	0.6156	1012.4
9	0.6936	202.50	0.6825	0.6362	1017.8
10	0.6787	203.00	0.6841	0.4124	1018.6
11	0.6579	204.00	0.6876	0.4124	1024.5
12	0.6456	205.00	0.6904	0.5708	1034.5
13	0.6232	205.20	0.6972	0.7183	1026.4
14	0.6075	206.00	0.7031	0.4119	1031.4
15	0.5716	206.80	0.7207	0.6789	1025.9
16	0.5068	208.00	0.7679	0.8259	1011.4
17	0.4554	209.80	0.8209	0.5331	1012.6
18	0.3914	213.00	0.9082	1.1114	1028.3
REBOILER	0.3026	218.00	1.0731	1.1114	1057.3

TRAY HOLDUP TOP = 0.00948 MOLES BOTTOM = 0.00877 MOLES

TIME CONSTANT, TRAY HOLDUP/LIQUID RATE = 0.06152 MINUTES

TABLE XXXIV

BOTTOMS COMPOSITION/REFLUX RATE EXPERIMENTAL FREQUENCY RESPONSE RESULTS FOR PULSE TEST 6S

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
9.4414	0.0000	19.5007

MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1.0000	-0.00	-0.0000	0.0000
1.0000	-0.07	-0.0000	0.0001
1.0000	-0.37	-0.0000	0.0005
1.0000	-0.74	-0.0001	0.0010
0.9996	-3.69	-0.0033	0.0050
0.9992	-5.17	-0.0066	0.0070
0.9985	-7.39	-0.0134	0.0100
0.9965	-11.09	-0.0303	0.0150
0.9938	-14.80	-0.0542	0.0200
0.9902	-18.51	-0.0855	0.0250
0.9858	-22.25	-0.1245	0.0300
0.9742	-29.75	-0.2271	0.0400
0.9587	-37.32	-0.3663	0.0500
0.9390	-44.95	-0.5468	0.0600
0.9148	-52.65	-0.7739	0.0700
0.8858	-60.39	-1.0533	0.0800
0.8520	-68.17	-1.3909	0.0900
0.8135	-75.94	-1.7924	0.1000
0.6987	-95.08	-3.1147	0.1250
0.5651	-113.02	-4.9577	0.1500
0.4281	-128.18	-7.3688	0.1750
0.3074	-138.03	-10.2452	0.2000
0.1819	-136.55	-14.8037	0.2500
0.1543	-137.66	-16.2336	0.3000
0.1308	-140.36	-17.6708	0.3500
0.1322	-150.59	-17.5767	0.4000
0.1018	-176.65	-19.8465	0.4500
0.0425	-178.03	-27.4343	0.5000
0.0489	-143.66	-26.2157	0.5500
0.0410	-152.94	-27.7412	0.6000

TABLE XXXV

BOTTOMS COMPOSITION/REFLUX RATE OPEN LOOP TRANSFER FUNCTION BASED ON LINEAR MODEL FOR EXPERIMENTAL DATA SET 6F

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
1.2569	0.00	1.9863

	MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1	1.0000	-0.00	-0.0000	0.0000
2	1.0000	-0.06	-0.0000	0.0001
3	1.0000	-0.30	-0.0001	0.0005
4	1.0000	-0.60	-0.0003	0.0010
5	0.9990	-3.00	-0.0086	0.0050
6	0.9981	-4.20	-0.0169	0.0070
7	0.9960	-5.99	-0.0345	0.0100
8	0.9912	-8.96	-0.0772	0.0150
9	0.9844	-11.91	-0.1364	0.0200
10	0.9760	-14.81	-0.2113	0.0250
11	0.9659	-17.67	-0.3013	0.0300
12	0.9416	-23.24	-0.5226	0.0400
13	0.9128	-28.55	-0.7923	0.0500
14	0.8809	-33.59	-1.1019	0.0600
15	0.8470	-38.34	-1.4428	0.0700
16	0.8121	-42.80	-1.8074	0.0800
17	0.7772	-46.98	-2.1888	0.0900
18	0.7429	-50.89	-2.5813	0.1000
19	0.6620	-59.61	-3.5830	0.1250
20	0.5903	-67.06	-4.5780	0.1500
21	0.5283	-73.50	-5.5419	0.1750
22	0.4751	-79.16	-6.4645	0.2000
23	0.3899	-88.77	-8.1805	0.2500
24	0.3259	-96.77	-9.7396	0.3000
25	0.2764	-103.69	-11.1688	0.3500
26	0.2373	-109.80	-12.4928	0.4000
27	0.2058	-115.30	-13.7309	0.4500
28	0.1799	-120.30	-14.8979	0.5000
29	0.1584	-124.88	-16.0048	0.5500
30	0.1403	-129.10	-17.0597	0.6000

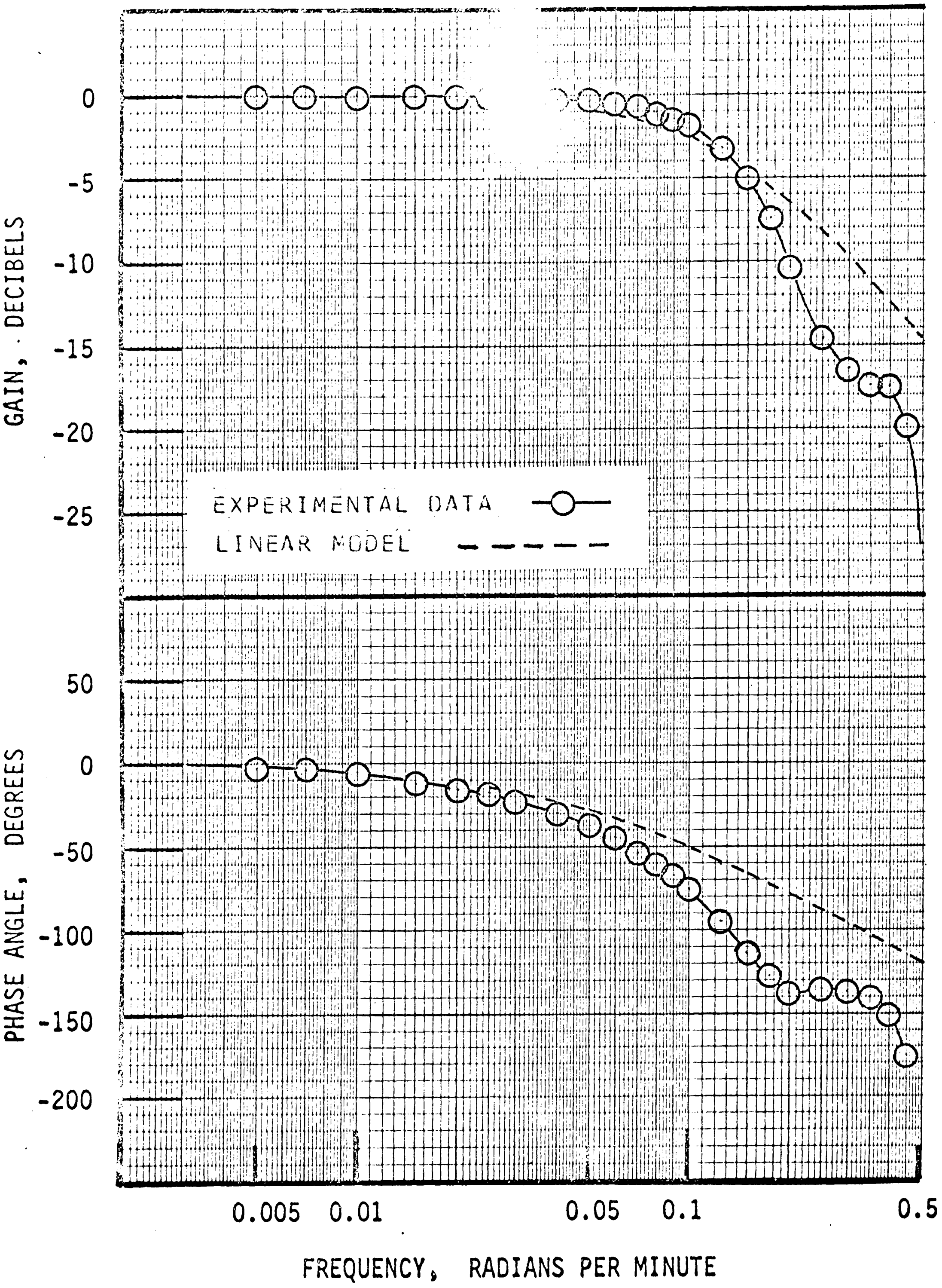

Figure 15. Bottoms Composition/Reflux Rate Open Loop Transfer Function based on Experimental and Linear Model Results for Test 6S

TABLE XXXVI

REFLUX COMPOSITION/REFLUX RATE EXPERIMENTAL FREQUENCY RESPONSE RESULTS FOR PULSE TEST 6S

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
1.8081	0.0000	5.1447

MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1.0000	-0.00	-0.0000	0.0000
1.0000	-0.05	-0.0000	0.0001
1.0000	-0.24	-0.0000	0.0005
1.0000	-0.49	-0.0001	0.0010
0.9996	-2.44	-0.0034	0.0050
0.9992	-3.42	-0.0066	0.0070
0.9984	-4.88	-0.0135	0.0100
0.9965	-7.31	-0.0304	0.0150
0.9938	-9.74	-0.0538	0.0200
0.9904	-12.17	-0.0838	0.0250
0.9863	-14.58	-0.1202	0.0300
0.9759	-19.37	-0.2115	0.0400
0.9631	-24.12	-0.3265	0.0500
0.9480	-28.81	-0.4636	0.0600
0.9309	-33.45	-0.6215	0.0700
0.9121	-38.03	-0.7994	0.0800
0.8916	-42.55	-0.9968	0.0900
0.8696	-47.04	-1.2138	0.1000
0.8081	-58.04	-1.8509	0.1250
0.7370	-68.69	-2.6504	0.1500
0.6571	-78.64	-3.6479	0.1750
0.5726	-87.20	-4.8431	0.2000
0.4288	-97.54	-7.3552	0.2500
0.3610	-103.21	-8.8510	0.3000
0.3115	-113.91	-10.1303	0.3500
0.2382	-122.78	-12.4615	0.4000
0.1858	-121.77	-14.6190	0.4500
0.1675	-119.76	-15.5203	0.5000
0.1570	-121.88	-16.0846	0.5500
0.1371	-127.90	-17.2615	0.6000

TABLE XXXVII

REFLUX COMPOSITION/REFLUX RATE OPEN LOOP TRANSFER FUNCTION BASED ON LINEAR MODEL FOR EXPERIMENTAL DATA SET 6F

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
0.0414	0.00	-27.6682

	MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1	1.0000	-0.00	0.0000	0.0000
2	1.0000	-0.02	0.0000	0.0001
3	1.0000	-0.12	-0.0000	0.0005
4	1.0000	-0.23	-0.0001	0.0010
5	0.9998	-1.17	-0.0021	0.0050
6	0.9995	-1.64	-0.0041	0.0070
7	0.9990	-2.34	-0.0084	0.0100
8	0.9979	-3.50	-0.0187	0.0150
9	0.9962	-4.65	-0.0328	0.0200
10	0.9942	-5.80	-0.0506	0.0250
11	0.9918	-6.92	-0.0718	0.0300
12	0.9860	-9.14	-0.1228	0.0400
13	0.9791	-11.28	-0.1832	0.0500
14	0.9716	-13.35	-0.2502	0.0600
15	0.9637	-15.36	-0.3214	0.0700
16	0.9556	-17.30	-0.3947	0.0800
17	0.9475	-19.18	-0.4688	0.0900
18	0.9395	-21.02	-0.5425	0.1000
19	0.9203	-25.44	-0.7217	0.1250
20	0.9024	-29.70	-0.8924	0.1500
21	0.8855	-33.87	-1.0565	0.1750
22	0.8692	-37.97	-1.2174	0.2000
23	0.8374	-46.07	-1.5414	0.2500
24	0.8052	-54.02	-1.8818	0.3000
25	0.7721	-61.84	-2.2466	0.3500
26	0.7380	-69.48	-2.6383	0.4000
27	0.7034	-76.94	-3.0565	0.4500
28	0.6684	-84.19	-3.4992	0.5000
29	0.6336	-91.23	-3.9636	0.5500
30	0.5993	-98.05	-4.4468	0.6000

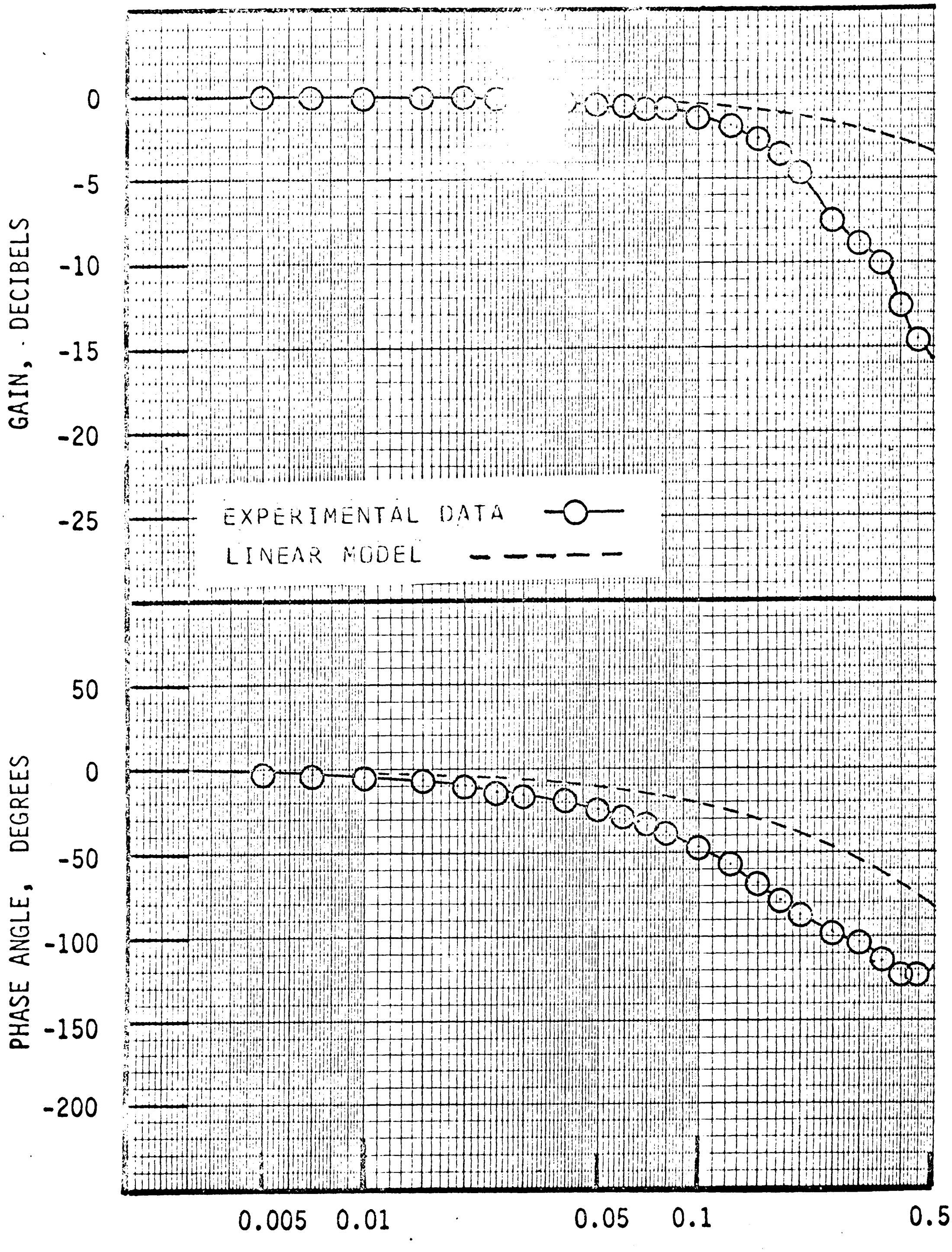

Figure 16. Reflux Composition/Reflux Rate Open Loop Transfer Function based on Experimental and Linear Model Results for Test 6S

TABLE XXXVIII

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         BINARY DISTILLATION STEADY-STATE TEST DATA
                HEAT AND MATERIAL BALANCES
                 EXPERIMENTAL DATA SET 6V

