AN EVALUATION OF THE SUJATA ABSORPTION CALCULATION METHOD

By

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PREFACE

A critical evaluation of the Sujata absorption calculation was made. The results predicted by the Sujata method were compared with results obtained from the classical Kremser-Brown and Edmister short-cut methods and from three operating industrial absorbers. In order to conduct this evaluation, a computer program was written using the Sujata calculation method on a complex column. The complex features of the column included the possibility of an additional feed, liquid side stream, vapor side stream, and intercooler on every tray.

I wish to express my sincere thanks for the advice and guidance given by Professors J. H. Erbar and R. N. Maddox and for the cooperation of the Oklahoma State University Computing Center. I would also like to thank Mr. Stan Wells of Phillips Petroleum Company and Mr. Warren Thompson of Sunray DX Company and the computing departments of both companies for the generous use of their facilities.

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CHAPTER I

INTRODUCTION

In the natural gas, petroleum, and petro-chemical industries, the separation of complex hydrocarbon mixtures is of particular importance. The separation efficiency and capital outlay for separation equipment are important factors in the economic success or failure of a process in these industries. Thus, the calculation method which describes the process is of the utmost importance in process design.

For many years the hydrocarbon absorption process was described by calculations based on time-saving assumptions and approximations which were either inaccurate or invalid in most cases. With the development of digital computer calculation methods, most of the approximations and assumptions could be discarded. More emphasis was placed on the approach, convergence technique, and generality of the calculation method. The engineering goal is a simple yet completely general calculation method which requires no assumptions, yet has a simple and rapid convergence technique. Although this goal may never be reached, one of the methods which most closely approaches this goal was developed by Sujata. (16)

The Sujata calculation method has three important and distinct features. 1) A minimum number of primary assumptions are required in the calculation. 2) The method is derived from and uses basic engineering concepts which are familiar to all chemical engineers. 3) The method was derived from general equations and can be applied to a wide variety of complex absorption systems.

The purpose of this study is to examine the Sujata absorption calculation method in detail. Three principal objectives are associated with the evaluation of this method. The first objective is to examine the approach, gnerality, and scope of the method. If necessary, minor modifications in the basic Sujata method will be suggested. The second objective is to determine the method's reliability and limitations in calculating results for various absorption systems. The third objective is to compare the results obtained from the Sujata method with results from the classical absorption calculations such as the Kremser-Brown and

Edmister methods. In addition the results are compared with data obtained from actual plant operation of three industrial absorption columns.

CHAPTER II

BACKGROUND

A. The Absorption Process

The process of diffusion of a component from a vapor to a liquid phase as a result of a concentration difference between the two phases is known as gaseous absorption. This fundamental mass transfer process results from molecular and eddy diffusion and is often described by some form of the two-film or penetration theories of mass transfer.

The absorption column multiplies the concentration difference existing between the vapor and liquid phases by the countercurrent contacting of the two streams. The result is an increased efficiency in the absorption of the vapor components by the liquid phase. The basic absorption column contains two feed elements as shown in Figure 1. The entering liquid phase is the absorbing medium and is known as the "lean oil." The entering vapor phase is known as the "wet gas" and consists of

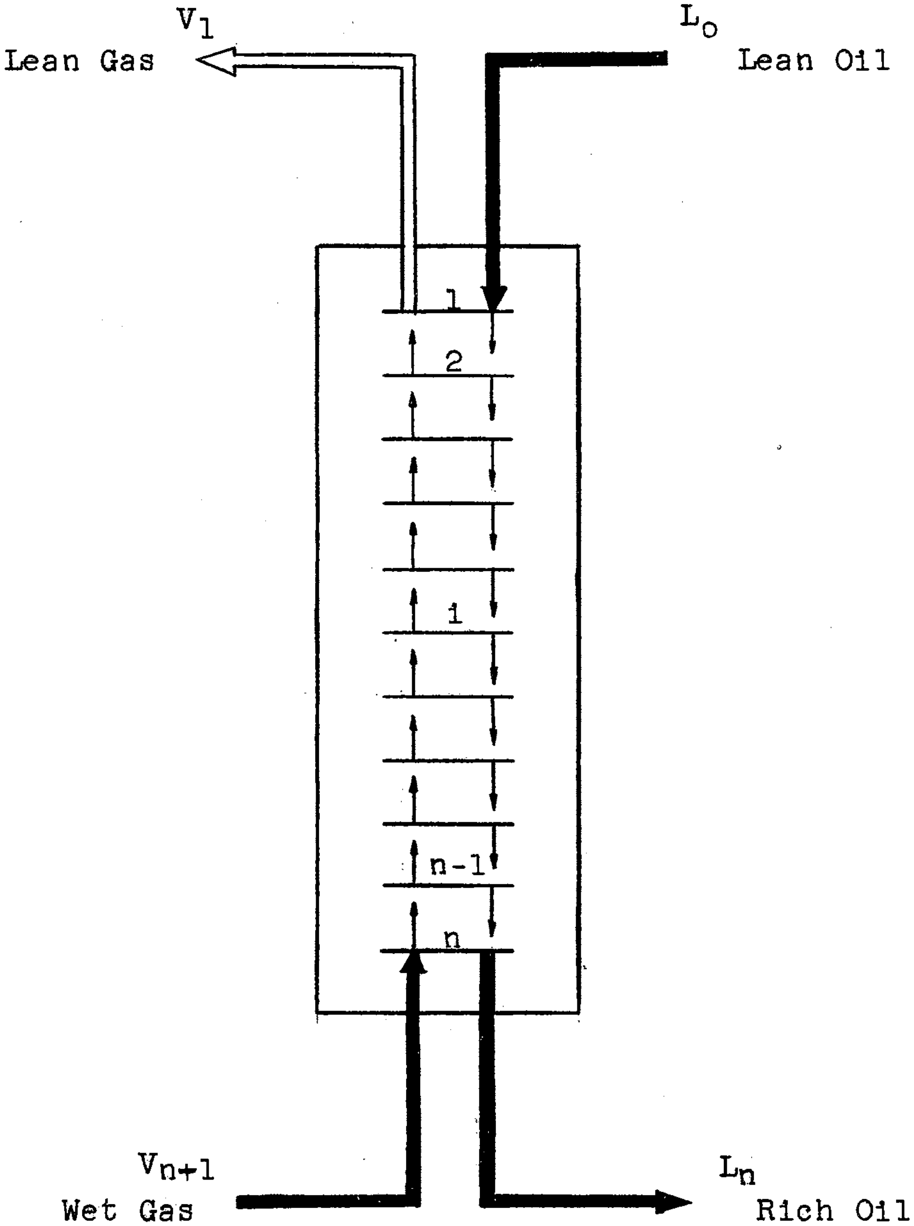

Figure 1. A "Simple" N Tray Absorption Column

those components to be absorbed by the oil and those components which are not absorbed and appear in the exit vapor stream or "lean gas." The absorber oil plus the absorbed vapor components leaving the column is known as the "rich oil."

The rich oil is usually fed to a stripping column which separates the absorbed vapor components from the original absorber oil. The mass transfer is now from the liquid to the vapor phase as a result of the reversed concentration difference. The lean oil leaving the stripper is fed back to the absorption column. The absorber-stripper system as shown in Figure 2 provides for the continuous separation of desired components from a vapor mixture.

B. Absorption Calculations

Absorption calculations are designed to describe, as completely as possible, the operation of absorption columns. The "simple" absorption column with n trays has a single wet gas feed entering the bottom tray and a lean oil entering the top tray as shown in Figure 1. If each tray is considered as a simple equilibrium stage defined by $2C + 6$ possible variables, then the total

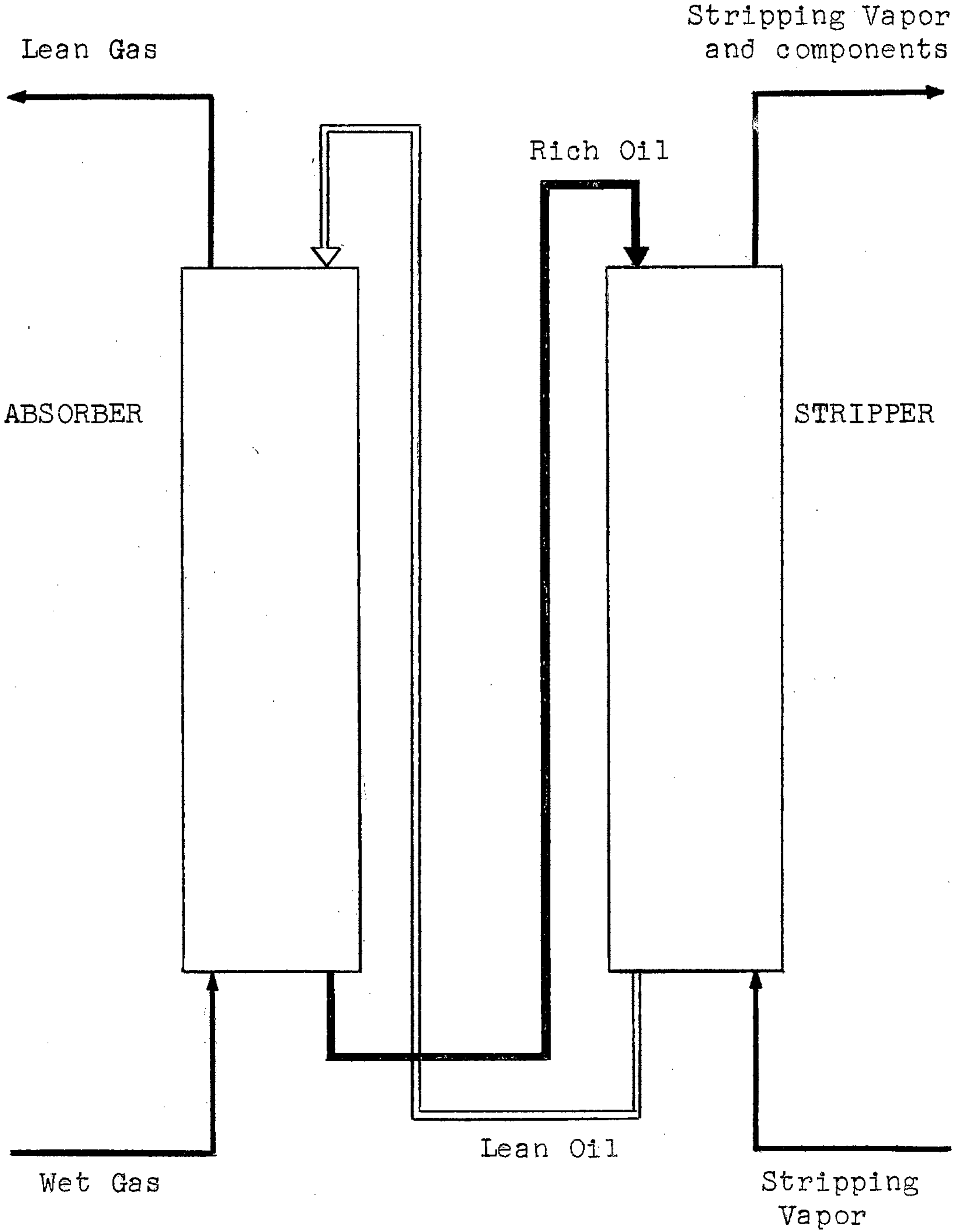

Figure 2. Absorber-Stripper Unit

number of variables associated with an n tray column (the specification of that number of trays represents a single variable) is given by

$$N_v = 1 + n(2C + 6). \tag{1}$$

Some of these variables are not independent and must be subtracted to obtain the degrees of freedom for the column. Each interstream within the column contains C + 2 restrictions which must be subtracted. For a column of n trays, the total number of restricted variables is

$$N_c = 2(n - 1)(C + 2). \tag{2}$$

The number of independent variables which completely describes the column is then $N_i = N_v - N_c$ or

$$N_i = 2C + 2n + 5. \tag{3}$$

The most common set of specifications for the degrees of freedom for a simple column is given below.

Pressure for each stage	n
Heat leak for each stage	n
Wet gas feed	C + 2
Lean oil feed	C + 2
Number of stages	1
TOTAL	2C + 2n + 5

The simple absorption column can be modified with a number of complex features. The i^{th} tray in a complex column can have an intercooler, vapor side stream, liquid side stream, or additional feed. Trays with all these complex features are shown in Figure 3.

The addition of a feed stream to a specified simple tray increases the number of independent variables needed to describe the tray from $2C + 6$ to $3C + 8$. The increase in the number of independent variables resulting from the addition of a feed stream is $C + 2$. In general, the location of the feed tray in a complex column is not fixed so that the location of the feed tray must also be specified. Thus, there are $C + 3$ additional independent variables associated with each feed tray.

The addition of a side stream to a specified simple tray increases the number of independent variables from $2C + 6$ to $2C + 7$. The increase is one. In general, the location of the side stream is not fixed so that the side stream tray location must also be specified. Thus, there are two additional independent variables associated with each side stream tray.

The addition of an intercooler to a simple tray requires no additional independent variables since a heat leak for each stage is already specified in the simple column.

For an n tray, complex column having m feed streams,

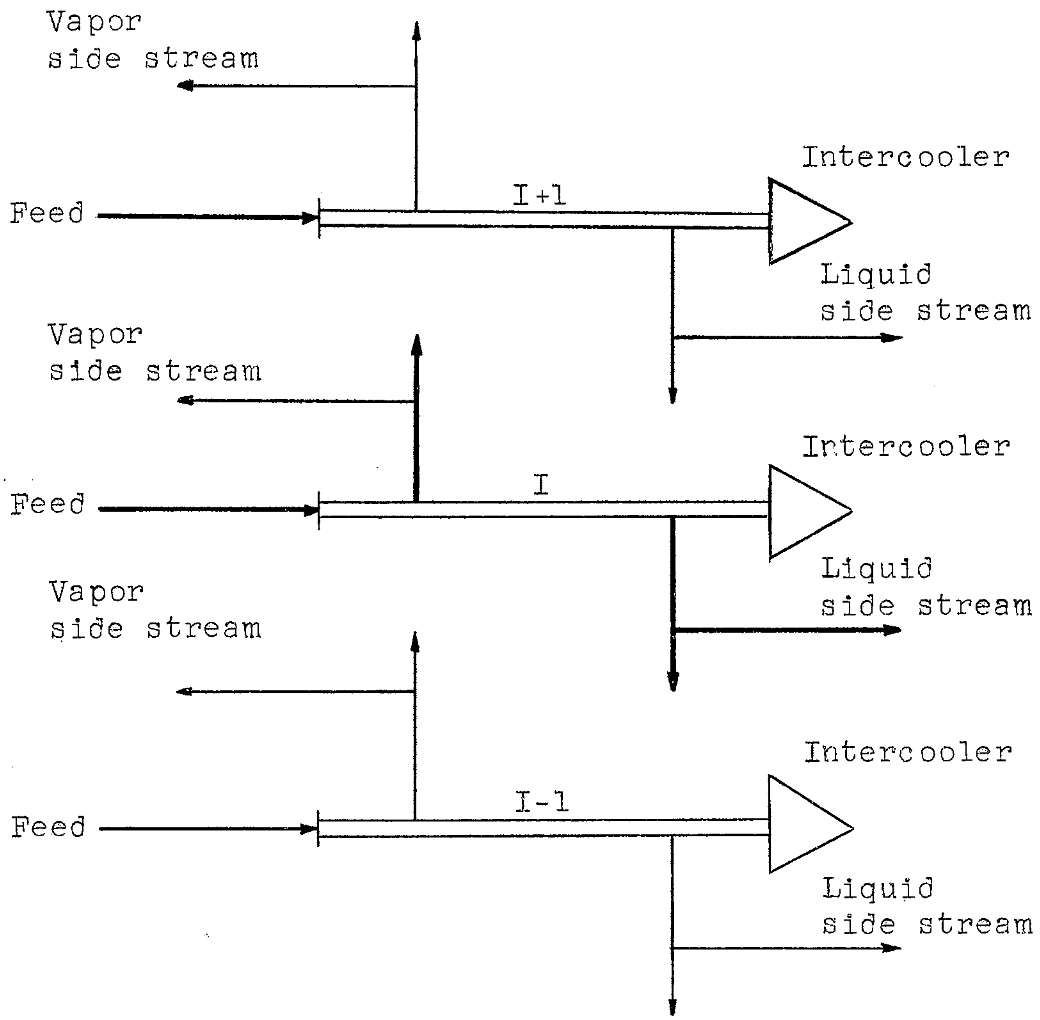

Figure 3. Complex Column Trays

k liquid side streams, and v vapor side streams, the most common set of specifications for the degrees of freedom is given below.

