A COMPUTER PROGRAM FOR THE

DESIGN OF PACKED EXTRACTION COLUMNS


BY

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# ABSTRACT

A computer program for the design of packed extraction columns has been developed.  This program can operate with a minimum of data of the type that can easily be determined or estimated.  The program can be used to investigate design alternates during the preparation of project cost estimates and for the final design of extraction columns.

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# INTRODUCTION

The objective of the work summarized in this presentation
is the development of a computer program for the design of a
packed extraction column. A computer program was developed,
since the calculations necessary for the specification of a packed
extraction column are lengthy and tedious, especially if a number
of design parameters must be estimated and if alternative designs
are investigated. The program developed will simplify the investi-
gation of design alternates and will allow the study of the effect of
variations in the basic parameters on column design.

Much work has been done on the development of calculation
procedures for the design of packed columns. Treybal (13) has
summarized these and suggested which equations are the most
useful. He has also reviewed the empirical and theoretical
correlations for the estimation of the parameters needed in the
design equations, if these parameters have not been determined
experimentally. The equations and calculation methods given in
his book are the basis for the work presented in the section
covering the development of the design equations, pages 5 to 43.

Calculation procedures for the estimation of the following

parameters have been included:

1. The equilibrium slope; equations (1) to (35), pages 6 to 10.

2. The extract diffusion coefficient; equation (85), page 30.

3. The mass transfer coefficient for the extract; equations (86) and (87), page 35.

4. The raffinate diffusion coefficient; equation (84), page 30.

5. The mass transfer coefficient for the raffinate; equations (91) to (93), page 36.

The equations used for calculations are based on three major assumptions. The first of which is that a ternary system is involved. The second is that the two solutions associated with the ternary are dilute. The third and final assumption is that the extract is the dispersed phase.

The computer program developed, allows the design of a column from the data input shown in Table 15, page 116 The allowed variations in the type of input are given in the discussion of data input on pages 47 to 50.

The program calculates a column design for solvent flows of 1.2 to 3.0 times the minimum solvent rate, in increments of 0.2. This is done for each packing size greater than the critical packing size and gives ten runs for each size of packing. A typical computer print out for 0.75 inch Raschig Rings is given in Table 10, page 111.

In addition to the development of a computer program, several runs were made to determine the effect of parameters such as solvent rate, etc., on column design. The results of these runs are discussed in detail on pages 55 to 58, and are plotted in Figures (6) through (14), pages 96 to 104.

The major conclusions reached from the above runs were:

1. For a given ratio of extract to raffinate flow, the height of a transfer unit and the number of transfer units are independent of packing size.

2. The tower cost drops off rapidly, with increasing ratios of extract to raffinate flows, until the ratio of extract flow to minimum extract flow is 1.6; then

the cost begins to level. Therefore, ratios larger than 1.6, should not be used for design purposes.

3. Variations in raffinate viscosity and the mutual solubility of the extracting solvent and raffinate solvent have no significant effect on column design.

4. The column cost decreases with decreasing solvent viscosity or interfacial tension.

5. The column cost also decreases with increasing density difference between the extract and raffinate phases.

# EQUATION DEVELOPMENT

The equations used for design calculations can be divided into three categories; equations developed by Treybal (13); equations developed from correlations presented by Treybal in the form of a graph, and equations derived by the author for use in the program.

No attempt will be made to derive the equations suggested by Treybal, since their derivations are presented in his book. However, the limitations placed on the design program by the assumptions made in their derivations will be detailed.

The major equations developed for use in the design program include the equations for the conversion of concentration to a weight fraction basis from a mole fraction basis (equations (36)-(37), page 10); the equation for the determination of the minimum solvent rate (equation (41), page 13); the equation for the calculation of the extract composition (equation (49), page 14), and the equations for the calculation of the cost of a packed extraction column (equations (104)-(111), pages 40 to 42).

## Estimation of Distribution Coefficient

The first value to be determined is the distribution co-efficient. If the distribution coefficient for the ternary system under study has not been determined experimentally, it can be estimated from the mutual solubility data for the three binary pairs of the ternary mixture. First, equations (1) through (27) are used to calculate the constants for the two suffix van laar equations (14) of activity coefficients, for each of the binary pairs.

The following equations are used for the calculation a-b binary constants.

$$Y_1 = x_{aa1}/x_{ba} + x_{ab}/x_{bb1} \tag{1}$$

$$Y_2 = Log(x_{ab}/x_{aa1})/Log(x_{ba}/x_{bb1}) \tag{2}$$

$$Y_3 = 2 x_{aa1} x_{ab} Log(x_{ab}/x_{aa1}) \tag{3}$$

$$Y_4 = x_{ba} x_{bb1} Log(x_{ba}/x_{bb1}) \tag{4}$$

$$\frac{A_{ab}}{A_{ba}} = (Y_1 Y_2 - 2)/(Y_1 - Y_3/Y_4) \tag{5}$$

$$Y_5 = Log(x_{ab}/x_{aa1}) \tag{6}$$

$$Y_6 = (1 + (A_{ab} \, x_{aa_1} / A_{ba} \, x_{ba}))^2 \tag{7}$$

$$Y_7 = (1 + (A_{ab} x_{ab} / A_{ba} \, x_{bb_1}))^2 \tag{8}$$

$$A_{ab} = Y_5 / (1/Y_6 - 1/Y_7) \tag{9}$$

The equations for the b-c binary constants are obtained by applying the rotation principle, i.e., substituting b for a and c for b, in equations (1) through (9).

$$Y_8 = x_{bb_2} / x_{cb} + x_{bc} / x_{cc_1} \tag{10}$$

$$Y_9 = \mathrm{Log}(x_{bc} / x_{bb_2}) / \mathrm{Log}(x_{cb} / x_{cc_1}) \tag{11}$$

$$Y_{10} = 2 \, x_{bb_2} x_{bc} \, \mathrm{Log}(x_{bc} / x_{bb_2}) \tag{12}$$

$$Y_{11} = x_{cb} \, x_{cc_1} \, \mathrm{Log}(x_{cb} / x_{cc_1}) \tag{13}$$

$$\frac{A_{bc}}{A_{cb}} = (Y_8 Y_9 - 2) / (Y_8 - Y_{10}/Y_{11}) \tag{14}$$

$$Y_{12} = \mathrm{Log}(x_{bc} / x_{bb_2}) \tag{15}$$

$$Y_{13} = (1 + (A_{bc} \, x_{bb_2} / A_{cb} \, x_{cb}))^2 \tag{16}$$

$$Y_{14} = (1 + (A_{bc} \, x_{bc} / A_{cb} \, x_{cc_1}))^2 \tag{17}$$

$$A_{bc} = Y_{12} / (1/Y_{13} - 1/Y_{14}) \tag{18}$$

The equations for the a-c binary constants are obtained by substituting c for a and b for c, in equations (10 through (18).

$$Y_{15} = x_{cc2} / x_{ac} + x_{ca} / x_{aa2} \tag{19}$$

$$Y_{16} = Log(x_{ca}/x_{cc2}) \; Log(x_{ac}/x_{aa2}) \tag{20}$$

$$Y_{17} = 2 \; x_{cc2} x_{ca} \; Log(x_{ca}/x_{cc2}) \tag{21}$$

$$Y_{18} = x_{ac} \; x_{aa2} \; Log(x_{ca}/x_{aa2}) \tag{22}$$

$$\frac{A_{ca}}{A_{ac}} = (Y_{15} \; Y_{16} \; -2)/(Y_{15} - \; Y_{17}/Y_{18}) \tag{23}$$

$$Y_{19} = Log \; (x_{ca}/x_{cc2}) \tag{24}$$

$$Y_{20} = (1 + (A_{ca} \; x_{cc2} \; /A_{ac} \; x_{ac}))^2 \tag{25}$$

$$Y_{21} = (1 + (A_{ca} \; x_{ca}/A_{ac} \; x_{aa2}))^2 \tag{26}$$

$$A_{ca} = Y_{19} \; /(1/Y_{20} \; - 1/Y_{21}) \tag{27}$$

Once the binary constants are determined, they are sub-stituted into equations 28 through 32. These equations are used because of the length of the ternary Van Laar equation (equation (33)) for the solute activity coefficient, given by Treybal [15].

$$Y_{22} = x_a \; A_{ca} \; (A_{ac}/A_{ca})^2 \tag{28}$$

$$Y_{23} = x_b \; A_{cb} \; (A_{bc}/A_{cb})^2 \tag{29}$$

$$Y_{24} = x_a \; x_b \; (A_{ac}/A_{ca}) \; (A_{bc}/A_{cb}) \tag{30}$$

$$Y_{25} = A_{ca} + A_{cb} - A_{ba} (A_{cb}/A_{bc}) \tag{31}$$

$$Y_{26} = (x_c + x_a (A_{ac}/A_{ca}) + x_b (A_{bc}/A_{cb}))^2 \tag{32}$$

$$\text{Log } \gamma_c = (Y_{22} + Y_{23} + Y_{24} + Y_{25})/Y_{26} \tag{33}$$

Treybal has shown (16) that, if dilute solutions are assumed, equation (33) and the mutual solubility data for the a-b binary can be used to calculate the distribution coefficient (m'). The assumption of dilute solutions is the basis for the equations used in the design program.

If the solute concentration $(x_c)$ is set equal to zero, the mutual solubility data for the a-rich layer of the a-b binary can then be substituted into equation (33) and $\text{Log } \gamma_{ca}$ calculated. The substitution of the data for the b-rich layer will give $\text{Log } \gamma_{cb}$. Equation (34) below is then used to calculate the distribution co-efficient.

$$m' = 10^{(\text{Log } \gamma_{ca} - \text{Log } \gamma_{cb})} \tag{34}$$

The distribution coefficient calculated using (34) is on a mole fraction basis. Since all the calculations performed in the design program are on a weight fraction basis, the distribution co-efficient must be converted to that basis. This is accomplished

simply if it can be assumed that extract solvent (b-component)

and the raffinate solvent (a-component) are relatively insoluble.