   STREAM         MOLES/MINUTE          MOLES BENZENE/MINUTE

   FEED                0.0596                 0.0369

   BOTTOMS             0.0282                 0.0082

   OVERHEAD            0.0340                 0.0302

   REFLUX              0.0705                 0.0625

   TOTAL MASS ERROR -0.0027          PERCENT  4.4510

   BENZENE ERROR       -.0015        PERCENT  3.9924

   COLUMN INTERNAL FLOW RATES
   TOP VAPOR           0.110072

   TOP LIQUID          0.076036      L/V TOP  0.690783

   BOTTOM VAPOR        0.114330

   BOTTOM LIQUID       0.139886      L/V BOTT 1.223524


   Q-VALUE        FEED =  1.0715      REFLUX =  1.0791

   F-FACTOR       TOP  =  0.9335      BOTTOM =  1.0419

                       FEED TRAY = 11


                      HEAT BALANCE DATA

                  INPUT         OUTPUT         ERROR         PERCENT
                 BTU/MIN        BTU/MIN       BTU/MIN         ERROR

OVERALL           2679.7         2149.4         530.4         19.79

CONDENSER         2687.9         2434.5         253.4          9.43

TOWER             3486.5         3209.5         277.0          7.94
```

TABLE XXXIX

BINARY DISTILLATION STEADY-STATE TEST DATA
TRAY TO TRAY CALCULATION RESULTS
EXPERIMENTAL DATA SET 6V

FEED TRAY = 11

TRAY	LIQUID MOLE FRACT	TEMPERATURE DEGREES F	EQUILIBRIUM CURVE SLOPE	EFFICIENCY MURPHERE	PRESSURE MM HG
FEED	0.6186	180.00			
REFLUX	0.8864	166.50			
1	0.8633	196.00	0.7114	0.6554	992.6
2	0.8373	196.50	0.7024	0.7515	989.0
3	0.8134	197.50	0.6954	0.6937	994.2
4	0.7975	198.00	0.6914	0.4639	994.9
5	0.7746	198.50	0.6868	0.6678	992.3
6	0.7519	199.50	0.6836	0.6560	997.7
7	0.7259	200.00	0.6818	0.7478	993.4
8	0.7010	200.50	0.6821	0.7064	989.6
9	0.6760	201.50	0.6845	0.7056	993.4
10	0.6588	202.50	0.6874	0.3255	1000.9
11	0.6349	203.00	0.6934	0.3255	997.2
12	0.6241	204.00	0.6969	0.3531	1007.7
13	0.6094	204.50	0.7023	0.3969	1008.3
14	0.5831	205.00	0.7144	0.5471	1003.1
15	0.5521	206.50	0.7328	0.5103	1011.1
16	0.4840	208.00	0.7896	0.7861	999.4
17	0.4129	209.50	0.8762	0.6497	985.1
18	0.3529	213.00	0.9731	0.9054	1006.7
REBOILER	0.2895	217.50	1.1021	0.9054	1041.4

TRAY HOLDUP   TOP = 0.00949 MOLES   BOTTOM = 0.00867 MOLES

TIME CONSTANT, TRAY HOLDUP/LIQUID RATE = 0.06195 MINUTES

TABLE XXXX

BOTTOMS COMPOSITION/VAPOR RATE
EXPERIMENTAL FREQUENCY RESPONSE RESULTS
FOR PULSE TEST 6V

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
6.4870	0.0000	16.2409

MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1.0000	-0.00	-0.0000	0.0000
1.0000	-0.04	0.0000	0.0001
1.0000	-0.18	0.0000	0.0005
1.0000	-0.37	0.0001	0.0010
1.0004	-1.83	0.0035	0.0050
1.0008	-2.56	0.0068	0.0070
1.0016	-3.67	0.0137	0.0100
1.0035	-5.53	0.0303	0.0150
1.0060	-7.43	0.0524	0.0200
1.0091	-9.37	0.0789	0.0250
1.0126	-11.37	0.1088	0.0300
1.0200	-15.56	0.1723	0.0400
1.0269	-20.02	0.2303	0.0500
1.0315	-24.78	0.2695	0.0600
1.0324	-29.82	0.2771	0.0700
1.0282	-35.11	0.2413	0.0800
1.0176	-40.60	0.1518	0.0900
0.9999	-46.26	-0.0007	0.1000
0.9218	-60.66	-0.7068	0.1250
0.7989	-74.34	-1.9499	0.1500
0.6482	-85.37	-3.7652	0.1750
0.5026	-90.74	-5.9762	0.2000
0.3910	-82.77	-8.1574	0.2500
0.4298	-92.92	-7.3354	0.3000
0.3274	-115.26	-9.6993	0.3500
0.1846	-99.05	-14.6731	0.4000
0.3175	-89.61	-9.9660	0.4500
0.3480	-128.36	-9.1680	0.5000
0.0891	-221.12	-20.9990	0.5500
0.9605	-26.86	-0.3505	0.6000

TABLE XXXXI

BOTTOMS COMPOSITION/VAPOR RATE
OPEN LOOP TRANSFER FUNCTION BASED ON LINEAR MODEL FOR EXPERIMENTAL DATA SET 6F

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
2.2192	0.00	6.9241

	MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1	1.0000	-0.00	-0.0000	0.0000
2	1.0000	-0.06	-0.0000	0.0001
3	1.0000	-0.32	-0.0001	0.0005
4	1.0000	-0.64	-0.0004	0.0010
5	0.9990	-3.22	-0.0089	0.0050
6	0.9980	-4.51	-0.0175	0.0070
7	0.9959	-6.43	-0.0357	0.0100
8	0.9908	-9.62	-0.0799	0.0150
9	0.9839	-12.79	-0.1411	0.0200
10	0.9751	-15.91	-0.2187	0.0250
11	0.9647	-18.99	-0.3119	0.0300
12	0.9396	-24.99	-0.5414	0.0400
13	0.9097	-30.74	-0.8216	0.0500
14	0.8766	-36.20	-1.1439	0.0600
15	0.8414	-41.38	-1.4999	0.0700
16	0.8052	-46.26	-1.8816	0.0800
17	0.7689	-50.85	-2.2823	0.0900
18	0.7331	-55.17	-2.6962	0.1000
19	0.6486	-64.88	-3.7599	0.1250
20	0.5736	-73.26	-4.8284	0.1500
21	0.5084	-80.58	-5.8758	0.1750
22	0.4523	-87.06	-6.8909	0.2000
23	0.3626	-98.09	-8.8126	0.2500
24	0.2952	-107.24	-10.5966	0.3000
25	0.2438	-115.02	-12.2603	0.3500
26	0.2037	-121.75	-13.8201	0.4000
27	0.1720	-127.64	-15.2895	0.4500
28	0.1466	-132.84	-16.6787	0.5000
29	0.1260	-137.45	-17.9958	0.5500
30	0.1091	-141.56	-19.2472	0.6000

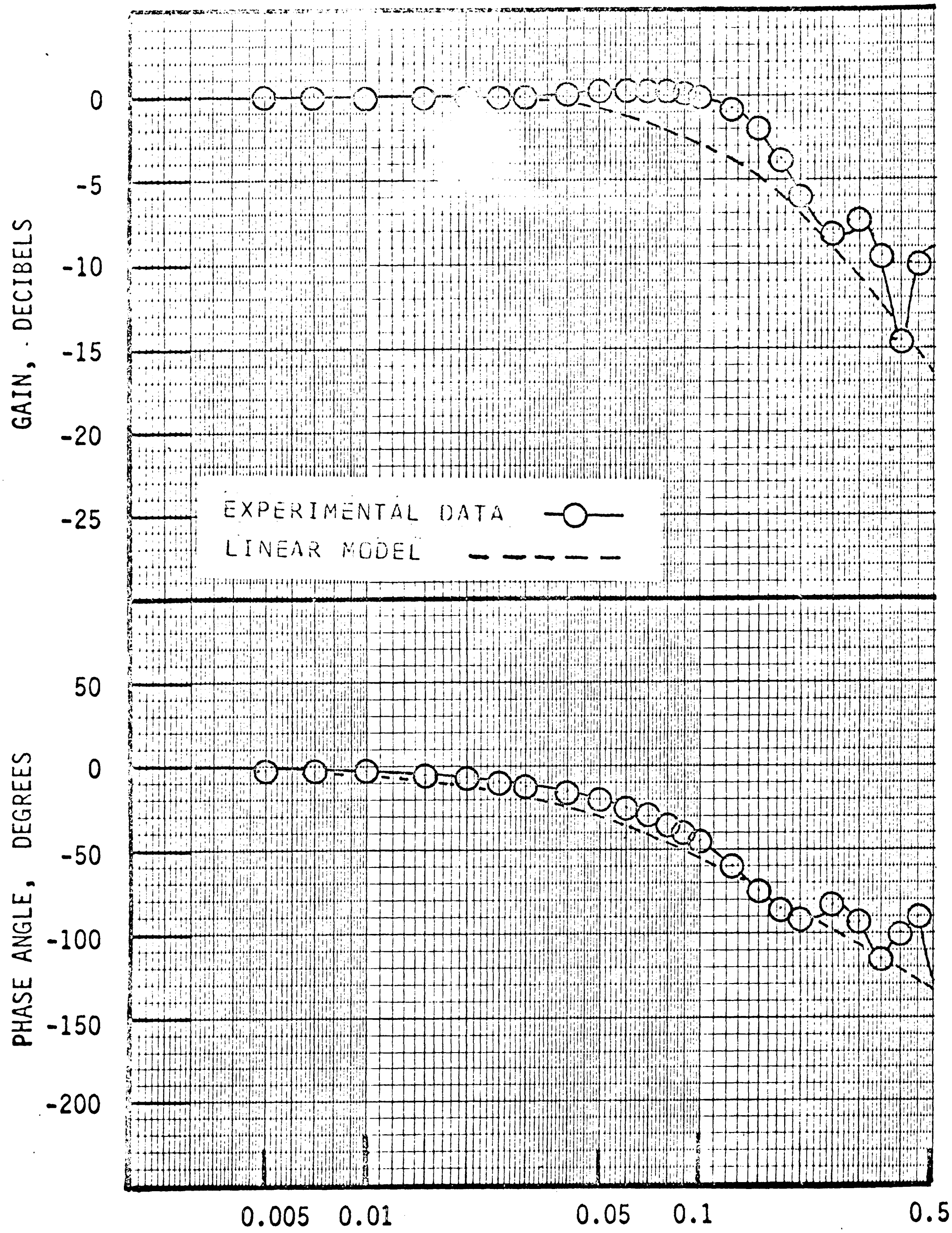

Figure 17. Bottoms Composition/Vapor Rate Open Loop Transfer Function based on Experimental and Linear Model Results for Test 6V

TABLE XXXXII

REFLUX COMPOSITION/VAPOR RATE EXPERIMENTAL FREQUENCY RESPONSE RESULTS FOR PULSE TEST 6V

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
0.8205	0.0000	-1.7187

MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1.0000	-0.00	0.0000	0.0000
1.0000	-0.05	-0.0000	0.0001
1.0000	-0.25	-0.0000	0.0005
1.0000	-0.49	-0.0000	0.0010
0.9999	-2.45	-0.0009	0.0050
0.9998	-3.44	-0.0017	0.0070
0.9996	-4.91	-0.0035	0.0100
0.9991	-7.37	-0.0080	0.0150
0.9983	-9.83	-0.0144	0.0200
0.9974	-12.30	-0.0229	0.0250
0.9961	-14.77	-0.0335	0.0300
0.9928	-19.74	-0.0624	0.0400
0.9882	-24.75	-0.1028	0.0500
0.9821	-29.80	-0.1571	0.0600
0.9741	-34.88	-0.2277	0.0700
0.9642	-40.00	-0.3171	0.0800
0.9519	-45.14	-0.4279	0.0900
0.9373	-50.29	-0.5625	0.1000
0.8895	-63.10	-1.0167	0.1250
0.8263	-75.53	-1.6571	0.1500
0.7509	-87.15	-2.4879	0.1750
0.6696	-97.46	-3.4843	0.2000
0.5189	-112.71	-5.6990	0.2500
0.4128	-121.23	-7.6852	0.3000
0.3400	-123.41	-9.3705	0.3500
0.3322	-115.15	-9.5708	0.4000
0.4511	-114.12	-6.9142	0.4500
0.6003	-127.96	-4.4323	0.5000
0.7017	-139.19	-3.0767	0.5500
1.3706	-126.40	2.7385	0.6000

TABLE XXXXIII

REFLUX COMPOSITION/VAPOR RATE OPEN LOOP TRANSFER FUNCTION BASED ON LINEAR MODEL FOR EXPERIMENTAL DATA SET 6F

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
0.0445	0.00	-27.0260

	MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1	1.0000	-0.00	0.0000	0.0000
2	1.0000	-0.03	-0.0000	0.0001
3	1.0000	-0.16	-0.0000	0.0005
4	1.0000	-0.33	-0.0001	0.0010
5	0.9996	-1.63	-0.0034	0.0050
6	0.9992	-2.29	-0.0067	0.0070
7	0.9984	-3.26	-0.0135	0.0100
8	0.9965	-4.88	-0.0302	0.0150
9	0.9939	-6.49	-0.0532	0.0200
10	0.9906	-8.08	-0.0822	0.0250
11	0.9867	-9.65	-0.1167	0.0300
12	0.9772	-12.72	-0.2006	0.0400
13	0.9660	-15.68	-0.3007	0.0500
14	0.9536	-18.53	-0.4129	0.0600
15	0.9404	-21.27	-0.5336	0.0700
16	0.9269	-23.91	-0.6595	0.0800
17	0.9132	-26.45	-0.7883	0.0900
18	0.8997	-28.91	-0.9182	0.1000
19	0.8669	-34.76	-1.2410	0.1250
20	0.8359	-40.30	-1.5565	0.1500
21	0.8067	-45.63	-1.8656	0.1750
22	0.7788	-50.80	-2.1720	0.2000
23	0.7253	-60.78	-2.7896	0.2500
24	0.6739	-70.34	-3.4276	0.3000
25	0.6243	-79.47	-4.0916	0.3500
26	0.5767	-88.18	-4.7803	0.4000
27	0.5316	-96.46	-5.4890	0.4500
28	0.4891	-104.33	-6.2125	0.5000
29	0.4495	-111.80	-6.9456	0.5500
30	0.4129	-118.90	-7.6837	0.6000

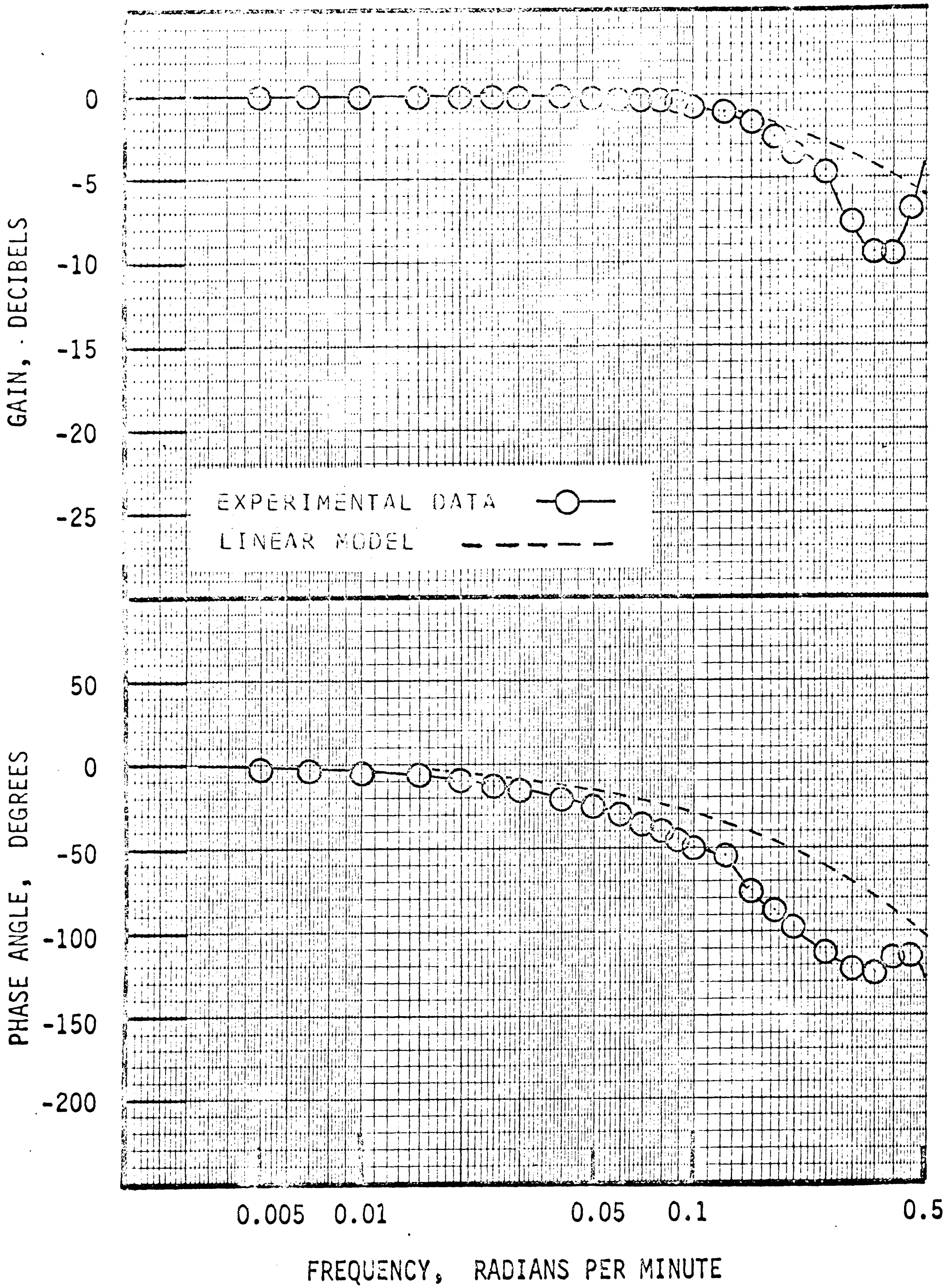

Figure 18. Reflux Composition/Vapor Rate Open Loop Transfer Function based on Experimental and Linear Model Results for Test 6V

TABLE XXXXIV

BINARY DISTILLATION STEADY-STATE TEST DATA
HEAT AND MATERIAL BALANCES
EXPERIMENTAL DATA SET 6VA

STREAM	MOLES/MINUTE		MOLES BENZENE/MINUTE
FEED	0.0622		0.0395
BOTTOMS	0.0201		0.0031
OVERHEAD	0.0437		0.0376
REFLUX	0.0696		0.0599
TOTAL MASS ERROR	-0.0016	PERCENT	2.5975
BENZENE ERROR	-.0012	PERCENT	2.9296
COLUMN INTERNAL FLOW RATES			
TOP VAPOR	0.118536		
TOP LIQUID	0.074862	L/V TOP	0.631562
BOTTOM VAPOR	0.123329		
BOTTOM LIQUID	0.141831	L/V BOTT	1.150021

Q-VALUE FEED = 1.0771 REFLUX = 1.0750

F-FACTOR TOP = 1.0013 BOTTOM = 1.1376

FEED TRAY = 11

HEAT BALANCE DATA

	INPUT BTU/MIN	OUTPUT BTU/MIN	ERROR BTU/MIN	PERCENT ERROR
OVERALL	2863.1	2279.7	583.4	20.38
CONDENSER	2982.1	2694.4	287.7	9.65
TOWER	3684.4	3388.7	295.7	8.03

TABLE XXXXV

BINARY DISTILLATION STEADY-STATE TEST DATA
TRAY TO TRAY CALCULATION RESULTS
EXPERIMENTAL DATA SET 6VA

FEED TRAY = 11

TRAY	LIQUID MOLE FRACT	TEMPERATURE DEGREES F	EQUILIBRIUM CURVE SLOPE	EFFICIENCY MURPHERE	PRESSURE MM HG
FEED	0.6349	180.00			
REFLUX	0.8600	170.50			
1	0.8342	198.00	0.7014	0.5322	1011.6
2	0.8029	198.50	0.6927	0.6944	1005.3
3	0.7703	199.50	0.6861	0.7742	1006.2
4	0.7512	200.00	0.6835	0.4714	1005.3
5	0.7219	200.50	0.6817	0.7664	999.5
6	0.6944	201.50	0.6825	0.7640	1002.3
7	0.6743	202.50	0.6847	0.5867	1008.5
8	0.6518	203.00	0.6889	0.6949	1005.5
9	0.6322	204.00	0.6942	0.6416	1011.7
10	0.6112	204.50	0.7016	0.4944	1009.2
11	0.6047	205.00	0.7042	0.4944	1014.0
12	0.5658	206.50	0.7241	0.7155	1018.1
13	0.5322	207.20	0.7469	0.5040	1011.9
14	0.4787	209.20	0.7950	0.6342	1015.6
15	0.4106	211.20	0.8793	0.6613	1010.4
16	0.3180	214.50	1.0406	0.7809	1010.5
17	0.2421	217.50	1.2175	0.6308	1013.2
18	0.1907	223.00	1.3626	0.5589	1069.4
REBOILER	0.1529	227.00	1.4833	0.5589	1110.7

TRAY HOLDUP   TOP = 0.00899 MOLES   BOTTOM = 0.00793 MOLES

TIME CONSTANT, TRAY HOLDUP/LIQUID RATE = 0.05592 MINUTES

TABLE XXXXVI

BINARY DISTILLATION STEADY-STATE TEST DATA
HEAT AND MATERIAL BALANCES
EXPERIMENTAL DATA SET 8R

STREAM	MOLES/MINUTE	MOLES BENZENE/MINUTE
FEED	0.0609	0.0413
BOTTOMS	0.0170	0.0026
OVERHEAD	0.0457	0.0398
REFLUX	0.0688	0.0600

TOTAL MASS ERROR -0.0018 PERCENT 2.9785

BENZENE ERROR -.0012 PERCENT 2.8278

COLUMN INTERNAL FLOW RATES

TOP VAPOR	0.118917		
TOP LIQUID	0.073216	L/V TOP	0.615690
BOTTOM VAPOR	0.121704		
BOTTOM LIQUID	0.136926	L/V BOTT	1.125070

Q-VALUE FEED = 1.0458 REFLUX = 1.0634

F-FACTOR TOP = 1.0572 BOTTOM = 1.1932

FEED TRAY = 9

HEAT BALANCE DATA

	INPUT BTU/MIN	OUTPUT BTU/MIN	ERROR BTU/MIN	PERCENT ERROR
OVERALL	2828.2	2134.0	694.1	24.54
CONDENSER	2977.8	2596.0	381.8	12.82
TOWER	3626.3	3314.0	312.4	8.61

TABLE XXXXVII

BINARY DISTILLATION STEADY-STATE TEST DATA
TRAY TO TRAY CALCULATION RESULTS
EXPERIMENTAL DATA SET 8R

FEED TRAY = 9

TRAY	LIQUID MOLE FRACT	TEMPERATURE DEGREES F	EQUILIBRIUM CURVE SLOPE	EFFICIENCY MURPHERE	PRESSURE MM HG
FEED	0.6777	181.00			
REFLUX	0.8720	167.50			
1	0.8342	191.00	0.7014	0.9105	903.6
2	0.8022	191.50	0.6925	0.8594	897.7
3	0.7781	192.50	0.6874	0.7019	902.3
4	0.7616	193.20	0.6848	0.5112	905.6
5	0.7391	193.80	0.6824	0.7515	904.8
6	0.7172	194.80	0.6817	0.7932	910.0
7	0.7002	195.20	0.6821	0.6583	908.5
8	0.6819	196.00	0.6837	0.7685	912.2
9	0.6682	196.20	0.6857	0.5090	908.0
10	0.6514	197.00	0.6890	0.5090	913.3
11	0.6304	197.20	0.6948	0.5090	906.9
12	0.5954	198.50	0.7084	0.6448	910.0
13	0.5511	199.50	0.7334	0.6304	904.1
14	0.4840	201.50	0.7896	0.7287	901.4
15	0.4206	203.50	0.8653	0.5817	899.5
16	0.3156	206.20	1.0455	0.8372	885.4
17	0.2372	209.20	1.2304	0.6288	886.8
18	0.1885	214.00	1.3693	0.4981	929.0
REBOILER	0.1529	218.50	1.4833	0.4981	975.1

TRAY HOLDUP TOP = 0.00902 MOLES BOTTOM = 0.00807 MOLES

TIME CONSTANT, TRAY HOLDUP/LIQUID RATE = 0.05896 MINUTES

TABLE XXXXVIII

BOTTOMS COMPOSITION/REFLUX RATE EXPERIMENTAL FREQUENCY RESPONSE RESULTS FOR PULSE TEST 8R

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
11.7213	0.0000	21.3795

MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1.0000	-0.00	-0.0000	0.0000
1.0000	-0.09	-0.0000	0.0001
1.0000	-0.43	-0.0001	0.0005
1.0000	-0.85	-0.0003	0.0010
0.9990	-4.27	-0.0085	0.0050
0.9981	-5.98	-0.0166	0.0070
0.9961	-8.54	-0.0339	0.0100
0.9912	-12.81	-0.0764	0.0150
0.9845	-17.07	-0.1359	0.0200
0.9758	-21.31	-0.2127	0.0250
0.9653	-25.55	-0.3068	0.0300
0.9389	-33.96	-0.5479	0.0400
0.9056	-42.28	-0.8610	0.0500
0.8661	-50.47	-1.2486	0.0600
0.8210	-58.51	-1.7133	0.0700
0.7710	-66.33	-2.2586	0.0800
0.7171	-73.88	-2.8881	0.0900
0.6603	-81.09	-3.6053	0.1000
0.5128	-96.95	-5.8017	0.1250
0.3738	-107.71	-8.5463	0.1500
0.2671	-109.74	-11.4652	0.1750
0.2141	-102.29	-13.3866	0.2000
0.2225	-93.21	-13.0547	0.2500
0.2438	-98.83	-12.2578	0.3000
0.2497	-105.39	-12.0522	0.3500
0.3875	-57.90	-8.2345	0.4000
0.4787	-207.13	-6.3993	0.4500
0.2210	-206.63	-13.1119	0.5000
0.1681	-203.59	-15.4895	0.5500
0.1301	-204.35	-17.7154	0.6000

TABLE IL

BOTTOMS COMPOSITION/REFLUX RATE OPEN LOOP TRANSFER FUNCTION BASED ON LINEAR MODEL FOR EXPERIMENTAL DATA SET 11F

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
1.8049	0.00	5.1293

	MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1	1.0000	-0.00	-0.0000	0.0000
2	1.0000	-0.08	-0.0000	0.0001
3	1.0000	-0.38	-0.0001	0.0005
4	0.9999	-0.77	-0.0006	0.0010
5	0.9983	-3.83	-0.0150	0.0050
6	0.9966	-5.35	-0.0293	0.0070
7	0.9932	-7.63	-0.0596	0.0100
8	0.9848	-11.39	-0.1331	0.0150
9	0.9734	-15.08	-0.2339	0.0200
10	0.9594	-18.69	-0.3603	0.0250
11	0.9430	-22.21	-0.5100	0.0300
12	0.9047	-28.90	-0.8700	0.0400
13	0.8616	-35.11	-1.2939	0.0500
14	0.8163	-40.81	-1.7630	0.0600
15	0.7708	-46.01	-2.2610	0.0700
16	0.7265	-50.76	-2.7748	0.0800
17	0.6843	-55.09	-3.2946	0.0900
18	0.6447	-59.04	-3.8133	0.1000
19	0.5574	-67.58	-5.0760	0.1250
20	0.4861	-74.63	-6.2646	0.1500
21	0.4280	-80.62	-7.3703	0.1750
22	0.3803	-85.83	-8.3970	0.2000
23	0.3074	-94.67	-10.2464	0.2500
24	0.2547	-102.10	-11.8794	0.3000
25	0.2150	-108.61	-13.3497	0.3500
26	0.1842	-114.45	-14.6960	0.4000
27	0.1595	-119.79	-15.9457	0.4500
28	0.1393	-124.72	-17.1182	0.5000
29	0.1226	-129.30	-18.2275	0.5500
30	0.1086	-133.58	-19.2839	0.6000

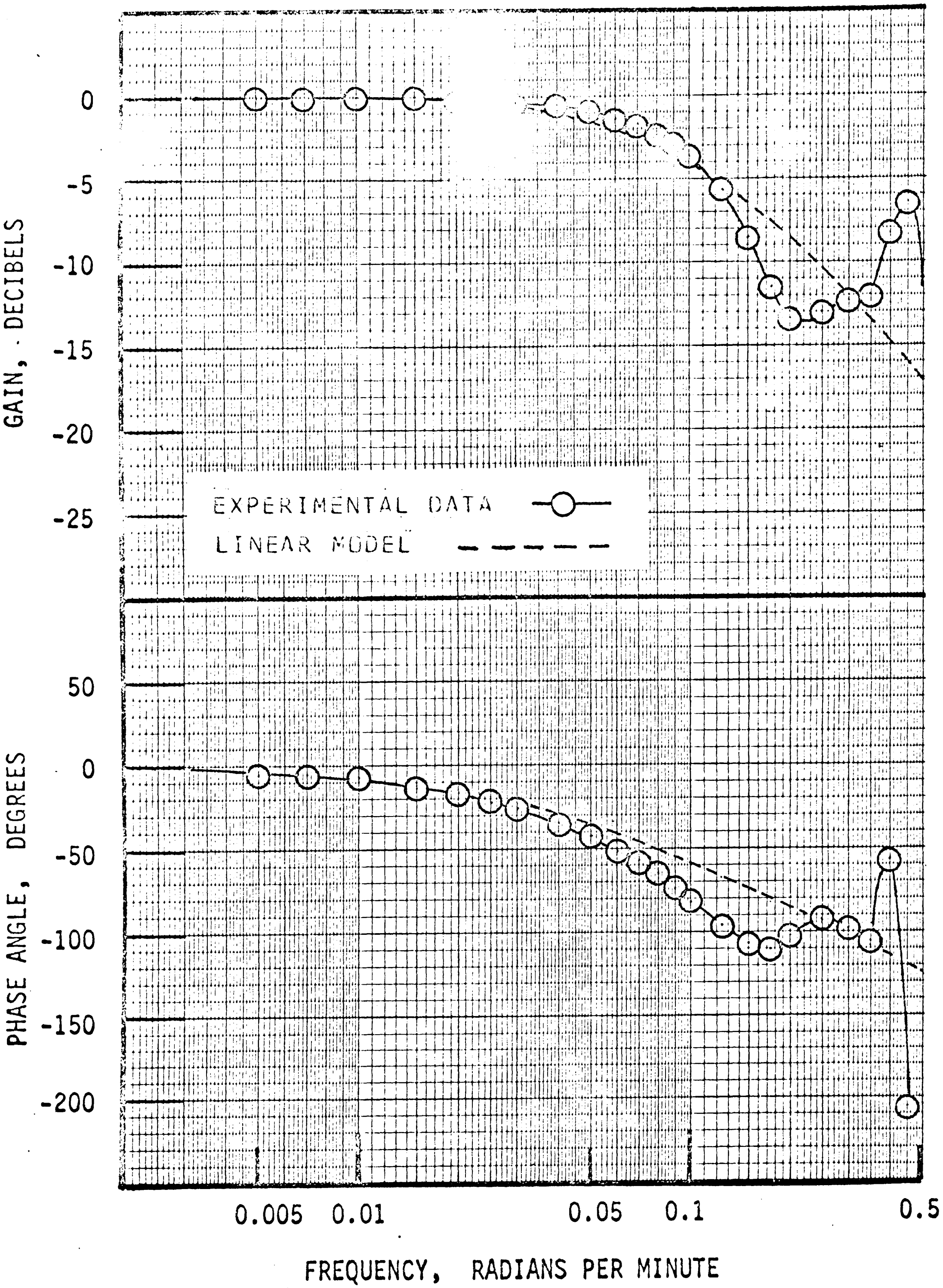

Figure 19. Bottoms Composition/Reflux Rate Open Loop Transfer Function based on Experimental and Linear Model Results for Test 8R

TABLE L

DISTILLATE COMPOSITION/REFLUX RATE EXPERIMENTAL FREQUENCY RESPONSE RESULTS FOR PULSE TEST 8R

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
0.8750	0.0000	-1.1600

MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1.0000	-0.00	0.0000	0.0000
1.0000	-0.06	0.0000	0.0001
1.0000	-0.28	-0.0000	0.0005
1.0000	-0.55	-0.0000	0.0010
0.9999	-2.77	-0.0007	0.0050
0.9998	-3.88	-0.0014	0.0070
0.9997	-5.54	-0.0028	0.0100
0.9993	-8.32	-0.0063	0.0150
0.9987	-11.10	-0.0113	0.0200
0.9979	-13.88	-0.0180	0.0250
0.9970	-16.67	-0.0264	0.0300
0.9943	-22.26	-0.0493	0.0400
0.9907	-27.88	-0.0813	0.0500
0.9858	-33.52	-0.1245	0.0600
0.9794	-39.19	-0.1807	0.0700
0.9714	-44.88	-0.2520	0.0800
0.9616	-50.58	-0.3405	0.0900
0.9497	-56.28	-0.4480	0.1000
0.9110	-70.39	-0.8097	0.1250
0.8597	-84.06	-1.3133	0.1500
0.7992	-96.83	-1.9473	0.1750
0.7360	-108.28	-2.6624	0.2000
0.6377	-126.47	-3.9074	0.2500
0.6163	-142.20	-4.2041	0.3000
0.6553	-162.28	-3.6711	0.3500
0.9224	-189.28	-0.7014	0.4000
0.2171	-167.41	-13.2669	0.4500
0.2990	-196.32	-10.4879	0.5000
0.3315	-209.55	-9.5895	0.5500
0.3414	-225.44	-9.3338	0.6000

TABLE LI

REFLUX COMPOSITION/REFLUX RATE OPEN LOOP TRANSFER FUNCTION BASED ON LINEAR MODEL FOR EXPERIMENTAL DATA SET 11F

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
0.0273	0.00	-31.2814

	MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1	1.0000	-0.00	0.0000	0.0000
2	1.0000	-0.03	-0.0000	0.0001
3	1.0000	-0.17	-0.0001	0.0005
4	1.0000	-0.34	-0.0002	0.0010
5	0.9992	-1.70	-0.0070	0.0050
6	0.9984	-2.38	-0.0136	0.0070
7	0.9968	-3.39	-0.0276	0.0100
8	0.9929	-5.05	-0.0615	0.0150
9	0.9877	-6.68	-0.1073	0.0200
10	0.9813	-8.26	-0.1641	0.0250
11	0.9738	-9.78	-0.2303	0.0300
12	0.9567	-12.64	-0.3847	0.0400
13	0.9378	-15.24	-0.5581	0.0500
14	0.9184	-17.60	-0.7397	0.0600
15	0.8994	-19.74	-0.9211	0.0700
16	0.8814	-21.70	-1.0967	0.0800
17	0.8647	-23.51	-1.2631	0.0900
18	0.8493	-25.20	-1.4188	0.1000
19	0.8166	-29.09	-1.7598	0.1250
20	0.7905	-32.73	-2.0417	0.1500
21	0.7691	-36.26	-2.2804	0.1750
22	0.7507	-39.78	-2.4904	0.2000
23	0.7191	-46.82	-2.8640	0.2500
24	0.6906	-53.90	-3.2157	0.3000
25	0.6629	-60.97	-3.5705	0.3500
26	0.6354	-67.99	-3.9395	0.4000
27	0.6076	-74.92	-4.3272	0.4500
28	0.5798	-81.71	-4.7346	0.5000
29	0.5520	-88.36	-5.1611	0.5500
30	0.5245	-94.84	-5.6052	0.6000

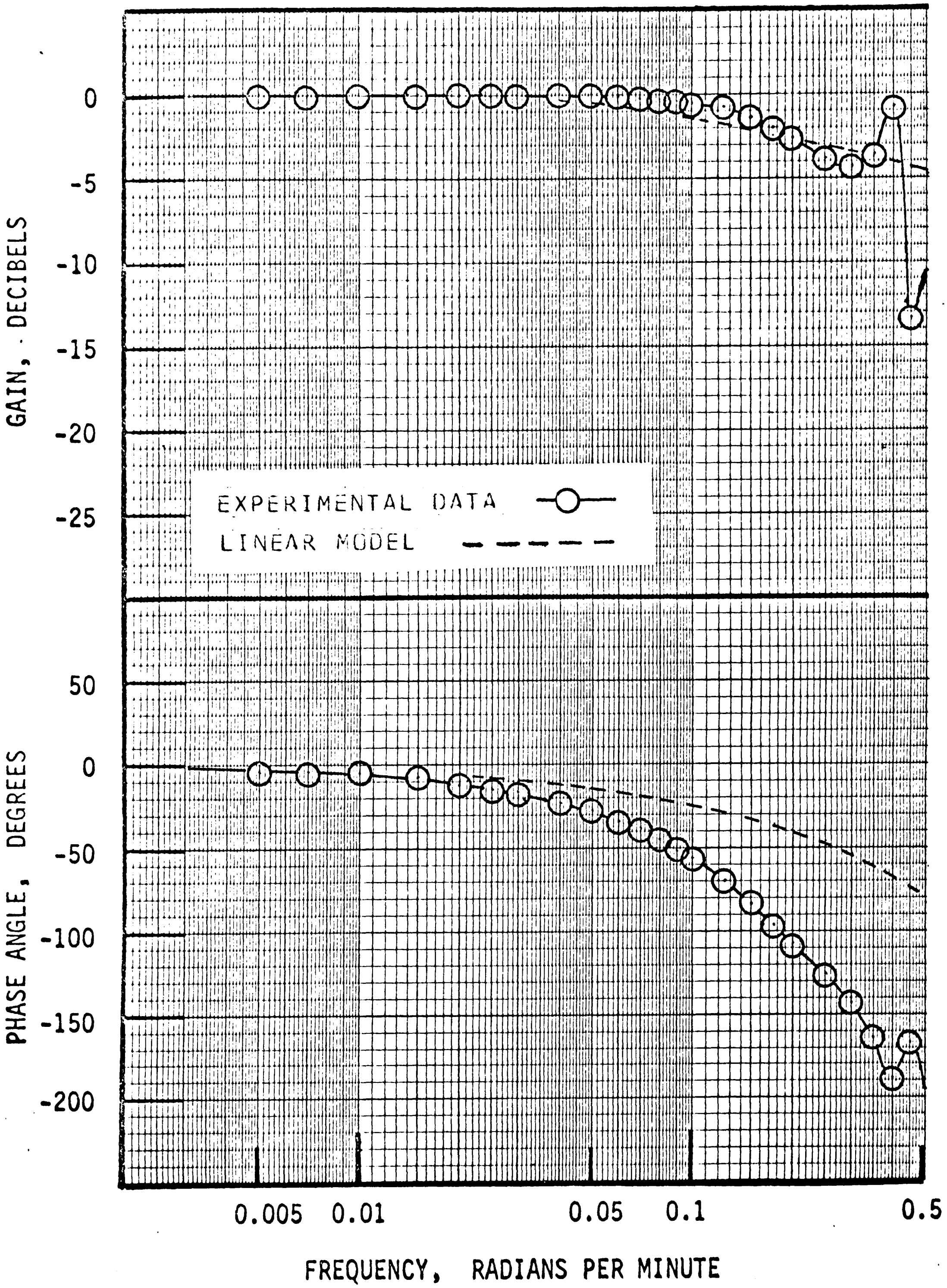

Figure 20. Distillate Composition/Reflux Rate Open Loop Transfer Function based on Experimental and Linear Model Results for Test 8R

TABLE LII

BINARY DISTILLATION STEADY-STATE TEST DATA
HEAT AND MATERIAL BALANCES
EXPERIMENTAL DATA SET 8RA

STREAM	MOLES/MINUTE		MOLES BENZENE/MINUTE
FEED	0.0611		0.0418
BOTTOMS	0.0170		0.0026
OVERHEAD	0.0457		0.0398
REFLUX	0.0688		0.0600
TOTAL MASS ERROR	-0.0016	PERCENT	2.6927
BENZENE ERROR	-.0006	PERCENT	1.4457

COLUMN INTERNAL FLOW RATES

TOP VAPOR	0.118917		
TOP LIQUID	0.073216	L/V TOP	0.615690
BOTTOM VAPOR	0.121702		
BOTTOM LIQUID	0.137079	L/V BOTT	1.126347

Q-VALUE FEED = 1.0456 REFLUX = 1.0634

F-FACTOR TOP = 1.0574 BOTTOM = 1.1957

FEED TRAY = 9

HEAT BALANCE DATA

	INPUT BTU/MIN	OUTPUT BTU/MIN	ERROR BTU/MIN	PERCENT ERROR
OVERALL	2827.1	2134.1	692.9	24.51
CONDENSER	2977.8	2596.0	381.8	12.82
TOWER	3625.3	3314.1	311.2	8.58

TABLE LIII

BINARY DISTILLATION STEADY-STATE TEST DATA
TRAY TO TRAY CALCULATION RESULTS
EXPERIMENTAL DATA SET 8RA

FEED TRAY = 9

TRAY	LIQUID MOLE FRACT	TEMPERATURE DEGREES F	EQUILIBRIUM CURVE SLOPE	EFFICIENCY MURPHREE	PRESSURE MM HG
FEED	0.6844	181.00			
REFLUX	0.8720	167.50			
1	0.8336	191.00	0.7012	0.9272	903.3
2	0.8056	191.50	0.6933	0.7452	899.1
3	0.7739	192.50	0.6866	0.9369	900.5
4	0.7594	193.20	0.6845	0.4511	904.6
5	0.7367	193.80	0.6823	0.7610	903.8
6	0.7180	194.80	0.6817	0.6787	910.4
7	0.7002	195.20	0.6821	0.6892	908.5
8	0.6828	196.00	0.6836	0.7302	912.6
9	0.6694	196.20	0.6855	0.6360	908.0
10	0.6483	197.00	0.6898	0.6360	912.0
11	0.6204	197.20	0.6981	0.6360	902.4
12	0.5831	198.50	0.7144	0.6463	904.3
13	0.5342	199.50	0.7454	0.6514	896.2
14	0.4798	201.50	0.7939	0.5892	899.4
15	0.3995	203.50	0.8958	0.7126	889.1
16	0.3121	206.20	1.0529	0.7007	883.5
17	0.2323	209.20	1.2436	0.6463	884.2
18	0.1848	214.00	1.3807	0.4914	926.9
REBOILER	0.1503	218.50	1.4919	0.4914	973.5

TRAY HOLDUP TOP = 0.00901 MOLES BOTTOM = 0.00800 MOLES

TIME CONSTANT, TRAY HOLDUP/LIQUID RATE = 0.05836 MINUTES

TABLE LIV