Pressure for each stage	n
Heat leak for each stage	n
Feed streams and location	m(C + 3)
Liquid side streams and location	2k
Vapor side streams and location	2v
Number of stages	1
TOTAL	2(n + k + v) + m(C + 3) + 1

A general absorption calculation method must be able to handle each of these complex features.

The engineering analysis of the absorption process has been largely restricted to two basic approaches. The more fundamental mass transfer approach to absorption has been developed from the two-film and the penetration mass transfer theories. This type of absorption calculation usually has been limited to use with packed columns. In this approach the number of transfer units and the "height" of the unit become the basic variables to be evaluated.

A less fundamental but more widely used approach in engineering calculations treats the operation of an absorption column as a stagewise process. Most stagewise treatments make the primary assumption of an ideal or equilibrium stage. An accompanying implicit assumption is that an over-all column efficiency can be used to correct the assumption of an ideal stage. A notable exception to both these limiting assumptions is an absorption calculation method developed by Ravicz. (14) This method provides for a non-ideal, vapor-liquid contacting device. As a result of the consideration of a non-ideal stage, individual tray and component efficiencies are also included in this method.

The basic approach which led to the development of the Sujata calculation method treats absorption as a stagewise process using equilibrium or ideal stages. This general approach might be termed the absorption factor approach because of the repeated use of and emphasis on an absorption factor. The development of this absorption factor approach is discussed in the following section.

C. Literature Survey

One of the earliest successful attempts in making a theoretical analysis of the absorption process was made by Kremser (10) in 1930. In this analysis the pressure, temperature, and flow rates of both the liquid and vapor were assumed to be constant throughout the column. Having defined the absorption process as a vapor pressure phenomenon, Kremser assumed Raoult's law was valid and using partial pressures defined an absorption factor for each component as

$$A = \frac{G\,q}{100} \,. \tag{4}$$

This absorption factor, defined in terms of the molal oil-to-gas ratio G and the equilibrium q in terms of partial pressures, completely described the absorption process on an equilibrium tray.

A component material balance made over a theoretical tray as shown in Figure 4 can be expressed in terms of the liquid content X and the vapor content Y as

$$L(X_i - X_{i-1}) = V(Y_{i+1} - Y_i) \,. \tag{5}$$

This equation may be rearranged using the equilibrium relation $X_i = q\,Y_i$ to give

$$Y_i = \frac{Y_{i+1} + AY_{i-1}}{1 + A} \,. \tag{6}$$

For an absorber having n trays, equation (5) may be applied to each tray to obtain the general expression for the vapor content on the last or n^{th} tray. This equation is

$$Y_n = \frac{Y_{n+1}(A^n - 1) + A^n(A - 1)Y_o}{A^{n+1} - 1} \,. \tag{7}$$

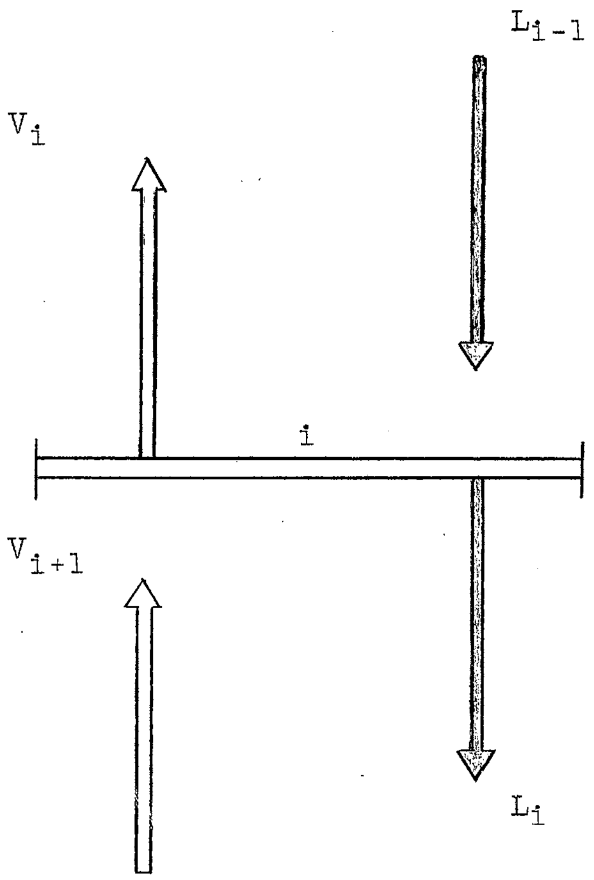

Figure 4. "Simple" Theoretical Tray

From this relationship the rich oil content X_n can be calculated using the equilibrium relation $X_n = q\, Y_n$. The lean gas leaving the column can be found by combining the equilibrium relation with the over-all material balance to get

$$A(Y_n - Y_o) = Y_{n+1} - Y_1 \ . \qquad (8)$$

Then substituting in for Y_n in equation (8) gives the general expression for the lean gas content.

$$Y_1 = \frac{(A - 1)Y_{n+1}}{A^{n+1} - 1} + \frac{A(A^n - 1)Y_o}{A^{n+1} - 1} \qquad (9)$$

Thus, the Kremser equations express the product stream content in terms of the entering streams and column conditions.

The basic absorption factor approach to absorption calculations developed by Kremser was modified by Brown (1) to eliminate the dependence of the absorption factor on the validity of Raoult's law. By assuming ideal solutions and using an equilibrium constant expressed in the form $K = y/x$, Brown redefined the Kremser absorption factor as

$$A = \frac{L}{KV} \ . \qquad (10)$$

Unlike the absorption factor defined by Kremser, this factor is free from any errors introduced by assuming

Raoult's law is valid. Brown also assumed that the pressure, temperature, and liquid and vapor rates remained constant throughout the column. Using these assumptions and the same approach used by Kremser, the equations developed by Brown are completely analogous to those developed by Kremser. The only difference between the two sets of equations is the new definition of the absorption factor.

The assumption of constant liquid and vapor flow rates throughout the column, as made in the Kremser-Brown method, can cause appreciable errors. Horton and Franklin (8) suggested a method in which the limiting assumption of constant column liquid and vapor rates was not made. Individual tray absorption factors were defined for each component on the i^{th} tray as

$$A_i = \frac{L_i}{K_i V_i} . \qquad (11)$$

By using tray absorption factors and the general approach used by Kremser, a general equation for an absorber with n theoretical trays was developed. This general equation may be expressed as

$$Y_n = (A_1 A_2 \cdots A_{n-1} + A_2 A_3 \cdots A_{n-1} + \cdots + A_{n-1} + 1) Y_{n+1} + \frac{L_o X_o}{V_{n+1}} (A_1 A_2 A_3 \cdots A_{n-1}) . \qquad (12)$$

or may be rearranged in the more familiar form

$$\frac{Y_{n+1} - Y_1}{Y_{n+1}} = \frac{(A_1 A_2 \ldots A_n + A_2 A_3 \cdots A_n + \cdots + A_n)}{(A_1 A_2 \ldots A_n + A_2 A_3 \ldots A_n + \ldots + A_n + 1)} - \frac{L_o X_o}{V_{n+1} Y_{n+1}} \frac{(A_2 A_3 \ldots A_n + A_3 A_4 \ldots A_n + \ldots + A_n + 1)}{(A_1 A_2 \ldots A_n + A_2 A_3 \ldots A_n + \ldots + A_n + 1)} . \tag{13}$$

The term $\frac{Y_{n+1} - Y_1}{Y_{n+1}}$ defines the absorption efficiency of the column.

Horton and Franklin noted that if the series of absorption factors was expressed by an average or effective absorption factor A_e in the form

$$\frac{A_e^{n+1} - A_e}{A_e^{n+1} - 1} ,$$

then their equations would reduce to the Kremser-Brown equation form. If the proper value of the effective absorption factor could be found, then the solution using A_e would correspond to the solution obtained using the individual tray absorption factors. Horton and Franklin suggested the use of the effective factor as a short-cut procedure. They suggested that the effective factor be selected at a position in the column which was dependent on the molecular weight of the component. For very light components the effective factor position would be near the top of the column while for very heavy components the position would be near the bottom of the column. A table was provided by Horton and Franklin as a guide in selecting empirical effective factors.

The calculation requires the absorption and temperature distributions to be determined for each tray. Horton and Franklin assumed that the percentage absorption on each tray was constant and the temperature was proportional to the "contraction" or reduction in the vapor rate on each tray. These approximations can be expressed mathematically as

$$\left(\frac{V_1}{V_{n+1}}\right)^{1/n} = \frac{V_m}{V_{m+1}} \tag{14}$$

and

$$\frac{V_{n+1} - V_{m+1}}{V_{n+1} - V_1} = \frac{T_n - T_m}{T_n - T_o} . \tag{15}$$

The results of this short-cut method may be used as an approximate answer or be refined using the more accurate but time consuming individual tray factor equations.

Edmister (2) found that in many cases that the effective factors were essentially independent of the number of trays and primarily functions of the terminal conditions. By solving for the effective absorption factor A_e in a two tray absorber, the expression

$$A_e = \sqrt{A_n (A_1 + 1) + 0.25} - 0.50 \tag{16}$$

can be used to define A_e in terms of the terminal tray absorption factors.

Following the development of the Kremser-Brown, Horton-Franklin, and Edmister calculation methods, several short-cut methods were developed.

A different approach to absorption calculations was made in a graphical method first suggested by Lewis (12) and which is commonly referred to as the Sherwood graphical method. (15) This short-cut method is similar to the McCabe-Thiele graphical method since both methods incorporate the equilibrium line, operating line, and tie line concepts. The equilibrium line represents the phase equilibrium on a tray and is defined by the equilibrium equation

$$K = \frac{Y(1 + \sum X)}{X(\sum_{j} Y)} \quad . \tag{17}$$

The operating line represents the relationship between the passing streams, the vapor leaving and the liquid entering a tray. If it is assumed that the L/V ratio remains constant throughout the column, then the operating line can be defined by a slope (the ratio of lean oil to wet gas) and a point (the wet gas composition). The procedure consists of estimating the component absorption and then checking that assumption with the graphical results. A successive approximation technique in which the fractional absorption of each component is adjusted is used to determine the final solution.

A short-cut method has been proposed by Landes and Bell. (11) The Kremser-Brown method provides the initial estimates for the lean oil and lean gas rates. Plate-to-plate calculations are carried out over the top two plates. The temperature, L/V ratio, and the absorption factors for these two top trays and the bottom tray are plotted against the tray number. An average absorption factor for the key component is obtained graphically and compared with the specified absorption factor. If the calculated average absorption factor differs greatly from the required absorption factor, then the lean oil and lean gas rates are revised and the calculation is repeated.

Hull and Raymond (9) developed a semi-empirical calculation method for calculating the component yields and temperature conditions of ordinary, nonintercooled, nonreboiled light-hydrocarbon absorbers. The material balance used in the calculations was derived by Horton and Franklin.

This material balance equation can be expressed as

$$\frac{Y_{n+1}V_{n+1} - Y_1V_1}{Y_{n+1}V_{n+1} - L_oX_o/A_c} = \frac{A_e^{n+1} - A_e}{A_e^{n+1} - 1} \qquad (18)$$

The lean gas temperature is found by a trial and error procedure in which the difference in the lean gas and lean oil temperatures is correlated with the top-section heat of absorption. A semi-empirical heat balance equation of the form

$$W_oC_p(T_n - T_o) + W_1C_p(T_1 - T_{n+1}) + W_sC_p(T_n - T_{n+1}) = H_s - 0.024UA'(T_{av} - T_{amb}) \qquad (19)$$

is used to calculate the rich oil temperature. The average tray temperature used in the heat balance is correlated with the weight ratio of lean oil to wet gas feed and the product stream temperatures. The effective absorption factors A_e can be determined by the same methods used by Horton and Franklin or by Edmister. Hull and Raymond developed a correlation between the A_e and the fractional distance between the bottom-section and average column conditions as an alternate procedure.

The various short-cut procedures previously discussed have been gradually replaced by more rigorous but also more time consuming calculation methods. Lewis and Matheson (13) developed a more rigorous multi-component distillation calculation. In general this method may be applied to absorber calculations as well. The procedure consists of assuming a product distribution and then calculating the temperature and flow rates for each tray. The top-down method assumes the lean gas composition and uses a dew point calculation to determine the temperature of the top tray. The total liquid rate leaving the tray is estimated and the component liquid rates are determined by the equilibrium relationship $l_i = L_i/K_iV_i \; v_i = A_i \; v_i$. The component vapor rates from the tray below are determined by a material balance over the top of the column. The general expression for this material balance is

$$v_{i+1} = l_i + v_1 - l_o \quad . \qquad (20)$$

The tray temperatures are determined by bubble or dew point calculations. These calculations can become extremely unstable in absorption systems. In a slight modification of the original method, the total liquid rate assumption is checked with a heat balance around the top of the column. The procedure is then repeated on the next lower tray. The initial lean gas composition assumption is checked by comparing the calculated wet gas with the given wet gas. A similar bottom-up method may also be used.

Thiele and Geddes (17) also developed a multicomponent distillation calculation method. In this method the product distribution need not be assumed. The products are calculated using l_i/d ratios in the basic equation

$$\frac{l_{i+1}}{d} = A_{i+1}\left[\frac{l_i}{d} + 1\right] \tag{21}$$

The calculation is based on the l_o/d ratio which is defined as the reflux ratio in the distillation column. In absorption calculations only the l/v ratios are available so that the basic Thiele-Geddes method must be modified.

An absorption calculation based on a modified Thiele-Geddes method was developed for the digital computer by Holland. (7) A material balance around the top of the column down to tray j-1 results in

$$v_1 + l_{i-1} = l_o + v_i \quad . \tag{22}$$

Using the equilibrium relation $l_i = A_i v_i$, the material balance equation may be rearranged to give

$$\frac{v_i}{v_1} = A_{i-1}\,\frac{v_{i-1}}{v_1} + (1 - \frac{l_o}{v_1}) \quad . \tag{23}$$

The equation for an n tray column is obtained by substituting v_i/v_1 into the expression for v_{i+1}/v_1. This general equation in terms of the terminal streams is

$$\frac{v_{n+1}}{v_1} = \omega + \Omega(1 - l_o/v_1) \qquad (24)$$

where

$$\omega = A_n A_{n-1} \cdots A_3 A_2 A_1$$

and

$$\Omega = 1 + A_n + A_n A_{n-1} + \cdots + A_n A_{n-1} \cdots A_3 A_2 \; .$$

The over-all material balance equation given by

$$v_1 - v_{n+1} = l_o - l_n \qquad (25)$$

may be substituted into equation (24) to give

$$\frac{l_n}{v_1} = \frac{l_o + (\Omega + \omega - 1)v_{n+1}}{l_o + v_{n+1}} \; . \qquad (26)$$

The component vapor rates for each tray are found by calculating l_n/v_1 from equation (26) and the term $1 - l_o/v_1$ from equation (24) and substituting these values into the material balance equation (23).

The primary assumption of the lean gas rate must be adjusted after each calculation pass. The component vapor rates are adjusted using the relation

$$(v_1)_{co} = \frac{v_{n+1} + l_o}{1 + \theta_o (l_n/v_1)_{cal}} \qquad (27)$$

The convergence variable θ_o is defined by

$$(l_n/v_1)_{co} = \theta_o \, (l_n/v_1)_{cal} \qquad (28)$$

The value of θ_o is the positive root of the function

$$g(\theta_o) = \sum (v_1)_{co} - V_1 = 0 \; . \qquad (29)$$

Either Newton's method or regula falsi interpolation is recommended as the procedure for finding the root of the function.

Edmister (3) also developed a more convenient form for the component distribution equations by introducing the absorption functions. The rich oil equation is given by

$$\begin{aligned} l_n &= v_1(A_1A_2A_3\ldots A_n+A_2A_3\ldots A_n+\ldots+A_n) \\ &\quad - l_o(A_2A_3\ldots A_n+A_3A_4\ldots A_n+\ldots A_n) \end{aligned} \tag{30}$$

and was redefined as

$$l_n = v_1\Sigma_a - l_o(\Sigma_a - \Pi_a) \tag{31}$$

where

$$\Sigma a = A_1A_2A_3\ldots A_n+A_2A_3\ldots A_n+\ldots+A_n$$

and

$$\Pi a = A_1A_2A_3\ldots A_n\ .$$

Combining the rich oil equation with an over-all material balance results in an equation for the lean gas as given by

$$v_1 = v_{n+1}\left[\frac{1}{1+\Sigma_a}\right] + l_o\left[1 - \frac{\Pi a}{1+\Sigma_a}\right]. \tag{32}$$

Two new absorption functions ϕ_a and ϕ_s were defined as

$$\phi_a = \frac{1}{1+\Sigma_a} \tag{33}$$

and

$$1 - \phi_s = 1 - \frac{\Pi a}{1+\Sigma_a} \tag{34}$$

The lean gas equation written in terms of these functions is

$$v_1 = v_{n+1}\,\phi_a + l_o(1-\phi_s)\,. \tag{35}$$

The term $v_{n+1}\phi_a$ represents the unabsorbed portion of the wet gas and the term $l_o(1 - \phi_s)$ represents the amount stripped from the lean oil. Thus, ϕ_a is the fraction of the wet gas which is not absorbed and ϕ_s is the fraction which is not stripped from the lean oil. The values of both functions must always be between zero and unity which is a definite advantage in solving for the column products.