This is a valid assumption for most industrial systems since, if

a significant solubility exists, a more expensive recovery system

would be required. The following equation is used to convert the

distribution coefficient calculated from equation (34) on the pre-

ceding page to a weight fraction basis (4).

$$m = m' \ M_a/M_b \tag{35}$$

## Calculation of the Minimum Solvent Rate

Before the minimum solvent rate is calculated, the mole

fractions of the components of the feed and solvent have to be

converted to a weight fraction basis. Equation (36) will be used

for the extract concentration and equation (37) for the raffinate

concentration.

$$X_{ce} = x_{ce} M_c / (x_{ce} M_c \ (1 - x_{ce}) \ M_b) \tag{36}$$

$$X_{cr} = x_{cr} M_c / (x_{cr} M_c \ (1 - x_{cr}) \ M_a) \tag{37}$$

Another check is necessary before proceeding with the solvent

calculations, since it is possible that the solvent proposed for a given

extraction process may already contain the solute it is desired

to recover. As an absolute minimum, the solute concentration

in the solvent should not be in equilibrium with the raffinate from

the column. This will be checked with the following equation.

$$X_{ce_2} \lesseqgtr m \; X_{cr_2} \qquad (37A)$$

The minimum solvent rate must be determined, before the

operating ratio of solvent to feed $(E_2 / R_2)$ can be fixed. The

operating line of Figure 1, page 12, gives the following material

balance.

$$R_2 \; (X_{cr_1} - X_{cr_2}) = E_2 \; (X_{ce_1} - X_{ce_2}) \qquad (38)$$

Since dilute solutions are assumed, the extract flow $(E_2)$

and the feed to the column $(R_2)$ can be used without causing a

significant error. Both $R_2$ and $E_2$ do not vary appreciably

throughout the column. $R_2$ and $E_2$ are also used, since the

transfer units are normally concentrated at the dilute end. The

slope of the operating line can be described as

$$R_2 / E_2 = (X_{ce_1} - X_{ce_2}) / (X_{cr_1} - X_{cr_2}) \qquad (39)$$

# FIGURE 1

## OPERATING DIAGRAM FOR
## CONTINUOUS COUNTERCURRENT EXTRACTION
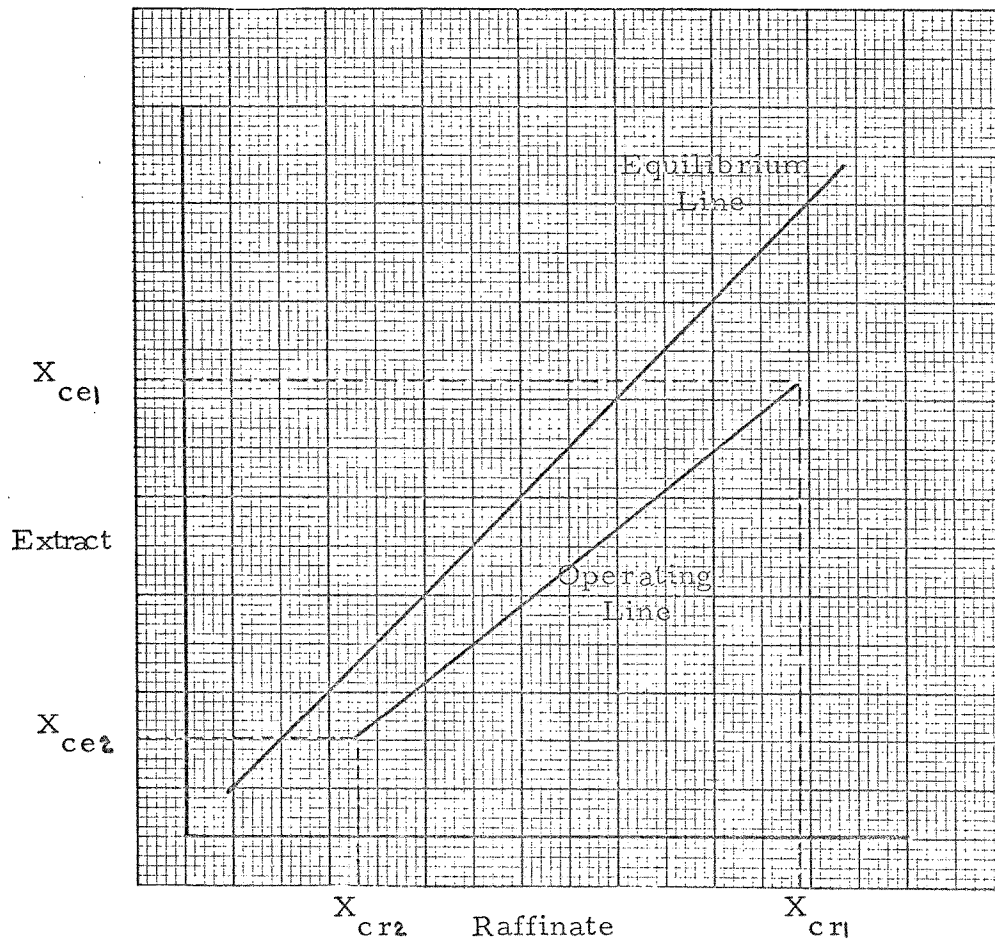
The minimum solvent rate occurs when the operating line intersects the equilibrium line (see Figure 1, page 12). This determines the minimum solvent rate since at this point the extract flow from the column is in equilibrium with the feed. The following then holds.

$$X_{ce_1} = m X_{cr_1} \tag{40}$$

Equations (39) and (40) are combined to give the equation for the minimum solvent rate.

$$(E_2)_{min} = R_2 / ((m X_{cr_1} - X_{ce_2}) / (X_{cr_1} - X_{cr_2})) \tag{41}$$

Calculation of Extract and Raffinate Rates

Once the minimum solvent rate has been determined, the ratio of actual extract flow to minimum extract flow $(G_1)$ can be determined. A column would actually be designed for a flow greater than the minimum. The design program will investigate designs for ratios of 1.2 to 3.0 times the minimum. The ratio is described by

$$G_1 = E_2 / (E_2)_{min} \tag{42}$$

The operating ratio of extract to raffinate (P) is then given by

$$P = G_1 \ (E_2)_{min} \ / \ R_2 \qquad (43)$$

The raffinate flow from the column ($R_2$) is calculated by,

$$R_2 = R_1 \ - \ (X_{cr_1} - X_{cr_2})R_1 \qquad (44)$$

while the solvent feed ($E_2$) and extract ($E_1$) rates can be calculated from

$$E_2 = R_2 \, P \qquad (45)$$

$$E_1 = E_2 + R_1 \ (X_{cr_1} - X_{cr_2}) \qquad (46)$$

Also, once the solvent flow to the column has been calculated, the concentration of the extract leaving the column ($X_{ce_1}$) can be determined by

$$Y_{27} = R_1 \ (X_{cr_1} - X_{cr_2}) + R_2 \ P \ X_{ce_2} \qquad (47)$$

$$Y_{28} = R_1 \ (X_{cr_1} - X_{cr_2}) + R_2 \ P \qquad (48)$$

$$X_{ce_1} = Y_{27} / Y_{28} \qquad (49)$$

The next step in the calculations will be the determination of the critical packing size.

## Critical Packing Size

For each combination of feed and extracting solvent, there exists a minimum packing diameter or critical packing size (19). For Raschig Rings and Berl Saddles, the following equation holds.

$$d_{fc} = 0.24 \ (\sigma / \Delta \rho)^{0.5} \tag{50}$$

Treybal (19), recommends that the packing size selected be greater than critical packing diameter $(d_{fc})$, since for packing diameters equal to or less than $d_{fc}$ the mean drop diameter $d_p$ of the dispersed phase droplets is dependent upon dispersed phase flow rate. The design program will calculate a column design for the packing sizes greater than $d_{fc}$ up to a packing diameter of 3.0 inch.

## Dispersed Phase Hold-up and Flooding Velocities

There are two related criteria to be concerned with when determining the diameter of a packed extraction column. The

first concerns dispersed phase hold-up ($\phi_d$) and the second

column flooding. Treybal (20) has indicated that for packing

sizes greater than $d_{fc}$ the diameter of the dispersed phase

droplets is relatively independent of the dispersed phase flow

rates. The dispersed phase hold-up increases linearly with

flow rate, up to transition point where droplets begin to

coalesce and hold-up begins to increase sharply. For design

purposes, it is necessary that the dispersed phase hold-up be

less than that at transition since efficient mass transfer cannot

occur when the dispersed phase droplets coalesce. For packed

columns, the hold-up at transition is given by (21),

$$\phi_{dt} = (((P_1)^2 + 8P_1)^{0.5} - 3P_1)/4(1-P_1) \tag{51}$$

The ratio of volumetric flow rates ($P_1$) in equation (51)

above is calculated from

$$(V_r)_{av} = (R_1 + R_2)/ 2\rho_r \tag{52}$$

$$(V_e)_{av} = (E_1 + E_2)/ 2\rho_e \tag{53}$$

$$P_1 = (V_e)_{av}/(V_r)_{av} \tag{54}$$

Many correlations are available for the calculation of flooding velocities. Treybal (22) recommends two correlations for flooding calculations, with one being specific for cases where the continuous phase is water. The second correlation (3) which does not have this restriction will be used and is presented in Figure 2, page 18. The equations below represent the coordinates of Figure 2.

FA = Flooding Abscissa

$$= (V_{rf}^{0.5} + V_{ef}^{0.5})^2 \; \rho_r / \; a_f \, \mu_r \tag{55}$$

FO = Flooding Ordinate

$$= (28,700/\rho_r)^{0.2} \; (2.42 \, \mu_r / \rho_r - \rho_e) \; (a_f/\varepsilon)^{1.5} \tag{56}$$

The curved line of the original correlation was approximated by two straight lines, for which equations have been developed. Since Figure 2 is plotted on log-log paper, it is of the form

$$y = a \, x^b \tag{57}$$

FIGURE 2

FLOODING IN A PACKED TOWER (3)



Flooding Abscissa
(equation (55))
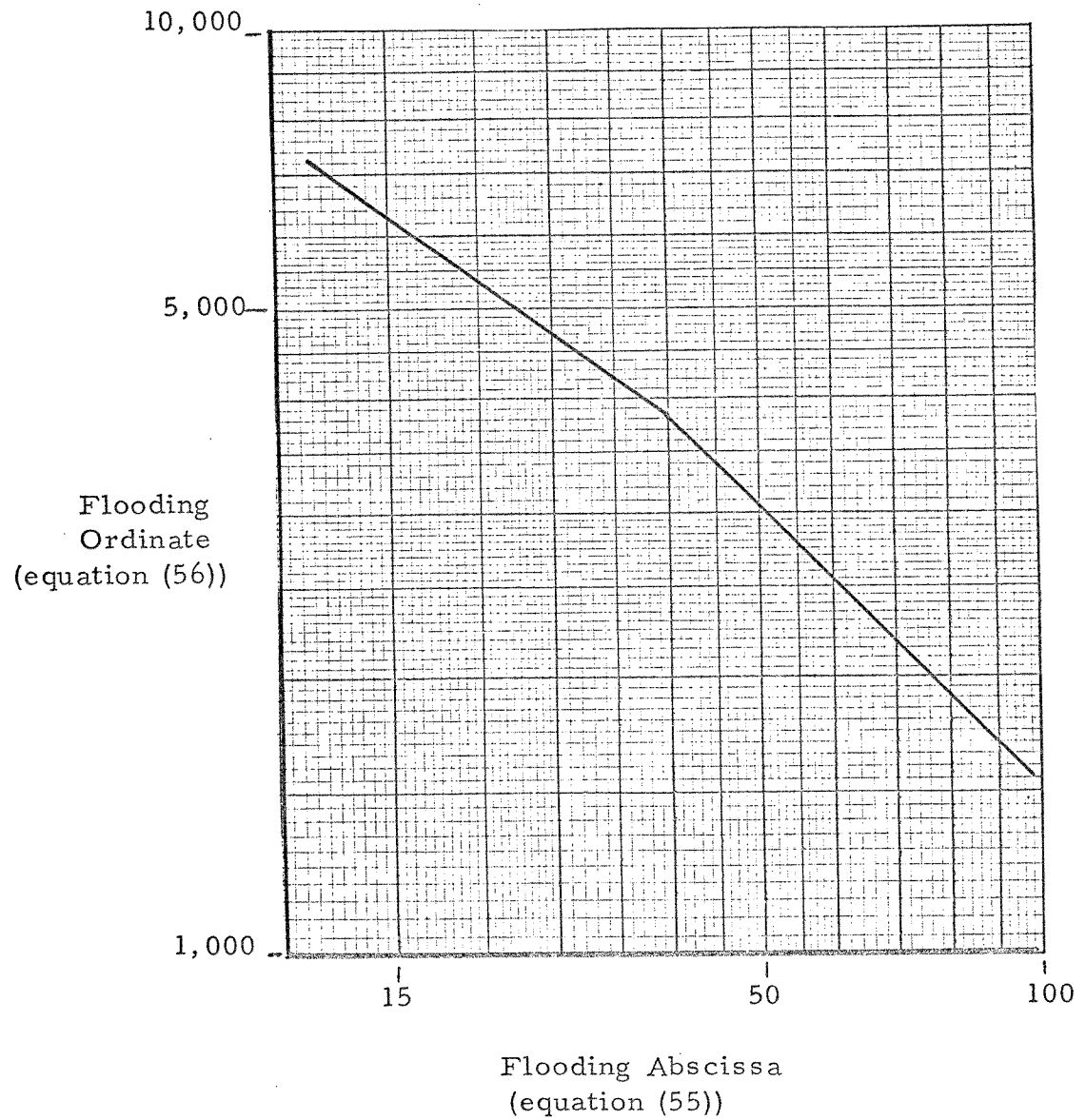
The slope (b) and the y intercept (a) were calculated and the equations rearranged to give

$$FA = (140,000/FO)^{1.02} \quad \text{for } 160 \leqq FO \leqq 3,800 \tag{58}$$

$$FA = (54,000/FO)^{1.39} \quad \text{for } 3,800 < FO \leqq 54,000 \tag{59}$$

Since the ratio of the flow rates of the raffinate and extract at flooding must equal the ratio of volumetric rates calculated in equation (54), the following relationship of flooding velocities holds

$$P_1 = V_{ef}/V_{rf} \tag{60}$$

Equation (55) and equation (60) were combined and rearranged to give the equation used for calculating the raffinate flooding velocity.