```
            BINARY DISTILLATION STEADY-STATE TEST DATA
                    HEAT AND MATERIAL BALANCES
                   EXPERIMENTAL DATA SET 9V

      STREAM        MOLES/MINUTE              MOLES BENZENE/MINUTE

      FEED               0.0623                     0.0429

      BOTTOMS            0.0182                     0.0036

      OVERHEAD           0.0458                     0.0401

      REFLUX             0.0690                     0.0604

      TOTAL MASS ERROR -0.0017          PERCENT   2.6892

      BENZENE ERROR      -.0008          PERCENT   1.8484

      COLUMN INTERNAL FLOW RATES
      TOP VAPOR          0.119466

      TOP LIQUID         0.073695        L/V TOP   0.616866

      BOTTOM VAPOR       0.122733

      BOTTOM LIQUID      0.139268        L/V BOTT 1.134725


      Q-VALUE       FEED =   1.0524       REFLUX =   1.0687

      F-FACTOR      TOP  =   1.0400       BOTTOM =   1.1641

                         FEED TRAY =   9


                         HEAT BALANCE DATA

                 INPUT          OUTPUT         ERROR          PERCENT
                BTU/MIN        BTU/MIN        BTU/MIN         ERROR

  OVERALL        2851.7         2142.9          708.8          24.86

  CONDENSER      2987.0         2589.6          397.4          13.30

  TOWER          3650.2         3338.8          311.4           8.53
```

TABLE LV

BINARY DISTILLATION STEADY-STATE TEST DATA
TRAY TO TRAY CALCULATION RESULTS
EXPERIMENTAL DATA SET 9V

FEED TRAY = 9

TRAY	LIQUID MOLE FRACT	TEMPERATURE DEGREES F	EQUILIBRIUM CURVE SLOPE	EFFICIENCY MURPHERE	PRESSURE MM HG
FEED	0.6886	181.00			
REFLUX	0.8762	168.00			
1	0.8415	193.50	0.7038	0.8716	944.2
2	0.8147	194.00	0.6957	0.7380	940.3
3	0.7907	194.80	0.6899	0.7220	942.1
4	0.7732	195.20	0.6865	0.5616	940.5
5	0.7519	196.00	0.6836	0.7344	943.3
6	0.7313	196.50	0.6820	0.7710	941.7
7	0.7156	197.20	0.6817	0.6293	945.3
8	0.6953	198.00	0.6824	0.8863	948.2
9	0.6844	198.50	0.6834	0.4607	952.8
10	0.6725	199.10	0.6850	0.4607	954.5
11	0.6579	199.50	0.6876	0.4607	953.9
12	0.6349	200.50	0.6934	0.5662	958.3
13	0.6047	201.00	0.7042	0.5778	951.7
14	0.5521	202.50	0.7328	0.7358	949.1
15	0.4965	204.00	0.7774	0.6158	944.4
16	0.4084	206.00	0.8826	0.7710	929.9
17	0.3251	208.80	1.0263	0.6527	927.8
18	0.2550	213.00	1.1843	0.6707	951.8
REBOILER	0.1974	218.00	1.3426	0.6707	994.2

TRAY HOLDUP TOP = 0.00913 MOLES BOTTOM = 0.00838 MOLES

TIME CONSTANT, TRAY HOLDUP/LIQUID RATE = 0.06017 MINUTES

TABLE LVI

BOTTOMS COMPOSITION/VAPOR RATE EXPERIMENTAL FREQUENCY RESPONSE RESULTS FOR PULSE TEST 9V

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
45.5919	0.0000	33.1778

MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1.0000	-0.00	-0.0000	0.0000
1.0000	-0.07	-0.0000	0.0001
1.0000	-0.35	-0.0001	0.0005
1.0000	-0.70	-0.0004	0.0010
0.9989	-3.48	-0.0096	0.0050
0.9978	-4.88	-0.0188	0.0070
0.9956	-6.96	-0.0384	0.0100
0.9901	-10.43	-0.0864	0.0150
0.9825	-13.88	-0.1536	0.0200
0.9727	-17.32	-0.2402	0.0250
0.9609	-20.72	-0.3463	0.0300
0.9314	-27.43	-0.6170	0.0400
0.8947	-33.96	-0.9666	0.0500
0.8516	-40.24	-1.3957	0.0600
0.8031	-46.21	-1.9046	0.0700
0.7506	-51.76	-2.4920	0.0800
0.6955	-56.80	-3.1544	0.0900
0.6394	-61.19	-3.8843	0.1000
0.5080	-68.36	-5.8820	0.1250
0.4161	-69.01	-7.6164	0.1500
0.3850	-66.41	-8.2901	0.1750
0.3966	-67.89	-8.0334	0.2000
0.3930	-87.98	-8.1130	0.2500
0.2390	-115.01	-12.4325	0.3000
0.1030	-38.91	-19.7468	0.3500
0.5736	-51.19	-4.8273	0.4000
0.2921	-50.69	-10.6881	0.4500
0.3729	-104.88	-8.5686	0.5000
0.2511	-137.49	-12.0041	0.5500
0.1196	-124.49	-18.4461	0.6000

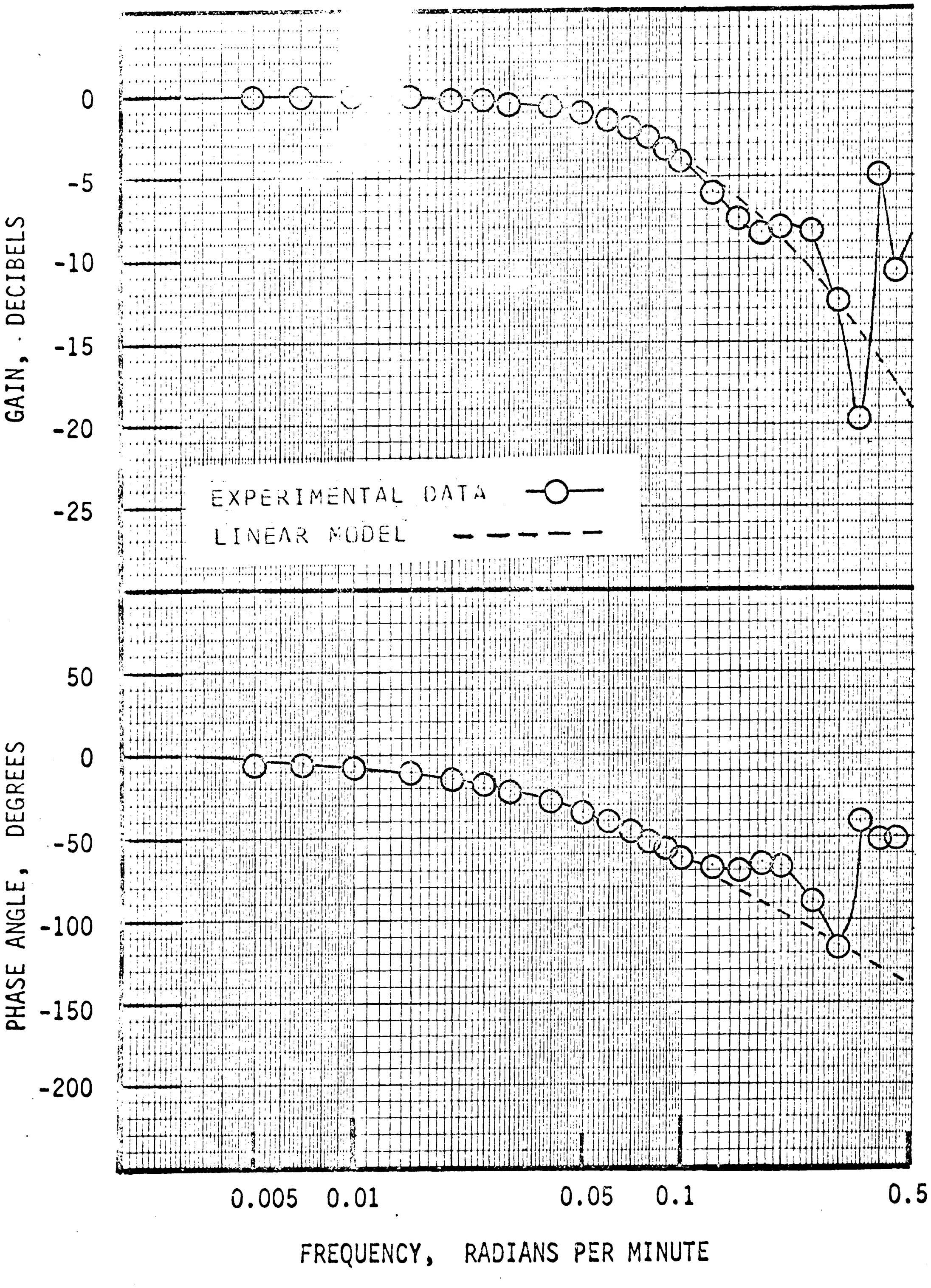

Figure 21. Bottoms Composition/Vapor Rate Open Loop Transfer Function based on Experimental and Linear Model Results for Test 9V

TABLE LVII

DISTILLATE COMPOSITION/VAPOR RATE EXPERIMENTAL FREQUENCY RESPONSE RESULTS FOR PULSE TEST 9V

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
1.2751	0.0000	2.1109

MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1.0000	-0.00	-0.0000	0.0000
1.0000	-0.06	-0.0000	0.0001
1.0000	-0.32	-0.0000	0.0005
1.0000	-0.65	-0.0001	0.0010
0.9997	-3.25	-0.0029	0.0050
0.9994	-4.54	-0.0056	0.0070
0.9987	-6.49	-0.0115	0.0100
0.9970	-9.73	-0.0259	0.0150
0.9947	-12.96	-0.0460	0.0200
0.9918	-16.19	-0.0717	0.0250
0.9882	-19.41	-0.1031	0.0300
0.9792	-25.82	-0.1826	0.0400
0.9679	-32.17	-0.2837	0.0500
0.9544	-38.46	-0.4057	0.0600
0.9389	-44.66	-0.5475	0.0700
0.9217	-50.77	-0.7080	0.0800
0.9031	-56.78	-0.8854	0.0900
0.8833	-62.67	-1.0781	0.1000
0.8306	-76.84	-1.6116	0.1250
0.7775	-90.16	-2.1861	0.1500
0.7281	-102.71	-2.7558	0.1750
0.6853	-114.75	-3.2822	0.2000
0.6175	-138.99	-4.1873	0.2500
0.5483	-166.46	-5.2197	0.3000
0.4426	-201.25	-7.0797	0.3500
0.3709	87.19	-8.6139	0.4000
0.7006	-184.06	-3.0900	0.4500
0.3129	-196.04	-10.0909	0.5000
0.3160	-200.77	-10.0070	0.5500
0.3390	-218.57	-9.3969	0.6000

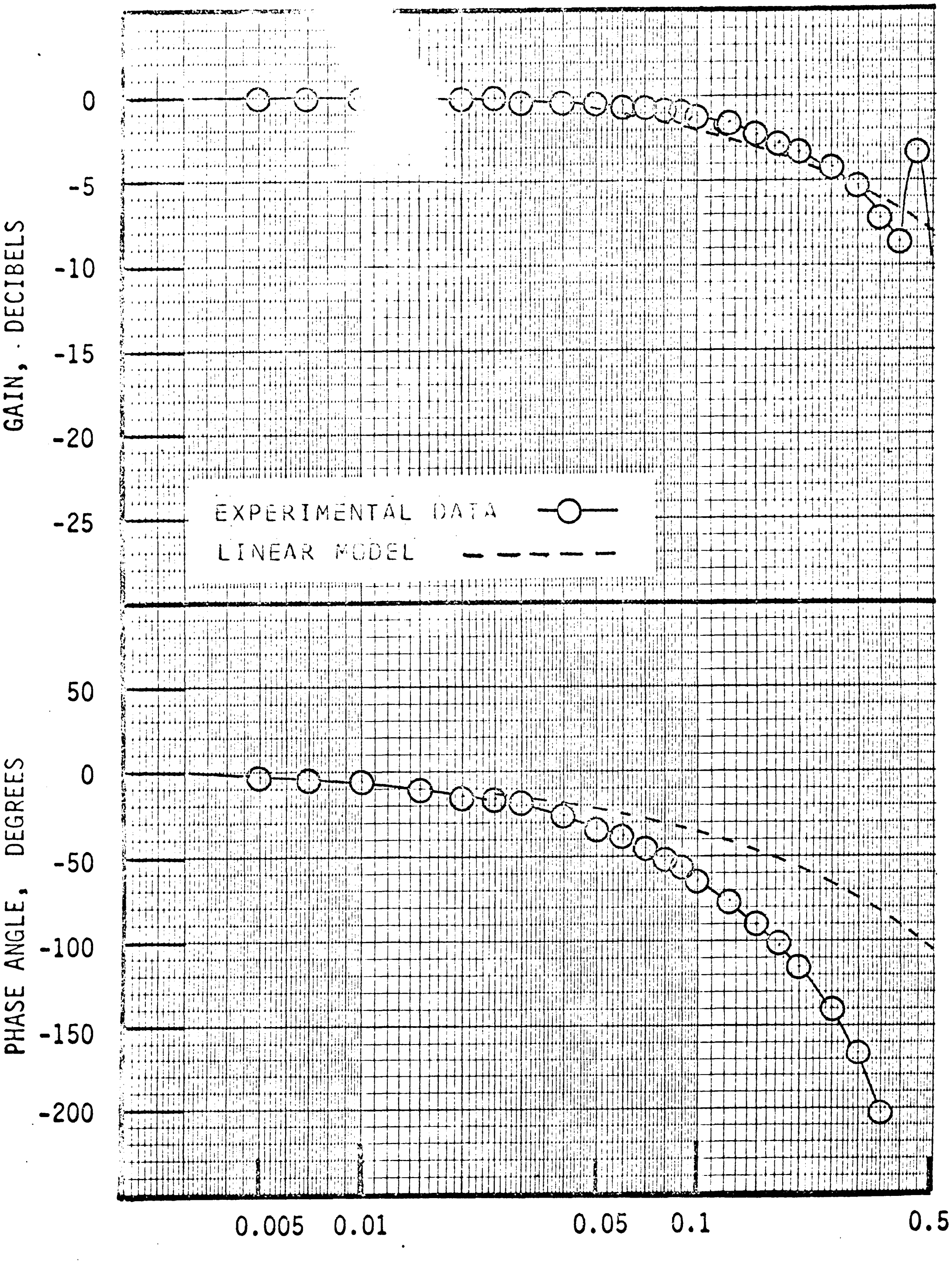

Figure 22. Distillate Composition/Vapor Rate Open Loop Transfer Function based on Experimental and Linear Model Results for Test 9V

TABLE LVIII

BINARY DISTILLATION STEADY-STATE TEST DATA
HEAT AND MATERIAL BALANCES
EXPERIMENTAL DATA SET 9VA

STREAM	MOLES/MINUTE	MOLES BENZENE/MINUTE
FEED	0.0623	0.0428
BOTTOMS	0.0182	0.0036
OVERHEAD	0.0458	0.0402
REFLUX	0.0690	0.0605

TOTAL MASS ERROR -0.0017 PERCENT 2.7520

BENZENE ERROR -.0009 PERCENT 2.1538

COLUMN INTERNAL FLOW RATES

TOP VAPOR	0.119513		
TOP LIQUID	0.073723	L/V TOP	0.616857
BOTTOM VAPOR	0.122780		
BOTTOM LIQUID	0.139277	L/V BOTT	1.134359

Q-VALUE FEED = 1.0525 REFLUX = 1.0687

F-FACTOR TOP = 1.0395 BOTTOM = 1.1612

FEED TRAY = 9

HEAT BALANCE DATA

	INPUT BTU/MIN	OUTPUT BTU/MIN	ERROR BTU/MIN	PERCENT ERROR
OVERALL	2851.8	2142.8	709.1	24.86
CONDENSER	2987.1	2589.3	397.8	13.32
TOWER	3650.2	3338.9	311.2	8.53

TABLE LIX

BINARY DISTILLATION STEADY-STATE TEST DATA
TRAY TO TRAY CALCULATION RESULTS
EXPERIMENTAL DATA SET 9VA

FEED TRAY = 9

TRAY	LIQUID MOLE FRACT	TEMPERATURE DEGREES F	EQUILIBRIUM CURVE SLOPE	EFFICIENCY MURPHREE	PRESSURE MM HG
FEED	0.6878	181.00			
REFLUX	0.8772	168.00			
1	0.8439	193.50	0.7046	0.8445	945.2
2	0.8121	194.00	0.6950	0.8996	939.2
3	0.7866	194.80	0.6890	0.7958	940.3
4	0.7732	195.20	0.6865	0.4379	940.5
5	0.7497	196.00	0.6834	0.8380	942.3
6	0.7321	196.50	0.6820	0.6721	942.1
7	0.7180	197.20	0.6817	0.5739	946.3
8	0.6936	198.00	0.6825	1.1027	947.5
9	0.6823	198.50	0.6836	0.4734	951.3
10	0.6694	199.10	0.6855	0.4734	953.1
11	0.6536	199.50	0.6885	0.4734	951.8
12	0.6304	200.50	0.6948	0.5432	956.2
13	0.5963	201.00	0.7080	0.6132	947.7
14	0.5609	202.50	0.7271	0.5163	953.3
15	0.4965	204.00	0.7774	0.7122	944.4
16	0.3849	206.00	0.9185	0.9359	917.9
17	0.3321	208.80	1.0124	0.4155	931.5
18	0.2588	213.00	1.1750	0.7008	953.9
REBOILER	0.1974	218.00	1.3426	0.7008	994.2

TRAY HOLDUP TOP = 0.00913 MOLES BOTTOM = 0.00835 MOLES

TIME CONSTANT, TRAY HOLDUP/LIQUID RATE = 0.05999 MINUTES

TABLE LX

BINARY DISTILLATION STEADY-STATE TEST DATA
HEAT AND MATERIAL BALANCES
EXPERIMENTAL DATA SET 10V

STREAM	MOLES/MINUTE		MOLES BENZENE/MINUTE
FEED	0.0635		0.0439
BOTTOMS	0.0182		0.0037
OVERHEAD	0.0464		0.0406
REFLUX	0.0689		0.0603
TOTAL MASS ERROR	-0.0011	PERCENT	1.7305
BENZENE ERROR	-.0004	PERCENT	0.8488

COLUMN INTERNAL FLOW RATES

TOP VAPOR	0.120123		
TOP LIQUID	0.073770	L/V TOP	0.614120
BOTTOM VAPOR	0.123353		
BOTTOM LIQUID	0.140499	L/V BOTT	1.139003

Q-VALUE FEED = 1.0509 REFLUX = 1.0701

F-FACTOR TOP = 1.0461 BOTTOM = 1.1711

FEED TRAY = 9

HEAT BALANCE DATA

	INPUT BTU/MIN	OUTPUT BTU/MIN	ERROR BTU/MIN	PERCENT ERROR
OVERALL	2866.6	2149.5	717.1	25.01
CONDENSER	3002.7	2595.9	406.9	13.55
TOWER	3664.2	3353.9	310.2	8.47

TABLE LXI

BINARY DISTILLATION STEADY-STATE TEST DATA
TRAY TO TRAY CALCULATION RESULTS
EXPERIMENTAL DATA SET 10V

FEED TRAY = 9

TRAY	LIQUID MOLE FRACT	TEMPERATURE DEGREES F	EQUILIBRIUM CURVE SLOPE	EFFICIENCY MURPHERE	PRESSURE MM HG
FEED	0.6911	181.00			
REFLUX	0.8751	167.50			
1	0.8403	193.50	0.7034	0.8643	943.6
2	0.8134	194.00	0.6954	0.7333	939.7
3	0.7859	194.50	0.6889	0.8328	935.4
4	0.7739	195.00	0.6866	0.3786	937.8
5	0.7623	195.50	0.6849	0.3818	940.3
6	0.7321	196.00	0.6820	1.1210	934.5
7	0.7195	197.00	0.6817	0.4918	944.0
8	0.6961	197.50	0.6824	1.0221	941.0
9	0.6865	198.00	0.6832	0.5059	945.2
10	0.6750	198.50	0.6846	0.5059	946.5
11	0.6605	199.00	0.6871	0.5059	947.5
12	0.6412	199.50	0.6916	0.5345	946.1
13	0.6010	200.50	0.7059	0.7762	942.3
14	0.5619	201.80	0.7265	0.5905	943.2
15	0.4923	203.50	0.7814	0.7731	934.8
16	0.3950	205.20	0.9026	0.8408	911.3
17	0.3367	208.00	1.0033	0.4652	922.2
18	0.2638	212.80	1.1626	0.7062	953.7
REBOILER	0.2024	217.50	1.3277	0.7062	989.5

TRAY HOLDUP TOP = 0.00911 MOLES BOTTOM = 0.00835 MOLES

TIME CONSTANT, TRAY HOLDUP/LIQUID RATE = 0.05942 MINUTES

TABLE LXII

DISTILLATE COMPOSITION/VAPOR RATE
EXPERIMENTAL FREQUENCY RESPONSE RESULTS
FOR PULSE TEST 10V

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
0.9588	0.0000	-0.3657

MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1.0000	-0.00	0.0000	0.0000
1.0000	-0.00	0.0000	0.0001
1.0000	-0.02	0.0003	0.0005
1.0001	-0.04	0.0012	0.0010
1.0033	-0.22	0.0287	0.0050
1.0065	-0.32	0.0560	0.0070
1.0131	-0.52	0.1130	0.0100
1.0290	-0.98	0.2481	0.0150
1.0503	-1.66	0.4263	0.0200
1.0763	-2.60	0.6388	0.0250
1.1061	-3.82	0.8761	0.0300
1.1734	-7.17	1.3889	0.0400
1.2448	-11.64	1.9023	0.0500
1.3140	-17.08	2.3722	0.0600
1.3757	-23.31	2.7705	0.0700
1.4258	-30.14	3.0810	0.0800
1.4613	-37.42	3.2946	0.0900
1.4802	-45.02	3.4066	0.1000
1.4507	-64.61	3.2317	0.1250
1.3195	-83.74	2.4083	0.1500
1.1199	-100.58	0.9834	0.1750
0.9086	-112.81	-0.8324	0.2000
0.7140	-122.80	-2.9260	0.2500
0.9491	-156.10	-0.4534	0.3000
0.4429	-144.76	-7.0747	0.3500
0.3025	-149.08	-10.3868	0.4000
0.4604	-152.47	-6.7378	0.4500
0.5208	-187.93	-5.6661	0.5000
0.3351	-207.48	-9.4966	0.5500
0.7724	-171.21	-2.2432	0.6000

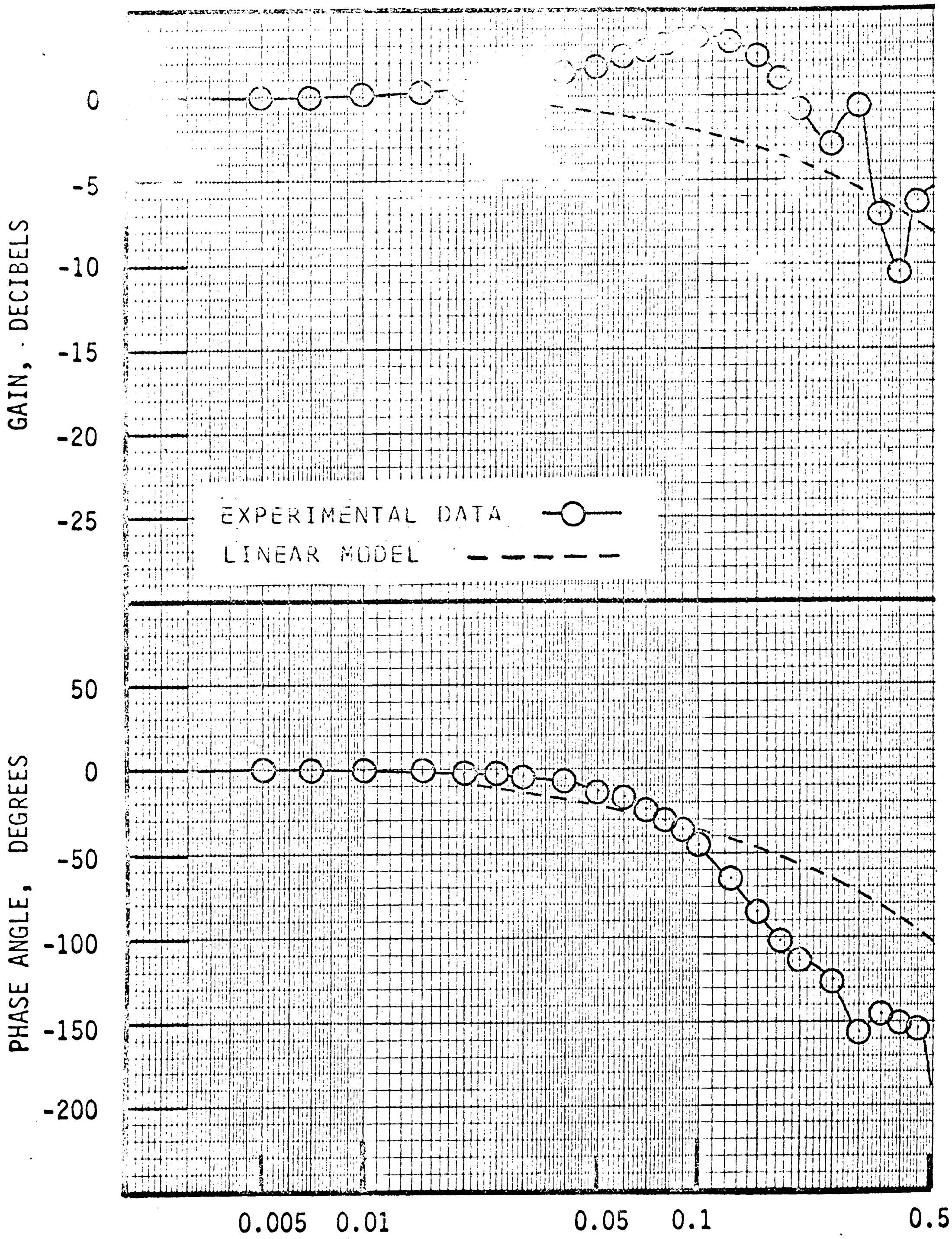

Figure 23. Distillate Composition/Vapor Rate Open Loop Transfer Function based on Experimental and Linear Model Results for Test 10V

TABLE LXIII

BOTTOMS COMPOSITION/VAPOR RATE EXPERIMENTAL FREQUENCY RESPONSE RESULTS FOR PULSE TEST 10V

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
30.3720	0.0000	29.6495

MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1.0000	-0.00	-0.0000	0.0000
1.0000	-0.06	-0.0000	0.0001
1.0000	-0.30	-0.0001	0.0005
1.0000	-0.61	-0.0003	0.0010
0.9990	-3.03	-0.0085	0.0050
0.9981	-4.23	-0.0166	0.0070
0.9961	-6.04	-0.0339	0.0100
0.9913	-9.04	-0.0761	0.0150
0.9846	-12.02	-0.1348	0.0200
0.9761	-14.96	-0.2097	0.0250
0.9660	-17.86	-0.3004	0.0300
0.9412	-23.49	-0.5267	0.0400
0.9112	-28.86	-0.8077	0.0500
0.8775	-33.91	-1.1350	0.0600
0.8416	-38.57	-1.4981	0.0700
0.8051	-42.83	-1.8835	0.0800
0.7694	-46.68	-2.2765	0.0900
0.7361	-50.13	-2.6614	0.1000
0.6678	-57.54	-3.5077	0.1250
0.6195	-64.50	-4.1587	0.1500
0.5764	-72.16	-4.7852	0.1750
0.5219	-80.01	-5.6479	0.2000
0.3888	-85.38	-8.2060	0.2500
0.5746	-58.14	-4.8121	0.3000