This calculation procedure may also use the effective factor concept. The effective absorption factor A_e and the effective stripping factor S_e can be used to define the functions ϕ_a and ϕ_s.

$$\phi_a = \frac{A_e - 1}{A_e^{n+1} - 1} \tag{36}$$

$$\phi_s = \frac{S_e - 1}{S_e^{n+1} - 1} \tag{37}$$

The more rigorous calculation procedure is suitable for computer calculation.

CHAPTER III

THE SUJATA CALCULATION METHOD

A. General Description

The absorber-stripper calculation method described by Sujata (16) is an iterative, tray-by-tray method developed for computer use. The column products for a given absorption system are calculated from the rate, composition, and condition of the column feeds.

The Sujata calculation method may be divided into six major sections. The diagram in Figure 5 shows the relationship between each of these six sections. The method may be briefly described as follows. The initial temperature profile and the total vapor and liquid profiles are assumed. The component flow rates for each tray are calculated using a material balance and the equilibrium relation. A heat balance around each tray is used to determine the validity of the initial temperature assumption. If the heat balance is not satisfied for each tray, then the tray temperatures are adjusted

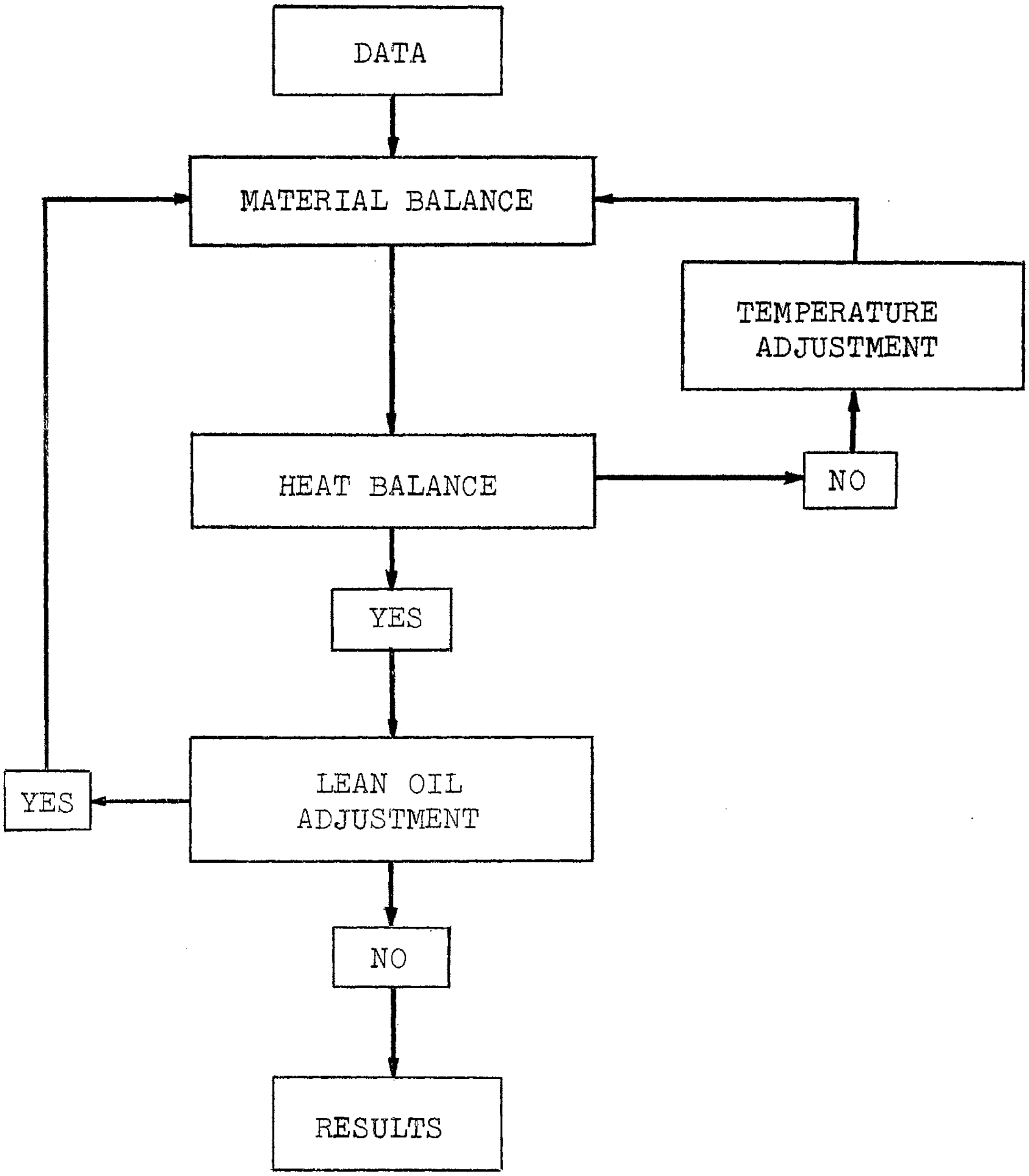

Figure 5. Sujata Absorption Calculation Procedure

and the calculation is repeated. Thus, the tray temperature is the principal iteration variable. When the initial assumptions have been verified, the calculated separation of the key component is compared with the desired separation. If the desired separation has not been obtained, then the lean oil rate is adjusted. The entire calculation is repeated until the desired key component separation has been obtained.

Three basic assumptions are made in nearly every stagewise absorption calculation. 1) Each tray is an equilibrium stage. 2) The vapor-liquid equilibrium is represented by an equilibrium constant in the form $K = y/x$. 3) The column has no unspecified heat losses. One of the advantages of the Sujata method is that these three assumptions are the only primary assumptions made in the calculation. In some cases the assumption of constant column pressure is also made. Most other absorption calculation methods require an excessive number of assumptions such as an average column temperature, vapor rate, liquid rate, or absorption factor.

The Sujata calculation method can be used for both absorption and stripping columns. The calculations are identical with the exception that the stripping vapor rate is adjusted in the stripping column.

The calculation is divided into six major sections as shown in Figure 5. The procedure is described in detail in the following sections.

B. Material Balance Section

The general n tray complex absorption column for which the calculation method is designed has three distinct types of trays: the bottom or 1st tray, the internal or ith trays, and the top or nth tray. These three types of trays are shown in Figure 6. The ith tray has an entering vapor and liquid stream, an exit vapor and liquid stream, and the possibility of a feed stream, vapor side stream, and liquid side stream. (The original Sujata method did not include the possibility of side streams in the column.) A material balance around each of these three types of trays for a single component results in the following equations:

$$f_1 + (1 - \alpha_2)l_2 = l_1 + v_1 \tag{38}$$

$$f_i + (1 - \beta_{i-1})v_{i-1} + (1 - \alpha_{i+1})l_{i+1} = l_i + v_i \tag{39}$$

$$f_n + (1 - \beta_{n-1})v_{n-1} = l_n + v_n \quad . \tag{40}$$

The equilibrium relation between the component liquid and vapor streams leaving the tray is given by

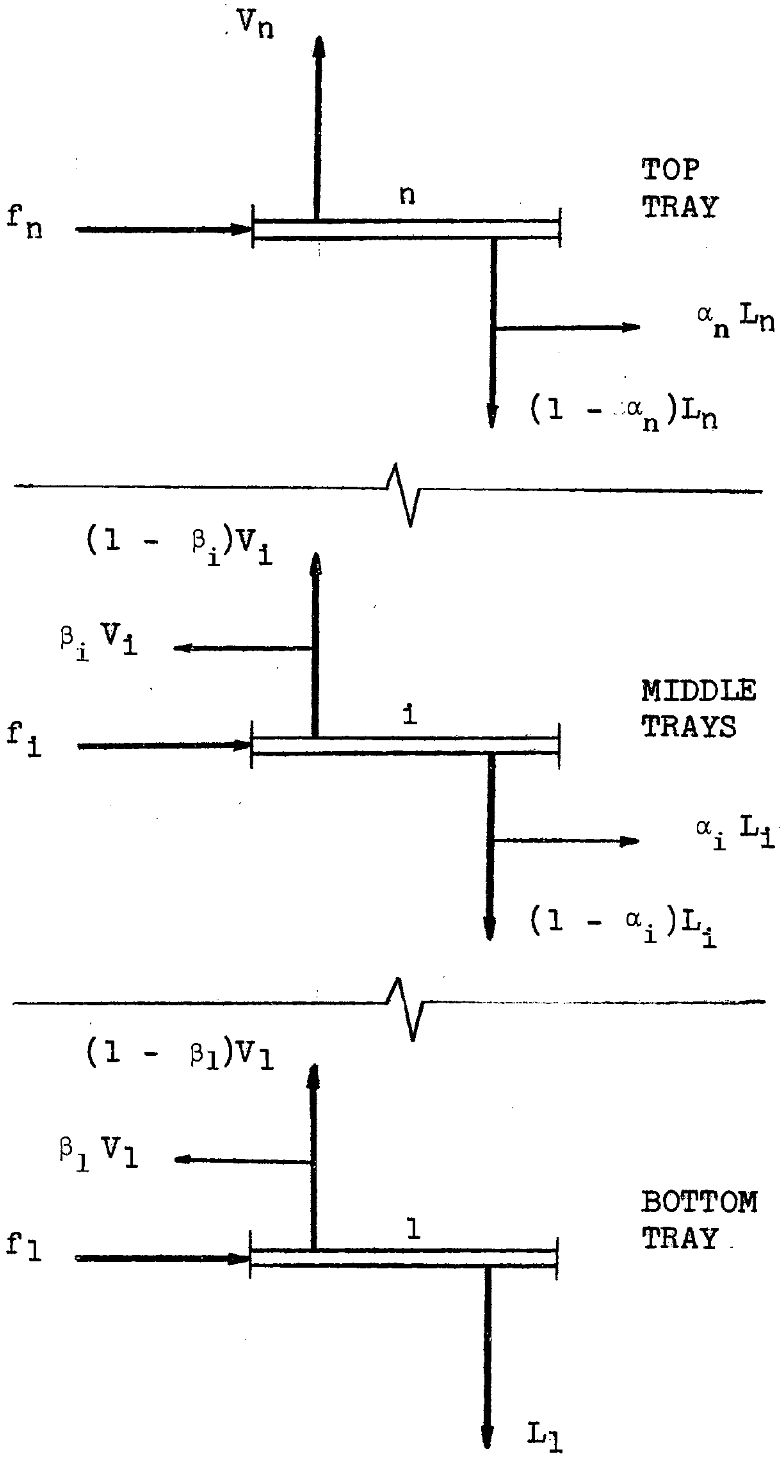

Figure 6. Three Types of Complex Column Trays

$$v_i = \frac{K_i V_i}{L_i} l_i = S_i l_i \quad . \qquad (41)$$

It is obvious that the stripping factor in the equilibrium relation depends on the initial vapor rate V_i, liquid rate L_i, and the temperature assumptions.

Substituting the equilibrium relation into the three tray material balance equations results in a set of n equations in terms of the liquid component streams l_i. These equations are

$$(1 + S_1)l_1 - (1 - \alpha_2)l_2 = f_1 \qquad (42)$$

$$(1 + S_i)l_i - (1 - \alpha_{i+1})l_{i+1} - (1 - \beta_{i-1})S_{i-1}l_{i-1} = f_i \qquad (43)$$

$$(1 + S_n)l_n - (1 - \beta_{n-1})S_{n-1}l_{n-1} = f_n \quad . \qquad (44)$$

This set of n simultaneous equations is written for each component. For any component the set of n equations may be rearranged into the matrix form shown in Figure 7. Matrices of this form are known as tridiagonal matrices.

The set of equations can be solved using a variety of matrix methods. The method selected for solving the matrices in the calculations associated with this thesis is based on a convenient method developed for the tridiagonal matrix. (6) The first step is to define two new quantities. For the first tray in the column

$$F'_1 = \frac{-(1 - \alpha_1)}{(1 + S_1)} \qquad (45)$$

$$\begin{bmatrix} (1+S_1) & -(1-\alpha_2) & 0 & 0 \\ -(1-\beta_1)S_1 & (1+S_2) & -(1-\alpha_3) & 0 \\ 0 & -(1-\beta_2)S_2 & (1+S_3) & -(1-\alpha_4) \\ 0 & 0 & -(1-\beta_3)S_3 & (1+S_4) \end{bmatrix} \begin{bmatrix} l_1 \\ l_2 \\ l_3 \\ l_4 \end{bmatrix} = \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \end{bmatrix}$$

Figure 7. Tri-diagonal Matrix for a Four Tray Absorption Column

$$G'_1 = \frac{f_1}{(1 + S_1)} \tag{46}$$

and for all remaining trays

$$F'_i = \frac{-(1 - \alpha_i)}{(1+S_i) + (1-\beta_{i-1})S_{i-1}F'_{i-1}} \tag{47}$$

$$G'_i = \frac{f_i + (1-\beta_{i-1})S_{i-1}G'_{i-1}}{(1+S_i) + (1-\beta_{i-1})S_{i-1}F'_{i-1}} \quad . \tag{48}$$

The unknown component liquid streams leaving the i^{th} tray may be expressed in terms of F_i and G_i by the equations

$$l_n = G'_n \tag{49}$$

$$l_i = G'_i - F'_i\, l_{i+1} \quad . \tag{50}$$

This form of solution is particularly well suited for computer calculations.

When the matrix has been solved for each of the components, the component liquid rates leaving each tray are known. The initial assumptions of the total liquid and vapor rates leaving each tray must be checked. If the sum of the calculated component rates leaving the tray does not equal the assumed rate, then the initial rate assumption must be corrected and the material balance calculation repeated. The initial rate assumption for the next trial is the sum of the calculated component rates calculated in the previous trial. This may be expressed as

$$L_i^{(m+1)} = \sum_j l_i^{(m)} . \tag{51}$$

When the component rates for each tray equal the initial assumption, then the calculation proceeds to the heat balance section.

C. Heat Balance Section

The heat balance section of the calculation is designed to check the initial temperature profile assumption used in the equilibrium relation of the material balance section. This is done by calculating the deviation or residue in the heat balance around each tray. The deviation in the heat balance is defined as the difference between the enthalpy of the exit and entering streams for a given tray. When the deviation G_i is approximately equal to zero for all trays, the initial temperature assumptions are correct. The heat balance deviation for each of the three types of trays is calculated from the following equations:

$$G_1 = Q_1 - f_1\bar{h}_1 + l_1(H_1S_1+h_1) - (1 - \alpha_2)l_2h_2 \tag{52}$$

$$G_i = Q_i - f_i\bar{h}_i + l_i(H_iS_i+h_i) - (1 - \alpha_{i+1})l_{i+1}h_{i+1} - (1 - \beta_{i-1})H_{i-1}S_{i-1}l_{i-1} \tag{53}$$

$$G_n = Q_n - f_n\bar{h}_n + l_n(H_nS_n+h_n) - (1 - \beta_{n-1})H_{n-1}S_{n-1}l_{n-1} \tag{54}$$

If the deviation for each tray is not approximately equal to zero, all tray temperatures are adjusted by a procedure outlined in the next section. If all the deviations are approximately equal to zero, then the temperature assumptions are correct and the lean oil rate is adjusted if necessary.