$$V_{rf} = (2.42 \, a_f \mu_r (FA))/(1 + (P_1)^{0.5})^2 \, \rho_r \tag{61}$$

The extract flooding rate can be calculated from

$$V_{ef} = V_{rf} P_1 \tag{62}$$

The calculation method used is as follows:

(a)  FO is calculated from equation (56).

(b)  FA is calculated from equation (58) or

equation (59).

(c)  The raffinate flooding velocity $V_{rf}$ is

calculated from equation (61).

(d)  The extract flooding velocity $V_{ef}$ is then

calculated from equation (62).

Once the flooding rates and the dispersed phase hold-up at

transition have been determined, the calculation of tower diameter

can proceed.

## Calculation of Tower Diameter

Before the tower diameter can be calculated, design bases

must be established.  The design criteria to be established con-

cern the allowable limits for both the dispersed phase hold-up and

superficial velocities of the raffinate and extract.

The upper limit of dispersed phase hold-up has already been

determined and is the hold-up at transition (equation (51).  The

lower limit will be set arbitrarily at $\phi_d = 0.05$.

The extract superficial velocity will be set at between 45 and 60 percent of the extract flooding rate. The only limitation on the raffinate velocity will be that it be less than 60 percent of flooding. Design velocities for extraction columns are generally set lower than those for absorption towers, since the correlations for mass transfer in extraction columns are not as highly developed as those for absorption. The lower operating velocities will allow for design inaccuracies.

The method of calculation will be as follows:

(a) To start with, a dispersed phase hold-up of $\phi_d$ = 0.15 will be assumed.

(b) The superficial velocities for extract $(V_e)$ and raffinate $(V_r)$ will then be computed and compared to the limits set above.

(c) The dispersed phase hold-up will be increased, if $V_e$ and $V_r$ are too small, or decreased, if $V_e$ and $V_r$ are too large, in increments of 0.1.

(d) The superficial velocities will then be calculated again.

This procedure will be repeated until $V_e$ and $V_r$ are within the

prescribed range. The dispersed phase hold-up values will also be limited to the range of variation previously set up for it. The detailed calculation procedures for the superficial velocities will be covered next.

Since the superficial velocities for the extract and raffinate must be in the same ratio ($P_i$ ) as the volumetric flow rates given by equation (54). The following then holds

$$P_i = V_e / V_r \tag{63}$$

For values of dispersed phase hold-up less than that at transition the following relationship (23) holds

$$V_k (1 - \phi_d) = V_e / \varepsilon \, \phi_d + V_r / \varepsilon \, (1 - \phi_d) \tag{64}$$

Where $V_k$ is defined as a limiting mean drop velocity at $V_r = 0$, for low values of $V_e$. Equations (63) and (64) can be combined to give

$$V_k / V_r = 1/(\varepsilon \, \phi_d (1 - \phi_d)) + 1/(P_i \varepsilon \, (1 - \phi_d)^2) \tag{65}$$

To simplify subsequent calculations a new ratio will be defined

as

$$P_2 = V_k / V_e \tag{66}$$

Once $P_2$ has been calculated, the mean drop diameter can

be calculated from (24),

$$d_p = 0.00762(\sigma'/\rho_r - \rho_e)^{0.5} \ (P_2 \varepsilon \ \phi_d) \tag{67}$$

Next the dimensionless value $P_3$ (25) will be calculated from

$$P_3 = 1644(\rho_r)^2 \ (\sigma')^3 / (\mu_r)^4 \ (\rho_r - \rho_e) \tag{68}$$

The terminal drop velocity $(V_t)$ will be determined next.

Treybal recommends using the Hu-Kintner (6) correlation for

the calculation of $V_t$, which is then used to calculate the

characteristic drop velocity $(V_k)$. Once $V_k$ has been calculated,

the superficial velocities can then be calculated from equations (66)

and (63) since $P_2$ and $P_1$ are known.

The correlation for $V_t$ is the log-log plot shown in Figure 3,

page 25. The curve of the original correlation can be approxi-

mated by three straight lines, without causing significant

calculation errors.   The ordinate of Figure 3 is

TVO = Terminal Velocity Ordinate

$$= 19,400 \ (\rho_r - \rho_e) \ d_p^2 \ (P_3)^{0.15}/\sigma'$$

(69)

TVA = Terminal Velocity Abscissa

$$= V_t \ d_p \ \rho_r \ / \ 2.42 \mu_r \ (P_3)^{0.15}$$

(70)

The value of TVO calculated from equation (69) is then substituted

into the appropriate equation developed from the correlation given

in Figure 3, page 25.   These equations are

$$TVA = 0.26 \ (TVO)^{1.25} \quad \text{for} \quad 3.0 \leqq TVO \lt 7.2$$

(71)

$$TVA = 0.6 \ (TVO)^{0.8} \quad \text{for} \quad 7.2 \leqq TVO \lt 78.0$$

(72)

$$TVA = 3.4 \ (TVO)^{0.424} \quad \text{for} \quad 78.0 \leqq TVO \leqq 1000.0$$

(73)

Equation (70) can be rearranged and solved for $V_t$, which gives

$$V_t = 2.42 \ (TVA) \mu_r \ (P_3)^{0.15}/d_p \ \rho_r$$

(74)

FIGURE 3

TERMINAL VELOCITY CORRELATION FOR
LIQUID DROPS (6)



Terminal Velocity Abscissa
(equation (70))
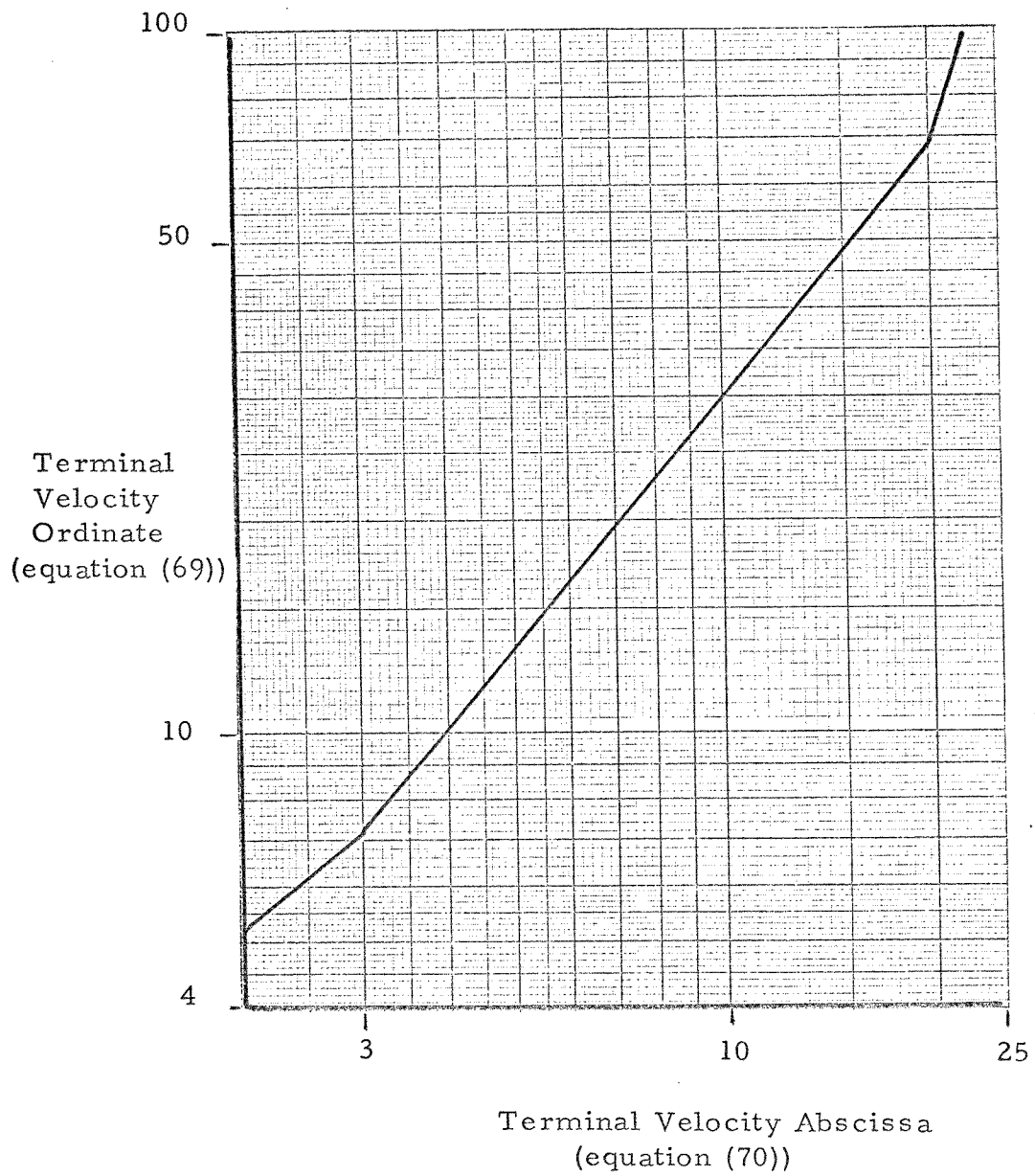
The value of TVA calculated is then substituted into equation

(74) and $V_t$ calculated.

Once the terminal drop velocity ($V_t$) has been calculated,

the characteristic drop velocity ($V_k$) can be calculated. This

is accomplished by means of the correlation (4) presented in

Figure 4, page 28. The slightly curved line of the original

correlation can be represented by a straight line, without any

significant error. The ordinate of Figure 4 is given by,

$$Y_{29} = 4.18 \times 10^8 \ (\rho_r - \rho_e)/\rho_e \ V_t^2 \tag{75}$$

$$Y_{30} = (0.38 \ d_f - 7.62 \times 10^{-3})(\sigma'/\rho_r - \rho_e)^{0.5} \tag{76}$$

$$V_k 0 = Y_{29} \ Y_{30} \tag{77}$$

While the abscissa is given by,

$$V_k A = (V_k/V_t) \ (1 - e^{-7.2T}) \tag{78}$$

For packed tower diameters (T) greater than 0.5 ft; the term

$(1 - e^{-7.2T})$ in equation (78), can be neglected. Equation (78)

then becomes

$$V_k A = V_k / V_t \tag{79}$$

The correlation given in Figure 4, page 28, is in the form
of a semi-logarithmetic plot which is described by

$$y = a e^{cx} \tag{80}$$

The correlation given in Figure 4, when put in the form of
equation (80) gives

$$V_k A = \ln( V_k 0 / 0.028 ) / 6.42 \tag{81}$$

The value of $V_k 0$ calculated from equation (77) is then substituted
into equation (81) for calculation of $V_k A$. Equation (79) can be
rearranged to give

$$V_k = V_t (V_k A) \tag{82}$$

$V_k A$ is then substituted into equation (82) and $V_k$ calculated.