0.2873	-120.61	-10.8331	0.3500
0.2883	-119.48	-10.8025	0.4000
0.3034	-115.84	-10.3603	0.4500
0.4046	-133.58	-7.8593	0.5000
0.3777	-170.39	-8.4570	0.5500
0.1407	-160.01	-17.0370	0.6000

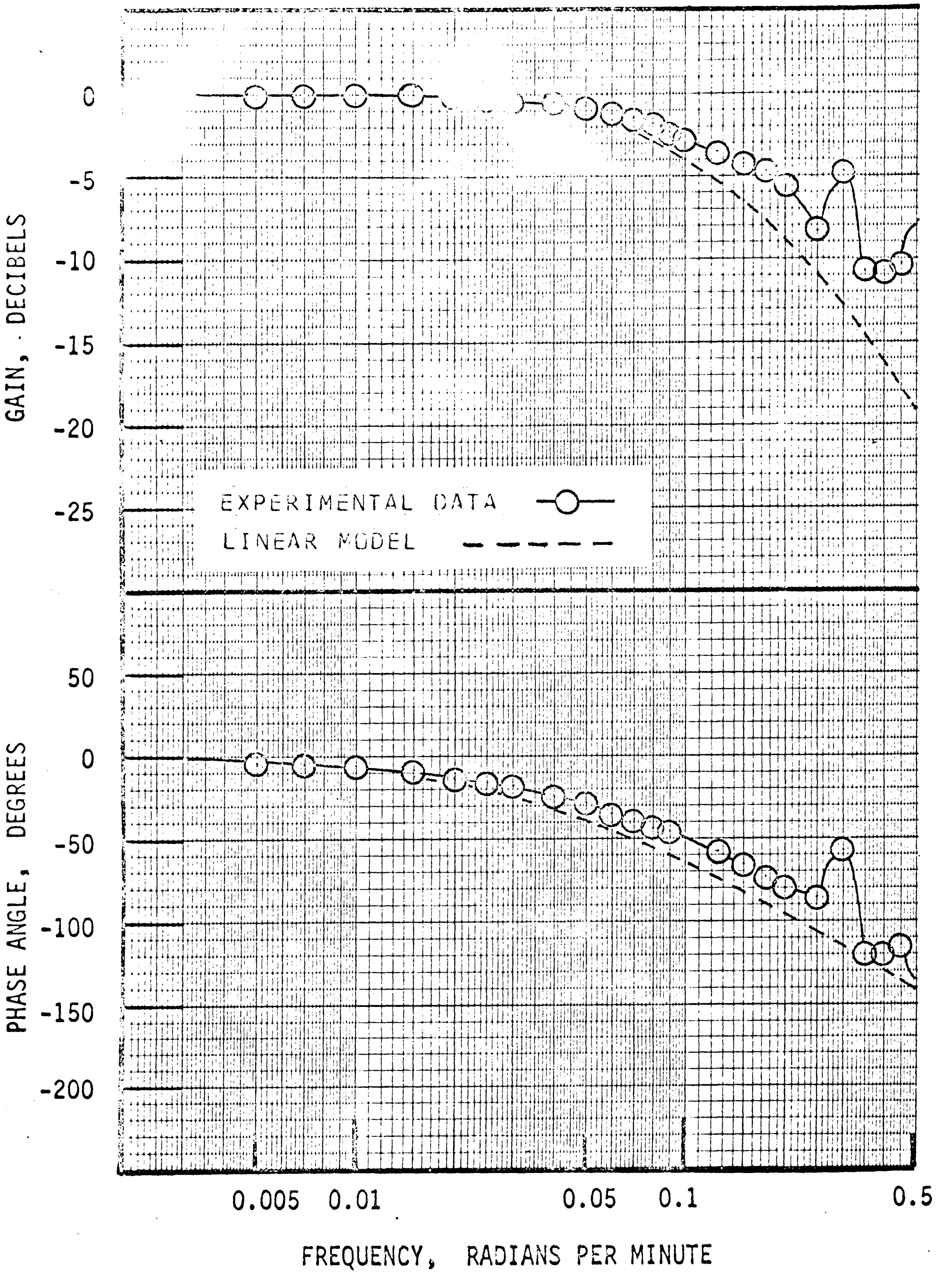

Figure 24. Bottoms Composition/Vapor Rate Open Loop Transfer Function based on Experimental and Linear Model Results for Test 10V

TABLE LXIV

BINARY DISTILLATION STEADY-STATE TEST DATA
HEAT AND MATERIAL BALANCES
EXPERIMENTAL DATA SET 10VA

STREAM	MOLES/MINUTE		MOLES BENZENE/MINUTE
FEED	0.0634		0.0436
BOTTOMS	0.0178		0.0036
OVERHEAD	0.0470		0.0412
REFLUX	0.0678		0.0594
TOTAL MASS ERROR	-0.0014	PERCENT	2.1667
BENZENE ERROR	-.0012	PERCENT	2.8658

COLUMN INTERNAL FLOW RATES

TOP VAPOR	0.119400		
TOP LIQUID	0.072433	L/V TOP	0.606642
BOTTOM VAPOR	0.122632		
BOTTOM LIQUID	0.139064	L/V BOTT	1.133999

Q-VALUE FEED = 1.0510 REFLUX = 1.0687

F-FACTOR TOP = 1.0441 BOTTOM = 1.1621

FEED TRAY = 9

HEAT BALANCE DATA

	INPUT BTU/MIN	OUTPUT BTU/MIN	ERROR BTU/MIN	PERCENT ERROR
OVERALL	2857.3	2135.1	722.2	25.27
CONDENSER	2984.8	2576.7	408.2	13.67
TOWER	3640.9	3326.9	314.0	8.62

TABLE LXV

BINARY DISTILLATION STEADY-STATE TEST DATA
TRAY TO TRAY CALCULATION RESULTS
EXPERIMENTAL DATA SET 10VA

FEED TRAY = 9

TRAY	LIQUID MOLE FRACT	TEMPERATURE DEGREES F	EQUILIBRIUM CURVE SLOPE	EFFICIENCY MURPHERE	PRESSURE MM HG
FEED	0.6869	181.00			
REFLUX	0.8762	167.50			
1	0.8391	193.00	0.7030	0.9388	935.5
2	0.8141	193.50	0.6955	0.6998	932.4
3	0.7859	194.00	0.6889	0.8893	927.9
4	0.7732	194.50	0.6865	0.4229	929.9
5	0.7557	195.00	0.6840	0.6302	929.8
6	0.7360	195.70	0.6822	0.7778	931.7
7	0.7219	196.20	0.6817	0.5966	933.0
8	0.6994	197.00	0.6822	1.0861	934.9
9	0.6866	198.00	0.6832	0.4201	945.6
10	0.6759	198.20	0.6845	0.4201	942.4
11	0.6631	199.00	0.6866	0.4201	948.7
12	0.6447	199.50	0.6907	0.4886	947.7
13	0.6140	200.50	0.7005	0.6204	948.5
14	0.5745	201.50	0.7191	0.6147	944.8
15	0.5047	203.00	0.7697	0.7885	933.5
16	0.3973	205.20	0.8992	0.9158	912.5
17	0.3379	208.20	1.0011	0.4672	925.7
18	0.2656	212.50	1.1582	0.6891	950.2
REBOILER	0.2049	217.20	1.3204	0.6891	986.4

TRAY HOLDUP TOP = 0.00911 MOLES BOTTOM = 0.00843 MOLES

TIME CONSTANT, TRAY HOLDUP/LIQUID RATE = 0.06059 MINUTES

TABLE LXVI

REFLUX COMPOSITION/VAPOR RATE OPEN LOOP TRANSFER FUNCTION BASED ON LINEAR MODEL FOR EXPERIMENTAL DATA SET 11F

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
0.0340	0.00	-29.3686

	MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1	1.0000	-0.00	0.0000	0.0000
2	1.0000	-0.05	-0.0000	0.0001
3	1.0000	-0.24	-0.0002	0.0005
4	1.0000	-0.47	-0.0004	0.0010
5	0.9989	-2.37	-0.0095	0.0050
6	0.9979	-3.31	-0.0185	0.0070
7	0.9957	-4.71	-0.0376	0.0100
8	0.9904	-7.03	-0.0836	0.0150
9	0.9833	-9.30	-0.1463	0.0200
10	0.9745	-11.50	-0.2242	0.0250
11	0.9643	-13.64	-0.3157	0.0300
12	0.9407	-17.68	-0.5311	0.0400
13	0.9144	-21.37	-0.7769	0.0500
14	0.8872	-24.74	-1.0392	0.0600
15	0.8603	-27.80	-1.3068	0.0700
16	0.8345	-30.60	-1.5716	0.0800
17	0.8102	-33.18	-1.8283	0.0900
18	0.7876	-35.57	-2.0739	0.1000
19	0.7385	-41.00	-2.6332	0.1250
20	0.6982	-45.94	-3.1206	0.1500
21	0.6643	-50.62	-3.5526	0.1750
22	0.6349	-55.16	-3.9463	0.2000
23	0.5842	-64.02	-4.6695	0.2500
24	0.5396	-72.66	-5.3578	0.3000
25	0.4988	-81.04	-6.0413	0.3500
26	0.4607	-89.14	-6.7314	0.4000
27	0.4251	-96.92	-7.4310	0.4500
28	0.3918	-104.38	-8.1390	0.5000
29	0.3609	-111.51	-8.8530	0.5500
30	0.3323	-118.34	-9.5704	0.6000

TABLE LXVII

BOTTOMS COMPOSITION/VAPOR RATE OPEN LOOP TRANSFER FUNCTION BASED ON LINEAR MODEL FOR EXPERIMENTAL DATA SET 11F

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
3.2250	0.00	10.1706

	MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1	1.0000	-0.00	-0.0000	0.0000
2	1.0000	-0.08	-0.0000	0.0001
3	1.0000	-0.41	-0.0002	0.0005
4	0.9999	-0.81	-0.0006	0.0010
5	0.9982	-4.07	-0.0153	0.0050
6	0.9966	-5.69	-0.0299	0.0070
7	0.9930	-8.12	-0.0609	0.0100
8	0.9845	-12.12	-0.1359	0.0150
9	0.9729	-16.06	-0.2389	0.0200
10	0.9585	-19.92	-0.3681	0.0250
11	0.9418	-23.67	-0.5212	0.0300
12	0.9026	-30.86	-0.8899	0.0400
13	0.8585	-37.54	-1.3249	0.0500
14	0.8121	-43.72	-1.8076	0.0600
15	0.7655	-49.40	-2.3214	0.0700
16	0.7200	-54.62	-2.8534	0.0800
17	0.6766	-59.41	-3.3937	0.0900
18	0.6357	-63.82	-3.9349	0.1000
19	0.5455	-73.46	-5.2635	0.1250
20	0.4715	-81.57	-6.5301	0.1500
21	0.4109	-88.56	-7.7247	0.1750
22	0.3610	-94.70	-8.8498	0.2000
23	0.2845	-105.18	-10.9192	0.2500
24	0.2293	-113.96	-12.7937	0.3000
25	0.1880	-121.54	-14.5171	0.3500
26	0.1563	-128.18	-16.1197	0.4000
27	0.1315	-134.07	-17.6223	0.4500
28	0.1117	-139.34	-19.0397	0.5000
29	0.0957	-144.08	-20.3826	0.5500
30	0.0826	-148.37	-21.6592	0.6000

TABLE LXVIII

BINARY DISTILLATION STEADY-STATE TEST DATA
HEAT AND MATERIAL BALANCES
EXPERIMENTAL DATA SET 12F

STREAM	MOLES/MINUTE		MOLES BENZENE/MINUTE
FEED	0.0623		0.0400
BOTTOMS	0.0186		0.0022
OVERHEAD	0.0455		0.0392
REFLUX	0.0686		0.0591
TOTAL MASS ERROR	-0.0018	PERCENT	2.8635
BENZENE ERROR	-.0014	PERCENT	3.5370
COLUMN INTERNAL FLOW RATES			
TOP VAPOR	0.118384		
TOP LIQUID	0.072861	L/V TOP	0.615465
BOTTOM VAPOR	0.121250		
BOTTOM LIQUID	0.138068	L/V BOTT	1.138706

Q-VALUE FEED = 1.0460 REFLUX = 1.0624

F-FACTOR TOP = 1.0634 BOTTOM = 1.1931

FEED TRAY = 9

HEAT BALANCE DATA

	INPUT BTU/MIN	OUTPUT BTU/MIN	ERROR BTU/MIN	PERCENT ERROR
OVERALL	2859.6	2139.6	720.0	25.18
CONDENSER	2972.9	2566.1	406.8	13.68
TOWER	3659.7	3346.4	313.2	8.56

TABLE LXIX

BINARY DISTILLATION STEADY-STATE TEST DATA
TRAY TO TRAY CALCULATION RESULTS
EXPERIMENTAL DATA SET 12F

FEED TRAY = 9

TRAY	LIQUID MOLE FRACT	TEMPERATURE DEGREES F	EQUILIBRIUM CURVE SLOPE	EFFICIENCY MURPHERE	PRESSURE MM HG
FEED	0.6421	181.00			
REFLUX	0.8622	167.50			
1	0.8160	190.50	0.6961	1.0239	886.8
2	0.7788	191.50	0.6875	0.9182	888.0
3	0.7467	192.00	0.6831	0.8733	881.8
4	0.7298	192.50	0.6819	0.4824	881.9
5	0.6994	193.50	0.6822	0.9577	883.4
6	0.6777	194.00	0.6842	0.7385	881.3
7	0.6570	195.00	0.6878	0.7645	886.7
8	0.6394	195.20	0.6921	0.7099	881.9
9	0.6252	196.00	0.6965	0.5351	886.2
10	0.6035	196.50	0.7048	0.5351	884.6
11	0.5764	197.80	0.7180	0.5351	891.1
12	0.5332	198.50	0.7462	0.6524	881.4
13	0.4808	199.50	0.7929	0.6290	871.3
14	0.4228	201.50	0.8623	0.5852	872.1
15	0.3610	204.00	0.9587	0.5531	877.1
16	0.2751	207.50	1.1355	0.7229	882.8
17	0.2062	210.50	1.3168	0.6053	888.5
18	0.1553	215.20	1.4752	0.5898	927.5
REBOILER	0.1179	219.20	1.6058	0.5898	964.4

TRAY HOLDUP TOP = 0.00886 MOLES BOTTOM = 0.00781 MOLES

TIME CONSTANT, TRAY HOLDUP/LIQUID RATE = 0.05655 MINUTES

TABLE LXX

DISTILLATE COMPOSITION/FEED COMPOSITION EXPERIMENTAL FREQUENCY RESPONSE RESULTS FOR PULSE TEST 12F

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
0.2461	0.0000	-12.1779

MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1.0000	-0.00	0.0000	0.0000
1.0000	-0.08	-0.0000	0.0001
1.0000	-0.41	-0.0000	0.0005
1.0000	-0.83	-0.0001	0.0010
0.9996	-4.13	-0.0034	0.0050
0.9992	-5.78	-0.0068	0.0070
0.9984	-8.27	-0.0139	0.0100
0.9963	-12.42	-0.0318	0.0150
0.9934	-16.60	-0.0578	0.0200
0.9894	-20.81	-0.0930	0.0250
0.9842	-25.06	-0.1386	0.0300
0.9696	-33.69	-0.2680	0.0400
0.9481	-42.51	-0.4628	0.0500
0.9178	-51.50	-0.7447	0.0600
0.8771	-60.60	-1.1391	0.0700
0.8249	-69.62	-1.6719	0.0800
0.7617	-78.32	-2.3639	0.0900
0.6900	-86.33	-3.2234	0.1000
0.5052	-100.33	-5.9307	0.1250
0.3858	-102.07	-8.2724	0.1500
0.3715	-99.79	-8.5999	0.1750
0.4098	-106.07	-7.7486	0.2000
0.4263	-139.09	-7.4047	0.2500
0.2837	-170.27	-10.9441	0.3000
0.2048	-166.62	-13.7749	0.3500
0.2629	-182.67	-11.6050	0.4000
0.2255	-219.73	-12.9372	0.4500
0.1188	-231.17	-18.5031	0.5000
0.1552	-215.42	-16.1816	0.5500
0.1960	-251.65	-14.1539	0.6000

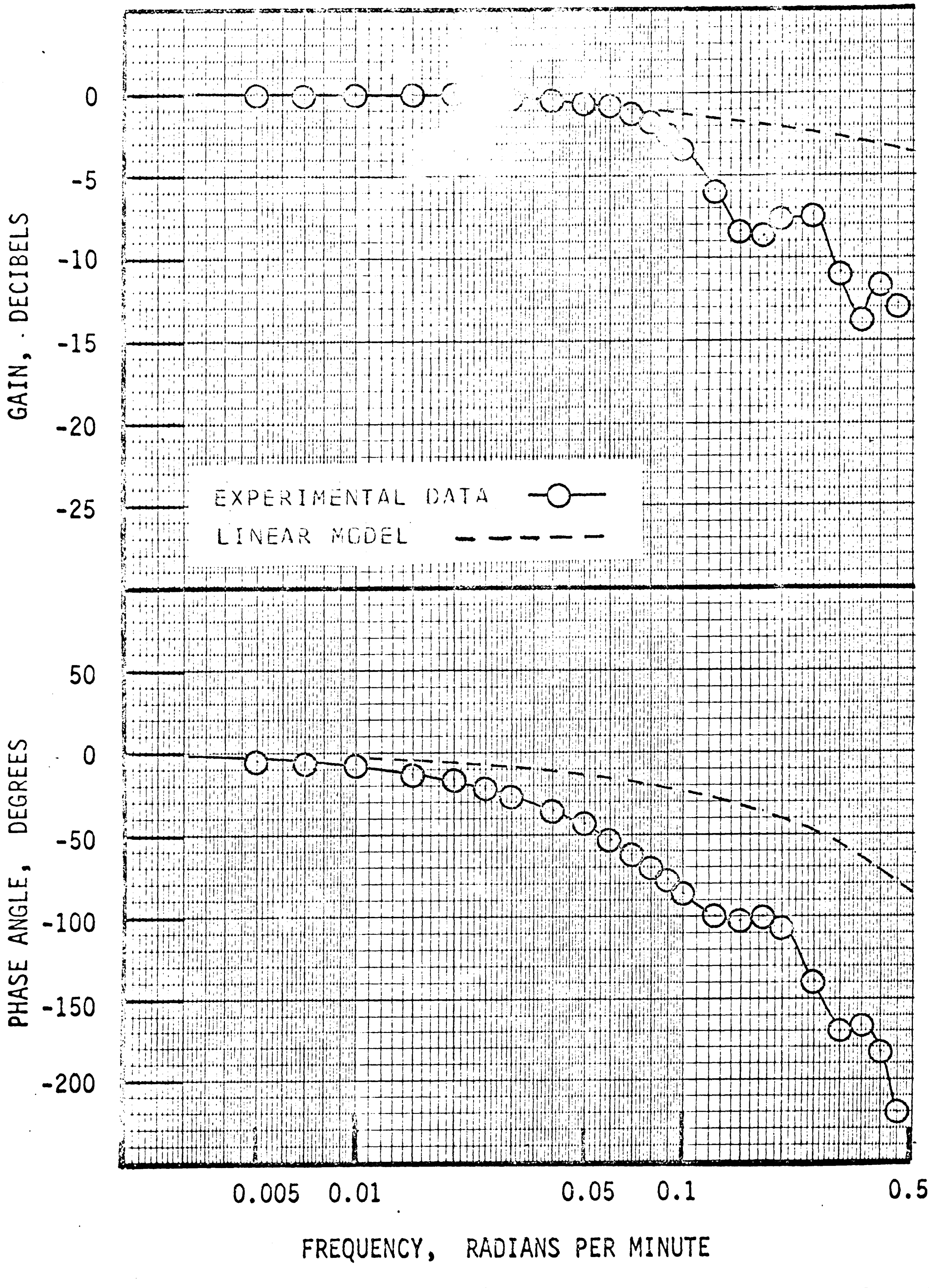

Figure 25. Distillate Composition/Feed Composition Open Loop Transfer Function Based on Experimental and Linear Model Results for Test 12 F

TABLE LXXI

BOTTOMS COMPOSITION/FEED COMPOSITION EXPERIMENTAL FREQUENCY RESPONSE RESULTS FOR PULSE TEST 12F

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
1.2490	0.0000	1.9312

MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1.0000	-0.00	-0.0000	0.0000
1.0000	-0.09	-0.0000	0.0001
1.0000	-0.47	-0.0001	0.0005
1.0000	-0.94	-0.0003	0.0010
0.9992	-4.72	-0.0067	0.0050
0.9985	-6.60	-0.0132	0.0070
0.9969	-9.44	-0.0270	0.0100
0.9930	-14.19	-0.0614	0.0150
0.9873	-18.97	-0.1109	0.0200
0.9798	-23.80	-0.1768	0.0250
0.9704	-28.68	-0.2609	0.0300
0.9448	-38.62	-0.4929	0.0400
0.9088	-48.86	-0.8302	0.0500
0.8605	-59.40	-1.3050	0.0600
0.7982	-70.19	-1.9582	0.0700
0.7211	-81.08	-2.8398	0.0800
0.6303	-91.82	-4.0090	0.0900
0.5288	-101.95	-5.5349	0.1000
0.2658	-117.78	-11.5089	0.1250
0.1316	-77.75	-17.6174	0.1500
0.2415	-55.75	-12.3399	0.1750
0.3415	-71.13	-9.3331	0.2000
0.3454	-116.70	-9.2336	0.2500
0.1508	-142.18	-16.4324	0.3000
0.1698	-103.91	-15.4034	0.3500
0.2231	-138.66	-13.0319	0.4000
0.1035	-167.28	-19.7035	0.4500
0.1432	-107.40	-16.8831	0.5000
0.2616	-145.83	-11.6474	0.5500

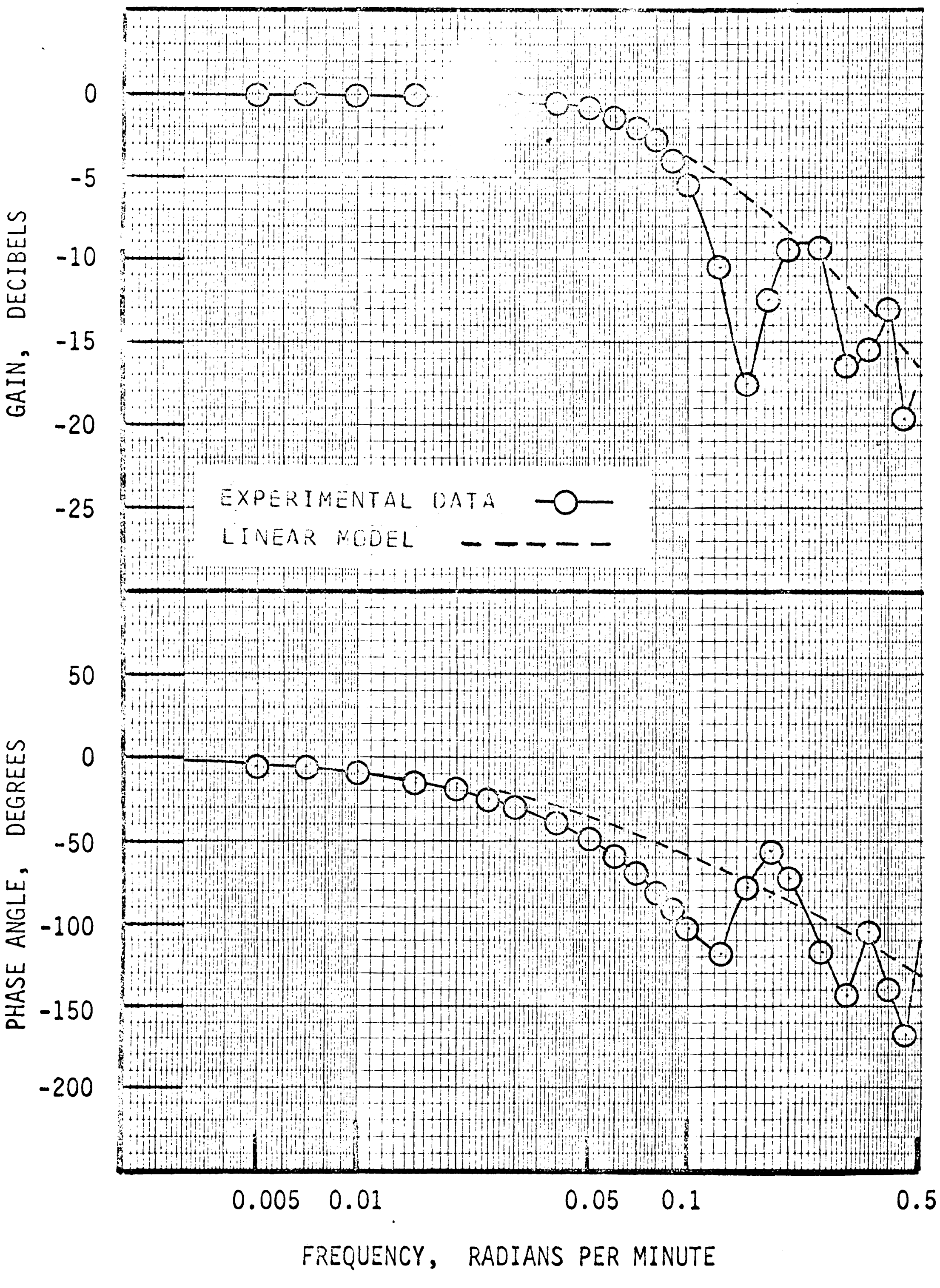

Figure 26. Bottoms Composition/Feed Composition Open Loop Transfer Function based on Experimental and Linear Model Results for Test 12F

TABLE LXXII

BINARY DISTILLATION STEADY-STATE TEST DATA
HEAT AND MATERIAL BALANCES
EXPERIMENTAL DATA SET 12FA

STREAM	MOLES/MINUTE	MOLES BENZENE/MINUTE
FEED	0.0626	0.0410
BOTTOMS	0.0187	0.0026
OVERHEAD	0.0455	0.0392
REFLUX	0.0685	0.0590

TOTAL MASS ERROR -0.0016 PERCENT 2.5671

BENZENE ERROR -.0008 PERCENT 1.9362

COLUMN INTERNAL FLOW RATES
TOP VAPOR 0.118335

TOP LIQUID 0.072832 L/V TOP 0.615474

BOTTOM VAPOR 0.121196

BOTTOM LIQUID 0.138323 L/V BOTT 1.141315

Q-VALUE FEED = 1.0457 REFLUX = 1.0625

F-FACTOR TOP = 1.0605 BOTTOM = 1.1724

FEED TRAY = 9

HEAT BALANCE DATA

	INPUT BTU/MIN	OUTPUT BTU/MIN	ERROR BTU/MIN	PERCENT ERROR
OVERALL	2857.6	2139.0	718.6	25.15
CONDENSER	2972.7	2566.4	406.3	13.67
TOWER	3657.9	3345.5	312.4	8.54

TABLE LXXIII

BINARY DISTILLATION STEADY-STATE TEST DATA
TRAY TO TRAY CALCULATION RESULTS
EXPERIMENTAL DATA SET 12FA

FEED TRAY = 9

TRAY	LIQUID MOLE FRACT	TEMPERATURE DEGREES F	EQUILIBRIUM CURVE SLOPE	EFFICIENCY MURPHERE	PRESSURE MM HG
FEED	0.6544	181.00			
REFLUX	0.8611	167.50			
1	0.8224	190.50	0.6979	0.8293	891.4
2	0.7921	191.50	0.6902	0.7093	893.5
3	0.7586	192.00	0.6844	0.8610	886.8
4	0.7398	192.50	0.6825	0.5107	886.1
5	0.7164	193.50	0.6817	0.6844	890.7
6	0.6961	194.00	0.6824	0.6322	889.2
7	0.6785	195.00	0.6841	0.5820	896.1
8	0.6588	195.20	0.6874	0.7077	890.4
9	0.6447	196.00	0.6907	0.5361	895.8
10	0.6270	196.50	0.6959	0.5361	895.1
11	0.6047	197.80	0.7042	0.5361	904.0
12	0.5754	198.50	0.7186	0.5575	900.8
13	0.5342	199.50	0.7454	0.6115	896.2
14	0.4766	201.50	0.7972	0.6682	897.9
15	0.4073	204.00	0.8842	0.6628	900.1
16	0.3192	207.50	1.0382	0.7419	905.8
17	0.2471	210.50	1.2047	0.5997	910.7
18	0.1856	215.20	1.3782	0.6547	945.0
REBOILER	0.1387	219.20	1.5317	0.6547	977.1

TRAY HOLDUP   TOP = 0.00892 MOLES   BOTTOM = 0.00808 MOLES

TIME CONSTANT, TRAY HOLDUP/LIQUID RATE = 0.05840 MINUTES