D. Temperature Adjusting Section

The temperature adjusting section of the calculation uses a basic Newton's method to predict the next temperature profile for the material balance calculations. If the temperature assumptions are reasonable, then the deviation in the heat balance will be small compared to the total enthalpy of the streams entering or leaving the tray. Therefore, the deviation in the heat balance may be considered as a total differential quantity. That is, $dG_i \approx G_i$. Since each deviation is a function of the temperature on the tray above, the tray below, and the tray itself, the total differential may be expressed for each of the three types of trays as

$$dG_1 = \frac{\partial G_1}{\partial t_2} dt_2 + \frac{\partial G_1}{\partial t_1} dt_1 \quad (55)$$

$$dG_i = \frac{\partial G_i}{\partial t_{i-1}} dt_{i-1} + \frac{\partial G_i}{\partial t_i} dt_i + \frac{\partial G_i}{\partial t_{i+1}} dt_{i+1} \quad (56)$$

$$dG_n = \frac{\partial G_n}{\partial t_{n-1}} dt_{n-1} + \frac{\partial G_n}{\partial t_n} dt_n \quad . \tag{57}$$

A set of n simultaneous equations is formed in which the differential temperature changes dt_i are the unknowns. If it is assumed that the material balances are not changed by the differential change in tray temperature, then dt_i represents the temperature change required to make the heat balance deviation dG_i equal to zero. In reality the differential temperature change results in small changes in the material balances. Thus, dt_i represents a temperature change which will make the heat balance deviation dG_i approach zero in successive approximations.

The set of equations developed from equations (55), (56), and (57) form a tridiagonal matrix. The solution to this system of equations may be obtained using the method developed for the tridiagonal matrix in the material balance section.

The coefficients of the temperature adjusting equations are obtained by differentiating the heat balance equations with respect to the indicated tray temperature. Thus,

$$\frac{\partial G_i}{\partial t_{i+1}} = - \sum_{j} \left[\frac{\partial h_{i+1}}{\partial t_{i+1}} \; l_{i+1} \right] \tag{58}$$

$$\frac{\partial G_i}{\partial t_{i+1}} = -\sum_j \left[\frac{\partial H_{i+1}}{\partial t_{i+1}} v_{i+1} \right] \qquad (59)$$

$$\frac{\partial G_i}{\partial t_i} = \sum_j \left[\frac{\partial h_i}{\partial t_i} l_i + \frac{\partial H_i}{\partial t_i} v_i \right] . \qquad (60)$$

The tray temperature for the next iteration in the material balance calculations is given by

$$t_i^{(m+1)} = t_i^{(m)} + dt_i^{(m)} . \qquad (61)$$

When the correct tray temperatures have been calculated, the separation obtained is compared with the desired separation of the key component.

E. Lean Oil Adjusting Section

The lean oil adjusting section determines the key component separation and, if necessary, adjusts the lean oil rate to give the desired separation. The separation is measured by the fractional absorption of the key component which is given by

$$EA = \frac{l_1}{\sum f_i} \qquad (62)$$

If the desired fractional absorption is not obtained, the lean oil rate is adjusted.

The fractional absorption EA also may be expressed in terms of an effective Kremser absorption factor A.

$$EA = \frac{A^{n+1} - A}{A^{n+1} - 1} \qquad (63)$$

Rearranging equation (63) to express A in terms of EA results in

$$A^{n+1} - \frac{A}{1 - EA} + \frac{EA}{1 - EA} = 0 \tag{64}$$

An effective absorption factor A^* based on the desired separation ED is evaluated from

$$(A^*)^{n+1} - \frac{A^*}{1 - ED} + \frac{ED}{1 - ED} = 0 \tag{65}$$

The new lean oil rate is defined in terms of A and A^*. The equation is

$$L_{n+1}^{(m+1)} = L_{n+1}^{(m)} + \left(\frac{A^*}{A} - 1\right) \sum_{j} l_1 \quad . \tag{66}$$

where m is the iteration number. The modified Sujata calculation method associated with this thesis does not use the original Sujata lean oil adjusting technique of equation (66). The new lean oil rate is given by

$$L_{n+1}^{(m+1)} = L_{n+1}^{(m)} \left(\frac{ED}{EA}\right)^{1.2} \quad . \tag{67}$$

This lean oil adjusting equation is an empirical relation suggested by previous absorption calculation work. (4)

When the lean oil rate has been adjusted, the entire calculation is repeated until the desired fractional absorption has been obtained.

For a stripping column the stripping vapor rate must be adjusted rather than the lean oil rate as in the absorption column. The procedure is entirely analogous to the lean oil adjusting technique. A fractional stripping factor for the key component is defined as

$$ES = \frac{V_n}{\sum_i f_i} . \tag{68}$$

The modified Sujata method uses the empirical relation

$$V_o^{(m+1)} = V_o^{(m)} \left(\frac{ED}{ES} \right)^{1.2} \tag{69}$$

where ED is the desired stripping vapor rate. The stripping vapor rate is adjusted until the desired fractional stripping has been obtained.

CHAPTER IV

EVALUATION PROCEDURE

A. Evaluation Objectives

The primary objective of this thesis is the evaluation of the Sujata calculation method. This evaluation is specifically concerned with the comparison of the Sujata method's results with both actual absorber performance and predictions made by two classical absorption methods. The investigation is an attempt to find answers to three principal questions: 1) How well does each absorption calculation method predict actual column performance? 2) What errors exist in these predictions and what are their relative magnitudes? 3) Why do these errors exist?

B. Calculation Methods

The investigation uses three absorption calculations: the Sujata method, the Kremser-Brown method, and the Edmister method. The Sujata calculation method has already been described in detail. The two remaining classical calculation methods are described briefly below.

The Kremser-Brown method was the pioneering absorption calculation method. Three primary assumptions are made: 1) The pressure, temperature, liquid rates, and vapor rates are constant throughout the column. 2) The liquid-vapor equilibrium is described by $K = y/x$. 3) The column consists of ideal trays. A series of material balances written around each tray is used to obtain expressions for the product compositions in terms of the feed streams and the column absorption factor A. The column absorption factor is determined by the specified absorption ED of a component by solving

$$ED = \frac{A^{n+1} - A}{A^{n+1} - 1} \quad . \tag{70}$$

The lean gas composition is given by the equation

$$y_1 = \frac{A - 1}{A^{n+1} - 1} y_{n+1} + \frac{A(A^n - 1)}{A^{n+1} - 1} y_o \tag{71}$$

and the rich oil composition is given by $x_n = y_n/K_{av}$ where y_n is given by

$$y_n = \frac{A^n - 1}{A^{n+1} - 1} y_{n+1} + \frac{A^n(A - 1)}{A^{n+1} - 1} y_o \tag{72}$$

The average K value K_{av} for the column is based on the average column temperature T_{av}. The average column temperature is defined as

$$T_{av} = 1/4(T_{ro} + T_{lg} + T_{wg} + T_{lo}). \qquad (73)$$

In the Kremser-Brown method both the feed and product stream temperatures must be specified. There is no heat balance involved in the calculations.

The lean oil rate is calculated in the following manner. The average L/V for the column is defined by

$$(\frac{L}{V})_{av} = K_{av} A \qquad (74)$$

so that the lean oil rate can be predicted by

$$L_o = (\frac{L}{V})_{av} V_{n+1} \qquad (75)$$

The Edmister method was developed after the introduction of the concept of an "effective" absorption factor A_e. If the correct effective absorption factor can be found, the solution of the Kremser-Brown equations using A_e instead of an average column absorption factor will correspond to the solution obtained by considering individual tray absorption factors. Three primary assumptions are associated with this method: 1) The liquid-vapor equilibrium is described by $K = y/x$. 2) The column consists of ideal trays. 3) The effective absorption factors are functions of the terminal trays only. The expression for the effective factor A_e obtained by considering a two tray column is

$$A_e = \sqrt{A_n(A_1 + 1) + 0.25} - 0.50 \qquad (75)$$

The feed streams and lean gas temperatures are specified. An over-all heat balance is used to determine the rich oil temperature. The lean oil rate is found by a trial and error procedure in which the calculated key component absorption is compared with the desired absorption.

C. Column Test Data

The test data used in the evaluation of the Sujata calculation method was divided into two sets. The first set consisted of a sample calculation on a test absorber which was presented by Sujata in the article describing the calculation method. The second set of test data consisted of column test data taken from the field analysis of three operating industrial absorbers. The information for all three of these absorbers was obtained from data used in a study of non-theoretical tray absorbers made by Ravicz. (14)

A brief description of each of the test columns appears below. The feed compositions and rates for each column appear in the tables of Appendix A.

Set I: Sujata Sample Calculation

Sujata supplied the set of test data for this 8-tray, 8-component complex absorption column operating at 310 psia. The complex features of the column include an intercooler on tray 2 and an additional feed stream entering tray 5.

Set II: Field Data

Column A

The Phillips Petroleum Company is the source for the test data for this 20-tray, 9-component bubble cap absorption column operating at 232 psia. The available column details indicate that the column diameter was 6.0 ft., plate spacing 27 in., length of the liquid path 3.39 ft., and a fractional cross-section for vapor flow of 0.768. The absorber oil was described as a mineral seal oil fraction having a molecular weight of 223.

Column B

The "X" Petroleum Company (name withheld by request) is the source for the test data for this 27-tray, 15-component Koch Kaskade-type absorption column operating at a pressure of 740 psia. The available column details indicate that the column diameter was 4.5 ft., plate spacing 26 in., and a fractional cross-section for vapor flow of 0.390. The absorber oil consisted of two components. The first component is a light oil having an average molecular weight of 165. The second component is the absorption oil fraction having a molecular weight of 210.

Column C

This column was designated as Unit 3 of the N.G.A.A. Low Pressure Data and is a 24-tray, 8-component absorption column operating at a pressure of 400 psia. The available column details indicate that the column diameter was 5.0 ft., plate spacing 24 in., liquid path 2.917 ft., weir height 1-7/8 in., and a fractional cross-section for vapor flow of 0.687. The absorber oil was described as an oil having a molecular weight of 207.

D. Evaluation Procedure

The first step in the evaluation of the Sujata method was to test the computer program developed using the Sujata calculation method. This test was made by comparing the results given by the computer program with those given in Sujata's sample calculation. All of the necessary input data was given in the sample calculation except for the source of the equilibrium and enthalpy data. For the evaluation in this thesis, all equilibrium and enthalpy data are obtained from the N.G.S.M.A. Data

Book (18) since it is probably the most readily available source for such information.

The input data needed for the sample calculation appears in Table III of Appendix A. The results for both the Sujata sample calculation and the computer program are listed in Tables IV-V of Appendix A.

The results of the comparison show that the sample calculation and the computer program give virtually the same product predictions. The deviations between the two product streams were very small even for the light components. It was concluded that these deviations were a result of differences in the equilibrium data used in the two calculations. The product stream temperatures and the temperature profile of the column were generally low but followed the same general pattern. The most significant temperature deviation was 10° F which occurred in the rich oil stream. These temperature deviations seem to be a result of significant differences in the enthalpy data used in the two calculations. The small product stream and temperature deviations indicated that the computer program was working properly.

In order to determine how well the Sujata method will predict actual column performance, the program was run using the column test data supplied by columns A, B, and C. There are two methods for analyzing the performance of a given absorption column. The first method fixes the lean oil rate in the calculation. The second method fixes the absorption of a key component. Both methods were used in this evaluation. When the key component absorption was specified, calculations were made for two, three, five, and ten theoretical trays. In all data cases propane was selected as the key component and equilibrium and enthalpy data used were obtained from the N.G.S.M.A. Data Book.

CHAPTER V

RESULTS

A. Tabulated Results

The Kremser-Brown, Edmister, and Sujata calculation methods were run on each of the absorption systems defined by columns A, B, and C. Two sets of calculations were performed on Column B for which information was also available for a well-stripped lean oil. This second data case for Column B is designated B2 while the first case is B1.

The calculated results for the Kremser-Brown and Edmister methods were obtained from a computer program developed by Erbar. (4) The Sujata calculation results were obtained from a computer program written for this thesis. (See Appendix B for a detailed discussion of the computer program.) The results of all three absorption calculations for each of the three absorption systems appear in Tables VI-XXIX of Appendix A. The first table in each set of tables for columns A, B, and C defines the absorption system for the column under consideration.

B. Analysis of Results

It is obvious that for a valid evaluation of any calculation method which predicts column performance, the field analysis of the operating column must be accurate. The measurement of feed and product stream temperatures is not difficult and presumedly the temperatures given in the field analysis will be reasonably correct. However, the accuracy of the analysis of the component rates in the feed and product streams in an operating absorber is certainly subject to question. If a material balance around the column exists for each component, then the component rates are likely to be reasonably correct. Several components in columns B1 and B2 are not in over-all material balance. Therefore, the predictions made by the calculation methods may not be valid and are not included in the following analysis of results.

The evaluation of the calculation methods is based on how well the method predicts the component product rates, the lean oil rate required for a specified key component absorption, and the product stream temperatures.

The predictions of these variables made by the Kremser-Brown, Edmister, and Sujata methods are listed in Table I. The comments on each method are a summary of the general trend observed in the results of columns A and C as compared with the field analysis of the column.

TABLE I

SUMMARY OF RESULTS

Kremser-Brown Calculation Method	
Predicted Variable	Observations
Lean Gas Product Rates	Within field analysis accuracy
Lean Oil Rate	High by 6 to 13%
Rich Oil Temperature	Specified, not calculated
Lean Gas Temperature	Specified, not calculated

Edmister Calculation Method	
Predicted Variable	Observations
Lean Gas Product Rates	Within field analysis accuracy
Lean Oil Rate	Varied from 5% low to 11% high
Rich Oil Temperature	High by 4 to 28° F
Lean Gas Temperature	Specified, not calculated

I (Continued)

Sujata Calculation Method	
Predicted Variable	Observations
Lean Gas Product Rates	Within field analysis accuracy
Lean Oil Rate	Low by 12 to 15%
Rich Oil Temperature	Varied from 3° low to 4° high
Lean Gas Temperature	High by 6° to 10° F

If the lean oil rate is fixed at the value given by the field analysis, the Sujata calculation method gives the following results.

TABLE II

RESULTS OF SUJATA CALCULATION METHOD FOR A FIXED LEAN OIL RATE

Sujata Calculation Method	
Predicted Variable	Observations
Lean Gas Product Rates	Slightly low
Lean Oil Rate	Specified, not calculated
Rich Oil Temperature	Low by 0.3° to 2° F
Lean Gas Temperature	High by 6° to 12° F

C. Discussion of Results

The general trends observed in the comparison of the calculation methods and the probable reasons for their existence are discussed for each of the three calculation methods in the following sections.

KREMSER-BROWN METHOD

Although the Kremser-Brown method is the least rigorous of the three calculation methods, the results (Tables VI-XXIX in Appendix A) indicate that this method is capable of predicting column products quite accurately. However, there are two factors which should be considered before the conclusion is made that the Kremser-Brown method is universally accurate. First, both the feed and product stream temperatures, which must be specified, were given the field analysis values which are the best possible estimates. In general the product stream temperatures must be estimated. An error in the temperature estimates may cause a significant error in the predicted column products. The second influencing factor is the fact that both columns A and C have relatively constant temperature, liquid, and vapor profiles. Since the primary assumption of the Kremser-Brown method is constant temperature, liquid, and vapor profiles, the predicted products are expected to be accurate.

The lean oil rate predicted by the Kremser-Brown method was generally 6 to 13% greater than the lean oil rate given by the field analysis. This overestimate is to be expected since the lean oil rate is predicted by

$$L_o = (L/V)_{av} V_{av} \tag{77}$$

where V_{av} is arbitrarily taken as the wet gas rate. Thus, the vapor rate used in calculating the lean oil rate is the greatest vapor rate in the column and will be greater than any average vapor rate. Therefore, the lean oil rate predicted is larger than actually required for the specified absorption.

EDMISTER METHOD

The results (Tables VI-XXIX in Appendix A) indicate that the Edmister method is capable of predicting column products quite accurately. Again there are two factors which greatly influence the apparent accuracy of the method. First, the feed and lean gas product stream temperatures were given the field analysis values which are the best possible estimates. Since the temperatures of both product streams depend on the lean gas temperature estimate, a significant error in the predicted column products may result if this estimate is in error. The second influencing factor is the fact that the temperature, liquid, and vapor profiles are nearly linear for both columns A and C. This means that any effective factor defined by the terminal tray absorption factors will not differ greatly from the individual tray absorption factors. Therefore, the predicted results are expected to be accurate.

The lean oil rate is determined by a trial and error procedure in which the assumed lean oil rate is checked with an over-all heat balance. This heat balance requires the specification of the lean gas temperature. Since the lean oil rate predicted by the Edmister method was both high and low, it appears that the predicted lean oil rate depends largely on the accuracy of the lean gas temperature estimate.

The Edmister method predicted rich oil temperatures which were consistently greater than those measured in the field. The greatest rich oil temperature error (28° F) occurred when the lean oil rate was 11% high. It appears that the error in the rich oil temperature is probably a direct result of the corresponding error in the predicted lean oil rate. If the lean oil rate is increased with all other column variables remaining constant, the total absorption will also increase. Therefore, the increase in the rich oil temperature is only a reflection of the increased rich oil enthalpy resulting from the increased lean oil rate.