Once the characteristic drop velocity ($V_k$) has been calculated,
the extract superficial velocity ($V_e$) and the raffinate superficial

FIGURE 4

CHARACTERISTIC DROP VELOCITIES
FOR PACKINGS (4)



$V_k 0$
(equation (77))

$V_k A$
(equation (78))
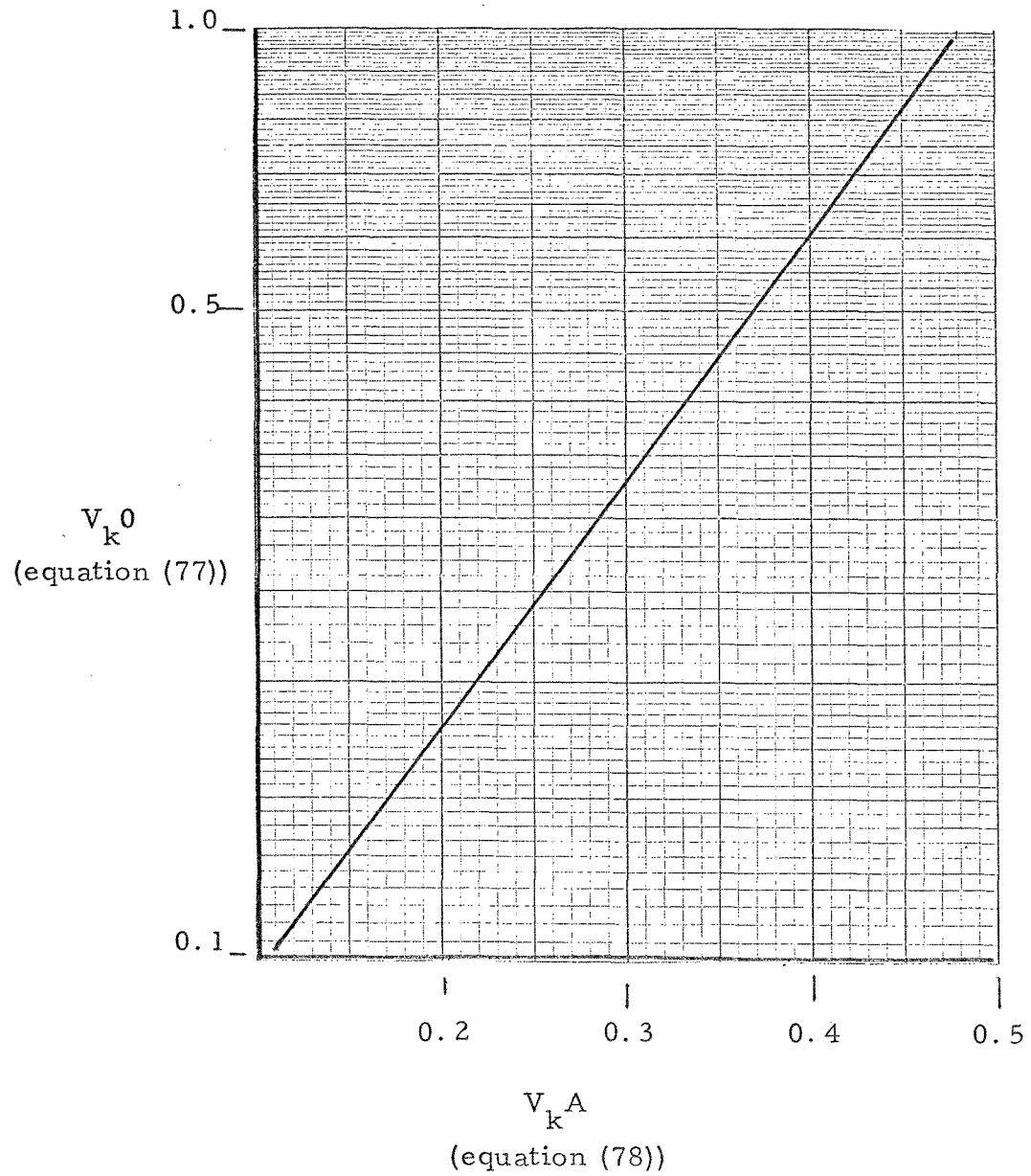
velocity $(V_r)$ can be calculated from

$$V_e = V_k / P_2 \tag{83}$$

$$V_r = V_e / P_1 \tag{84}$$

Where $P_2$ is calculated from equation (66), page 23, and $P_1$ is calculated from equation (54), page 16, the superficial velocities calculated are then compared to the flooding velocities to see if they are within the previously prescribed limits (see page 20). If they are not, the dispersed phase hold-up ( $\phi_d$) value is adjusted and the superficial values recalculated. This process is repeated until the superficial velocities are within the prescribed range. The above, as stated before, is subject to the limits set on the dispersed phase hold-up ( $0.05 \leq \phi_d < \phi_{dt}$).

Estimation of Diffusion Coefficient

Once the tower diameter has been calculated, the next variable to be determined is the height of packing required. In order to do this, the extract phase and raffinate phase mass transfer coefficients $(k_e, k_r)$ must be calculated. Before the

mass transfer coefficients can be determined, the diffusion

coefficient for the solute in the raffinate ($D_{cr}$) and the diffusion

coefficient for the solute in the extract ($D_{ce}$) must be calculated.

Theoretical approaches to the problem of calculating

diffusion coefficients have not succeeded, so Treybal (26)

recommends the use of the following empirical correlation

developed by Wilke and Chang (34, 35).

$$D_{ab} = 7.4 \times 10^{-8} \ (\psi M_b)^{0.5} \ T_1 / \mu \ (V_a)^{0.6} \tag{83}$$

The above gives diffusivities with units of sq cm/sec, which

must be converted to the English system. After conversion to

the English system and a change of subscripts to conform to

previous usage, the diffusivity of the solute in the raffinate is

given by

$$D_{cr} = 2.87 \times 10^{-7} \ (\psi_a M_a)^{0.5} \ T_1 / \mu_r \ V_c^{0.6} \tag{84}$$

The diffusivity of the solute in the extract is then

$$D_{ce} = 2.87 \times 10^{-7} \ (\psi_b M_b)^{0.5} \ T_1 / \mu_e \ V_c^{0.6} \tag{85}$$

The solvent association factor ($\psi$) used in equation (84) and (85) can be found from Table 1, page 32. The molal volume ($V_c$) of the solute may be estimated by using Kopp's Law. This law states that the molal volume of a molecule at its normal boiling point is equal to the sum of the atomic volumes of its constituents. Table 2, page 33, is a list of atomic volumes and Table 3, page 34, is a list of molecular volumes. Both tables are used for the estimation of the solute molecular volumes.

Equations (84) and (85) may only be used for dilute solutions of solute, which is one of the basic assumptions of the design program. In addition, they cannot be used for solutions of electrolytes; where a chemical reaction occurs, or where complexes are formed.

Once the diffusion coefficients are estimated, the calculation of the mass transfer coefficient can proceed.

## Calculation of Height of Dispersed Phase Transfer Unit

Treybal (27) recommends two correlations for the calculation of dispersed phase mass transfer coefficients, with the

## TABLE 1

## SOLVENT ASSOCIATION FACTORS ($\varphi$)

| ($\varphi$) | Solvent |
| --- | --- |
| 2.6 | Water |
| 1.9 | Methyl Alcohol |
| 1.5 | Ethyl Alcohol |
| 1.0 | Benzene |
| 1.0 | Ethyl Ether |
| 1.0 | Heptane |
| 1.0 | For unassociated solvents such as Benzene, etc. |

## TABLE 2

## ATOMIC VOLUMES FOR COMPLEX MOLECULES

|  | Atomic Volume |  | Atomic Volume |
|---|---|---|---|
| Bromine | 27.0 | Nitrogen, in secondary amines | 12.0 |
| Carbon | 14.8 | Oxygen (except as noted below) | 7.4 |
| Chlorine | 24.6 | Oxygen, in methyl esters | 9.1 |
| Hydrogen | 3.7 | Oxygen, in methyl ethers | 9.9 |
| Iodine | 37.0 | Oxygen, in higher ethers and esters | 11.0 |
| Nitrogen, double bonded | 15.6 | Oxygen, in acids | 12.0 |
| Nitrogen, in primary amines | 10.5 | Sulfur | 25.6 |

| | |
|---|---|
| For three-membered ring, as in ethylene oxide, deduct | 0.6 |
| For four-membered ring, as in cyclobutane, deduct | 8.5 |
| For five-membered ring, as in furan, thiophene, deduct | 11.5 |
| For pyridine, deduct | 15 |
| For benzene ring, deduct | 15 |
| For naphthalene ring, deduct | 30 |
| For anthracene ring, deduct | 47.5 |

## TABLE 3

## MOLECULAR VOLUMES FOR SIMPLE SUBSTANCES

| Substance | Molecular Volume | Substance | Molecular Volume |
|-----------|------------------|-----------|------------------|
| $H_2$ | 14.3 | $N_2O$ | 36.4 |
| $O_2$ | 25.6 | $NH_3$ | 25.8 |
| $N_2$ | 31.2 | $H_2O$ | 18.9 |
| Air | 29.9 | $H_2S$ | 32.9 |
| CO | 30.7 | COS | 51.5 |
| $CO_2$ | 34.0 | $Cl_2$ | 48.4 |
| $SO_2$ | 44.8 | $Br_2$ | 53.2 |
| NO | 23.6 | $I_2$ | 71.5 |
| $D_2O$* | 20.0 | | |

*Estimated Value

basis for choosing between the two being the diameter of the

dispersed phase droplets $(d_p)$. For values of $d_p$ greater than

the transition size for terminal velocity $(d_{pt})$, the correlation

of Handlos and Barron (5) will be used, with the substitution

of $V_k (1 - \phi_d)$ for $V_t$.

$$k_e = 0.00375 \, V_k \, (1 - \phi_d)/(1 + \mu_e/\mu_r) \tag{86}$$

For values of $d_p \langle d_{pt}$, the correlation of Spells (12) will be used,

where

$$k_e = 17.9 \, D_{ce}/d_p \tag{87}$$

In order to use equations (86) and (87), the transition drop

size $(d_{pt})$ must be calculated. The following equation suggested

by Treybal (28) will be used for calculation of $d_{pt}$.

$$d_{pt} = 0.006 \, (\sigma'/(\rho_r - \rho_e) \, P_3^{0.15})^{0.5} \tag{88}$$

Before the height of the dispersed phase transfer unit can

be calculated, the interfacial liquid surface associated with free

hold-up must be calculated from (29),

$$a = 6 \varepsilon \, \phi_d/d_p \tag{89}$$

The height of a dispersed phase transfer unit is then calculated from (30, 10),

$$H_{te} = V_e / k_e \, a \tag{90}$$

## Calculation of Height of Continuous Phase Transfer Unit

For the calculation of the continuous phase mass transfer coefficient, Treybal (31) recommends the following correlation of Ruby and Elgin (11), with $V_k \, (1 - \phi_d)$ replacing $V_s$.

$$Y_{31} = (d_p \, (1 - \phi_d) \, \rho_r / 2.42 \mu_r)^{-0.43} \tag{91}$$

$$Y_{32} = (2.42 \, \mu_r / \rho_r \, D_{cr})^{-0.58} \tag{92}$$

$$k_r = 0.725 \, (Y_{31}) \, (Y_{32}) \, V_k \, (1 - \phi_d)^2 \tag{93}$$

The height of a continuous phase transfer unit is then calculated from (30, 10) the following

$$H_{tr} = V_r / k_r \, a \tag{94}$$

Once the raffinate and extract mass transfer coefficient are

determined, the height of an overall transfer unit can be
calculated.