```
                 PULSE DATA TO FREQUENCY RESPONSE
                   PROGRAM TEST DATA RESULTS


            STEADY-STATE     PHASE ANGLE      STEADY-STATE
                GAIN           DEGREES          DECIBELS
              0.9996           0.0000           -0.0035

   MAGNITUDE        PHASE ANGLE          GAIN          FREQUENCY
     RATIO            DEGREES          DECIBELS       RADIANS/MIN

    1.0000              -0.00            0.0000          0.0000
    1.0000              -0.06           -0.0000          0.0001
    1.0000              -0.28           -0.0001          0.0005
    1.0000              -0.57           -0.0004          0.0010
    0.9996              -1.70           -0.0038          0.0030

    0.9988              -2.83           -0.0106          0.0050
    0.9976              -3.95           -0.0207          0.0070
    0.9961              -5.08           -0.0342          0.0090
    0.9952              -5.64           -0.0422          0.0100
    0.9892              -8.42           -0.0945          0.0150

    0.9810             -11.17           -0.1669          0.0200
    0.9707             -13.87           -0.2586          0.0250
    0.9585             -16.51           -0.3684          0.0300
    0.9446             -19.08           -0.4953          0.0350
    0.9292             -21.57           -0.6377          0.0400

    0.9126             -23.98           -0.7942          0.0450
    0.8950             -26.30           -0.9632          0.0500
    0.8767             -28.52           -1.1430          0.0550
    0.8578             -30.64           -1.3319          0.0600
    0.8193             -34.61           -1.7308          0.0700

    0.7809             -38.20           -2.1484          0.0800
    0.7434             -41.46           -2.5757          0.0900
    0.7074             -44.41           -3.0068          0.1000
    0.5548             -55.47           -5.1176          0.1500
    0.3715             -66.75           -8.6017          0.2500

    0.3164             -69.88           -9.9953          0.3000
    0.2426             -73.68          -12.3028          0.4000
    0.2172             -74.92          -13.2642          0.4500
    0.1963             -75.81          -14.1428          0.5000
    0.1647             -77.11          -15.6682          0.6000

    0.1416             -77.91          -16.9790          0.7000
    0.1241             -78.31          -18.1241          0.8000
    0.1106             -78.45          -19.1235          0.9000
    0.0999             -78.57          -20.0110          1.0000
    0.0846             -80.99          -21.4571          1.2500

    0.0668             -77.47          -23.5066          1.5000
    0.0574             -76.66          -24.8169          1.7500
    0.0504             -75.71          -25.9524          2.0000
    0.0408             -77.65          -27.7786          2.5000
    0.0339             -70.94          -29.3861          3.0000
```

Digital Computer Programs

The following are the digital computer programs written in Fortran IV for the IBM 7040 computer used during this investigation.

Steady-State Program SSDDR. The purpose of this program was to reduce to useful form the experimental data collected during this investigation. An overall heat and mass balance, the individual tray efficiencies and the values of the constants required for the dynamic programs were calculated by this program.

The equilibrium relationship between the vapor, Y, and the liquid, X, is expressed as a polynomial in X. This correlation was developed based on 760 mm of Hg pressure data. The empirical correlations of heat capacity data, specific gravity, and vapor pressures are expressed as polynomials in temperature, T. Liquid composition, expressed as mole fraction benzene, is correlated as a function of liquid refractive index reading determined at 30 °C. All empirical correlations appear at the start of the program as arithmetic statement functions.

This steady-state program consists of a group of programs written for the particular column used during this investigation and would have to be modified for any other distillation column. Each major section will be briefly explained in the following paragraphs.

Refractive Index Data Reduction. This section converts the raw refractive index data for each tray and process stream to the mole fraction benzene. This section also calculates the weight fraction and the equilibrium vapor composition in mole fraction benzene for each tray.

Flow Meter Correction. This section corrects the calibration curve for each transmitting rotameter for changes in density of the actual stream. The calibration curves were developed for benzene at 80 °F and must be corrected for changes in density caused by variations in temperature and composition.

Material Balance. A material balance is calculated for the overall column along with the per cent error based on input to the column.

Benzene Balance. In a similar manner an overall benzene balance is calculated for the system along with the per cent error.

Q-Values for the Feed and Reflux. The Q-values or the thermal condition of the feed and reflux streams are calculated for use in the system heat balance and in the tray calculations. These calculations are based on the stream temperatures and compositions.

F-Factor Calculation. The F-factor above and below the feed tray for the column is calculated. The F-factor is a measure of the column loading or approach to flooding.

Heat Balance. An overall heat balance plus condenser and tower heat balances are calculated for the process. The per cent error is computed based on the heat input to the section.

Tray to Tray Calculations. The tray to tray calculations are used to determine the individual tray efficiencies in the column. For the two trays where liquid samples are not available the program assumes that the tray in question and the tray below it have the same efficiency. A logical routine is used to determine in what operating section of the column these two trays are located for each test.

Overall Efficiency. The Murpheer tray efficiencies are converted to an overall column efficiency and averaged for the sections above and below the feed tray. This estimate of the column operating efficiency is used in the dynamic programs.

Feedforward Controller Program Constants. Constants for use in the dynamic linear model program are calculated and punched out in the correct format for use in program FFCLM.

Program Input Data. The required input data and format for this program consists of the following cards:

Card 1	JOB, where JOB is the number of complete sets of experimental data which follows. Format I2
Card 2	Description Card, this card is used for identification and will appear as a header card for the data output. This card may be a blank card. Format 72H

Card 3-5	Refractive index and temperature of the reflux, refractive index and temperature of the feed and the refractive index and temperature of the bottom product. Temperature in degrees Fahrenheit. Format 2F10.4
Cards 6-15	Refractive index and temperature of each tray starting with tray 1 and going through tray 9. The trays are numbered from the top down. Temperature in degrees Fahrenheit. Format 2F10.4
Cards 16-22	Refractive index and temperature of each tray starting with tray 11 and ending with tray 17. Format 2F10.4
Card 23	Temperature of trays 10 and 18. Format 2F10.4
Card 24	Process flow rates for streams feed, reflux, distillate and bottoms given in pounds per minute. Values taken from calibration curves of transmitters. Format 4F10.4
Card 25	Process heat balance data. Heat input by the steam to the reboiler, heat removed by the cooling water to the overhead condenser and the temperature of the overhead vapor. Heat balance data given in BTU/min. Format 3F10.2
Card 26	Feed tray location. Trays are numbered from the top down. The reboiler being tray 10. Format I2
Card 27	Second set of data starting with card 2.