SUJATA METHOD

The results predicted by the Sujata calculation with a fixed key component absorption were excellent. The difference between the predicted and measured product streams was so small that it was considered to be well within the experimental uncertainty of both the field analysis and the physical data used in the calculation. The excellent results were expected since the calculation involves a minimum number of limiting assumptions. The column products predicted by the Sujata method were slightly more accurate than those predicted by either the Kremser-Brown or Edmister methods.

The lean oil rate prediction made by the Sujata method was from 12 to 15% lower than the measured rate. If the results for the fixed key component absorption are compared with the results for the fixed lean oil rate, it is apparent that a very small change in the absorption can produce a large change in the predicted lean oil rate. Thus, the major portion of the lean oil error is quite possibly a result of both the equilibrium and enthalpy data used in the calculation.

The temperatures predicted for the product streams were very close to those measured in the field. The error in the rich oil temperature ranged from 2.5° low to 4° F high. This range of errors is considerably better than the 4° to 28° error predicted by the Edmister method. The major portion of the error is probably a result of the enthalpy data used in the calculation. The lean gas temperature was from 6° to 11° high. Since the predicted lean oil rate is lower than the measured rate, the increase in lean gas temperature is probably a reflection of the increased lean gas enthalpy caused by the reduction in absorption throughout the column.

Bubble and dew point calculations were made on the product streams predicted by the Sujata method. The maximum difference between the temperatures obtained by bubble or dew point and the Sujata calculations was less than 1° for both columns A and C.

The results of the Sujata calculation using a fixed lean oil rate showed the same general trend as those described for the calculation using a fixed key component absorption. However, the predicted column products were not as accurate as the predictions made by the fixed key component absorption calculation or by the Kremser-Brown and Edmister methods. The predicted temperatures for the column products were approximately the same as for the fixed key component absorption calculation. A comparison of the two types of Sujata calculations indicates that the predicted lean oil is sensitive to the equilibrium and enthalpy data used in the calculation.

CHAPTER VI

CONCLUSIONS

The primary objective in the evaluation of the Kremser-Brown, Edmister, and Sujata calculation methods was to determine how well the calculation methods predicted actual column performance. Two factors are particularly important if the evaluation is to be meaningful and valid. First, the field analysis which provides the column test data must be accurate since all comparisons of the calculated results are made with this data. The second factor is that accurate equilibrium and enthalpy data are needed for the accurate prediction of column products and temperatures. In the evaluation for this thesis, both these factors seem to be reasonably satisified.

The analysis of results showed that the classical absorption calculation methods developed by Kremser-Brown and Edmister can accurately predict column products. The accuracy of these predictions is subject to two principal conditions. The column under consideration must reasonably satisfy the simplifying assumptions made in the calculation theory. The estimates of the product temperatures required for the calculation must also be accurate. If both these conditions are satisfied, then the classical methods are capable of predicting accurate column products. Of the two classical methods, the Edmister method gives slightly better results and requires one less temperature specification. From considerations of the underlying theory, the Edmister method is expected to be the more universally accurate method.

The classical calculation methods have three limitations which seriously affect both their application and usefulness. 1) The columns under consideration must satisfy the simplifying assumptions made by the calculation theory. 2) The column must be a "simple" absorption column with no complex features such as additional feed streams, side streams, or intercoolers. (However, in 1957 Edmister (3) modified his calculation method slightly so that complex features may be included.) 3) The results obtained from the calculations may not accurately predict the internal conditions and state of the column.

The Sujata calculation method is not restricted by these three limitations placed on the classical methods. The only restriction made by the Sujata method is the consideration of each tray as a theoretical stage. The calculation can be used for a complex absorption system having a feed stream, liquid side stream, vapor side stream, or intercooler on any or all trays of the column. The calculation can predict all internal liquid and vapor rates and tray temperatures in the column. The analysis of results showed that the Sujata method was the most accurate of the three methods in predicting both the column products and temperatures. The predicted column products were well within the experimental uncertainty of the column test data and the physical data used in the calculation. The predicted temperatures were reasonably correct but probably could have been improved with the introduction of better equilibrium and enthalpy data. Thus, the Sujata method can be applied to almost any complex absorption system and be expected to give accurate results if given accurate equilibrium and enthalpy data.

The exact nature of the limitations of the Sujata method has not been fully investigated. In all the operating absorption systems used in this evaluation, the Sujata method converged rapidly and gave excellent results. However, the point at which the calculation does not converge has not been established in this study. Friday and Smith (5) examined the nature of convergence of both distillation and absorption calculations. An analysis of the approach used by Sujata showed that this type of calculation should converge rapidly for column feeds having a wide boiling range. As the boiling range of the feed decreases, the convergence difficulty increases. Therefore, although the Sujata calculation method could be applied to distillation problems, it is most likely that convergence difficulties will appear.

LIST OF NOMENCLATURE

A - absorption factor defined by $A = L/KV$
A' - top-section heat transfer area
A_e - effective absorption factor
C - number of components in the system
Cp - component heat capacity
EA - calculated key component absorption
ED - desired (specified) key component absorption
ES - calculated key component stripping
f - component feed rate to a tray
F' - variable used in solving a tridiagonal matrix
G - tray heat balance deviation
G' - variable used in solving a tridiagonal matrix
h - component liquid state enthalpy
$\bar{h}$ - component feed state enthalpy
H - component vapor state enthalpy
Hs - component heat of absorption
K - component equilibrium constant defined by $K = y/x$
l - component liquid rate leaving a tray
L - total liquid rate leaving a tray
n - number of trays in the column

P - column pressure

Q - intercooler duty

S - stripping factor defined by $S = KV/L$

T - temperature

U - top-section heat transfer coefficient

v - component vapor rate leaving a tray

V - total vapor rate leaving a tray

W - component mass flow rate leaving a tray

X - component liquid content in a stream

Y - component vapor content in a stream
y - component vapor content in a stream

Greek Symbols

α - fraction removed by the liquid side stream

β - fraction removed by the vapor side stream

θ_o - convergence variable in the Holland method

Subscripts

amb- ambient condition
av - average value
cal- calculated value
co - corrected value
i - tray reference
j - component reference
m - tray reference
n - total number of trays (last tray)
o - reference for stream entering tray 1

lg - lean gas stream
lo - lean oil stream
ro - rich oil stream
wg - wet gas stream

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APPENDIX A

CALCULATION RESULTS

TABLE III

SUJATA SAMPLE CALCULATION

Absorption System

Trays: 8
Pressure: 310 psia
Type: Complex absorber
Complex Features: Intercooler, side feed

Column Feed Rates			
Component	Wet Gas	Lean Oil	Side Feed
C_1*	357.846	0.0	13.992
C2	19.823	0.0	2.706
C_3	24.725	0.0	3.944
iC_4	6.321	0.0	1.155
nC_4	11.653	0.0	5.399
C6	9.632	0.0	5.596
OIL	0.0	245.000	134.409
TOTALS	430.000	245.000	165.000
Temperature	88.0° F	77.5° F	80.0° F
Feed Tray	1	8	5

Rich Oil Temperature: 90.2°
Intercooler Duty: 140,000 BTU/hr

*C_1 contains approximately 7% CO_2

TABLE IV

COMPARISON OF PRODUCT STREAMS FOR SUJATA SAMPLE CALCULATION

Lean Gas Product Rates

Component	Sujata Results	Program Results
C_1	320.22	323.168
C_2	8.54	8.031
C_3	0.37	0.403
iC_4	0.0	0.006
nC_4	0.0	0.005
C_6	0.0	0.0
OIL	0.03	0.003
TOTALS	329.20	331.616
Temperature	79.4° F	80.5° F

Rich Oil Product Rates

Component	Sujata Results	Program Results
C_1	51.62	48.670
C_2	13.99	14.498
C_3	28.30	28.265
iC_4	7.47	7.470
nC_4	15.05	15.047
C_6	15.03	15.027
OIL	379.38	379.406
TOTALS	510.80	508.384
Temperature	90.2° F	79.9° F

TABLE V

COMPARISON OF TRAY TEMPERATURES FOR THE SUJATA SAMPLE CALCULATION

Temperature Profiles (° F)								
TRAY	1	2*	3	4	5	6	7	8
Sujata Results	90.2	81.1	82.5	82.0	81.5	81.3	80.3	79.4
Program Results	79.9	77.2	80.3	80.4	80.4	80.6	80.6	80.5

*Tray 2 intercooler removes 140,000 BTU/hr

TABLE VI

COLUMN A ABSORPTION SYSTEM

Column Specifications

Trays: 20
Pressure: 232 psia
Type: Bubble cap
Diamter: 6.0 ft.
Plate Spacing: 27 in.
Source: Phillips Petroleum Company

	Column Feed Rates		Column Product Rates	
Comp.	Wet Gas	Lean Oil	Lean Gas	Rich Oil
N_2	210.4564	0.0	211.048	0.368
C_1	985.4553	0.0	971.475	12.032
C_2	88.8290	0.0	81.152	7.251
C_3	51.2475	0.0	37.767	13.398
iC_4	6.1475	0.0	2.744	3.389
nC_4	14.2126	0.0225	2.091	12.137
C_5	6.4230	0.5130	0.523	6.410
C_7	3.8265	0.1778	0.0	3.993
OIL	0.0	203.6867	0.0	203.724
TOTALS	1366.6000	204.4000	1306.800	262.700
Temp.	65.0° F	67.0° F	72.0° F	80.0° F

OIL: Molecular weight of 223.

TABLE VII

CALCULATED RESULTS FOR COLUMN A TWO THEORETICAL TRAYS

Lean Gas Product Rates			
Component	Kremser-Brown	Edmister	Sujata
N2	209.686	209.641	209.633
C1	971.751	970.851	970.747
C2	81.436	81.408	81.202
C3	37.854	37.852	37.849
iC4	2.947	2.776	2.999
nC4	5.160	4.467	5.333
C5	0.812	0.437	1.085
C7	0.006	0.003	0.014
OIL	0.0	0.0	0.028
TOTALS	1309.653	1307.431	1308.891
Temperature	72.0° F	72.0° F	78.6° F
Lean Oil Rate	229.477	198.330	191.412
Lean Oil Temperature	67.0° F	67.0° F	67.0° F
Rich Oil Temperature	80.0° F	82.0° F	78.1° F

TABLE VIII

CALCULATED RESULTS FOR COLUMN A
THREE THEORETICAL TRAYS

Lean Gas Product Rates			
Component	Kremser-Brown	Edmister	Sujata
N_2	209.720	209.641	209.658
C_1	972.340	970.851	971.204
C_2	81.713	81.408	81.426
C_3	37.849	37.852	37.850
iC_4	2.710	2.776	2.802
nC_4	4.285	4.467	4.579
C_5	0.391	0.437	0.695
C_7	0.0	0.0	0.008
OIL	0.0	0.0	0.029
TOTALS	1309.008	1307.432	1308.252
Temperature	72.0° F	72.0° F	79.2° F
Lean Oil Temperature	67.0°	67.0° F	67.0° F
Lean Oil Rate	219.568	192.453	184.109
Rich Oil Temperature	80.0° F	83.0° F	78.5° F

TABLE IX

CALCULATED RESULTS FOR COLUMN A
FIVE THEORETICAL TRAYS

Lean Gas Product Rates			
Component	Kremser-Brown	Edmister	Sujata
N_2	209.729	209.643	209.665
C_1	972.510	970.898	971.315
C_2	81.802	81.464	81.484
C_3	37.850	37.854	37.851
iC_4	2.479	2.573	2.636
nC_4	3.303	3.563	3.808
C_5	0.091	0.115	0.388
C_7	0.0	0.0	0.008
OIL	0.0	0.0	0.029
TOTALS	1307.764	1306.110	1307.183
Temperature	72.0° F	72.0° F	78.9° F
Lean Oil Rate	216.737	192.380	181.528
Lean Oil Temperature	67.0° F	67.0° F	67.0° F
Rich Oil Temperature	80.0° F	84.0° F	78.6° F

TABLE X

CALCULATED RESULTS FOR COLUMN A TEN THEORETICAL TRAYS

	Lean Gas Product Rates		
Component	Kremser-Brown	Edmister	Sujata
N_2	209.730	209.639	209.672
C_1	972.518	970.817	971.449
C_2	81.806	81.445	81.517
C_3	37.846	37.852	37.852
iC_4	2.353	2.473	2.560
nC_4	2.414	2.782	3.220
C_5	0.002	0.004	0.259
C_7	0.0	0.0	0.008
OIL	0.0	0.0	0.028
TOTALS	1306.669	1305.012	1306.564
Temperature	72.0° F	72.0° F	78.3° F
Lean Oil Rate	216.596	194.148	178.071
Lean Oil Temperature	67.0° F	67.0° F	67.0° F
Rich Oil Temperature	80.0° F	84.0° F	77.6° F

TABLE XI

CALCULATED RESULTS FOR COLUMN A TWO THEORETICAL TRAYS WITH A FIXED LEAN OIL RATE

Lean Gas Product Rates	
Component	Sujata Method
N_2	209.580
C_1	969.802
C_2	80.716
C_3	37.070
iC_4	2.862
nC_4	5.021
C_5	1.008
C_7	0.013
OIL	0.028
TOTALS	1306.100
Temperature	78.4° F
Lean Oil Rate	204.400
Lean Oil Temperature	78.0° F
Rich Oil Temperature	

TABLE XII

COLUMN B1 ABSORPTION SYSTEM

Column Specifications

Trays: 27
Pressure: 740 psia
Type: Koch Kaskade
Diameter: 4.5 ft.
Plate Spacing: 26 in.
Source: "X" Petroleum Company

	Column Feed Rates		Column Product Rates	
Comp.	Wet Gas	Lean Oil	Lean Gas	Rich Oil
N_2	38.228	0.0	43.529	0.0
C_1	748.344	0.0	723.987	41.524
C_2	67.413	0.0	35.895	18.960
C_3	55.664	0.0	7.471	28.544
iC_4	5.501	0.0	0.568	5.641
nC_4	12.587	2.909	0.406	15.699
iC_5	1.492	1.892	0.081	3.397
nC_5	1.305	2.601	0.081	4.010
C_6	0.373	2.199	0.081	2.651
C_7	1.492	0.237	0.0	0.203
C_8	0.0	0.402	0.0	0.407
C_9	0.0	3.997	0.0	4.214
C_{10}	0.0	6.788	0.0	7.136
OIL 1	0.0	37.201	0.0	38.670
OIL 2	0.0	178.274	0.0	185.743
TOTALS	932.400	236.500	812.100	356.800
Temp.	88.0° F	103.0° F	112.0° F	114.0° F

OIL 1: Molecular weight of 165
OIL 2: Molecular weight of 210

TABLE XIII

CALCULATED RESULTS FOR COLUMN B1
TWO THEORETICAL TRAYS

Lean Gas Product Rates

Component	Kremser-Brown	Edmister	Sujata
N_2	37.672	37.606	37.620
C_1	705.003	699.227	700.442
C_2	51.232	50.472	50.553
C_3	27.116	27.125	27.119
iC_4	1.458	1.515	1.516
nC_4	2.425	2.573	3.698
iC_5	0.105	0.118	0.565
nC_5	0.063	0.073	0.585
C_6	0.141	0.148	0.209
C_7	0.003	0.003	0.013
C_8	0.0	0.0	0.006
C_9	0.0	0.0	0.027
C_{10}	0.0	0.0	0.020
OIL 1	0.0	0.0	0.065
OIL 2	0.0	0.0	0.016
TOTALS	825.218	818.860	822.454
Temperature	112.0° F	112.0° F	123.2° F
Lean Oil Rate	252.229	173.172	171.838
Lean Oil Temperature	103.0° F	103.0° F	103.0° F
Rich Oil Temperature	114.0° F	125.0° F	118.8° F

TABLE XIV

CALCULATED RESULTS FOR COLUMN B1
THREE THEORETICAL TRAYS

Lean Gas Product Rates			
Component	Kremser-Brown	Edmister	Sujata
N_2	37.741	37.671	37.678
C_1	710.314	704.245	704.981
C_2	52.664	51.757	51.714
C_3	27.120	27.125	27.119
iC_4	1.214	1.295	1.312
nC_4	1.757	1.952	3.231
iC_5	0.045	0.057	0.551
nC_5	0.022	0.029	0.591
C_6	0.133	0.142	0.220
C_7	0.0	0.0	0.010
C_8	0.0	0.0	0.007
C_9	0.0	0.0	0.028
C_{10}	0.0	0.0	0.022
OIL 1	0.0	0.0	0.070
OIL 2	0.0	0.0	0.018
TOTALS	831.012	824.274	827.551
Temperature	112.0° F	112.0° F	125.2° F
Lean Oil Rate	220.643	156.059	152.061
Lean Oil Temperature	103.0° F	103.0° F	103.0° F
Rich Oil Temperature	114.0° F	126.0° F	118.3° F