## Calculation of Height of Overall Transfer Unit

The equation used for the calculation of the height of an
overall transfer unit depends on which resistance is controlling,
either the continuous or dispersed phase. In cases where the
dispersed phase resistance is controlling, or $H_{te} < H_{tr}$, the
following is used.

$$H_{toe} = H_{te} + (m \, V_e / V_r) \, H_{tr} \qquad (95)$$

Conversely, in cases where the continuous phase resistance is
controlling, or $H_{tr} < H_{te}$, the following is used.

$$H_{tor} = H_{tr} + (V_r / m \, V_e) \, H_{te} \qquad (96)$$

No attempt has been made to correct equations (95) and
(96) for axial mixing, since both Treybal (30) and Li and
Ziegler (7) concur on the fact; that while a great deal of work
has been done on axial mixing, no useful design correlations have
been developed. Because of this, no attempt has been made to

correct the height of an overall transfer unit for axial mixing.

## Calculation of the Number of Overall Transfer Units

Since the assumption of dilute solutions has been made, the number of overall transfer units can be calculated directly, without performing a graphical integration. The number of transfer units based on raffinate is calculated from

$$Y_{33} = (X_{cr_1} - (X_{ce_2}/m))/(X_{cr_2} - (X_{ce_2}/m)) \qquad (97)$$

$$N_{tor} = \ln (Y_{33}(1-1/F) + 1/F)/(1-1/F) \qquad (98)$$

The number of transfer units based on the extract is calculated from

$$Y_{34} = (X_{ce_1} - mX_{cr_2})/(X_{ce_2} - mX_{cr_2}) \qquad (99)$$

$$N_{toe} = \ln (Y_{34}(1-F) + F)/(1-1/F) \qquad (100)$$

The extraction factor (F) in equations (98) and (100) is calculated from

$$F = m P \qquad (101)$$

The operating ratio of extract to raffinate flow rate (P) is
obtained from equation (43), page 14.

## Calculation of Packed Height

For cases where the dispersed phase resistance is con-
trolling, the height of packing is given by

$$HOP = H_{toe} N_{toe} \tag{102}$$

Where the continuous phase resistance is controlling the height
of packing is given by

$$HOP = H_{tor} N_{tor} \tag{103}$$

## Calculation of Packed Tower Cost

In order to compare different design alternates, the tower
cost for each alternate will be calculated. The first step is to
calculate the cost of the packing. The unit cost of the packing can
either be found in cost estimating information such as that presented
by Peters (8) or may be obtained directly from a packing manu-
facturer such as U. S. Stoneware. The packed volume (PV) is

calculated as follows.

$$PV = 0.785 \, (HOP) \, T^2 \qquad (104)$$

The packing cost (PC) is then calculated by

$$PC = PV \, (dollars/cu \, ft) \qquad (105)$$

Since the main purpose of calculating the cost of the tower is the comparison of design alternates, as to effect on column cost, some simplifying assumption concerning the tower design will be made. First, it will be assumed that the wall thickness will be 0.375 inches and that this thickness will not vary with column height. Secondly, it will be assumed that the column has flat heads. The third assumption was that items such as nozzles, hand holes, and thermowells would add ten percent to the weight of the column. The fourth assumption was the allowance of three feet of column before and after the packed section. The density · of metal used is 488 lbs per cu ft. The weight of the heads is calculated as follows

$$Heads \, (lbs) = No. \, Heads \times Thickness \times Density \times Area \times 1.1$$
$$= 26.4 \, T^2 \qquad (106)$$

The weight of the shell is calculated from

Shell (lbs) = Shell Cross Section x Column Ht. x Density x 1.1

$$= 421 \ (HOP + 6) \ ((T + 0.0313)^2 - T^2) \tag{107}$$

The weight of the column is given by

Tower Weight = TW

$$= 26.4T^2 + 421 \ (HOP + 6) \ ((T + 0.0313)^2 - T^2) \tag{108}$$

The fabrication cost of the column can be calculated from the costs presented by Peters (9). These costs are based on the year 1969. They were up-dated to a 1969 basis using the Marshall and Stevens Index as follows

$$1969 \ Cost = 1957 \ Cost \ (1969 \ Index/1957 \ Index) \tag{109}$$

$$1969 \ Cost = 1957 \ Cost \ (285/217) = 1957 \ Cost \ (1.31)$$

The cost data is plotted in Figure 5, page 42, and is in the form of a log-log plot. The equation developed from Figure 5 is

$$Fabrication \ Cost = FC = 19.1 \ TW^{0.607} \tag{110}$$

The tower cost (TC) is then calculated from

$$\text{Tower Cost} = TC = FC + PC \tag{111}$$

## FIGURE 5

### FABRICATION COST FOR
### CARBON STEEL COLUMNS (9)



Fabrication
Cost
(dollars/lb)

Tower Weight
(lbs)
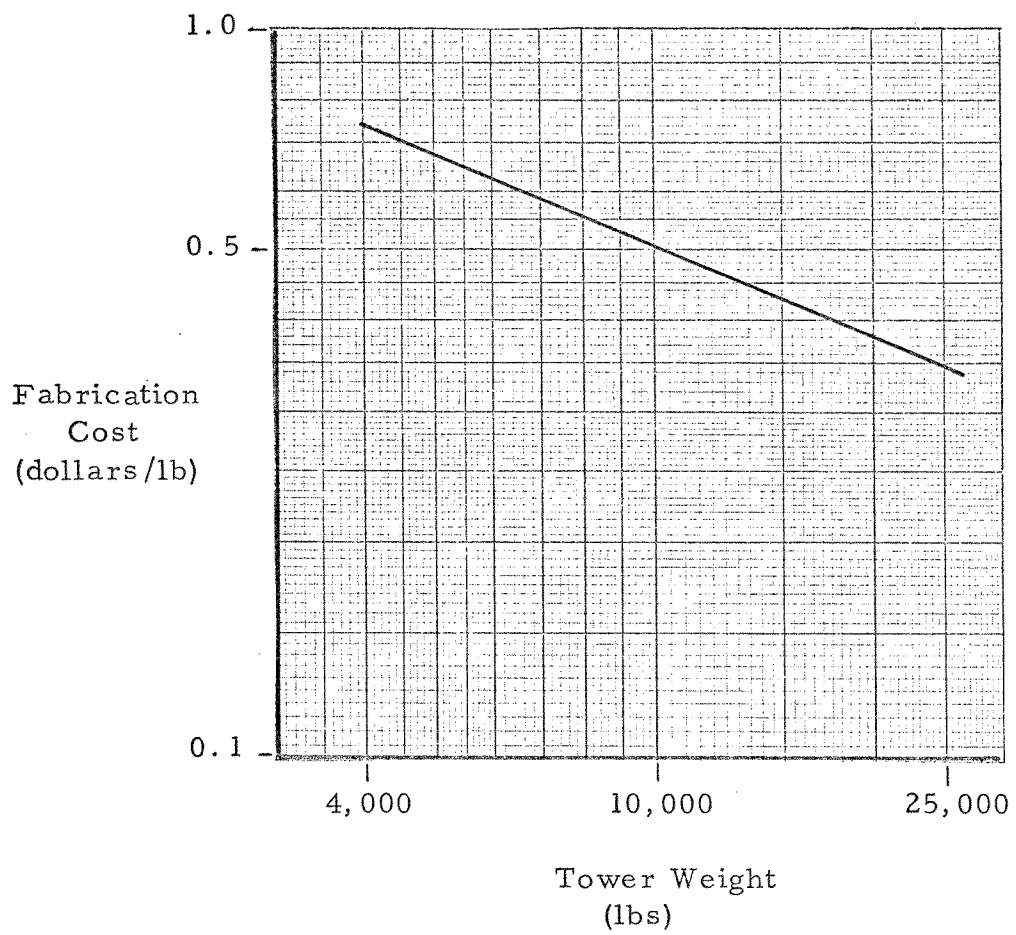
## PROGRAM ORGANIZATION

The computer program developed for the design of packed extraction columns requires a minimum of input data. This is desirable, since in the early stages of plant design, a minimum of data is available. This lack of data normally makes preliminary costs estimates highly inaccurate, since usually there is insufficient time available for the lengthy calculations associated with the estimation of the equilibrium slope and other system variables. The program can be used to calculate a column size for different extracting solvent rates, different solvents, and different packings. It will also calculate an estimated column purchase cost for each alternate.

During the latter stages of plant design more data is usually available. The program has been designed to accept this data and to by-pass the portion of the program used to estimate it. Again, different operating conditions can be investigated.

What follows is a general description of the computer program and its operation. The program organization is given in detail in Block Diagrams 1 through 21 (pages 69 to 89).

## Program Design Bases

The equations presented in the Equation Development, pages 5 to 43, have been developed into a computer program for the design of packed extraction columns. This program is coded in Fortran IV, in accordance with the Fortran IV Reference Manual (70-00-604-1; July 1968), for the Radio Corporation of America, Spectra-70, digital computer. Although the limitations of the design equation used have already been discussed during their development, they will be summarized again in order to emphasize them. These assumptions are:

1. Both the raffinate and extract solutions are considered dilute.

2. The extract phase is the dispersed phase and the raffinate the continuous phase.

3. It has been assumed that no chemical reactions occur.

4. The packing used can either be Berl Saddles or Raschig Rings.

The computer program is limited to the two packings given in (d) above, since the equation used (equation (50), page 15) for

the determination of the critical packing diameter is applicable

only to Berl Saddles and Raschig Rings.  If another type of

packing were used, the equation for the calculation of its

critical packing diameter would have to be substituted for the

one presently included in the design program.

## Program Variable Names

The definition of the variable names used in the computer

program can be found in the listing of equation and program

nomenclature given on pages 60 to 68.  The program variables are

defined in terms of the nomenclature used in the equations presented

in the section on equation development.  The definitions of the

equation variables are also given in this listing.

The basis used for the selection of the variable names was

that the name selected should represent an abbreviation of its

actual definition.  For example, the program variable name

RAFDEN represents the raffinate density.  There were two

limitations on the naming of program variables.  The first was

that the name could not be longer than six characters.  The

second was that the name of a floating point variable could not

begin with I, J, K, L, M, and N.  Thus, while a logical

abbreviation of the number of transfer units would be NTU(I),

it had to be changed to XNTU(I).

## Data Input

The format of the twelve data cards required is given in

Table 15, page 116.  The content of each card is listed in terms

of the program variable names, along with the card columns

associated to each variable.

Ten columns on each data card are assigned to each piece of

data.  The data may be punched in any position in the ten columns

allowed for it, but the position of the decimal point must be shown

correctly.