```
C     STEADY-STATE DATA REDUCTION    R F JANIS JR   CHEM ENGR
C
      DIMENSION RI(18), XM(20), XW(20), YM(20), P(20),
     1YMT(20), Y(20), X(20), SLOPE(20), C1(20), C2(20),
     2 T(20), EFF(20)
C
C     REFRACTIVE INDEX CONVERSION
C
      RICONV(X)  = 58.64761 - 127.84375*X + 29.01563*(X**2)
     1 + 62.78125*(X**3) - 28.26270*(X**4)
C
C     CONVERT MOLE FRACTION TO WEIGHT FRACTION
C
      WFCONV( X ) = (78.11*X)/(78.11*X + (1.-X)*100.2)
C
C     SPECIFIC GRAVITY OF BENZENE
C
      SGB( T ) = 0.91612 - 0.00052*T
C
C     SPECIFIC GRAVITY OF N-HEPTANE
C
      SGH( T ) = 0.71538 - 0.00046*T
C
C     FLOW METER CORRECTION FOR DENSITY CHANGE
C
```

```
      FLCORR( FL, SG ) = FL*(SG/0.8745)*SQRT(0.12238*
     1 (8.02 - SG)/SG)
C
C     AVAEAGE MOLECULAR WEIGHT
C
      AVGMW( XM ) = 78.11*XM + 100.2*(1.-XM)
C
C     ENTHALPY LIQUID BENZENE,  BTU/LBS   T = F
C
      HBL( T ) = 64.28691 + 0.42988*T
C
C     ENTHALPY BENZENE VAPOR,  BTU/LBS   T = F
C
      HBV( T ) = 265.9368 + 0.19585*T + 0.00042*(T**2)
C
C     ENTHALPY N-HEPTANE LIQUID,   BTU/LBS   T = F
C
      HHL( T ) = 86.99278 + 0.52914*T + 0.00016*(T**2)
C
C     ENTHALPY N-HEPTANE VAPOR  BTU/LBS   T = F
C
      HHV( T ) = 258.18898 + 0.2800*T + 0.00083*(T**2)
C
C     VAPOR LIQUID EQUILIBRIUM DATA
C
```

```
      YEQM( X ) = 0.00049 + 2.10229*X - 2.39221*(X**2)
     1 + 1.68481*(X**3) - 0.39923*(X**4)
C
C     VAPOR PRESSURE OF BENZENE
C
      VAPPB(T) = EXP(2.302585*(6.90565-1211.033/
     1 ( 220.760 + (T-32.0)/1.8)))
C
C     VAPOR PRESSURE OF N-HEPTANE
C
      VAPPH(T) = EXP(2.302585*(6.90240-1268.115/
     1 ( 216.900 + (T-32.0)/1.8)))
C
C     DATA INPUT
C
      READ(5,1020) JOB
      DO 100 JJ = 1, JOB
      READ(5,1033)
    2 READ(5,1000) RIR, TR, RIF, TF,RIB, TB
      READ(5,1000)(RI(I), T(I), I = 1, 9 )
      READ(5,1000)(RI(I), T(I),I = 11, 17   )
      READ(5,1000) T(10), T(18)
      READ(5,1001) F, R, D, B
      READ(5,1010) BTUIN, BTUOUT, TDV
      READ(5,1020)  M
```

```
      WRITE(6,1029)
      WRITE(6,1000) RIR, TR, RIF, TF, RIB, TB
      WRITE(6,1000)(RI(I), T(I), I=1,9)
      WRITE(6,1000)(RI(I), T(I), I=11,17)
      WRITE(6,1000) T(10), T(18)
      WRITE(6,1001) F, R, D, B
      WRITE(6,1010) BTUIN, BTUOUT, TDV
      WRITE(6,1015) M
C     REFRACTIVE INDEX DATA REDUCTION
C
C
      XMR = RICONV(RIR)
      XWR = WFCONV(XMR)
      XMF = RICONV(RIF)
      XWF = WFCONV(XMF)
      XMB = RICONV(RIB)
      XWB = WFCONV(XMB)
      DO 10 I = 1, 9
      XM(I) = RICONV(RI(I))
      YMT(I) = YEQM( XM(I) )
   10 XW(I) = WFCONV(XM(I))
      DO 11 I = 11, 17
      XM(I) = RICONV(RI(I))
      YMT(I) = YEQM( XM(I) )
   11 XW(I) = WFCONV(XM(I))
```

```
C
C     FLOW METER CORRECTION
C
      TT = 80.
      ASG = XWF*SGB(TT) + (1. - XWF)*SGH(TT)
      FC = FLCORR(F, ASG)
      ASG = XWB*SGB(TB) + (1. - XWB)*SGH(TB)
      BC = FLCORR(B,ASG)
      ASG = XWR*SGB(TR) + (1. - XWR)*SGH(TR)
      RC = FLCORR(R,ASG)
      DC = FLCORR(D,ASG)
      XWD = XWR
      XMD = XMR
      TD = TR
      FM = FC/AVGMW(XMF)
      BM = BC/AVGMW(XMB)
      DM = DC/AVGMW(XMD)
      RM = RC/AVGMW(XMR)
C
C     MATERIAL BALANCE
C
      ERTM = FM - BM - DM
      PCERT = ((ABS( ERTM ))/FM)*100.
      VAPBS = BTUIN/(78.11*XMB*(HBV(TB) - HBL(TB)) +
     1 100.2*(1.-XMB)*(HHV(TB) - HHL(TB)))
```

```
C
C     BENZENE BALANCE
C
      XFM = XMF*FM
      XBM = XMB*BM
      XDM = XMD*DM
      XRM = XMR*RM
      ERCM = XFM - XBM - XDM
      PCERC = ( ABS(ERCM) / XFM )*100.
      WRITE(6,1002)
      WRITE(7,1002)
      WRITE(6,1047)
      WRITE(7,1047)
      WRITE(6,1033)
      WRITE(7,1033)
      WRITE(6,1003)
      WRITE(7,1003)
      WRITE(6,1004) FM, XFM
      WRITE(7,1004) FM, XFM
      WRITE(6,1005) BM, XBM
      WRITE(7,1005) BM, XBM
      WRITE(6,1006) DM, XDM
      WRITE(7,1006) DM, XDM
      WRITE(6,1007) RM, XRM
      WRITE(7,1007) RM, XRM
```

```
      WRITE(6, 1008) ERTM, PCERT
      WRITE(7, 1008) ERTM, PCERT
      WRITE(6, 1009) ERCM, PCERC
      WRITE(7, 1009) ERCM, PCERC
C
C     CALCULATE Q-VALUE FEED
C
      TFP = T(M)
      QF = (78.11*XMF*(HBV(TFP) - HBL(TF)) + 100.2*
     1(1.0-XMF)*(HHV(TFP) - HHL(TF)))/(78.11*XMF*
     2 (HBV(TFP) - HBL(TFP)) + 100.2*(1.0-XMF)*
     3(HHV(TFP) - HHL(TFP)))
C
C     CALCULATION Q-VALUE REFLUX
C
      QR = (78.11*XMR*(HBV(T(1)) - HBL(TR)) + 100.2*
     1 (1.0-XMR)*(HHV(T(1)) - HHL(TR)))/(78.11*XMR*
     2 (HBV(T(1)) - HBL(T(1))) + 100.2*(1.0-XMR)
     3*(HHV(T(1)) - HHL(T(1))))
      XLIQT = QR*RM
      VAPT = QR*RM + DM
      XLIQB = QF*FM + XLIQT
      VAPB = VAPT + (QF - 1.)*FM
      VAPBE = (ABS(VAPBS - VAPB)/VAPB)*100.
      XVRT = XLIQT/VAPT
```

```
      XVRB = XLIQB/VAPB
      WRITE(6,1024) VAPT
      WRITE(7,1024) VAPT
      WRITE(6,1025) XLIQT, XVRT
      WRITE(7,1025) XLIQT, XVRT
      WRITE(6,1026) VAPB
      WRITE(7,1026) VAPB
      WRITE(6,1027) XLIQB, XVRB
      WRITE(7,1027) XLIQB, XVRB
      WRITE(6, 1014) QF, QR
      WRITE(7, 1014) QF, QR
C
C     F-FACTOR CALCULATION
C
      DO 13 I = 1, 17
      IF(10-I) 12, 13, 12
   12 P(I) = XM(I)*VAPPB(T(I)) + (1. - XM(I))*VAPPH(T(I))
   13 CONTINUE
      PB = XMB*VAPPB(TB) + (1. - XMB)*VAPPH(TB)
      FFT = ((VAPT*555.0*(T(1) + 460.))/
     2 (P(1)*60.0*0.339))*SQRT((P(1)*
     1AVGMW(XM(1)))/(555.0*(T(1) + 460.)))
      FFB = (( VAPB*555.0*(T(17) + 460.))/
     2 (P(17)*0.339*60.0))*SQRT((P(17)*
     1AVGMW(XM(17)))/(555.0*(T(17) + 460.)))
```

```
      WRITE(6,1021) FFT, FFB
      WRITE(7,1021) FFT, FFB
      WRITE(6,1048) M
      WRITE(7,1048) M
C
C     HEAT BALANCE OVERALL
C
      BTUF = FM*(78.11*XMF*HBL(TF) + 100.2*(1. - XMF)*HHL(TF))
      BTUD = DM*(78.11*XMD*HBL(TD) + 100.2*(1. - XMD)*HHL(TD))
      BTUB = BM*(78.11*XMB*HBL(TB) + 100.2*(1. - XMB)*HHL(TB))
      BTUER = BTUIN + BTUF - BTUOUT - BTUD - BTUB
      BTUTI = BTUIN + BTUF
      PBER = ( ABS(BTUER) / BTUTI)*100.
      BTUTO = BTUOUT + BTUD + BTUB
      WRITE(6, 1011)
      WRITE(7, 1011)
      WRITE(6, 1012) BTUTI, BTUTO, BTUER, PBER
      WRITE(7, 1012) BTUTI, BTUTO, BTUER, PBER
C
C     CONDENSER HEAT BALANCE
C
      BTUDV = (DM + RM)*(78.11*XMR*HBV(TDV) +
     1  100.2*(1.0-XMR)*HHV(TDV))
      BTUR = RM*(78.11*XMR*HBL(TR) + 100.2*(1. - XMR)*HHL(TR))
      BTUCO = BTUR + BTUD + BTUOUT
```

```
      BTUCER = BTUDV - BTUCO
      PBCER = (ABS(BTUCER)/BTUDV)*100.
      WRITE(6,1013) BTUDV, BTUCO, BTUCER, PBCER
      WRITE(7,1013) BTUDV, BTUCO, BTUCER, PBCER
C
C     HEAT BALANCE TOWER
C
      BTUTI = BTUIN + BTUF + BTUR
      BTUTO = BTUDV + BTUB
      BTUTER = BTUTI - BTUTO
      PBTER = (ABS(BTUTER)/BTUTI)*100.
      WRITE(6, 1022) BTUTI, BTUTO, BTUTER, PBTER
      WRITE(7, 1022) BTUTI, BTUTO, BTUTER, PBTER
C
C     TRAY TO TRAY CALCULATIONS - TRAY EFFICIENCIES
C
      YM(2) = ( DM*XMR )/ VAPT + ( XLIQT/VAPT)*XM(1)
      YM(1) = XMR
      EFF(1) = ( YM(1) - YM(2) )/( YMT(1) - YM(2) )
      DO 50  I = 2, 18
      IF( I - M ) 20, 50, 30
C
C     TOP SECTION
C
   20 IF( I - 10) 21, 22, 23
```

```
   21 YM(I+1) = YM(I) + XVRT*(XM(I) - XM(I-1))
      EFF(I)  = (YM(I) - YM(I+1))/(YMT(I) - YM(I+1))
      GO TO 50
   22 YM(I+2) = YM(I) + XVRT*(XM(I+1) - XM(I-1))
      GO TO 50
   23 IF( I - 11) 50, 50, 24
   24 YM(I+1) = YM(I) + XVRT*(XM(I) - XM(I-1))
      EFF(I)  = (YM(I) - YM(I+1))/(YMT(I) - YM(I+1))
      GO TO 50
C
C     STRIPPING SECTION
C
   30 K = 19 + M - I
      IF( 18-K ) 50, 31, 32
   31 YM(K) = XVRB*XM(K-1) - XMB*(BM/VAPB)
      GO TO 50
   32 IF(11-K) 33, 50, 50
   33 YM(K) = YM(K+1) + XVRB*(XM(K - 1) - XM(K))
      EFF(K) = (YM(K) - YM(K+1))/(YMT(K) - YM(K+1))
   50 CONTINUE
C
C     CALCULATION OF MISSING TRAY EFF VALUES
C
C
C     REBOILER
```

```
C
      AEFFS = EFF(17)
   61 YM(19) = XMB + AEFFS*(YEQM(XMB) - XMB)
      XM(18) = XMB*BM/XLIQ + (VAPB/XLIQB)*YM(19)
      YM(18) = AEFFS*(YEQM(XM(18)) - YM(19)) + YM(19)
      X17 = (VAPB/XLIQB)*(YM(18) - YM(19)) + XM(18)
      ERROR = (XM(17) - X17)/XM(17)
      IF(ABS(ERROR) - 0.001) 63, 63, 62
   62 AEFFS = AEFFS + 0.5*ERROR*AEFFS
      GO TO 61
   63 EFF(18) = AEFFS
      EFF(19) = AEFFS
      IF(M-9) 76, 66, 64
   64 IF(11-M) 76, 72, 80
C
C     FEED TRAY M = 9
C
   66 AEFFF = EFF(12)
   67 DO 68 J = 1, 2
      K = 12 -J
      YM(K) = AEFFF*(YEQM(XM(K)) - YM(K+1)) + YM(K+1)
   68 XM(K-1) = (VAPB/XLIQB)*(YM(K) - YM(K+1)) + XM(K)
      YM(M) = AEFFF*(YEQM(XM(M)) - YM(M+1)) + YM(M+1)
      X8 = (VAPT/XLIQT)*YM(M) + (XLIQB/XLIQT)*XM(M)
     1 - (VAPB/XLIQT)*YM(M+1) - (FM/XLIQT)*XMF
```

```
      ERROR = (XM(8) - X8)/XM(8)
      IF(ABS(ERROR) - 0.001) 70, 70, 69
   69 AEFFF = AEFFF + 0.5*ERROR*AEFFF
      GO TO 67
   70 DO 71 J = 9, 11
   71 EFF(J) = AEFFF
      GO TO 85
C
C     FEED TRAY M = 11
C
   72 AEFFF = EFF(12)
      XM(11) = (VAPB/XLIQB)*(YM(12) - YM(13)) + XM(12)
   73 YM(11) = AEFFF*(YEQM(XM(11)) - YM(12)) + YM(12)
      XM(10) = (VAPT/XLIQT)*YM(11) + (XLIQB/XLIQT)*XM(11)
     1 - (FM/XLIQT)*XMF - (VAPB/XLIQT)*YM(12)
      YM(10) = AEFFF*(YEQM(XM(10)) - YM(11)) + YM(11)
      X9 = (VAPT/XLIQT)*(YM(10) - YM(11)) + XM(10)
      ERROR = (XM(9) - X9)/XM(9)
      IF(ABS(ERROR) - 0.001) 75, 75, 74
   74 AEFFF = AEFFF + 0.5*ERROR*AEFFF
      GO TO 73
   75 EFF(10) = AEFFF
      EFF(11) = AEFFF
      GO TO 85
C
```

```
C     FEED TRAY ABOVE TRAY 9
C
   76 AEFF = EFF(12)
      XM(10) = (VAPB/XLIQB)*(YM(11) - YM(12)) + XM(11)
   77 YM(10) = AEFF*(YEQM(XM(10)) - YM(11)) + YM(11)
      X9 = (VAPB/XLIQB)*(YM(10) - YM(11)) + XM(10)
      ERROR = (XM(9) - X9)/XM(9)
      IF(ABS(ERROR) - 0.001) 79, 79, 78
   78 AEFF = AEFF + 0.5*ERROR*AEFF
      GO TO 77
   79 EFF(10) = AEFF
      EFF(11) = AEFF
      GO TO 84
C
C     FEED TRAY BELOW TRAY 11
C
   80 AEFF = EFF(8)
      XM(10) = (VAPT/XLIQT)*(YM(11) - YM(12)) + XM(11)
   81 YM(10) = AEFF*(YEQM(XM(10)) - YM(11)) + YM(11)
      X9 = (VAPT/XLIQT)*(YM(10) - YM(11)) + XM(10)
      ERROR = (XM(9) - X9)/XM(9)
      IF(ABS(ERROR) - 0.001) 83, 83, 82
   82 AEFF = AEFF + 0.5*ERROR*AEFF
      GO TO 81
   83 EFF(10) = AEFF
```

```
      WRITE(6,1045) HUPMT, HUPMB
      WRITE(7,1045) HUPMT, HUPMB
      WRITE(6,1046) CC1
      WRITE(7,1046) CC1
      WRITE(6,1029)
      WRITE(6,1030)
      WRITE(6,1031)( YM(I), YMT(I), I = 1,9 )
      WRITE(6,1031)( YM(I), YMT(I), I = 11, 17 )
C
C     CONVERSION OF TRAY EFFICIENCY TO OVERALL EFFICIENCY
C
      MM = M - 1
      DO 91 J = 1,MM
      XLDBA = SLOPE(J)*VAPT/XLIQT
      EFF(J) = ALOG(1. + EFF(J)*(XLDBA - 1.0))/ALOG(XLDBA)
   91 EFFO = EFFO + EFF(J)
      A = MM
      EFFO = EFFO/A
      DO 92 J = 1,M
      XLDBA = SLOPE(J)*VAPT/XLIQT
   92 EFF(J) = (XLDBA**EFFO - 1.0)/(XLDBA - 1.0)
      EFFO = 0.0
      DO 93 J = M,19
      XLDBA = SLOPE(J)*VAPB/XLIQB
      EFF(J) = ALOG(1.0 + EFF(J)*(XLDBA - 1.0))/ALOG(XLDBA)
```

```
   93 EFFO = EFFO + EFF(J)
      A = M
      EFFO = EFFO/(20.0 - A)
      DO 94 J = M,19
      XLDBA = SLOPE(J)*VAPB/XLIQB
   94 EFF(J) = (XLDBA**EFFO - 1.0)/(XLDBA - 1.0)
C
C     CALCULATION OF CONSTANTS FOR FEEDFORWARD CONTROLLER
C
      XMFA = (XMF*FM + (QF-1.0)*FM*YM(M+1))/(QF*FM)
      XLIQFA = QF*FM
      R1 = (XM(18) - XMB)
      R2 = (YM(19) - XMB)
      R3 = XM(19)/XLIQB
      R4 = BM/XLIQB
      ASG = XWB*SGB(TB) + (1.0-XWB)*SGH(TB)
      HRB = (4.0*8.33*ASG)/AVGMW(XMB)
      R5 = HRB/XLIQB
      DO 95 L = 1, 18
   95 C1(L) = (XM(L) - XM(L+1))
      C1(19) = 0.0
      VLRB = VAPB/XLIQB
      VLRT = VAPT/XLIQT
      XLRBT = XLIQB/XLIQT
      VRBT = VAPB/VAPT
```

```
      EFF(11) = AEFF
   84 EFF(M) = (YM(M) - YM(M+1))/(YEQM(XM(M)) - YM(M+1))
   85 CONTINUE
      P(10) = XM(10)*VAPPB( T(10)) + (1.0-XM(10))*VAPPH(T(10))
      P(18) = XM(18)*VAPPB(T(18)) + (1.0-XM(18))*VAPPH(T(18))
      XM(19) = XMB
      EFFO = 0.0
      DO 90 J = 1, 19
   90 SLOPE(J) = 2.10229 - 4.78442*XM(J) + 5.05443*(XM(J)**2)
     1 - 1.59692*(XM(J)**3)
C
C     TRAY HOLDUP
C
C     TOP TRAYS
C
      L = M/2
      ASG = XM(L)*SGB(T(L)) + (1.-XM(L))*SGH(T(L))
      XL = 0.180*XLIGT*AVGMW(XM(L))/ASG
      ZC = 0.78375 - 0.2175*FFT + 0.010*XL
      HUPFT3 = 0.02825*ZC
      HUPMT = 62.4*HUPFT3*ASG/AVGMW(XM(L))
C
C     BOTTOM TRAYS
C
      L = (M+18)/2
```

```
 ASG = XM(L)*SGB(T(L)) + (1.-XM(L))*SGH(T(L))
 XL = 0.180*XLIQB*AVGMW(XM(L))/ASG
 ZC = 0.78375 - 0.2175*FFB + 0.010*XL
 HUPFT3 = 0.02825*ZC
 HUPMB = 62.4*HUPFT3*ASG/AVGMW(XM(L))
 WRITE(6,1002)
 WRITE(7,1002)
 WRITE(6,1032)
 WRITE(7,1032)
 WRITE(6,1033)
 WRITE(7,1033)
 WRITE(6,1015) M
 WRITE(7,1015) M
 WRITE(6,1016)
 WRITE(7,1016)
 WRITE(6,1023) XMF, TF
 WRITE(7,1023) XMF, TF
 WRITE(6,1017) XMR, TR
 WRITE(7,1017) XMR, TR
 WRITE(6,1018)( I, XM(I), T(I), SLOPE(I), EFF(I),
1  P(I), I = 1, 18  )
 WRITE(7,1018)( I, XM(I), T(I), SLOPE(I), EFF(I),
1  P(I), I = 1, 18  )
 WRITE(6,1019) XMB, TB, SLOPE(19), EFF(19), PB
 WRITE(7,1019) XMB, TB, SLOPE(19), EFF(19), PB
```

```
FM1 = YM(M+1)*VLRB*XLRBT
FM2 = YM(M)*VLRT
FM3 = FM/XLIQT
FM4 = (XMF - XM(M)*QF)*XLRBT
BETA = 0.0031729
CC1 = HUPMB/XLIQB
CC4 = BETA*HUPMB/XLIQT
CC5 = HUPMT/XLIQT
T1 = (YM(2)-YM(1))/(QR*(XM(1) - YM(1)))
T2 = VAPT/(QR*(XM(1) - YM(1)))
WRITE(6,1002)
WRITE(6,1037)
WRITE(6,1033)
WRITE(6,1015) M
WRITE(6,1038)
WRITE(6,1039)(I, XM(I), YM(I), SLOPE(I), EFF(I),I=1,18)
WRITE(6,1040) XM(19), YM(19), SLOPE(19), EFF(19)
WRITE(6,1045) HUPMT, HUPMB
WRITE(6,1046) CC1
WRITE(6,1029)
WRITE(6,1049)
WRITE(7,1049)
WRITE(6,1033)
WRITE(7,1033)
WRITE(6,1044) M
```

```
      WRITE(7,1044) M
      WRITE(6,1050)(EFF(I), SLOPE(I), C1(I), I = 1, 19 )
      WRITE(7,1050)(EFF(I), SLOPE(I), C1(I), I = 1, 19 )
      WRITE(6,1050) XLRBT, VRBT, FM1, FM2, FM3, FM4
      WRITE(7,1050) XLRBT, VRBT, FM1, FM2, FM3, FM4
      WRITE(6,1043) R1, R2, R4, R5
      WRITE(7,1043) R1, R2, R4, R5
      WRITE(6,1043) VLRB, VLRT, QF, T1, T2
      WRITE(7,1043) VLRB, VLRT, QF, T1, T2
      WRITE(6,1043) CC1, CC4, CC5, QR
      WRITE(7,1043) CC1, CC4, CC5, QR
  100 CONTINUE
C
C     FORMAT STATEMENTS
C
 1000 FORMAT(2F10.4)
 1001 FORMAT(4F10.4)
 1002 FORMAT( 1H1, //37X, 5HTABLE, ///19X,
     1 42HBINARY DISTILLATION STEADY-STATE TEST DATA  )
 1003 FORMAT(///15X,13HSTREAM        , 22HMOLES/MINUTE          ,
     1 20HMOLES BENZENE/MINUTE  )
 1004 FORMAT(/15X, 4HFEED, 12X, F8.4, 14X, F8.4  )
 1005 FORMAT(/15X,7HBOTTOMS, 9X, F8.4, 14X, F8.4  )
 1006 FORMAT(/15X,8HOVERHEAD, 8X, F8.4, 14X, F8.4 )
 1007 FORMAT(/15X, 6HREFLUX, 10X, F8.4, 14X, F8.4  )
```