TABLE XV

CALCULATED RESULTS FOR COLUMN B1
FIVE THEORETICAL TRAYS

Lean Gas Product Rates			
Component	Kremser-Brown	Edmister	Sujata
N_2	37.775	37.700	37.703
C_1	712.905	706.550	706.954
C_2	53.558	52.562	52.324
C_3	27.117	27.123	27.120
iC_4	0.895	1.005	1.077
nC_4	0.962	1.180	2.707
iC_5	0.008	0.012	0.551
nC_5	0.003	0.004	0.607
C_6	0.122	0.135	0.228
C_7	0.0	0.0	0.010
C_8	0.0	0.0	0.007
C_9	0.0	0.0	0.029
C_{10}	0.0	0.0	0.022
OIL 1	0.0	0.0	0.072
OIL 2	0.0	0.0	0.019
TOTALS	833.344	826.271	829.430
Temperature	112.0° F	112.0° F	126.2° F
Lean Oil Rate	205.589	149.511	142.571
Lean Oil Temperature	103.0° F	103.0° F	103.0° F
Rich Oil Temperature	114.0° F	127.0° F	117.5° F

TABLE XVI

CALCULATED RESULTS FOR COLUMN B1
TEN THEORETICAL TRAYS

Lean Gas Product Rates

Component	Kremser-Brown	Edmister	Sujata
N_2	37.783	37.703	37.710
C_1	713.565	706.869	707.619
C_2	53.812	52.749	52.489
C_3	27.123	27.124	27.120
iC_4	0.524	0.664	0.863
nC_4	0.242	0.394	2.190
iC_5	0.0	0.0	0.553
nC_5	0.0	0.0	0.613
C_6	0.113	0.129	0.229
C_7	0.0	0.0	0.010
C_8	0.0	0.0	0.007
C_9	0.0	0.0	0.029
C_{10}	0.0	0.0	0.022
OIL 1	0.0	0.0	0.072
OIL 2	0.0	0.0	0.019
TOTALS	833.162	825.633	829.544
Temperature	112.0° F	112.0° F	125.9° F
Lean Oil Rate	201.758	150.532	138.085
Lean Oil Temperature	103.0° F	103.0° F	103.0° F
Rich Oil Temperature	114.0° F	127.0° F	116.1° F

TABLE XVII

CALCULATED RESULTS FOR COLUMN B1 TWO THEORETICAL TRAYS WITH A FIXED LEAN OIL RATE

Lean Gas Product Rates	
Component	Sujata Method
N_2	37.273
C_1	674.860
C_2	41.060
C_3	15.842
iC_4	0.643
nC_4	1.850
iC_5	0.333
nC_5	0.349
C_6	0.120
C_7	0.006
C_8	0.003
C_9	0.013
C_{10}	0.010
OIL 1	0.027
OIL 2	0.005
TOTALS	772.393
Temperature	92.5° F
Lean Oil Rate	236.500
Lean Oil Temperature	103.0° F
Rich Oil Temperature	96.0° F

TABLE XVIII

COLUMN B2 ABSORPTION SYSTEM

Column Specifications

Trays: 27
Pressure: 740 psia
Type: Koch Kaskade
Diameter: 4.5 ft.
Plate Spacing: 26 in.
Source: "X" Petroleum Company

	Column Feed Rates		Column Product Rates	
Comp.	Wet Gas	Lean Oil	Lean Gas	Rich Oil
N_2	38.228	0.0	43.529	0.0
C_1	748.344	0.0	723.987	41.524
C_2	67.413	0.0	35.895	18.960
C_3	55.664	0.0	7.471	28.544
iC_4	5.501	0.0	0.568	5.641
nC_4	12.587	0.0	0.406	15.699
iC_5	1.492	0.0	0.081	3.397
nC_5	1.305	0.0	0.081	4.010
C_6	0.373	0.236	0.081	2.651
C_7	1.492	0.236	0.0	0.203
C_8	0.0	0.402	0.0	0.407
C_9	0.0	3.997	0.0	4.214
C_{10}	0.0	6.778	0.0	7.136
OIL 1	0.0	37.201	0.0	38.670
OIL 2	0.0	178.639	0.0	185.743
TOTALS	932.400	236.500	812.100	356.800
Temp.	88.0° F	103.0° F	112.0° F	114.0° F

OIL 1: Molecular weight of 165
OIL 2: Molecular weight of 210

TABLE XIX

CALCULATED RESULTS FOR COLUMN B2
TWO THEORETICAL TRAYS

Lean Gas Product Rates			
Component	Kremser-Brown	Edmister	Sujata
N_2	37.672	37.607	37.618
C_1	705.003	699.321	700.272
C_2	51.232	50.480	50.531
C_3	27.116	27.124	27.117
iC_4	1.458	1.514	1.518
nC_4	2.425	2.572	2.586
iC_5	0.105	0.118	0.120
nC_5	0.063	0.073	0.075
C_6	0.141	0.147	0.027
C_7	0.003	0.003	0.013
C_8	0.0	0.0	0.006
C_9	0.0	0.0	0.027
C_{10}	0.0	0.0	0.020
OIL 1	0.0	0.0	0.065
OIL 2	0.0	0.0	0.017
TOTALS	825.217	818.960	820.011
Temperature	112.0° F	112.0° F	123.3° F
Lean Oil Rate	252.229	172.318	170.383
Lean Oil Temperature	103.0° F	103.0° F	103.0° F
Rich Oil Temperature	114.0° F	124.0° F	119.4° F

TABLE XX

CALCULATED RESULTS FOR COLUMN B2
THREE THEORETICAL TRAYS

Lean Gas Product Rates			
Component	Kremser-Brown	Edmister	Sujata
N_2	37.741	37.672	37.675
C_1	710.314	704.334	704.758
C_2	52.664	51.765	51.683
C_3	27.120	27.124	27.119
iC_4	1.214	1.294	1.315
nC_4	1.757	1.950	2.004
iC_5	0.045	0.057	0.061
nC_5	0.022	0.029	0.032
C_6	0.133	0.142	0.024
C_7	0.0	0.0	0.010
C_8	0.0	0.0	0.007
C_9	0.0	0.0	0.028
C_{10}	0.0	0.0	0.021
OIL 1	0.0	0.0	0.069
OIL 2	0.0	0.0	0.019
TOTALS	831.012	824.368	824.823
Temperature	112.0° F	112.0° F	125.2° F
Lean Oil Rate	220.643	155.237	150.887
Lean Oil Temperature	103.0° F	103.0° F	103.0° F
Rich Oil Temperature	114.0° F	125.0° F	119.2° F

TABLE XXI

CALCULATED RESULTS FOR COLUMN B2
FIVE THEORETICAL TRAYS

Lean Gas Product Rates			
Component	Kremser-Brown	Edmister	Sujata
N_2	37.775	37.701	37.699
C_1	712.905	706.642	706.661
C_2	53.558	52.572	52.280
C_3	27.117	27.125	27.120
iC_4	0.895	1.004	1.080
nC_4	0.962	1.179	1.340
iC_5	0.008	0.012	0.016
nC_5	0.003	0.004	0.006
C_6	0.122	0.135	0.024
C_7	0.0	0.0	0.010
C_8	0.0	0.0	0.007
C_9	0.0	0.0	0.029
C_{10}	0.0	0.0	0.022
OIL 1	0.0	0.0	0.071
OIL 2	0.0	0.0	0.019
TOTALS	833.344	826.374	826.385
Temperature	112.0° F	112.0° F	126.0° F
Lean Oil Rate	205.589	148.631	141.751
Lean Oil Temperature	103.0° F	103.0° F	103.0° F
Rich Oil Temperature	114.0° F	126.0° F	118.6° F

TABLE XXII

CALCULATED RESULTS FOR COLUMN B2
TEN THEORETICAL TRAYS

Lean Gas Product Rates			
Component	Kremser-Brown	Edmister	Sujata
N_2	37.783	37.704	37.707
C_1	713.565	706.956	707.267
C_2	53.812	52.757	52.434
C_3	27.123	27.124	27.120
iC_4	0.524	0.663	0.867
nC_4	0.242	0.393	0.689
iC_5	0.0	0.0	0.001
nC_5	0.0	0.0	0.0
C_6	0.113	0.129	0.024
C_7	0.0	0.0	0.010
C_8	0.0	0.0	0.007
C_9	0.0	0.0	0.029
C_{10}	0.0	0.0	0.022
OIL 1	0.0	0.0	0.070
OIL 2	0.0	0.0	0.019
TOTALS	833.162	825.727	826.264
Temperature	112.0° F	112.0° F	125.3° F
Lean Oil Rate	201.758	149.690	137.564
Lean Oil Temperature	103.0° F	103.0° F	103.0° F
Rich Oil Temperature	114.0° F	126.0° F	117.5° F

TABLE XXIII

CALCULATED RESULTS FOR COLUMN B2 TWO THEORETICAL TRAYS WITH A FIXED LEAN OIL RATE

Lean Gas Product Rates

Component	Sujata Method
N_2	37.407
C_1	683.646
C_2	45.379
C_3	21.150
iC_4	1.040
nC_4	1.688
iC_5	0.071
nC_5	0.043
C_6	0.024
C_7	0.011
C_8	0.006
C_9	0.026
C_{10}	0.020
OIL 1	0.062
OIL 2	0.016
TOTALS	790.588
Temperature	121.9° F
Lean Oil Rate	236.500
Lean Oil Temperature	103.0° F
Rich Oil Temperature	120.4° F

TABLE XXIV

COLUMN C ABSORPTION SYSTEM

Column Specifications

Trays: 24
Pressure: 400 psia
Type: (not specified)
Diameter: 5.0 ft.
Plate Spacing: 24 in.
Source: Unit 3, N.G.A.A. Low Pressure Data

	Column Feed Rates		Column Product Rates	
Comp.	Wet Gas	Lean Oil	Lean Gas	Rich Oil
CO_2	97.404	0.0	89.802	7.608
C_1	731.894	0.0	707.479	24.871
C_2	54.826	0.0	47.343	7.403
C_3	49.091	0.0	23.811	24.988
iC_4	6.943	0.0	0.400	8.427
nC_4	17.595	0.0	0.078	17.293
C_6	12.346	0.0	0.087	12.055
OIL	0.0	189.500	0.0	189.341
TOTALS	970.100	189.500	869.000	292.600
Temp.	69.0° F	71.0° F	78.0° F	92.0° F

OIL: Molecular weight of 207

TABLE XXV

CALCULATED RESULTS FOR COLUMN C TWO THEORETICAL TRAYS

Lean Gas Product Rates

Component	Kremser-Brown	Edmister	Sujata
CO_2	87.599	88.615	87.793
C_1	705.085	698.592	701.967
C_2	43.895	43.199	43.388
C_3	24.106	24.107	24.104
iC_4	1.591	1.653	1.658
nC_4	2.685	2.841	2.859
C_6	0.053	0.066	0.066
OIL	0.0	0.0	0.005
TOTALS	865.013	859.073	861.841
Temperature	78.0° F	78.0° F	88.6° F
Lean Oil Rate	267.280	243.000	189.735
Lean Oil Temperature	71.0° F	71.0° F	71.0° F
Rich Oil Temperature	92.0° F	118.0° F	89.5° F

TABLE XXVI

CALCULATED RESULTS FOR COLUMN C
THREE THEORETICAL TRAYS

Lean Gas Product Rates			
Component	Kremser-Brown	Edmister	Sujata
CO_2	88.734	89.554	88.720
C_1	708.364	701.869	704.527
C_2	44.954	44.165	44.226
C_3	24.101	24.107	24.100
iC_4	1.242	1.326	1.354
nC_4	1.732	1.914	1.982
C_6	0.005	0.008	0.008
OIL	0.0	0.0	0.005
TOTALS	869.132	862.942	864.932
Temperature	78.0° F	78.0° F	89.0° F
Lean Oil Rate	234.294	220.250	170.756
Lean Oil Temperature	71.0° F	71.0° F	71.0° F
Rich Oil Temperature	92.0° F	120.0° F	91.0° F

TABLE XXVII

CALCULATED RESULTS FOR COLUMN C
FIVE THEORETICAL TRAYS

Lean Gas Product Rates			
Component	Kremser-Brown	Edmister	Sujata
CO_2	89.312	90.000	89.107
C_1	709.947	703.390	705.555
C_2	45.574	44.733	44.636
C_3	24.104	24.107	24.102
iC_4	0.802	0.906	0.986
nC_4	0.733	0.893	1.025
C_6	0.0	0.0	0.0
OIL	0.0	0.0	0.005
TOTALS	870.474	864.028	865.416
Temperature	78.0° F	78.0° F	88.3° F
Lean Oil Rate	218.522	210.502	162.425
Lean Oil Temperature	71.0° F	71.0° F	71.0° F
Rich Oil Temperature	92.0° F	121.0° F	91.6° F

TABLE XVIII

CALCULATED RESULTS FOR COLUMN C
TEN THEORETICAL TRAYS

Lean Gas Product Rates			
Component	Kremser-Brown	Edmister	Sujata
CO_2	89.456	90.077	89.171
C_1	710.338	703.643	705.866
C_2	45.738	44.860	44.734
C_3	24.103	24.107	24.103
iC_4	0.327	0.430	0.583
nC_4	0.086	0.139	0.227
C_6	0.0	0.0	0.0
OIL	0.0	0.0	0.005
TOTALS	870.049	863.257	864.686
Temperature	78.0° F	78.0° F	86.8° F
Lean Oil Rate	214.633	210.724	158.532
Lean Oil Temperature	71.0° F	71.0° F	71.0° F
Rich Oil Temperature	92.0° F	120.0° F	91.2° F

TABLE XXIX

CALCULATED RESULTS FOR COLUMN C TWO THEORETICAL TRAYS WITH A FIXED LEAN OIL RATE

Lean Gas Product Rates

Component	Sujata Method
CO_2	88.191
C_1	702.503
C_2	43.684
C_3	24.665
iC_4	1.730
nC_4	3.007
C_6	0.072
OIL	0.006
TOTALS	863.858
Temperature	89.7° F
Lean Oil Rate	189.500
Lean Oil Temperature	71.0° F
Rich Oil Temperature	92.3° F

APPENDIX B

COMPUTER PROGRAM

COMPUTER PROGRAM

The Sujata absorption program is written in Fortran IV and was developed for the IBM 7094 computer. The program is written for a general, complex absorption column and has the following size limitations:

Variables	Symbol	Maximum Number
Trays	N	100
Components	NCP	30
Feed streams	MFD	20
Liquid side streams	MSD	10
Vapor side streams	MVSD	10
Intercoolers	MQ	10

The computer program is divided into six major calculation sections. Figure 8 is a block diagram of the calculation procedure.

Main Program

EXEC is the executive program for the entire calculation. The major calculation subroutines are called by EXEC as shown in Figure 9. These major subroutines may in turn call several smaller "support" subroutines. A brief description of the function of each subroutine appears in the following section.