A value must be given to each of the variables given in

Table 15, with the following exceptions:

1.  If the equilibrium slope (SLOPE) is known, its value

    is punched in columns 11 - 20 of the second data card.

    The mutual solubility data for the three binaries

    associated with the ternary system under study would

not be required, so blank cards are substituted for the third, fourth, and fifth data cards. Blank data cards are required since the position of the data cards is important for correct data input.

2. If the equilibrium slope is not known, columns 11 - 20 of the second data card are left blank. The mutual solubility data for the a, b binary is then punched on the third data card; the mutual solubility data for the b, c binary on the fourth data card; and the mutual solubility data for the c, a binary on the fifth data card. The mutual solubility data is punched in columns 1 - 40 according to the format of Table 15, page 116

3. If the distribution coefficients for the solute in the raffinate (DCR) and for the solute in the extract (DCE) are known, their values are punched in columns 1 - 10 and 11 - 20, respectively, of the sixth data card. No data is then needed for the solute molal volume (VOLMOL); for the column operating temperature (OPTEMF); for the extract solvent association factor (ASSOCE); and for the raffinate association factor (ASSOCR). The data positions allocated to the above are then left blank

(see Table 15, page 116), since this data is not needed

for the estimation of the distribution coefficients.

4. If both distribution coefficients are not know, then

    columns 1 - 20 on the sixth data card are left blank.

    The data needed for the estimation of the distribution

    coefficients must then be supplied. The required data

    is listed in (3) on the preceding page and is punched in

    according to the format of Table 15.

5. If only one distribution coefficient is known, the data

    is punched in the proper position on the sixth data card.

    The solute molal volume, the column operating temperature

    and the solvent association factor, for the unknown dis-

    tribution coefficient, must be then supplied.

The program is designed to handle calculations based on one

type of packing at a time and requires packing data for six sizes

of that packing. The number of packing sizes was based on the use

of packing diameters of 0.5, 0.75, 1.0, 1.5, 2.0, and 3.0 inches.

Packing is available in other sizes, such as 0.25, 0.75, and 1.25

inches, but since these sizes are not widely used, they were not

included.

The packing data supplied for each packing diameter (PD(J)) are the void fraction (PE(J)); the surface area (PA(J)); the density of the packing (PDEN(J)); and the cost of the packing (PCOST1(J)). This data is punched on the seventh through twelfth data cards, according to the format of Table 15, page 116. The packing data is punched in order of increasing size starting with the data for the 0.5 inch packing punched on the seventh data card.

If packing data is not available for six sizes of packing, the specification for the DO loop given in statement 93, page 91, must be changed. The statement now reads, DO 14 J=1, 6, 1; so that the number six would be changed to reflect the number of packing sizes available.

Program Operation

The general sequence of calculations follows that presented in the equation development portion of this presentation (pages 5 to 43). The following variable limits are maintained during the program operation:

1. The value of the dispersed phase hold-up must be equal

to or greater than 0.05 and less than the hold-up at

transition, as calculated by equation (51), page 16.

2.   The superficial raffinate velocity must be equal to

or less than 60 percent of its flooding velocity.

3.   The superficial extract velocity must be equal to or

greater than 45 percent of its flooding velocity.   Also,

the extract velocity must be less than or equal to 60

percent of its flooding velocity.

The first section of the program, statement numbers 23 to

102 (pages 90 to 92), calculates the variable values which are fixed

for each run;  such as the equilibrium slope (SLOPE 1) and the

raffinate flow from the column (R2).   The calculation of the

variables which are subscripted and whose values change during

a given program run is accomplished by statements number 103 to

244, pages 92 to 94.

For each packing size greater than the critical packing dia-

meter (PDC), the program will design and calculate a purchase

cost for a column to handle extract flows of from 1.2 to 3.0 times

the minimum solvent flow, in increments of 0.2.   This gives a

total of ten runs for each packing diameter greater than the critical

packing diameter.

## Internal Error Checks

There are several error messages programmed into the operation of the calculation routines. These will be described now; they have been inserted to indicate problem areas which would be obvious to a person doing hand calculations, but which will cause the computer program to abort.

The first of these concerns the value of the equilibrium slope supplied to the computer. If this value is negative, the computer will print out an appropriate error message and stop the program (see Block Diagram 2, page 70). Also, if the solute concentration in the extracting solvent feed to the column is in equilibrium with the exit raffinate concentration, an error message will be printed and the program stopped (see Block Diagram 8, page 76).

An error message is also printed if the critical packing diameter (PDC) calculated is larger than any of the packing diameters in the data input to the computer. Again, the program will stop after printing an error message (see Block Diagram 9, page 77). If the flooding ordinate calculated from equation (56), page 17, is outside the range of equations (58) and (59), page 19, an error

message will be printed out, along with the value of the flooding

ordinate and the value of the major program variables calculated

up to that point (see Block Diagram 11, page 79). These values

are printed out to simplify debugging.

If the value of the terminal velocity ordinate (TVO) calculated

from equation (69), page 24, is outside the range of equations (71),

(72), and (73) an error message will be printed out (see Block Dia-

gram 13, page 81). The value of TVO and the major program

values calculated up to that point will again be printed out.

Data Output

Tables 10 through 14, pages 111 to 115, are an example of the

format for the data output. The data is punched out in the form

of two tables, for each packing diameter larger than the critical

packing diameter, with one page of output for each packing dia-

meter.

For each packing diameter, the data output is based on ex-

tracting solvent to minimum extracting solvent ratios of 1.2 to

3.0, in increments of 0.2. Ten values are then printed for each

output variable. The logical presentation of the data would have

been one table containing all the data, but, because of the number of variables printed out, two tables were set up.

The first table contains the dispersed phase hold-up; the percent of flooding for the extract; the percent of flooding for the raffinate; the ratio of actual to minimum solvent rate; and the concentration of the extract from the column. The data is presented in the above order.

The second table contains the solvent flow rate; the number of transfer units; the height of a transfer unit; the diameter of the extraction column; the height of packing required; and the estimated purchase cost for the column. Again, the data is presented in the order given above.

## CONCLUSIONS

A computer run, for data given in Table 16, page 117, was made in order to check the program operation; determine the effect of packing size and the effect of the ratio of actual to minimum solvent rates on column design. The data used is synthetic, except for the packing data for Raschig Rings, which was obtained from U.S. Stoneware Co., Bulletin TP54R, 1963.

Tables 10 through 14, pages 111 to 115, are the computer print-outs of the data for the five packing sizes larger than the critical packing size. This data is the basis for Figures 12, 13, and 14, pages 102, 103, and 104.

Figure 14 is a plot of the height of an overall transfer unit (HTU(I)) and tower diameter (T(I)), verses the packing diameter (PD(M)), for a fixed solvent to feed ratio. The height of a transfer unit and the number of transfer units do not vary with packing size, while the tower diameter decreases with packing size. The most economical choice would be the largest packing size available, since the column diameter, for a given solvent to feed ratio, decreases with packing size. Treybal has established

a minimum packing size (19) but has made no mention of the effect of increasing packing size on column design.

Figure 13, page 103, is a plot of tower cost (TCOST(I)) and tower diameter (T(I)) verses the ratio of actual to minimum solvent feed rates (G1). The tower cost drops off rapidly until G1=1.6, then the cost begins to level. Figure 12, page 102, shows that the same effect is observed on the number of transfer units, while the height of a transfer unit shows a more constant decrease with increasing solvent rates. Based on the above, the ratio of actual to minimum solvent rate should be about 1.6, since higher rates would increase solvent recovery costs without significantly decreasing the column cost. In an actual design case, an economic balance between solvent recovery costs and extraction column costs would have to be made, in order to determine the actual ratio. The above result is not unique and has been predicted (32).

A number of runs, for 1.0 inch Raschig Rings and a ratio of actual to minimum solvent rates of 1.5, were made in order to determine the effect of various parameters on column design. The basic data used is found in Table 16, page 117. The results of

these runs are given in Tables 4 through 9, pages 105 to 110. The variation of two parameters had no significant effect on column design. They are the raffinate viscosity (Table 7, page 108) and the mutual solubility between extract and raffinate phases (Table 9, page 110).

Figure 6, page 96, and Figure 7, page 97, show the effect of increasing solvent density. These figures show that as the density difference between the solvent and raffinate increases, the column cost decreases. Therefore, for a given feed, a solvent whose density is much different than the feed should be used.

Figure 8, page 98, shows the effect of solvent viscosity. Based on this plot, a solvent with a low viscosity should be used in order to lower the column cost.

Figure 9, page 99, and Figure 10, page 100, shows the effect of raffinate density on column design. The same effect as was previously noted for extract density is true. That is, the greater the density difference, the more economical the column.

Treybal has noted (33) the effect of the extract viscosity and the difference in densities between the extract and raffinate. The results obtained above agree with his recommendations for selection of a solvent.

Figure 11, page 101, gives the effect on column design of interfacial tension. As the interfacial tension increases, the extraction column cost increases. This is because the height of a transfer unit increases. Treybal (33) discusses interfacial tension, but not in terms of its effect on column design.

# RECOMMENDATIONS

One of the basic assumptions of this program is the assumption of dilute solutions. If this assumption is not made, new calculation procedures would be needed. This program could be modified to design a column where dilute solutions are not the case.

In addition to the modification mentioned above, there are many more that could be made in order to make the design program universally applicable for design. This would require a great deal more effort. The program presented herein is suitable for the design of simple ternary systems extraction columns and is a start in the development of an extraction column design program.

# APPENDIX

## EQUATION AND PROGRAM NOMENCLATURE

| SYMBOL | PROGRAM CODE | DESCRIPTION |
|---|---|---|
| $a$ | A(I) | specific interfacial area, sq ft/cu ft, of active extractor volume. |
| $a_f$ | PA(J) | surface area of packing: sq ft/cu ft. |
| $A_{ab}$ | A2AB | limit of log $\gamma_a$ as $x_a \rightarrow o$, $x_b \rightarrow 1$. |
| $A_{ba}$ | ---- | limit of log $\gamma_b$ as $x_b \rightarrow o$, $x_a \rightarrow 1$. |
| $A_{ac}$ | ---- | limit of log $\gamma_a$ as $x_a \rightarrow o$, $x_c \rightarrow 1$. |
| $A_{ca}$ | A2CA | limit of log $\gamma_c$ as $x_c \rightarrow o$, $x_a \rightarrow 1$. |
| $A_{bc}$ | A2BC | limit of log $\gamma_b$ as $x_b \rightarrow o$, $x_c \rightarrow 1$. |
| $A_{cb}$ | ---- | limit of log $\gamma_c$ as $x_c \rightarrow o$, $x_b \rightarrow 1$. |
| ---- | A1AB | $A_{ab}/A_{ba}$ |
| ---- | A1BC | $A_{bc}/A_{cb}$ |
| ---- | A1CA | $A_{ca}/A_{ac}$ |
| $D_{ce}$ | DCE | diffusivity for solute in extract: sq ft/hr. |

EQUATION AND PROGRAM NOMENCLATURE (con't)

| SYMBOL | PROGRAM CODE | DESCRIPTION |
|---|---|---|
| $D_{cr}$ | DCR | diffusivity for solute in raffinate: sq ft/hr. |
| $d_f$ | PD(J) | packing diameter: ft. |
| $d_{fc}$ | PDC | critical diameter for packing piece: ft. |
| $d_p$ | DP | mean drop diameter: ft. |
| $d_{pt}$ | DPT | mean drop diameter at transition: ft. |
| $E_1$ | E1(I) | rate of flow of extract phase from column: lbs/hr. |
| $E_2$ | E2(I) | rate of flow of extract phase to column: lbs/hr. |
| $(E_2)_{min}$ | E2MIN | minimum rate of flow of solvent: lbs/hr. |
| F | F(I) | extraction factor, $m\,E_2/R_2$, dimensionless. |
| FA | FA | flooding abscissa, Figure 2. |
| FC | FC | fabrication cost: dollars. |
| FO | FO | flooding ordinate, Figure 2. |
| $G_1$ | G1(I) | ration of actual to minimum solvent feed. |