```
1008 FORMAT(/15X,16HTOTAL MASS ERROR, F8.4, 7X,
    1 7HPERCENT, F8.4  )
1009 FORMAT(/15X,18HBENZENE ERROR     , F6.4, 7X,
    1 7HPERCENT, F8.4 )
1010 FORMAT(3F10.2)
1011 FORMAT(///32X, 17HHEAT BALANCE DATA,//25X, 5HINPUT,
    1  8X, 6HOUTPUT, 7X,5HERROR, 7X, 7HPERCENT,/24X,
    2 7HBTU/MIN, 7X, 7HBTU/MIN, 5X, 7HBTU/MIN, 7X, 5HERROR )
1012 FORMAT(/11X, 7HOVERALL,5X, F8.1,5X,F8.1,5X,F8.1,
    1 5X, F8.2  )
1013 FORMAT( /11X,9HCONDENSER,3X,F8.1,5X,F8.1,5X,F8.1,
    1 5X, F8.2  )
1014 FORMAT(//15X, 7HQ-VALUE, 6X, 7HFEED = , F7.4, 5X,
    19HREFLUX = , F7.4  )
1015 FORMAT(//33X, 12HFEED TRAY = , I2 )
1016 FORMAT( //2X, 4HTRAY, 6X, 6HLIQUID, 4X, 11HTEMPERATURE,
    1 4X, 11HEQUILIBRIUM, 4X, 10HEFFICIENCY, 6X, 8HPRESSURE,
    2 /10X, 10HMOLE FRACT, 3X, 9HDEGREES F, 5X,
    4 11HCURVE SLOPE, 5X, 8HMURPHERE, 9X, 5HMM HG  )
1017 FORMAT( 2X, 6HREFLUX, F10.4, F13.2  )
1018 FORMAT( 3X, I2, F13.4, F13.2, 2F15.4, F14.1  )
1019 FORMAT( 2X, 8HREBOILER,  F8.4, F13.2,2F15.4, F14.1  )
1020 FORMAT(I2 )
1021 FORMAT(/15X, 8HF-FACTOR, 5X, 7HTOP  = , F7.4,
    1 5X, 9HBOTTOM = , F7.4  )
```

```
1022 FORMAT( /11X, 5HTOWER, 7X, F8.1, 5X, F8.1,
    1 5X, F8.1, 5X, F8.2  )
1023 FORMAT( 2X, 4HFEED, F12.4, F13.2  )
1024 FORMAT( /15X, 26HCOLUMN INTERNAL FLOW RATES, /15X,
    1 9HTOP VAPOR, 7X, F10.6  )
1025 FORMAT(/15X, 10HTOP LIQUID, 6X, F10.6, 5X,
    1 7HL/V TOP, F10.6  )
1026 FORMAT(/15X, 12HBOTTOM VAPOR, 4X, F10.6)
1027 FORMAT(/15X,13HBOTTOM LIQUID, 3X, F10.6, 5X,
    1 8HL/V BOTT, F9.6  )
1028 FORMAT(/15X, 13HB VAPOR STEAM, 3X, F10.6, 5X,
    1 7HPERCENT, F5.1  )
1029 FORMAT( 1H1 )
1030 FORMAT( 9X, 8HY-ACTUAL, 10X, 7HY-EQUIL  )
1031 FORMAT( 9X, F8.4, 10X, F8.4  )
1032 FORMAT( 24X, 32HTRAY TO TRAY CALCULATION RESULTS  )
1033 FORMAT(72H
    1                    ,   )
1034 FORMAT( 10X, 19HEFF TRIAL STRIPPING, 10X, F12.6 )
1035 FORMAT( 10X, 5HERROR, F20.6 )
1036 FORMAT( 10X, 23HEFF TRIAL RECTIFICATION, 6X, F12.6 )
1037 FORMAT( 22X, 38HIDEAL TRAY TO TRAY CALCULATION RESULTS)
1038 FORMAT(//9X,4HTRAY,6X, 6HLIQUID, 10X, 5HVAPOR, 7X,
    1 11HEQUILIBRIUM, 4X, 10HEFFICIENCY, /17X, 10HMOLE FRACT,
    2 5X, 10HMOLE FRACT, 5X, 11HCURVE SLOPE, 5X, 8HMURPHERE)
```

```
1039 FORMAT( 10X, I2, F13.4, 3F15.4   )
1040 FORMAT( 10X, 8HREBOILER, F7.4, 3F15.4   )
1041 FORMAT(4E15.8)
1042 FORMAT(3E15.8)
1043 FORMAT(5E15.8)
1044 FORMAT(10X, I2 )
1045 FORMAT(  /5X, 11HTRAY HOLDUP, 5X, 6HTOP = , F7.5,
    1 6H MOLES,  5X, 9HBOTTOM = , F7.5, 6H MOLES   )
1046 FORMAT(  /5X, 14HTIME CONSTANT,,
    1 27H TRAY HOLDUP/LIQUID RATE = , F7.5, 8H MINUTES  )
1047 FORMAT( 27X, 26HHEAT AND MATERIAL BALANCES    )
1048 FORMAT( /33X, 12HFEED TRAY = , I2   )
1049 FORMAT( 10X, 36HCONSTANTS FOR FEEDFORWARD CONTROLLER,
    1 30H PROGRAM BASED ON LINEAR MODEL    )
1050 FORMAT( 3E15.8 )
     STOP
     END
```

Pulse Data Conversion Program PDCONV. This program was used to convert the refractive index data collected as a function of time during the pulse tests to concentration data. The output data from this program was in the correct format for computer program PDTER, which was used to convert pulse data to frequency response data.

This program uses the same regression equation for mole fraction benzene versus refractive index as was used in the steady-state program SSDDR. The input data to this program consists of refractive index data as a constant interval of time. The input pulse data as a function of time must also be provided. In the case of a composition forcing function the actual refractive index data may be supplied to the program where it will be converted for use in this program. If the forcing function is a flow rate change, then the actual change from steady-state as a function of time must be supplied.

The output data consists of the actual composition for the stream plus the change from steady-state at time zero for the stream as a function of time. The output data for use in program PDTFR consists of the change from steady-state or time zero from both the input forcing function and the output pulse data of the process.

Input Data for Program PDCONV. The input data for this program consists of the following cards:

Card 1	Number of complete sets of data to be converted. Format I2
Card 2	K, where K tells the type of input forcing function data that will be read into the program. When K = 0, no input data conversion will be attempted. It is assumed then that the input data is in the form of difference data. When K = 1, it is assumed that the input forcing function data is in the form of refractive index data which must be converted to composition data and the actual difference calculated. Format I1
Card 3	Gives the time interval in minutes between input forcing function data points and the total time in minutes of the input pulse data which is included in the input data. Format 2F10.0
Card 4	M, where M is the number of input data points which are to be read. Format I3
Cards 5-X+5	Input pulse data. Where X is the number of cards required for M data points. Format 8F10.0
Card X+6	JOB, where JOB is the number of output streams to be analyzed for the above input pulse data. Format I2
Card X+7	Data identification card for the first set of output for the above input pulse data. Format 72H
Card X+8	JTYPE, where JTYPE is the type of output data which will be read into the program. JTYPE = 1, regression coefficients for the regression model of the output pulse data. Format I1
Card X+9	XINT, where XINT is the time interval between data points given in minutes. Format F10.0
Card X+10	N, where N is the number of data points for the output pulse data or the number of points to be calculated at interval XINT from the regression equation. Format I3

Cards X+11 to X+11+N/8	POUT, where POUT is the output pulse data at intervals XINT. Format 8F10.0. If the regression equation coefficients are to be read the format is 5E15.8. A total of ten regression coefficients are required.

This sequence is repeated for each set of output data called for on card X+6 starting with card X+7.

The total sequence is repeated starting with card 2 for the total number of sets stated on call 1.

```
C     DIGITAL COMPUTER PROGRAM PDCONV
C
C     PULSE DATA CONVERSION
C
C
C     INPUT DATA FORMAT
C
C     JX TOTAL NO. OF JOBS STACKED, I2
C     K, I1
C     INPUT DATA DESCRIPTION CARD, 72H
C     XINTI, PTIME, 2F10.0
C     M,  I3
C     PIN, 8F10.0
C     JOB, I2
C     DATA DESCRIPTION CARD, 72H
C     JTYPE, I1
C     XINT, F10.0
C     N, I3
C     POUT, 8F10.0 OR COEFF, 5E15.8
C     REPEAT STARTING WITH DESCRIPTION CARD FOR EACH SET IN JOB
C
      DIMENSION PIN(800), POUT(800), XM(800), T(800),
     1 PIN1(800), COEFF(10), DIFF(800), Z(200)
      RICONV(X) = 58.64761 - 127.84375*X + 29.01563*(X**2)
     1 + 62.78125*(X**3) - 28.26270*(X**4)
```

```
C
C     JX TOTAL NUMBER OF JOBS STACKED
C
      READ(5,101) JX
      DO 100 JJ = 1, JX
C
C     K = 0 DO NOT CALCULATE INPUT PULSE
C     K = 1 DO CALCULATE INPUT PULSE
C     XINT IS THE TIME INTERVAL BETWEEN DATA POINTS
C     M IS THE NUMBER OF INPUT PULSE DATA POINTS
C     PIN IS INPUT PULSE
C
      READ(5,111) K
      READ(5,112)
      READ(5,104) XINTI, PTIME
      READ(5,103) M
      READ(5,105)( PIN(I), I = 1, M )
      IF(K - 1) 3, 1, 3
    1 DO 2 J = 1, M
      Z(J) = RICONV( PIN(J) )
      PIN1(J) = PIN(J)
      A = J
      A = A - 1.0
      T(J) = XINTI*A
    2 PIN(J) = Z(1) - Z(J)
```

```
      WRITE(6,109)
      WRITE(6,106)
      WRITE(7,106)
      WRITE(6,112)
      WRITE(7,112)
      WRITE(6,107)
      WRITE(7,107)
      WRITE(6,108)( T(I), PIN1(I), Z(I), PIN(I), I = 1, M )
      WRITE(7,108)( T(I), PIN1(I), Z(I), PIN(I), I = 1, M )
    3 CONTINUE
C
C     OUTPUT PULSE DATA SECTION
C
C     JOB IS NUMBER OF DATA GROUPS STACKED FOR GIVEN
C     INPUT PULSE DATA
C     JTYPE IS TYPE OF INPUT PULSE DATA TO BE USED,
C     0 FOR ACTUAL PULSE DATA, 1 FOR REGRESSION MODEL
C     XINT IS TIME INTERVAL BETWEEN OUTPUT DATA POINTS
C     N IS THE NUMBER OF POUPUT DATA POINTS
C     POUT IS OUTPUT PULSE DATA
C     COEFF IS THE REGRESSION MODEL COEFFICIENTS, MUST
C     SUPPLY PROGRAM WITH 10 VALUES, 2 CARDS, WHEN USING
C     THIS OPTION
C
      READ(5,101) JOB
```

```
      DO 100 J = 1, JOB
      READ(5,102)
      READ(5,111) JTYPE
      READ(5,104) XINT
      READ(5,103) N
      IF(JTYPE-1) 5, 6, 5
    5 READ(5,105)( POUT(I), I = 1, N )
      GO TO 7
    6 READ(5,113)( COEFF(I), I = 1,10)
    7 X = XINTI/XINT
      DO 25 I = 1, N
      A = I
      A = A - 1.0
      T(I) = XINT*A
      IF(JTYPE -1) 8, 9, 8
    8 XM(I) = RICONV(POUT(I))
      GO TO 10
    9 DIFF(I) = COEFF(1) + COEFF(2)*T(I) + COEFF(3)*(T(I)**2)
     1 + COEFF(4)*(T(I)**3) + COEFF(5)*(T(I)**4) + COEFF(6)
     2*(T(I)**5)+ COEFF(7)*(T(I)**6) + COEFF(8)*(T(I)**7)
     3 + COEFF(9)*(T(I)**8) + COEFF(10)*(T(I)**9)
   10 IF(J-1) 20, 20, 11
   20 IF(I-1) 201, 201, 11
  201 DO 202 K = 1, M
  202 PIN1(K) = PIN(K)
```

```
11 CONTINUE
   IF(T(I) - PTIME) 21, 21, 24
21 Y = I
   C = (Y + X - 1.0)/X
   M = C
   C1 = M
   IF(C - C1) 22, 22, 23
22 PIN(I) = PIN1(M)
   DEL = (PIN1(M+1) - PIN1(M))/X
   GO TO 25
23 PIN(I) = PIN(I-1) + DEL
   GO TO 25
24 PIN(I) = PIN(I-1)
25 CONTINUE
   IF(JTYPE - 1) 26, 16, 26
26 A = 7.0/XINT
   K = A
   TEST = XM(K) - XM(1)
   IF( TEST ) 12, 14, 14
12 DO 13 I = 1, N
13 DIFF(I) = XM(1) - XM(I)
   GO TO 16
14 DO 15 I = 1,N
15 DIFF(I) = XM(I) - XM(1)
16 CONTINUE
```

```
      IF(JTYPE - 1) 27, 28, 27
   27 WRITE(6,109)
      WRITE(6,106)
      WRITE(7,106)
      WRITE(6,102)
      WRITE(7,102)
      WRITE(6,107)
      WRITE(7,107)
      WRITE(6,108)( T(I), POUT(I), XM(I), DIFF(I),I=1,N)
      WRITE(7,108)( T(I), POUT(I), XM(I), DIFF(I),I=1,N)
   28 WRITE(6,109)
      WRITE(6,106)
      WRITE(7,106)
      WRITE(6,102)
      WRITE(7,102)
      WRITE(6,110)( PIN(I), DIFF(I), T(I), I, I = 1, N )
      WRITE(7,110)( PIN(I), DIFF(I), T(I), I, I = 1, N )
  100 CONTINUE
  101 FORMAT( I2 )
  102 FORMAT( 72H
     1                    , )
  103 FORMAT( I3 )
  104 FORMAT( 2F10.0 )
  105 FORMAT( 8F10.0 )
  106 FORMAT(//20X, 31HEXPERIMENTAL PULSE TEST RESULTS//   )
```

```
107 FORMAT(//13X, 4HTIME, 7X, 10HREFRACTIVE, 3X,
   1 13HMOLE FRACTION, 2X, 10HDIFFERENCE, /12X, 7HMINUTES,
   2 7X, 5HINDEX, 9X, 7HBENZENE, 4X, 13HMOLE FRACTION  )
108 FORMAT(/5(12X, F6.2, F14.5, F15.4, F14.4/) )
109 FORMAT(1H1 )
110 FORMAT( 2F9.5, 12X, F9.5, 38X, I3 )
111 FORMAT( I1 )
112 FORMAT(72H
   1                          ,  )
113 FORMAT(5E15.8)
    STOP
    END
```

Digital Computer Program PDTFR. Program PDTFR was used for conversion of pulse data to frequency response data. The basic mathematical development for this program is outlined in Section III, Mathematical Development, page 13.

The program requires evenly spaced data points with the same interval for both the input and output pulse data. The program can improve on the numerical integration of the data by subdividing the interval between data points. The number of subdivisions is specified by an input data card. The only restriction on the number of subdivisions is that the number of subdivisions be an integral factor of the time interval. A linear relationship is assumed between data points for this subdivision.

Input Data Cards. The following are the data cards and format required for program PDTFR.

Card 1	Number of sets of data to be converted and the number of frequency values to be read into the program. Format I2, 8X, I3
Cards 2 to M+2	Frequency values to be analyzed in radians per minute. Format F10.0
Card M+3	Data description or identification card. Format 72H
Card M+4	Number of subdivisions between data points. If no subdivision is required punch 1.0. Format F10.0
Card M+5	Number of pulse data points to be read into the program. Format I3

Card M+6	Time interval between pulse data points. Format F10.0.
Cards M+7 to M+N+7	Input and output pulse data points. Format 2F9.0

This sequence of data cards is repeated for each set of data specified on card 1 starting with card M+3.

<u>Input Data Nomenclature</u>. The following variable names have been specified for the data input cards:

JOB	Number of sets of data to be converted.
M	Number of frequency values to be analyzed.
N	Number of pulse data points.
PIN(I)	Input pulse data at time ((I-1) XINT)
POUT(I)	Output pulse data at time ((I-1) XINT).
SUBINT	Number of subdivisions between data points.
W(J)	Frequency values, radians/min.
XINT	Time interval between data points, minutes.

```
C     DIGITAL COMPUTER PROGRAM PDTFR
C
C     CONVERSION OF PULSE DATA TO FREQUENCY RESPONSE DATA
C
      DIMENSION W(100), PIN(600), POUT(600), TRFFR(100),
     1PHASE(100), GAINM(100), GAIND(100), TRFFI(100)
C
C     INPUT DATA
C
C     NO OF SETS OF DATA, NO OF OMEGA VALUES, I2, 8X, I3
C     OMEGA VALUES, F10.0
C     DATA DESCRIPTION, 72H
C     NUMBER OF SUBDIVISIONS PER TIME INTERVAL, F10.0
C     NUMBER OF DATA POINTS, I3
C     TIME INTERVAL BETWEEN DATA POINTS, F10.0
C     INPUT DATA, OUT PULSE DATA, 2F9.0
C
      READ(5,100) JOB, M
      READ(5,101)( W(J), J = 1, M )
      DO 99 JN = 1, JOB
      READ(5,105)
      READ(5,101) SUBINT
      READ(5,102) N
      READ(5,101) XINT
      READ(5,104)( PIN(I), POUT(I), I = 1, N )
```

```
      WRITE(6,116)
      WRITE(6,114) XINT, N
      WRITE(6,115)( J, PIN(J), POUT(J), J = 1, N )
C
C     SERIES SUMMATION
C
C     INDEX J CHANGES OMEGA
C
C     INDEX I CONTROLS THE DATA POINT LOCATION
C
      XINT = XINT/SUBINT
      DO 98 J = 1, M
      SSIR = 0.0
      SSII = 0.0
      SSOR = 0.0
      SSOI = 0.0
      A = 0.0
      NN =  N - 1
      DO 10 I = 1, NN
C
      DELI = ( PIN(I+1) - PIN(I) )/SUBINT
      DELO = ( POUT(I+1) - POUT(I) )/SUBINT
      DELI1 = PIN(I)
      DELO1 = POUT(I)
      IT = SUBINT
```

```
      DO 9 K = 1, IT
      DELI2 = DELI1 + DELI
      DELO2 = DELO1 + DELO
      FUNTI = (DELI1 + DELI2)/2.0
      FUNTO = (DELO1 + DELO2)/2.0
      A = A + 1.0
      X = (( 2.0*A-1.0)/2.0 )*XINT*W(J)
      SSIR = SSIR + FUNTI*COS( X )
      SSII = SSII + FUNTI*SIN( X )
      SSOR = SSOR + FUNTO*COS( X )
      SSOI = SSOI + FUNTO*SIN( X )
      DELI1 = DELI2
    9 DELO1 = DELO2
   10 CONTINUE
C
C     CALCULATION OF TRANSFER FUNCTION FOR GIVEN OMEGA
C     TRFFR IS TRANSFER FUNCTION REAL PART
C     TRFFI IS TRANSFER FUNCTION IMANGARY PART
C
      TRFFR(J) = (SSOR*SSIR + SSOI*SSII)/
     1 (SSIR*SSIR + SSII*SSII)
      TRFFI(J) = (SSII*SSOR - SSOI*SSIR)/
     1 (SSIR*SSIR + SSII*SSII)
      GAINM(J) = SQRT(TRFFR(J)*TRFFR(J)+TRFFI(J)*TRFFI(J))
      GAIND(J) = 20.0*ALOG10( GAINM(J) )
```

```
   PHASE(J) = 57.29578*(ATAN( TRFFI(J)/TRFFR(J) ) )
   IF( TRFFR(J) ) 11, 14, 17
11 IF( TRFFI(J) ) 12, 13, 12
12 TAN = PHASE(J) - 180.
   GO TO 20
13 TAN = -180.
   GO TO 20
14 IF( TRFFI(J) ) 15, 21, 16
15 TAN = -90.
   GO TO 20
16 TAN = -270.
   GO TO 20
17 IF( TRFFI(J) ) 21, 21, 18
18 TAN = PHASE(J)
20 PHASE(J) = TAN
21 CONTINUE
22 IF( J - 1) 23, 23, 24
23 SSPHAS = PHASE(1)
   SSGAM = GAINM(1)
   SSGAD = GAIND(1)
24 PHASE(J) = PHASE(J) - SSPHAS
   GAINM(J) = GAINM(J)/SSGAM
   GAIND(J) = GAIND(J) - SSGAD
   IF( J-1 ) 98, 25, 26
25 WRITE(6,106)
```

```
    WRITE(7,106)
    WRITE(6,105)
    WRITE(7,105)
    WRITE(6,107)
    WRITE(7,107)
    WRITE(6,108) SSGAM, SSPHAS, SSGAD
    WRITE(7,108) SSGAM, SSPHAS, SSGAD
    WRITE(6,109)
    WRITE(7,109)
 26 B = J
    B1 = B/5.0
    J1 = J/5
    B2 = J1
    IF(B1-B2) 27, 28, 27
 27 WRITE(6,110)(GAINM(J), PHASE(J), GAIND(J), W(J) )
    WRITE(7,110)(GAINM(J), PHASE(J), GAIND(J), W(J), J )
    GO TO 98
 28 WRITE(6,117)( GAINM(J), PHASE(J), GAIND(J), W(J) )
    WRITE(7,111)(GAINM(J), PHASE(J), GAIND(J), W(J), J )
 98 CONTINUE
    WRITE(7,112) SSGAM, SSPHAS, SSGAD
    WRITE(7,113)( TRFFR(J), TRFFI(J), W(J), J, J=1,M  )
 99 CONTINUE
100 FORMAT( I2, 8X, I3 )
101 FORMAT( F10.0 )
```

```
102 FORMAT( I3 )
104 FORMAT( 2F9.0 )
105 FORMAT( 72H
   1                    ,  )
106 FORMAT( 1H1, 15X, 27HFREQUENCY RESPONSE RESULTS ,
   1 14HFOR PULSE TEST//   )
107 FORMAT(//17X, 12HSTEADY-STATE, 3X, 11HPHASE ANGLE,
   14X,12HSTEADY-STATE,/22X,4HGAIN,10X,7HDEGREES,7X,
   2 8HDECIBELS    )
108 FORMAT(18X, F8.4, 7X, F8.4, 7X, F8.4   )
109 FORMAT( //9X, 9HMAGNITUDE, 5X, 11HPHASE ANGLE, 7X,
   14HGAIN, 9X, 9HFREQUENCY, /11X, 5HRATIO, 9X,
   27HDEGREES, 7X, 8HDECIBELS, 6X, 11HRADIANS/MIN   )
110 FORMAT( 7X, F9.4, F16.2, F14.4, F15.4,16X, I3 )
111 FORMAT( 7X, F9.4, F16.2, F14.4, F15.4,16X, I3// )
112 FORMAT(3F10.5 )
113 FORMAT( 3F10.5, 40X, I3 )
114 FORMAT( F10.5, 10X, I3 )
115 FORMAT( 10X, I3, 2F15.6 )
116 FORMAT( 1H1 )
117 FORMAT( 7X, F9.4, F16.2, F14.4, F15.4// )
    STOP
    END
```

Digital Computer Program CEFFCM. Program CEFFCM was used to calculate the experimental feedforward controller matrix from the experimental open loop transfer functions. The matrix conversion is outlined in SectionIII, Mathematical Development, page 13 . Digital computer program PDTFR card output can be used as the data input to this program without repunching. Care must be used to insure that the open loop transfer function data cards are properly arranged.

This program is written in complex numbers and requires that the transfer function data be in the form of a real and imaginary number for each frequency value evaluated instead of in the form of the magnitude ratio and phase angle generally reported for the transfer function data. This method insures that the effects of normalization of the transfer functions does not affect these results. The final results of this program are corrected for steady-state gains before the final results are reported.

Input Data Cards. The following data cards are required for program CEFFCM:

Card 1	M, where M is the number of frequency values to be evaluated. Format I3
Card 2	Identification card. Format 72H
Card 3	Steady-state gain for the distillate composition/ feed composition transfer function. Format F10.0

Cards 4 to M+4	Real and imaginary parts of the distillate composition/feed composition transfer function and the corresponding frequency value. Format 3F10.0
Card M+5	Identification card.
Card M+6	Steady-state gain for the distillate composition/vapor rate transfer function. Format F10.0
Cards M+7 2M+7	Real and imaginary parts of the distillate composition/vapor rate transfer function. Format 2F10.0
Card 2M+8	Identification card.
Card 2M+9	Steady-state gain for the distillate composition/reflux rate transfer function. Format F10.0
Cards 2M+10 to 3M+10	Real and imaginary parts of the distillate composition/reflux rate transfer function. Format 2F10.0
Card 3M+11	Identification card.
Card 3M+12	Steady-state gain for the bottoms composition/feed composition transfer function. Format F10.0
Cards 3M+ 13 to 4M+13	Real and imaginary parts of the bottoms composition/feed composition transfer function. Format 2F10.0
Card 4M+14	Identification card
Card 4M+15	Steady-state gain of the bottoms composition/vapor rate transfer function. Format F10.0
Cards 4M+16 to 5M+16	Real and imaginary parts of the bottoms composition/vapor rate transfer function. Format 2F10.0
Card 5M+17	Identification card.

Card 5M+18	Steady-state gain of the bottoms composition/reflux rate transfer function. Format F10.0
Cards 5M+19 to 6M+19	Real and imaginary parts of the bottoms composition/reflux rate transfer function. Format 2F10.0