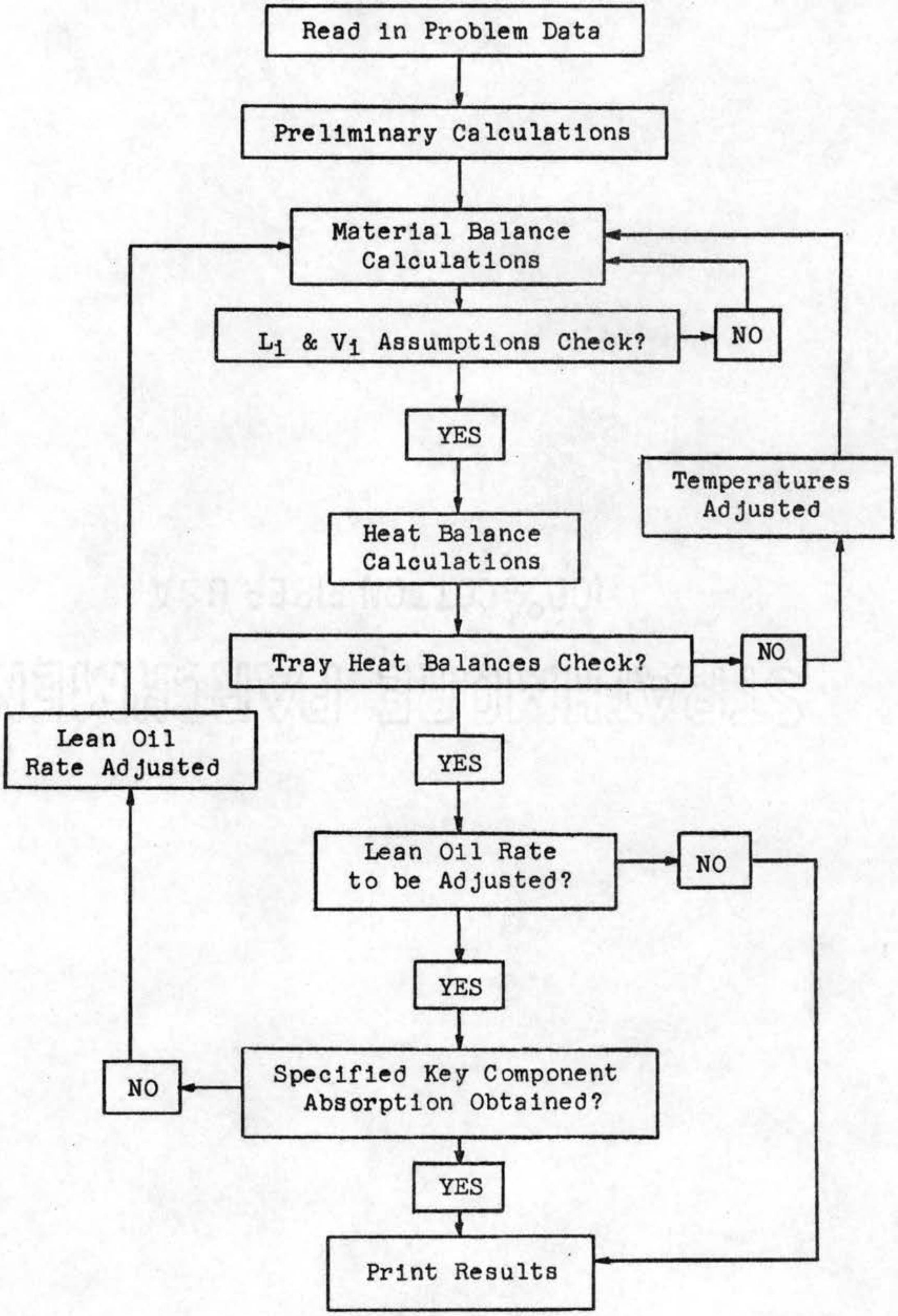


Figure 8. Sujata Program Block Diagram

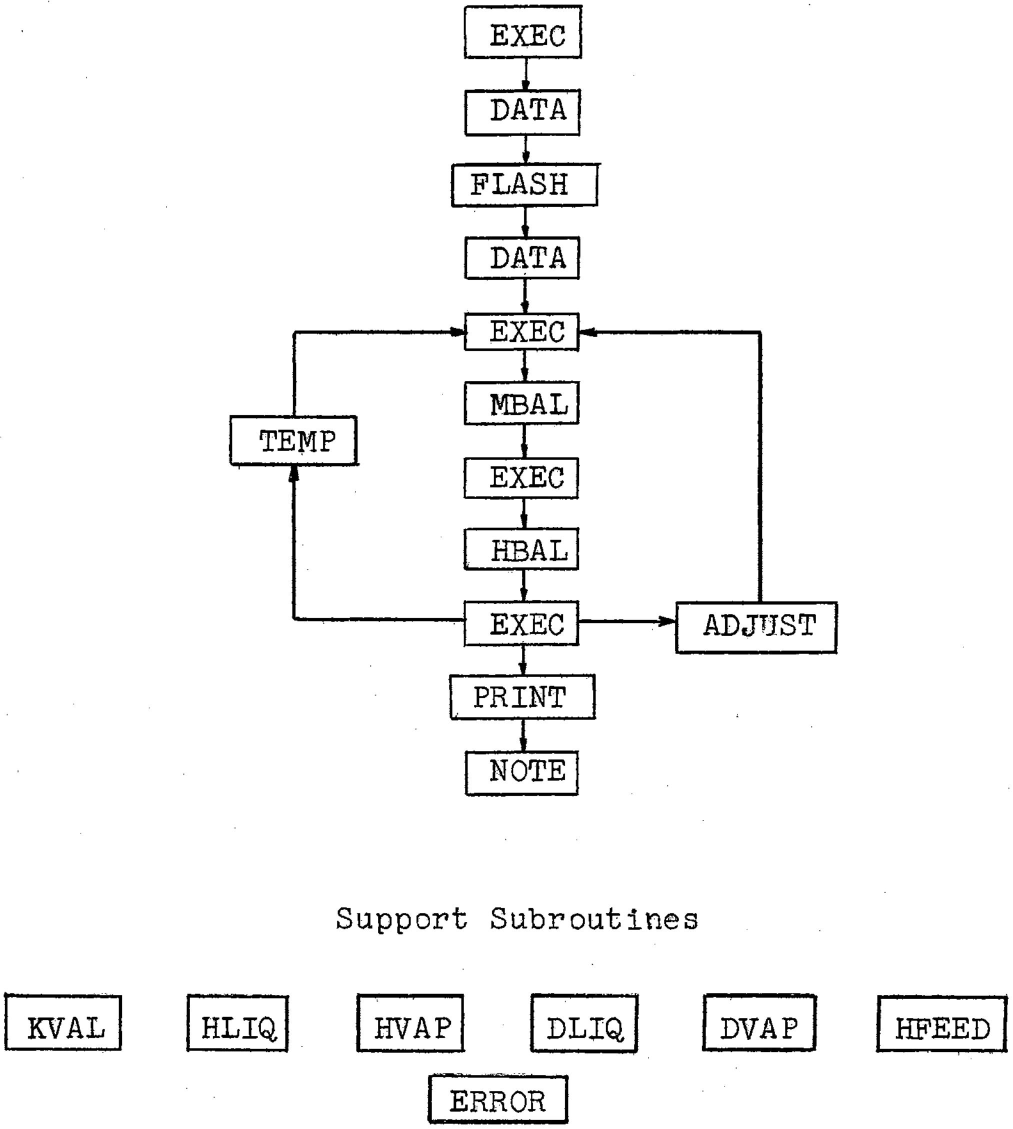


Figure 9. Subroutine Block Diagram

Subroutines

SUBROUTINE ADJUST

ADJUST is the subroutine that determines whether or not the specified key component absorption or stripping has been obtained. If the specified key component absorption has not been obtained, then the subroutine predicts a new lean oil rate. ADJUST is called by the main program EXEC.

SUBROUTINE DATA

DATA is the data input subroutine. All input data is read in by this subroutine. If preliminary calculations (bubble point, dew point, flash, etc.) are required, the subroutine calls the proper calculation subroutine. DATA is called only once by the main program EXEC.

SUBROUTINE DLIQ

DLIQ is the subroutine that calculates the derivative of the liquid component enthalpy at a given temperature. DLIQ is called by numerous subroutines throughout the program.

SUBROUTINE DVAP

DVAP is the subroutine that calculates the derivative of the vapor component enthalpy at a given temperature. DVAP is called by numerous subroutines throughout the program.

SUBROUTINE ERROR

ERROR is the subroutine that prints out the major error messages resulting from major calculation errors. The calculation is terminated with this error message. ERROR may be called by numerous subroutines throughout the program.

SUBROUTINE FLASH

FLASH is the subroutine that checks the validity of the stream conditions given by the input data. It also performs all the necessary bubble point, dew point, and flash calculations associated with the stream conditions. FLASH is called by DATA.

SUBROUTINE HBAL

HBAL is the subroutine that calculates the heat balance around each tray for a given temperature profile. HBAL is called by EXEC.

SUBROUTINE HFEED

HFEED is the subroutine that calculates the enthalpy of the feed streams. HFEED is called by FLASH.

SUBROUTINE HLIQ

HLIQ is the subroutine that calculates the enthalpy for a liquid component at a given temperature. HLIQ is called by numerous subroutines throughout the program.

SUBROUTINE HVAP

HVAP is the subroutine that calculates the enthalpy for a vapor component at a given temperature. HVAP is called by numerous subroutines throughout the program.

SUBROUTINE KVAL

KVAL is the subroutine that calculates the equilibrium constant for a component at a given temperature. KVAL is called by numerous subroutines throughout the program.

SUBROUTINE MBAL

MBAL is the subroutine that calculates the material balance around each tray for a given temperature profile. The initial liquid and vapor assumptions made for each tray are checked and adjusted if necessary. MBAL is called by the main program EXEC.

SUBROUTINE NOTE

NOTE is the subroutine that prints out the minor error messages resulting from small errors during the calculation. These error messages are warnings that the calculation is not completely correct. NOTE is called by PRINT.

SUBROUTINE OIL

OIL is the subroutine that estimates the lean oil rate required for a specified key component absorption. OIL is called by DATA.

SUBROUTINE PRINT

PRINT is the subroutine that prints out the final results of the calculation. PRINT is called by the main program EXEC.

SUBROUTINE TEMP

TEMP is the subroutine that predicts the new temperature profile for the column if the heat balances are not satisified. TEMP is called by the main program EXEC.

SUBROUTINE VAPOR

VAPOR is the subroutine that estimates the stripping vapor rate required for a specified key component stripping. VAPOR is called by DATA.

Input Data Specifications

The specific input data requirements and a discussion of each item can be found in the following sections.

Format Specifications

There are four types of format statements used in the program. Each type of format is discussed in detail in the IBM Fortran Manual. (19)

Fw.d This type of format is used for floating point numbers. The total word length is specified by w and the decimal point is located by d which is the number of digits to the right of the decimal. The floating point number 876.32143 would be represented by the format F8.5. If the decimal point is punched on the input data card, the specified decimal point location will be overriden.

Ew.d This type of format is used for floating point numbers with a specified exponent. The terms w and d again refer to the total word length and decimal point location. The E represents the power of ten to which the number preceeding the E is raised. The floating point number -0.010245 would be written as -.10245E-01 and would be represented by the format E11.5.

In This type of format is used for fixed point numbers. The total word length is specified by n. The fixed point number 523 would be represented by the format I3.

An This type of format is used for alphameric information. The field width is specified by n with a maximum n of six spaces. The alphameric information SUJATA ABSORPTION PROGRAM would be represented by 5A6.

Input Data Cards

The input data required for the program is arranged in the following order:

Card 1 "Problem Identification"

This card is used for the alphameric identification of the program. Any short identifying remarks may be used.

```
READ:    WORD(I)
FORMAT:  10A6
```

Card 2 "Column Variables"

This card contains the seven general column variables which define the absorption system. (All these column variables, except the column pressure, have a maximum number as the upper limit. See page 96.)

N	Number of trays
NCP	Number of components
MFD	Number of column feeds
MSD	Number of liquid side streams
MVSD	Number of vapor side streams
MQ	Number of intercoolers
P	Column pressure

```
READ:    N,NCP,MFD,MSD,MVSD,MQ,P
FORMAT:  6I3,F10.4
```

Card 3 "Program Controls"

This card contains the program control variables.

Each variable is discussed below.

KLOOP Lean Oil Prediction Variable

KLOOP = 1 The lean oil rate is specified in the input data.

KLOOP = 2 An initial estimate of the lean oil rate is given in the input data. The program adjusts the lean oil rate to the correct value.

KLOOP = 3 The initial estimate of the lean oil rate is made by the program.

KLOOP = 4 The stripping vapor rate is specified in the input data.

KLOOP = 5 The initial estimate of the stripping vapor rate is given in the input data. The program adjusts the vapor rate to the correct value.

KLOOP = 6 The initial estimate of the stripping vapor rate is made by the program.

KX Intermediate Output Variable

KX = 0 The intermediate calculations are not printed out with the results.

KX $\neq$ 0 The intermediate calculations are printed out with the results.

JOB Output Control Variable

JOB = 2 The component liquid and vapor profiles for each tray are printed out with the column products.

JOB = 3 The total tray and component liquid and vapor profiles are printed out with the column products.

KTX Initial Temperature Profile Variable

KTX = 0 An initial temperature profile is calculated by the program.

KTX $\neq$ 0 The initial temperature profile is specified in the input data.

READ: KLOOP,KX,JOB,KTX
FORMAT: 4I3

Card 4i "Component Identification"

This series of cards (one for each component) identifies the components used in the calculation.

READ: COMP(J)
FORMAT: 10A6

Card 5 "Absorption Variables"

This card defines the absorption variables. If the lean oil rate is to be adjusted (KLOOP $\neq$ 1), then the desired fractional absorption or the desired product rate for the key component must be specified in the input data. The variables are:

KEY	Key component
ED	Desired fractional absorption
XXX	Desired product rate for key component

READ: KEY,ED,XXX
FORMAT: I3,F10.7,F12.5

Card 6i "Intercooler Variables"

This series of cards (one for each intercooler) appears in the input data only if at least one intercooler is present in the system. The variables are:

NQ	Tray number
Q	Intercooler duty

READ: NQ,Q
FORMAT: I3,E12.6

Card 7_i "Liquid Side Stream Variables"

This series of cards (one for each liquid side stream) appears in the input data only if at least one liquid side stream is present in the system. The variables are:

NSD	Tray number
FR	Fraction of the liquid stream removed by the side stream.

READ: NSD,FR
FORMAT: I3,F10.5

Card 8_i "Vapor Side Stream Variables"

This series of cards (one for each vapor side stream) appears in the input data only if at least one vapor side stream is present in the system. The variables are:

NVSD	Tray number
VR	Fraction of the vapor stream removed by the side stream

READ: NVSD,VR
FORMAT: I3,F10.5

Card 9 "Convergence Limits"

This card contains the three principal convergence limits of the program. Each convergence limit represents the maximum fractional error that can result from incomplete convergence. The variables are:

ER1 = Convergence limit in the heat balance
ER2 = Convergence limit in the material balance
ER3 = Convergence limit in the lean oil rate

```
READ:    ER1,ER2,ER3
FORMAT:  3F10.5
```

Card 10_i "Equilibrium Coefficients"

This series of cards (one for each component) contains the equilibrium coefficients for the calculation of the equilibrium constant. Each card contains the coefficients for one component. The components must be in the same order as the components listed by Cards 4_i. The equilibrium constant equation in the program is of the form

$$\ln K = A0 + A1/T + A2/T^2 + A3/T^3.$$

NOTE: All temperatures must be in the form $^{\circ}R/100$.

```
READ:    A0,A1,A2,A3
FORMAT:  4E14.8
```

Card 11_i "Enthalpy Coefficients for the Vapor"

This series of cards (one for each component) contains the vapor state enthalpy coefficients. Each card contains the coefficients for one component.

The components must be in the same order as the components listed in Cards 4_i. The vapor enthalpy equation is of the form

$$HV = AV + BV*T + CV*T^2 \ .$$

NOTE: All temperatures must be of the form $^oR/100$.

READ: AV,BV,CV
FORMAT: 3E12.6

Card 12_i "Enthalpy Coefficients for the Liquid"

This series of cards (one for each component) contains the liquid state enthalpy coefficients. Each contains the coefficients for one component. The components must be in the same order as in Cards 4_i. The enthalpy equation is of the form

$$HL = AL + BL*T + CL*T^2 \ .$$

NOTE: All temperatures must be of the form $^oR/100$.

READ: AL,BL,CL
FORMAT: 3E12.6

Card 13_i "Feed Variables"

This series of cards (one for each feed stream) contains the column feed position and conditions. The variables are:

NFD	Feed tray number
MOD	Feed condition
TFD	Feed temperature ($^oR/100$)
FLK	Flashed feed ratio (L/F)
EN	Feed enthalpy

The feed streams may enter the column in any of seven conditions. The condition of the feed determines whether TFD, FLK, or EN must be specified in the input data. The feed condition is given by MOD.

MOD = 1 The feed is all liquid at a specified temperature. (TFD is specified.)
MOD = 2 The feed is all vapor at a specified temperature. (TFD is specified.)
MOD = 3 The feed is flashed at a given L/F ratio. (FLK is specified.)
MOD = 4 The feed is flashed at a given temperature. (TFD is specified.)
MOD = 5 The feed is at its bubble point.
MOD = 6 The feed is at its dew point.
MOD = 7 The feed is given at a specified enthalpy. (EN is specified.)

READ: NFD,MOD,TFD,FLK,EN
FORMAT: 2I3,2F10.5,F12.4

Card 14_i "Component Feed Rates"

This series of cards (one set for each feed stream) contains the component feed rates for each feed stream. Each card contains a maximum of six component feed rates. FD is the component feed rate variable.