## EQUATION AND PROGRAM NOMENCLATURE (con't)

| SYMBOL | PROGRAM CODE | DESCRIPTION |
|---|---|---|
| HOP | HOP(I) | height of packing: ft. |
| $H_{tr}$ | HTE(I) | height of continuous-phase (raffinate) transfer unit: ft. |
| $H_{te}$ | HTR(I) | height of dispersed-phase (extract) transfer unit: ft. |
| $H_{tor}$ | HTU(I) | overall height of continuous-phase (raffinate) transfer unit: ft. |
| $H_{toe}$ | HTU(I) | overall height of dispersed-phase (extract) transfer unit: ft. |
| $k_e$ | XKE | extract mass transfer coefficient: lb moles/(hr) (sq ft) (lb moles/cu ft). |
| $K_r$ | XKR | raffinate mass transfer coefficient: lb moles/(hr) (sq ft) (lb moles/cu ft). |
| $M_a$ | FEEDMW | molecular weight of major component of feed. |
| $M_b$ | SOLVMW | molecular weight of solvent. |
| $M_c$ | SOLUMW | molecular weight of solute. |
| m | SLOPE1 | equilibrium - distribution coefficient, weight fraction basis. |

EQUATION AND PROGRAM NOMENCLATURE (con't)

| SYMBOL | PROGRAM CODE | DESCRIPTION |
|---|---|---|
| $m'$ | SLOPE | equilibrium - distribution co-efficient, mole fraction basis. |
| $N_{tor}$ | XNTU(I) | number of overall transfer units based on continuous phase (raffinate). |
| $N_{toe}$ | XNTU(I) | number of overall transfer units based on dispersed phase (extract). |
| P | P(I) | operating ratio, defined by equation (43). |
| $P_1$ | P1 | ratio of volumetric flow rates, (Ve) av/(Vr) av. |
| $P_2$ | P2 | ratio, $V_k/V_e$. |
| $P_3$ | P3 | dimensionless, defined by equation (68). |
| PC | PCOST2(I) | packing cost: dollars. |
| ---- | PCOST1(J) | packing cost: dollars/cu ft. |
| PV | PV | packing volume: cu ft. |
| $R_1$ | R1 | rate of flow of raffinate phase to column: lbs/hr. |
| $R_2$ | R2 | rate of flow of raffinate phase from column: lbs/hr. |

## EQUATION AND PROGRAM NOMENCLATURE (con't)

| SYMBOL | PROGRAM CODE | DESCRIPTION |
|--------|--------------|-------------|
| T | T(I) | tower diameter: ft. |
| $T_1$ | OPTEMK | temperature: $^\circ$K. |
| ---- | OPTEMF | temperature: $^\circ$F. |
| TC | TCOST(I) | tower cost: dollars. |
| TVA | TVA | terminal velocity abscissa, Figure 3. |
| TVO | TVO | terminal velocity ordinate, Figure 3. |
| TW | TW | tower weight: lbs. |
| $V_c$ | VOLMOL | solute molal volume at normal boiling point: cu cm/g-mole. |
| $V_e$ | VE(I) | extract phase superficial velocity: ft/hr. |
| $(V_e)_{av}$ | VEAV(I) | extract phase volumetric rate: cu ft/hr. |
| $V_{ef}$ | VEF | extract phase flooding velocity: ft/hr. |
| $V_k$ | VK | characteristic velocity of drops: ft/hr. |
| $V_k A$ | VKA | characteristic drop velocity abscissa, Figure 4. |

EQUATION AND PROGRAM NOMENCLATURE (con't)

| SYMBOL | PROGRAM CODE | DESCRIPTION |
|---|---|---|
| $V_k O$ | VKO | characteristic drop velocity ordinate, Figure 4. |
| $V_r$ | VR(I) | raffinate phase superficial velocity: ft/hr. |
| $(Vr)_{av}$ | VRAV(I) | raffinate phase volumetric rate: cu ft/hr. |
| $V_{rf}$ | VRF | raffinate phase flooding velocity: ft/hr. |
| $V_t$ | VT | terminal drop velocity: ft/hr. |
| $x_{aa1}$ | XAA1 | mole fraction of component a in a rich layer, A-B binary. |
| $x_{aa2}$ | XAA2 | mole fraction of component a in a rich layer, C-A binary. |
| $x_{ab}$ | XAB | mole fraction of component a in b rich layer, A-B binary. |
| $x_{ac}$ | XAC | mole fraction of component a in c rich layer, C-A binary. |
| $x_{ba}$ | XBA | mole fraction of component b in a rich layer, A-B binary. |

## EQUATION AND PROGRAM NOMENCLATURE (con't)

| SYMBOL | PROGRAM CODE | DESCRIPTION |
|---|---|---|
| $x_{bb1}$ | XBB1 | mole fraction of component b in b rich layer, A-B binary. |
| $x_{bb2}$ | XBB2 | mole fraction of component b in b rich layer, B-C binary. |
| $x_{bc}$ | XBC | mole fraction of component b in c rich layer, B-C binary. |
| $x_{ca}$ | XCA | mole fraction of component c in a rich layer, C-A binary. |
| $x_{cb}$ | XCB | mole fraction of component c in b rich layer, B-C binary. |
| $x_{cc1}$ | XCC1 | mole fraction of component c in c rich layer, B-C binary. |
| $x_{cc2}$ | XCC2 | mole fraction of component c in c rich layer, C-A binary. |
| $x_{ce2}$ | CE2 | mole fraction of component c in solvent feed. |
| $x_{cr1}$ | CR1 | mole fraction of component c in feed. |
| $x_{cr2}$ | CR2 | mole fraction of component c in raffinate. |
| $X_{ce1}$ | XCE1(I) | weight fraction of component c in extract. |

## EQUATION AND PROGRAM NOMENCLATURE (con't)

| SYMBOL | PROGRAM CODE | DESCRIPTION |
|--------|--------------|-------------|
| $X_{ce2}$ | XCE2 | weight fraction of component c in solvent feed. |
| $X_{cr1}$ | XCR1 | weight fraction of component c in feed. |
| $X_{cr2}$ | XCR2 | weight fraction of component c in raffinate. |
| $\gamma$ | ---- | activity coefficient. |
| $\varepsilon$ | PE(J) | voids in packed section, volume fraction. |
| $\mu_e$ | EXVIS | extract viscosity: centipoise. |
| $\mu_r$ | RAFVIS | raffinate viscosity: centipoise. |
| $\rho_e$ | EXDEN | extract density: lbs/cu ft. |
| $\rho_r$ | RAFDEN | raffinate density: lbs/cu ft. |
| $\sigma$ | SURTEN | interfacial tension: dynes/cm. |
| $\phi_d$ | HOLDUP(I) | dispersed phase holdup, volume fraction void space in extractor. |
| $\psi_b$ | ASSOCE | association factor for extracting solvent. |
| $\psi_a$ | ASSOCR | association factor for feed solvent. |

# EQUATION AND PROGRAM NOMENCLATURE (con't)

## SUBSCRIPTS

a    =    major component of feed solution.

av   =    average.

b    =    extracting solvent.

c    =    solute.

d    =    dispersed phase.

e    =    extract.

e1   =    extracting solvent from column.

e2   =    extracting solvent to column.

f    =    flooding.

r    =    raffinate.

r1   =    raffinate phase to column.

r2   =    raffinate phase from column.

# BLOCK DIAGRAMS

Block Diagram 1

Block Diagram 2

Block Diagram 3

$$A1AB=(X1*X2/X3-2.0)/(X1-(X4/X5))$$

$$X6=(1.0\div(A1AB*XAA1/XBA))**2.0$$

$$X7=(1.0\div(A1AB*XAB/XBB1))**2.0$$

$$A2AB=X2/(1.0/X6-1.0/X7)$$

$$X1=XBB2/XCB+XBC/XCC1$$

$$X2=ALOG10(XBC/XBB2)$$

$$X3=ALOG10(XCB/XCC1)$$

4

5

Block Diagram 4

$$5$$

$$X4 = 2.0 * XBB2 * XBC * X2$$

$$X5 = XCB * XCC1 * X3$$

$$A1BC = (X1 * X2 / X3 - 2.0) / (X1 - (X4 / X5))$$

$$X6 = (1.0 + (A1BC * XBB2 / XCB)) ** 2.0$$

$$X7 = (1.0 + (A1BC * XBC / XCC1)) ** 2.0$$

$$A2BC = X2 / (1.0 / X6 - 1.0 / X7)$$

$$X1 = XCC2 / XAC + XCA / XAA2$$

$$X2 = ALOG10 (XCA / XCC2)$$

$$6$$

Block Diagram 5

6

X3=ALOG10(XAC/XAA2)

X4=2.0*XCC2*XCA*X2

X5=XAC*XAA2*X3

A1CA=(X1*X2/X3-2.0)/(X1-(X4/X5))

X6=(1.0+(A1CA*XCC2/XAC))**2.0

X7=(1.0+(A1CA*XCA/XAA2))**2.0

A2CA=X2/(1.0/X6-1.0/X7)

X8=(XAA1**2.0)*A2CA*(1.0/A1CA)**2.0

7

Block Diagram 6

7

X9=XBA**2.0*(1.0/A1BC)*A2BC*A1BC**2.0

X10=XAA1*XBA*(1.0/A1CA)*A1BC

X11=A2CA+(1.0/A1BC)*A2BC-(1.0/
A1AB)*A2AB*(1.0/A1BC)

X12=(XAA1*(1.0/A1CA)+XBA*A1BC)**2.0

GAMMA1=(X8+X9+X10*X11)/X12

X8=(XAB**2.0)*A2CA*(1.0/A1CA)**2.0

X9=XBB1**2.0*(1.0/A1BC)*A2BC*A1BC**2.0

X10=XAB**XBB1*(1.0/A1CA)*A1BC

8

Block Diagram 7



X12=(XAB*(1.0/A1CA)+XBB1*A1BC)**2.0

GAMMA2=(X8+X9+X10*X11)/X12

SLOPE=10.0**(GAMMA1-GAMMA2)

XCR1=(CR1*SOLUMW)/(CR1*SOLUMW+FEEDMW*(1.0-CR1))

XCR2=(CR2*SOLUMW)/(CR2*SOLUMW+FEEDMW*(1.0-CR2))

XCE2=(CE2*SOLUMW)/(CE2*SOLUMW+SOLVMW*(1.0-CE2))

SLOPE1=FEEDMW*SLOPE/SOLVMW

Block Diagram 8

Block Diagram 9



```
        ( 10 )
           |
           v
       +-------+
       | K=J   |<-------------------+
       +-------+                    |
           |                   DO J=1,6, 1
           v                        |
        /  IF  \                    |
       / (PDC-PD(J)) \  (0,+)   +-----------+
       \          /------------>| CONTINUE  |
        \        /              +-----------+
           |                         |
          (-)                        v
           |                   ( WRITE PDC )
           v                         |
   +----------------+                v
   | VRAV=(R1+R2)/  |              ( 3 )
   | (2.0*RAFDEN)   |
   +----------------+

   +-------------------------------------+
   | OPTEMK=(0.556*(OPTEMF-32.0))+273.0  |
   +-------------------------------------+
           |
           v
    ( WRITE PD(M) )<-----------------+
           |                    DO M=K, 6, 1
           v                         |
       +-------+                     |
       | G=I   |<------------+       |
       +-------+             |       |
           |            DO I=12, 30, 2
           v                 |       |
   +----------------+        |       |
   | G1 (I)=G/10.0  |        |       |
   +----------------+        |       |
           |                 |       |
           v                 v       v
        ( 11 )            ( 12 )  ( 13 )
```