```
C     DITIGAL COMPUTER PROGRAM CEFFCM
C
C     CALCULATION OF EXPERIMENTAL FEEDFORWARD CONTROLLER
C     MATRIX
C     DIMENSION W(100), TRFFR(2,100), TRFFI(2,100),
     1GAINM(100), GAIND(100), PHASE(100)
      COMPLEX P(2,3,100), T(2,100), PP
C
C     CONTROLLER CALCULATION
C
C     P(1,1,N), DISTILLATE/FEED TRANSFER FUNCTION
C     P(1,2,N), DISTILLATE/VAPOR TRANSFER FUNCTION
C     P(1,3,N), DISTILLATE/REFLUX TRANSFER FUNCTION
C     P(2,1,N), BOTTOMS/ FEED TRANSFER FUNCTION
C     P(2,2,N), BOTTOMS/VAPOR TRANSFER FUNCTION
C     P(2,3,N), BOTTOMS/REFLUX TRANSFER FUNCTION
C
      READ (5,100) JOB
      DO 50 JJ = 1, JOB
      READ(5,115)
      READ(5,100) M
      READ(5,101) A1
      READ(5,102)( P(1,1,I), W(I), I = 1, M )
      READ(5,101) B1
      READ(5,103)( P(1,2,I), I = 1,M )
```

```
      READ(5,101) C1
      READ(5,103)( P(1,3,I), I = 1,M )
      READ(5,101) A2
      READ(5,103)( P(2,1,I), I = 1,M )
      READ(5,101) B2
      READ(5,103)( P(2,2,I), I = 1,M )
      READ(5,101) C2
      READ(5,103)( P(2,3,I), I = 1,M )
C
C     T(1,I) = REFLUX RATE/ FEED COMPOSITION
C     T(2,I) = VAPOR RATE/FEED COMPOSITION
C
      DO 1 I = 1,M
      PP = P(2,2,I)*P(1,3,I) - P(1,2,I)*P(2,3,I)
      T(1,I) =  (P(2,2,I)*P(1,1,I)-P(1,2,I)*P(2,1,I))/PP
    1 T(2,I) = -(P(2,3,I)*P(1,1,I)-P(1,3,I)*P(2,1,I))/PP
C
C     DATA REDUCTION
C
      DO 50 J = 1, 2
      DO 25 I = 1, M
      TRFFR(J,I) = REAL(T(J,I))
      TRFFI(J,I) = AIMAG(T(J,I))
      GAINM(I) = SQRT( TRFFR(J,I)**2 + TRFFI(J,I)**2 )
      GAIND(I) = 20.0*ALOG10( GAINM(I) )
```

```
   PHASE(I) = 57.29578*(ATAN( TRFFI(J,I)/TRFFR(J,I) ))
   IF( TRFFR(J,I) ) 11, 14, 17
11 IF( TRFFI(J,I) ) 12, 13, 12
12 TAN = PHASE(I) - 180.0
   GO TO 20
13 TAN = -180.
   GO TO 20
14 IF( TRFFI(J,I) ) 15, 21, 16
15 TAN = -90.
   GO TO 20
16 TAN = -270.
   GO TO 20
17 IF( TRFFI(J,I) ) 21, 21, 18
18 TAN = PHASE(I)
20 PHASE(I) = TAN
21 CONTINUE
22 IF(I-1) 23, 23, 24
23 SSPHAS = PHASE(1)
   SSGAM = GAINM(1)
   SSGAD = GAIND(1)
24 PHASE(I) = PHASE(I) - SSPHAS
   GAINM(I) = GAINM(I)/SSGAM
   GAIND(I) = GAIND(I) - SSGAD
25 CONTINUE
   WRITE(6,106)
```

```
      WRITE(7,106)
      IF(J-1) 26, 26, 27
   26 WRITE(6,111)
      WRITE(7,111)
      GO TO 28
   27 WRITE(6,112)
      WRITE(7,112)
   28 WRITE(6,115)
      WRITE(7,115)
      WRITE(6,107)
      WRITE(7,107)
      WRITE(6,108) SSGAM, SSPAS,SSGAD
      WRITE(7,108) SSGAM, SSPAS,SSGAD
      WRITE(6,109)
      WRITE(7,109)
      WRITE(6,110)(I, GAINM(I), PHASE(I), GAIND(I),
     1 W(I), I = 1, M )
      WRITE(7,110)(I, GAINM(I), PHASE(I), GAIND(I),
     1 W(I), I = 1, M )
   50 CONTINUE
  100 FORMAT( I3 )
  101 FORMAT(/F10.0 )
  102 FORMAT( 3F10.0 )
  103 FORMAT( 2F10.0 )
  104 FORMAT( 10X, F9.5, 5F18.5 )
```

```
105 FORMAT( 7X, I3, 12F9.5, F12.5 )
106 FORMAT(1H1, ////30X, 5HTABLE, //17X,
   1 35HEXPERIMENTAL FEEDFORWARD CONTROLLER  )
107 FORMAT(//17X,12HSTEADY-STATE,3X,11HPHASE ANGLE, 4X,
   112HSTEADY-STATE,/22X,4HGAIN,10X,7HDEGREES,7X,8HDECIBELS)
108 FORMAT(18X, F8.4, 7X, F8.4, 7X, F8.4  )
109 FORMAT(//9X,9HMAGNITUDE,5X,11HPHASE ANGLE,7X,4HGAIN,
   1 9X,9HFREQUENCY,/11X,5HRATIO,9X,7HDEGREES,7X,
   2 8HDECIBELS,6X,11HRADIANS/MIN  )
110 FORMAT(/5(5X, I2, F9.4, F16.2, F14.4, F15.4/))
111 FORMAT(14X,24HREFLUX/FEED COMPOSITION ,
   1 19HCONTROLLER FUNCTION  )
112 FORMAT(15X,23HVAPOR/FEED COMPOSITION ,
   1 19HCONTROLLER FUNCTION  )
113 FORMAT( 5X, I3, 5X, 2F20.6 )
114 FORMAT( 1H1, 15X, 9HREAL PART, 10X, 13HIMANGARY PART )
115 FORMAT( 65H
   1             )
    STOP
    END
```

Digital Computer Program FFCLM. This program was used to calculate the open loop and feedforward controller transfer functions based on the linear model assumption for a distillation column consisting of eighteen trays, a reboiler and a total condenser. Details on the procedure followed is outlined in Section III, Mathematical Development, page 13 .

The program performs the required calculations at the given steady-state condition as a function of frequency. The program consists of a data input section, calculation of complex constants required, procedure for setting the complex variables, calculation up the tower, followed by the matrix inversion and data output section. These calculations are carried out in the complex variable domain.

Input Data. The following data cards are required for the operation of this program:

Card 1	NW, where NW is the number of frequency values to be read into the program and used. Format I2
Cards 2 to X	The frequency values to be used in this calculation. The frequency is given in radians per minute. Format 8F10.6
Cards X+1	JOB, where JOB is the number of steady-state conditions to be investigated. Format I2
Card X+2	Description card. Used for identification purposes. Format 72H
Card X+3	M, where M is the feed tray location. Trays are numbered starting from the top. Format 10X, I2

Card X+4 to X+23	Steady-state values of efficiency, equilibrium curve slope and the C1 constant for each tray. These are standard output cards from program SSDDR. Format 3E15.8
Cards X+24 and X+25	Values for XLRBT, VRBT, FM1, FM2, FM3, and FM4 from the steady-state calculations. Format 3E15.8
Card X+26	Values for constants R1, R2, R4, and R5 from the steady-state calculations. Format 5E15.8
Card X+27	Values for VLRB, VLRT, QF, from the steady-state program. Format 3E15.8
Card X+28	Values for constants CC1, CC4, CC5, and QR from the steady-state program. Format 5E15.8

This sequence of cards is repeated for each steady-state condition starting with card X+2 as specified on card X+1.

Nomenclature for Input Data Cards. The following variable names have been specified for the data input cards.

BETA	d(tray holdup)/d(XLIQB)
BM	Bottoms drawoff rate, moles/min.
C1(I)	(X(I) - X(I 1))/XLIQB
CC1	HUPMT/HUPMB
CC4	BETA (2 - QF) HUPMT/XLIQT
CC5	HUPMT/XLIQT
EFF(I)	Murpheer vapor efficiency for tray I
FM	Feed rate, moles/min.
FM1	Difference between the energy and mass transfer section composition on the feed tray divided by XLIQT
FM2	QF FM/XLIQT
FM3	X(M)/XLIQT

FM4	XLIQB/XLIQT
HUPMT	Tray holdup above the feed tray, moles
HUPMB	Tray holdup below the feed tray, moles
I	Tray number, trays are numbered from top down.
JOB	Number of steady-state data sets
M	Feed tray location. Trays are numbered from the top.
NW	Number of frequency values.
QF	Thermal condition of the feed.
QR	Thermal condition of the reflux.
R1	X(18)/XLIQB
R2	Y(19)/XLIQB
R4	BM/XLIQB
R5	Reboiler holdup/XLIQB
SL(I)	Equilibrium curve slope evaluated at X(I).
VAPB	Vapor rate below the feed tray, moles/min.
VAPT	Vapor rate above the feed tray, moles/min.
VLRB	VAPB/XLIQB
VLRT	VAPT/XLIQT
VRBT	VAPB/VAPT
XLIQB	Liquid rate below the feed tray, moles/min.
XLIQT	Liquid rate above the feed tray, moles/min.

```
C     DIGITAL COMPUTER PROGRAM FFCLM
C
C     OPEN LOOP AND FEEDFORWARD CONTROLLER TRANSFER
C     FUNCTIONS BASED ON LINEAR MODEL
C
      DIMENSION EFF(20), SL(20), C1(20), C2(20), W(100),
     1 TRFFI(100), GAINM(100), GAIND(100), PHASE(100),
     2 TRFFR(100)
      COMPLEX VAPB, VAPT, Z, XL(20), X(20), Y(20), B, CL,
     1 WT, R, DIST, F1, WF, CLF, P(3,4,100), G(8,100), XLMA,
     2 WB, F, XMA, CV, CLT, WR, VT, XR, DT, PP, RB
C
C     INPUT DATA
C
      READ(5,155) NW
      READ(5,156)(  W(I), I = 1,NW )
      READ(5,155) JOB
      DO 120 JJ = 1,JOB
   10 READ(5,150)
      READ(5,151)  M
      READ(5,152)( EFF(I), SL(I), C1(I), I = 1, 19 )
      READ( 5, 152) XLRBT, VRBT, FM1, FM2, FM3, FM4
      READ(5,154)   R1, R2, R4, R5
      READ(5,154) VLRB, VLRT, QF
      READ(5,154)   CC1, CC4, CC5, QR
```

```
C
C     CALCULATION OF COMPLEX CONSTANTS
C
   20 DO 80  I = 1,NW
      A = 0.0031729*W(I)
      CL = CMPLX(1.0,A)
      A = CC1*W(I)
      WB = CMPLX(1.0,A)
      A = CC4*W(I)
      WF = CMPLX(XLRBT,A)
      A = CC5*W(I)
      WT = CMPLX(1.0,A)
      A = 2.0*W(I)
      CV = CMPLX(1.0,A)
      A = 1.0*W(I)
      CLT = CMPLX(1.0,A)
      A = (CC5/VLRT)*W(I)*6.0
      WR = CMPLX(1.0,A)
      A = COS( 0.5*W(I) )
      B = -SIN( 0.5*W(I) )
      DT = CMPLX(A,B)
      A = R5*W(I)
      RB = CMPLX(R4,A)
C
C     SET COMPLEX VARIBLES
```

```
C
   30 DO 80 L = 1, 4
      A = L
      VAPB = (1.0,0.0)*(2.0-A)*(3.0-A)*(4.0-A)/6.0
      Z = (1.0,0.0)*(A-1.0)*(3.0-A)*(4.0-A)/2.0
      X(19) = (1.0,0.0)*(A-1.0)*(A-2.0)*(4.0-A)/2.0
      B = (1.0,0.0)*(A-1.0)*(A-2.0)*(A-3.0)/6.0
C
C     REBOILER
C
      VAPB = VAPB/CV
      XL(18) = CLT*B
      Y(19) = EFF(19)*SL(19)*X(19)
      X(18) = - R1*XL(18) + R2*VLRB*VAPB + VLRB*Y(19) +
     1 RB*X(19)
C
C     STRIPPING SECTION
C
   40 MM = 18 - M
      DO 41 J = 1,MM
      K = 19 - J
      XL(K-1) = CL*XL(K)
      Y(K) = EFF(K)*SL(K)*X(K) + (1.-EFF(K))*Y(K+1)
   41 X(K-1) = C1(K-1)*(VAPB - XL(K-1)) + VLRB*(Y(K) - Y(K+1))
     1 + WB*X(K)
```

```
C
C     FEED TRAY
C
C     ENERGY SECTION
C
   50 XL(M-1) = XLRBT*CL*XL(M) - XLRBT*QF*F
      VAPT = VRBT*VAPB - ((VRBT*(QF-1.0))/VLRB)*F
C
C     MASS TRANSFER SECTION
C
      Z = DT*Z
      Y(M) = EFF(M)*SL(M)*X(M) + (1.0-EFF(M))*Y(M+1)
      X(M-1) = - C1(K-1)*XL(M-1) - VLRB*XLRBT*Y(M+1)
     1 - FM1*VAPB + VLRT*Y(M) + FM2*VAPT- FM3*Z - FM4*F
     2 + WF*X(M)
C
C     RECTIFICATION SECTION
C
   60 MM = M-2
      DO 61 J = 1,MM
      K = M - J
      XL(K-1) = CL*XL(K)
      Y(K) = EFF(K)*SL(K)*X(K) + (1.0-EFF(K))*Y(K+1)
   61 X(K-1) = C1(K-1)*(VAPT - XL(K-1)) + VLRT*(Y(K) - Y(K+1))
     1 + WT*X(K)
```

```
C
C     TOP TRAY
C
   70 R = (1.0/QR)*CLT*XL(1)
      Y(1) = EFF(1)*SL(1)*X(1) + (1.0-EFF(1))*Y(2)
      VT = VAPT - (1.0/VLRT)*R
      XR = Y(1)/WR
      XR = DT*XR
      P(1,L,I) = XR
      P(2,L,I) = X(1)
   80 P(3,L,I) = R
C
C     MATRIX TERMS
C
C     OPEN LOOP MATRIX TERMS
C     G(1,I) = REFLUX COMP/VAPOR RATE
C     G(2,I) = REFLUX COMP/FEED COMP
C     G(3,I) = REFLUX COMP/REFLUX RATE
C     G(4,I) = BOTTOMS COMP/VAPOR RATE
C     G(5,I) = BOTTOMS COMP/FEED RATE
C     G(6,I) = BOTTOMS COMP/REFLUX RATE
C
C     FEEDFORWARD CONTROLLER TRANSFER FUNCTIONS
C     G(7,I) = REFLUX RATE/FEED COMPOSITION
C     G(8,I) = VAPOR RATE/FEED COMPOSITION
```

```
C
C     OPEN LOOP TRANSFER FUNCTION CALCULATIONS
C
      DO 81 I = 1, NW
      G(1,I) = - (P(1,1,I) - P(2,1,I)*P(1,3,I)/P(2,3,I))
      G(2,I) = P(1,2,I) - P(2,2,I)*P(1,3,I)/P(2,3,I)
      G(3,I) = P(1,4,I)/P(3,4,I) - (P(1,3,I)*P(2,4,I))/
     1 (P(2,3,I)*P(3,4,I))
      G(4,I) = P(2,1,I)/P(2,3,I)
      G(5,I) = - P(2,2,I)/P(2,3,I)
   81 G(6,I) = - P(2,4,I)/(P(2,3,I)*P(3,4,I))
C
C     FEEDFORWARD CONTROLLER TRANSFER FUNCTION CALCULATIONS
C
      DO 82 I = 1, NW
      PP = G(4,I)*G(3,I) - G(1,I)*G(6,I)
      G(7,I) = - (G(4,I)*G(2,I) - G(1,I)*G(5,I))/PP
   82 G(8,I) = - (G(6,I)*G(2,I) - G(3,I)*G(5,I))/PP
C
C     DATA REDUCTION
C
      DO 120 L = 1, 8
      DO 110 I = 1,NW
      TRFFR(I) = REAL(G(L,I))
      TRFFI(I) = AIMAG(G(L,I))
```

```
      GAINM(I) = SQRT( TRFFR(I)**2 + TRFFI(I)**2 )
      GAIND(I) = 20.0*ALOG10( GAINM(I) )
      PHASE(I) = 57.29578*( ATAN( TRFFI(I)/TRFFR(I) ) )
      IF( TRFFR(I) ) 90, 93, 96
   90 IF( TRFFI(I) ) 91, 92, 91
   91 TAN = PHASE(I) - 180.0
      GO TO 98
   92 TAN = -180.0
      GO TO 98
   93 IF( TRFFI(I) ) 94, 99, 95
   94 TAN = -90.0
      GO TO 98
   95 TAN = -270.0
      GO TO 98
   96 IF( TRFFI(I) ) 99, 99, 97
   97 TAN = PHASE(I)
   98 PHASE(I) = TAN
   99 CONTINUE
  100 IF(I-1) 101, 101, 102
  101 SSPHAS = PHASE(1)
      SSGAM = GAINM(1)
      SSGAD = GAIND(1)
  102 PHASE(I) = PHASE(I) - SSPHAS
      GAINM(I) = GAINM(I)/SSGAM
      GAIND(I) = GAIND(I) - SSGAD
```

```
  110 CONTINUE
C
C     DATA OUTPUT
C
      WRITE(6,161)
      GO TO (111, 112, 113, 114, 116, 117, 118, 119), L
  111 WRITE(6,168)
      GO TO 1141
  112 WRITE(6,169)
      GO TO 1141
  113 WRITE(6,173)
      GO TO 1141
  114 WRITE(6,174)
      GO TO 1141
  116 WRITE(6,175)
      GO TO 1141
  117 WRITE(6,176)
      GO TO 1141
  118 WRITE(6,162)
      GO TO 1142
  119 WRITE(6,163)
      GO TO 1142
 1141 WRITE(6,172)
      GO TO 1143
 1142 WRITE(6,177)
```

```
 1143 WRITE(6,150)
  115 WRITE(6,164)
      WRITE(6,165)  SSGAM, SSPAS, SSGAD
      WRITE(6,166)
      IF(L-6) 1151, 1151, 1152
 1151 WRITE(6,167)( I, GAINM(I), PHASE(I),
     1 GAIND(I), W(I), I = 1, 30   )
      GO TO 120
 1152 WRITE(6,167)(I, GAINM(I), PHASE(I),
     1 GAIND(I), W(I), I = 1, NW   )
  120 CONTINUE
C
C     FORMAT STATEMENTS
C
  150 FORMAT(72H
     1                    ,  )
  151 FORMAT( 10X, I2 )
  152 FORMAT( 3E15.8 )
  153 FORMAT( 3E15.8 )
  154 FORMAT( 5E15.8 )
  155 FORMAT( I2 )
  156 FORMAT( 8F10.6 )
  159 FORMAT( 1H1, 15X, 9HREAL PART, 10X, 13HIMANGARY PART   )
  160 FORMAT( 5X, I3, 5X, 2F17.6 )
  161 FORMAT( 1H1, //30X, 5HTABLE   )
```

```
162 FORMAT( //21X,  28HREFLUX RATE/FEED COMPOSITION   )
163 FORMAT( //21X,  27HVAPOR RATE/FEED COMPOSITION   )
164 FORMAT(  //17X, 12HSTEADY-STATE, 3X, 11HPHASE ANGLE,
   1  4X, 12HSTEADY-STATE, /22X, 4HGAIN, 10X, 7HDEGREES,
   2 7X, 8HDECIBELS   )
165 FORMAT( 18X, F8.4, 7X, F8.2, 7X, F8.4   )
166 FORMAT(   /9X, 9HMAGNITUDE, 5X, 11HPHASE ANGLE,
   1 7X, 4HGAIN, 9X, 9HFREQUENCY,  /11X, 5HRATIO, 9X,
   2 7HDEGREES, 7X, 8HDECIBELS, 6X, 11HRADIANS/MIN    )
167 FORMAT( /5(5X, I2, F9.4, F16.2, F14.4, F15.4/) )
168 FORMAT(//20X, 29HREFLUX COMPOSITION/VAPOR RATE   )
169 FORMAT(//17X, 35HREFLUX COMPOSITION/FEED COMPOSITION   )
170 FORMAT( 8F15.6, I3 )
171 FORMAT( 1H1 )
172 FORMAT(   8X, 28HOPEN LOOP TRANSFER FUNCTION ,
   1  25HBASED ON LINEAR MODEL FOR   )
173 FORMAT(//20X, 30HREFLUX COMPOSITION/REFLUX RATE   )
174 FORMAT(//20X, 30HBOTTOMS COMPOSITION/VAPOR RATE   )
175 FORMAT(//17X, 36HBOTTOMS COMPOSITION/FEED COMPOSITION   )
176 FORMAT(//19X, 31HBOTTOMS COMPOSITION/REFLUX RATE   )
177 FORMAT(  19X, 31HFEEDFORWARD CONTROLLER TRANSFER,
   1 /18X, 34HFUNCTION BASED ON LINEAR MODEL FOR   )
    STOP
    END
```

FEEDFORWARD CONTROL OF BINARY DISTILLATION

by

Rudolph Francis Janis, Jr.

ABSTRACT

The open-loop transfer functions relating distillate and bottoms composition to feed composition, reflux rate and boilup rate were determined from pulse tests of a binary distillation column. Similar transfer functions were determined by mathematical solution of the linearized differential equations describing the column. Comparison of these two sets of functions showed that the simple feedforward controller transfer functions based upon the linear model should provide adequate control for binary distillation columns in the low frequency range (below a frequency of 1.6 radians per dimensionless time -- dimensionless time is defined to be the tray holdup divided by the stripping section liquid rate).

The experimental data were determined for the benzene-n-heptane system at atmospheric pressure. The column was 8 inches in diameter and contained 18 sieve trays spaced 12 inches apart. A total condenser provided the reflux, and a thermosiphon reboiler provided the stripping vapor. Analyses were made by refractive index measurements.

The transient distillate and bottoms compositions were determined as responses to pulsed variations of feed composition, reflux rate

and boilup rate. These tests were performed at each of two different steady state conditions. Fourier transform analysis was used to convert the pulse data to frequency response data, and Bode diagrams were prepared.

The mathematical solution used the techniques of Lamb and Pigford for linearization and solution of the equations describing the column. This technique involves step-wise tray-to-tray calculations in the frequency domain.

The transfer functions developed by the two approaches were compared. They were in close agreement up to frequencies of about 1.6 radians per dimensionless time. Above this frequency the non-linear and higher order effects have an appreciable effect on the dynamics of the distillation column. Use of the linear model at frequencies above 1.6 radians per dimensionless time is not recommended.