READ: FD(I,J)
FORMAT: 6F12.6

Card 15 "Temperature Limits"

This card contains the maximum and minimum temperature limits of the physical data. The equilibrium and enthalpy data is fitted over this temperature range. The program will not allow calculation temperatures to exist outside this range. The variables are:

TMAX	Maximum temperature ($^{o}R/100$)
TMIN	Minimum temperature

READ: TMAX,TMIN
FORMAT: 2F10.5

Card 16_i "Initial Temperature Profile"

This series of cards contains the initial temperature profile used by the program and is present in the input data only if KTX $\neq$ 0 in Card 3. Each card contains six tray temperatures.

READ: T(J)
FORMAT: 6F12.5

Program Output

Intermediate Calculations:

If KX = 0 in Card 3, then the intermediate calculations will be printed out in addition to the final results. These intermediate calculations include the material balance, heat balance, and temperature profile for each pass of the calculation. This information is often useful in locating any errors indicated by the error messages of the program.

Results:

The program has two major output formats.

1) The temperature, liquid, and vapor component rates for each tray are listed along with the total column product rates and their enthalpies.

2) The tray temperatures and total and component liquid and vapor rates are listed along with the calculated column product rates and their enthalpies.

Error Comments:

The program contains two types of error comments. The first type of error comment is a warning that indicates the solution contains minor errors resulting from temperatures predicted outside the temperature range defined by TMAX and TMIN. (The equilibrium and enthalpy data is valid only within this range.) The program is allow to continue using either TMAX or TMIN rather than the predicted temperature. The magnitude of the error depends on the difference between the predicted and limiting temperatures. The error comment indicates both the subroutine in which the error occurred and the magnitude of the first correction. Errors of this type may cause the program to terminate. Error comments of this type appear as

```
  *****PROGRAM ERROR MESSAGES*****

      TEMPERATURE IS GREATER THAN TMAX IN SUBROUTINE ___
         T EXCEEDS TMAX BY ___

  *****WARNING--SOLUTION CONTAINS MINOR ERRORS
```

In most cases these errors can be corrected by expanding the temperature range of the equilibrium and enthalpy data.

The second type of error comment indicates a major error in the calculation. The program is terminated at that point and passes on to the next data set. This type of error comment is possible in all sections of the program in which a successive approximation technique is used. For most practical absorption systems an error comment of this type is likely to be the result of an error in the input data. Each error comment is listed below with a brief explanation of the error.

HEAT BALANCE DID NOT CONVERGE

The program has made 150 temperature adjusting passes. The deviation in the heat balance still exceeds the convergence limit set by ER1 in the input data.

DEVIATION IN THE HEAT BALANCE EXCEEDS LIMIT

The deviation in the heat balance is extremely large. It is likely that the heat balance calculation is diverging rather converging to the proper values.

MATERIAL BALANCE DID NOT CONVERGE

The program has made 50 material balance passes in subroutine MBAL. The deviation in the material balance still exceeds the convergence limit ER2 for at least one tray.

FINAL SOLUTION DID NOT CONVERGE

The program has made 50 lean oil adjusting passes. The calculated fractional absorption (or stripping) still exceeds the convergence limit ER3. The percentage change in the last lean oil adjustment is printed out with the error comment.

L/F SOLUTION DID NOT CONVERGE IN SUBROUTINE FLASH

The program has made 50 L/F ratio adjusting passes in subroutine FLASH. The correct L/F ratio of the feed could not be found.

DEW POINT DID NOT CONVERGE IN SUBROUTINE FLASH

The program has made 50 calculation passes in subroutine FLASH. The correct dew point temperature of the feed could not be found.

BUBBLE POINT DID NOT CONVERGE IN SUBROUTINE FLASH

The program has made 50 calculation passes in subroutine FLASH. The correct bubble point temperature of the feed could not be found.

FLASH TEMPERATURE DID NOT CONVERGE IN SUBROUTINE FLASH

The program has made 50 calculation passes in subroutine FLASH. The correct flash temperature of the feed could not be found.

TEMPERATURE WILL NOT CONVERGE IN VAPOR FEED

The program has made 50 calculation passes in subroutine FLASH. The correct feed temperature for the given vapor feed enthalpy could not be found.

TEMPERATURE WILL NOT CONVERGE IN LIQUID FEED

The program has made 50 calculation passes in subroutine FLASH. The correct feed temperature for the given liquid feed enthalpy could not be found.

TEMPERATURE WILL NOT CONVERGE IN FLASHED FEED

The program has made 50 calculation passes in subroutine FLASH. The correct feed temperature for the flashed feed enthalpy could not be found.

Calculation Variables:

The following is a list of the primary calculation variables used in the program. All these variables appear in COMMON.

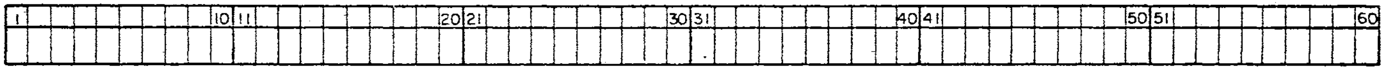
A0	1^{st} equilibrium constant coefficient
A1	2^{nd} equilibrium constant coefficient
A2	3^{rd} equilibrium constant coefficient
A3	4^{th} equilibrium constant coefficient
AAA	NOTE error message variable
AL	1^{st} liquid state enthalpy coefficient
AV	1^{st} vapor state enthalpy coefficient
BBB	NOTE error message variable
BL	2^{nd} liquid state enthalpy coefficient
BV	2^{nd} vapor state enthalpy coefficient
CL	3^{rd} liquid state enthalpy coefficient
CV	3^{rd} vapor state enthalpy coefficient
ED	desired fractional absorption or stripping
EN	feed enthalpy
ER1	convergence limit in the heat balance
ER2	convergence limit in the material balance
ER3	convergence limit in the lean oil rate
ER4	"spare" variable
ER5	"spare" variable
FD	component feed rate
FR	fraction taken off by a liquid side stream
H	heat balance deviation
HSUM	exit stream enthalpy plus intercooler duty
JOB	output control variable
JX	total number of NOTE error messages
KEY	key component number
KLOOP	lean oil rate control variable
KX	intermediate print out control variable
LX	ERROR message variable
MFD	number of feeds
MOD	condition of feed
MQ	number of intercoolers
MSD	number of liquid side streams
MVSD	number of vapor side streams

MX	lean oil adjustment "pass" variable
N	number of trays
NCP	number of components
NFD	feed tray location
NQ	intercooler tray location
NSD	liquid side stream tray location
NVSD	vapor side stream tray location
PL	total liquid rate leaving the tray
PV	total vapor rate leaving the tray
Q	intercooler duty
SFDH	total feed enthalpy
SMFD	total feed rate
T	tray temperature
TFD	feed temperature
TMAX	maximum temperature
TMIN	minimum temperature
VR	fraction taken off by the vapor side stream
XXX	desired key component product rate
XL	component liquid rate leaving a tray
YYY	a spare variable

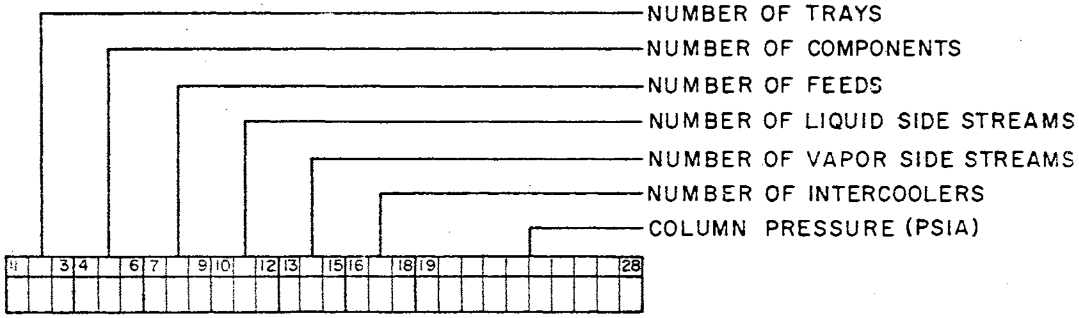
ABSORBER PROGRAM
INPUT DATA SHEET

PROJECT NO.____________________
NAME____________________
DATE____________________
PAGE_____ OF____ PAGES________

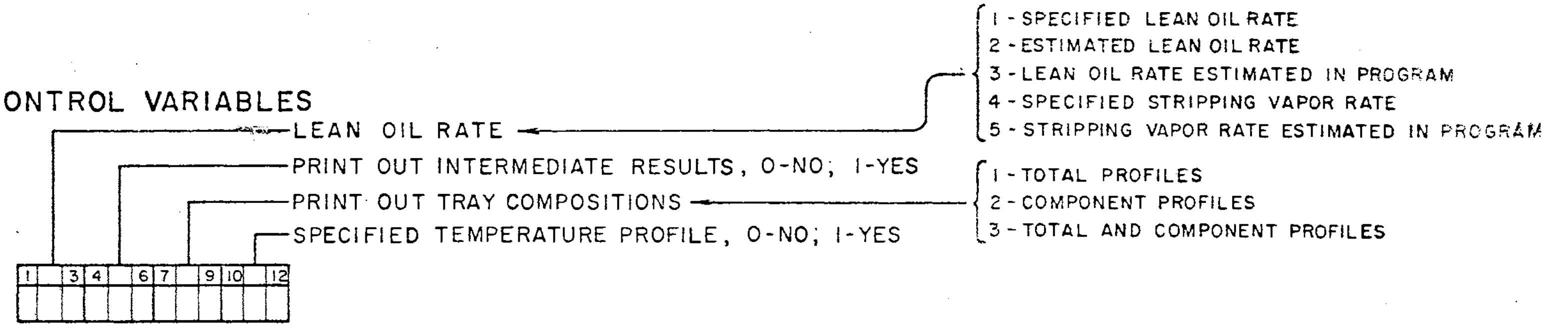
PROBLEM IDENTIFICATION



COLUMN VARIABLES


NUMBER OF TRAYS
NUMBER OF COMPONENTS
NUMBER OF FEEDS
NUMBER OF LIQUID SIDE STREAMS
NUMBER OF VAPOR SIDE STREAMS
NUMBER OF INTERCOOLERS
COLUMN PRESSURE (PSIA)

CONTROL VARIABLES


LEAN OIL RATE
- 1 - SPECIFIED LEAN OIL RATE
- 2 - ESTIMATED LEAN OIL RATE
- 3 - LEAN OIL RATE ESTIMATED IN PROGRAM
- 4 - SPECIFIED STRIPPING VAPOR RATE
- 5 - STRIPPING VAPOR RATE ESTIMATED IN PROGRAM

PRINT OUT INTERMEDIATE RESULTS, 0-NO; 1-YES

PRINT OUT TRAY COMPOSITIONS
- 1 - TOTAL PROFILES
- 2 - COMPONENT PROFILES
- 3 - TOTAL AND COMPONENT PROFILES

SPECIFIED TEMPERATURE PROFILE, 0-NO; 1-YES

ABSORBER PROGRAM
INPUT DATA SHEET

PROJECT NO. ____
NAME ____
DATE ____
PAGE ____ OF ____ PAGES ____

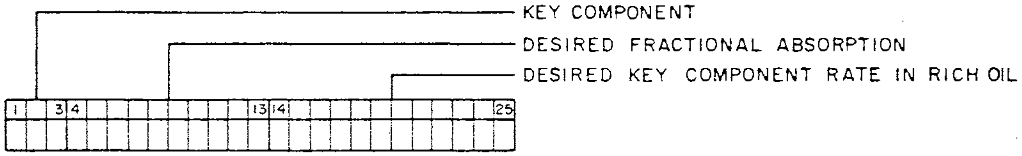
COMPONENT IDENTIFICATION

1 10 11 20 21 30 31 40 41 50 51 60

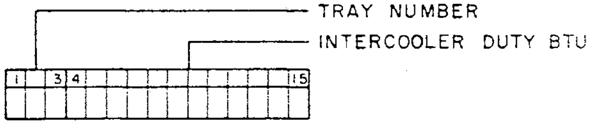
ABSORBER PROGRAM
INPUT DATA SHEET

PROJECT NO. ____________________
NAME ____________________
DATE ____________________
PAGE ______ OF ____ PAGES ________

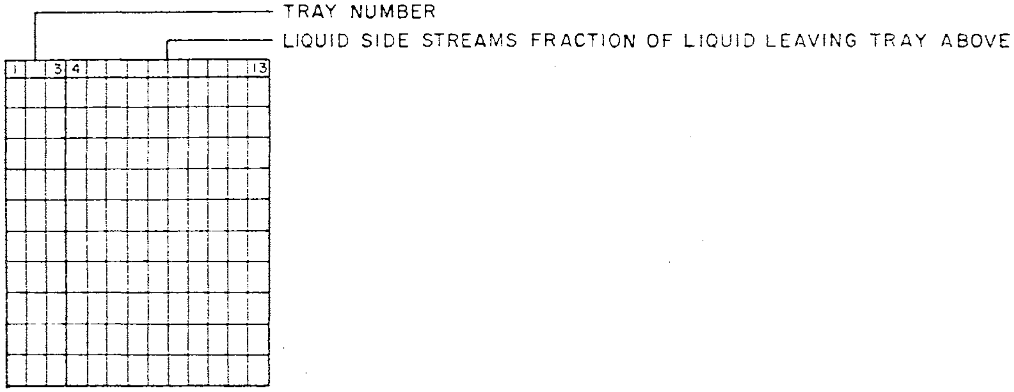
ABSORPTION VARIABLES



INTERCOOLER DATA



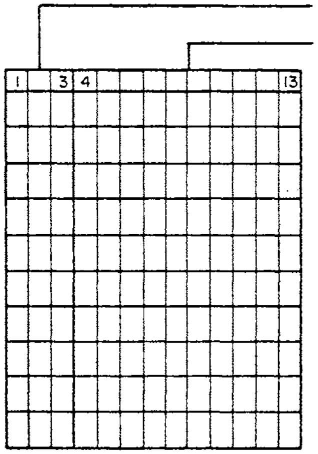
LIQUID SIDE STREAMS



ABSORBER PROGRAM
INPUT DATA SHEET

PROJECT NO.____________________
NAME__________________________
DATE__________________________
PAGE_____OF____PAGES__________

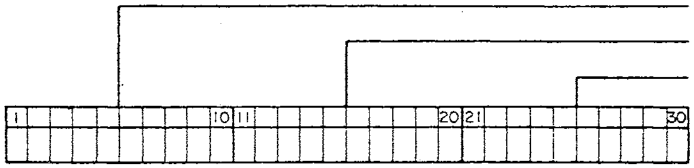
VAPOR SIDE STREAMS



TRAY

VAPOR SIDE STREAM FRACTION VAPOR LEAVING TRAY BELOW

CONVERGENCE LIMITS



HEAT BALANCE CONVERGENCE LIMIT

MATERIAL BALANCE LIMIT

LEAN OIL RATE LIMIT

ABSORBER PROGRAM
INPUT DATA SHEET

PROJECT NO. ____________
NAME ____________
DATE ____________
PAGE ______ OF ____ PAGES ____________

EQUILIBRIUM CONSTANT COEFFICIENTS

A	B	C	D
1 14	15 28	29 42	43 56

ABSORBER PROGRAM
INPUT DATA SHEET

PROJECT NO.____________________
NAME____________________
DATE____________________
PAGE______OF_____PAGES__________

VAPOR PHASE ENTHALPY

A	B	C
1 … 12	13 … 24	25 … 36

ABSORBER PROGRAM
INPUT DATA SHEET

PROJECT NO.____________________
NAME____________________
DATE____________________
PAGE______OF____PAGES__________

LIQUID PHASE ENTHALPY

A	B	C
12	13 24	25 36

ABSORBER PROGRAM
INPUT DATA SHEET

PROJECT NO.________________
NAME________________
DATE________________
PAGE_____OF____PAGES________

FEED VARIABLES

TRAY NUMBER
CONDITION OF FEED
TEMPERATURE
L/F RATIO
ENTHALPY

1 3 4 6 7 16 17 26 27 38

FEED RATES

1 2 3 4 5 6
1 12 13 24 25 36 37 48 49 60 61 72

7 8 9 10 11 12

13 14 15 16 17 18

19 20 21 22 23 24

25 26 27 28 29 30

ABSORBER PROGRAM
INPUT DATA SHEET

PROJECT NO.________ ____________
NAME________________________
DATE________________________
PAGE______ OF_____ PAGES__________

TEMPERATURE LIMITS

MAXIMUM TEMPERATURE
MINIMUM TEMPERATURE

1									10	11									20

VITA

Robert Ray Spear

Candidate for the Degree of

Master of Science

Thesis: AN EVALUATION OF THE SUJATA ABSORPTION CALCULATION METHOD

Major Field: Chemical Engineering

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Personal Data: Born in Pueblo, Colorado, May 14, 1942, the son of Daryl J. and Ruby E. Spear.

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