Block Diagram 10

$$\boxed{\text{11}}$$

$$P\ (I)=G1(I)*E2MIN/R2$$

$$XCE1(I)=(X14+R2*P(I)*XCE2)/(X14+R2*P(I))$$

$$E2(I)=R2*P(I)$$

$$E1(I)=E2(I)+X14$$

$$VEAV(I)=(E1(I)+E2(I))/(2.0*EXDEN)$$

$$P1=VEAV(I)/VRAV$$

$$FO=((28700.0*SURTEN/RAFDEN)**0.2)*(2.42*RAFVIS/X15)*((PA(M)/PE(M))**1.5)$$

$$\boxed{\text{12}}$$

Block Diagram 11



**12**

IF
(FO-160.0) → (-)

(0, +)

IF
(3800.0-FO)

(0, +)

FA=(140000.0/FO)**
1.02

(-)

IF
(54000.0-FO) → (-)

Write
FLOODING VELOCITY
ORDINATE OUTSIDE
RANGE OF
EQUATIONS

(0, +)

FA=(54000.0/FO)**1.39

VRF(I)=(PA(M)*2.42*
RAFVIS*FA)/(((1.0+P1**0.5)
**2.0)*RAFDEN)

Write
FO

VEF(I)=VRF(I)*P1

**13**

**31**

Block Diagram 12

(24)

(13)

HOLDUP(I)=0.15

P2=(1.0/(PE(M)*HOLDUP(I)*(1.0-HOLDUP
(I))))+(1.0/(P1*PE(M)*((1.0-HOLDUP(I))**
2.0)))

DP=0.00762*((SURTEN/X15)**0.5)*
P2*PE(M)*HOLDUP(I)

P3=(1644.0*(RAFDEN**2.0)*(SURT
EN**3.0))/((RAFVIS**4.0)*X15)

TVO=19400.0*X15*DP**2.0*P3**0.15/SURTEN

IF
(TVO-1.0)

(0)          (-)

(+)

IF
(TVO-7.2)

TVA=0.26*
TVO**1.25        (-)          (0)

(+)

(15)          (14)          (16)          (17)

## Block Diagram 13

Block Diagram 14

( 18 )

↓

VKO=X16*X17

↓

VKA=(ALOG(VKO/
0.028))/6.42

↓

VK=VT*VKA

↓

VE(I)=VK/P2

↓

VR(I)=VE(I)/P1

↓

P5(I)=VE(I)*100.0/
VEF(I)

↓

P6(I)=VR(I)*100.0/
VRF(I)

↓

T(I)=1.13*(VRAV/
VR(I))**0.5

↓

( 20 )

( 19 )

↓

Write
GAMMA1,
GAMMA2

↓

Write
SLOPE1,P2,
VRAV

↓

Write
HOLDUP (I),
P1, VEAV (I)

↓

Write
TVO, DP, P3

↓

( 3 )

Block Diagram 15



20

$$HOLDTP=((((P1**2.0)+(8.0*P1)))**0.5) - 3.0*P1)/(4.0*(1.0-P1))$$

IF
(HOLDUP(I)-0.05)

(-, 0)

(+)

IF
(HOLDUP(I)-HOLDTP)

(0, +)

(-)

IF
(VE(I)-(0.6*VEF(I)))

(+)

(-, 0)

21

22

23
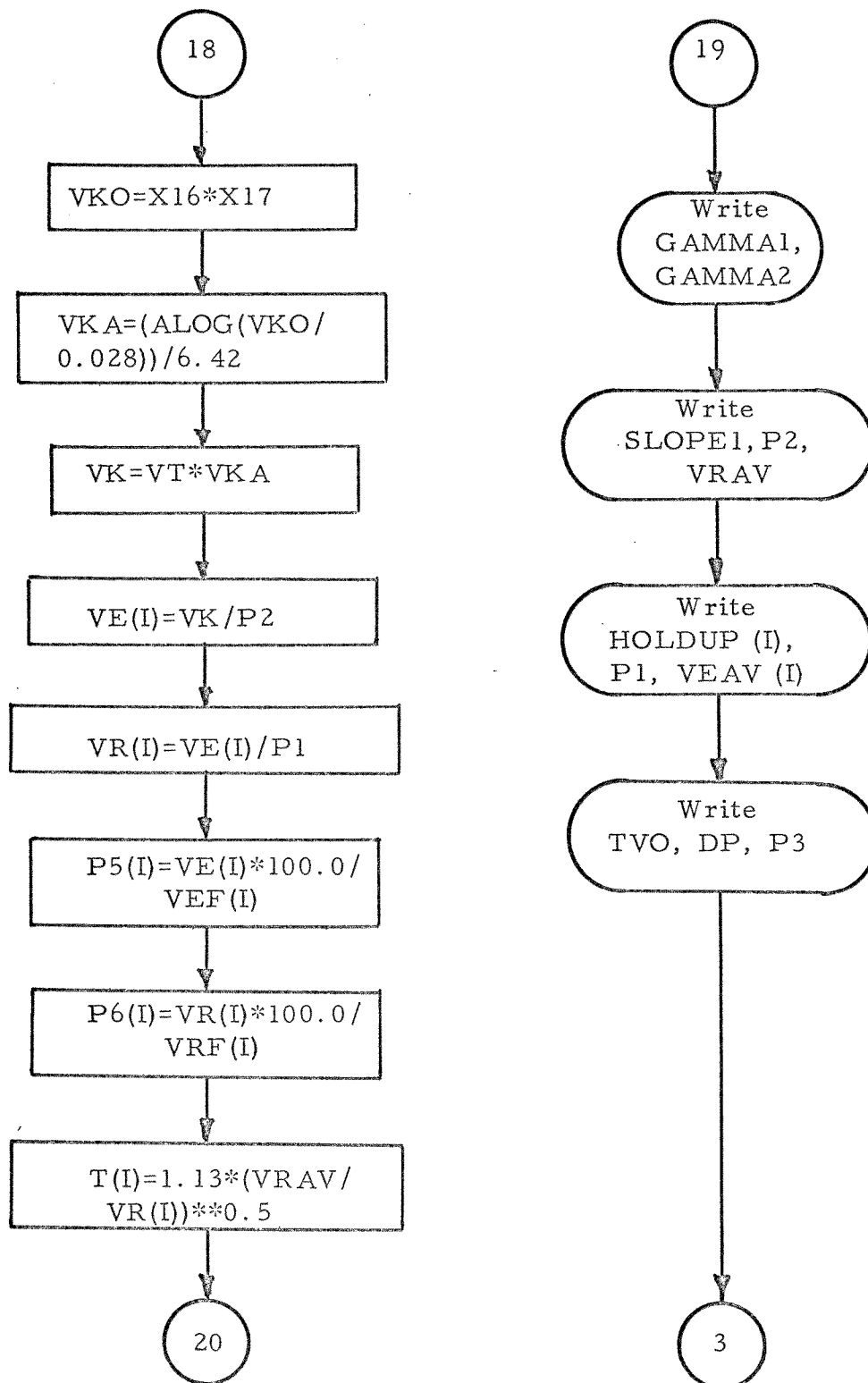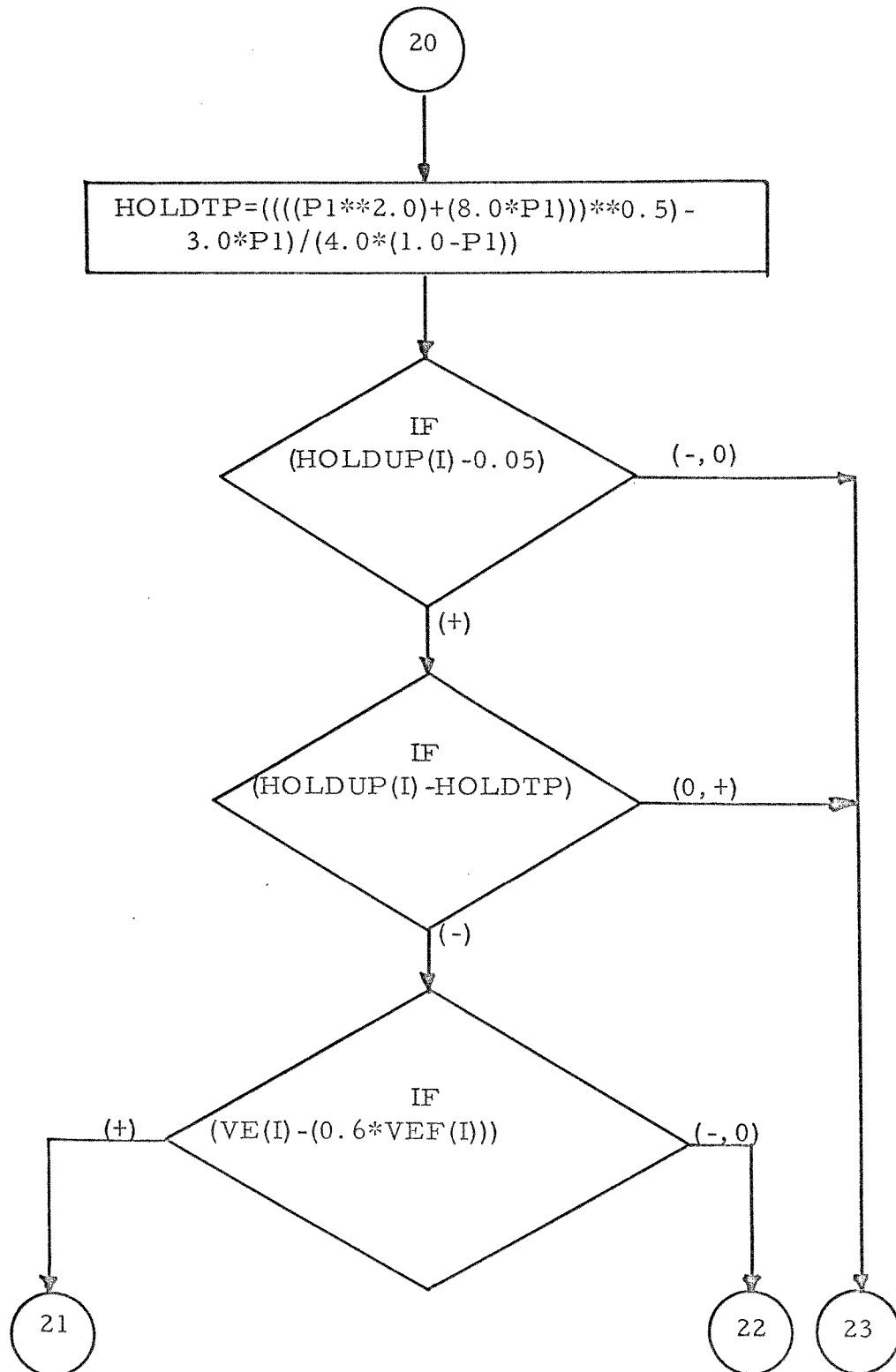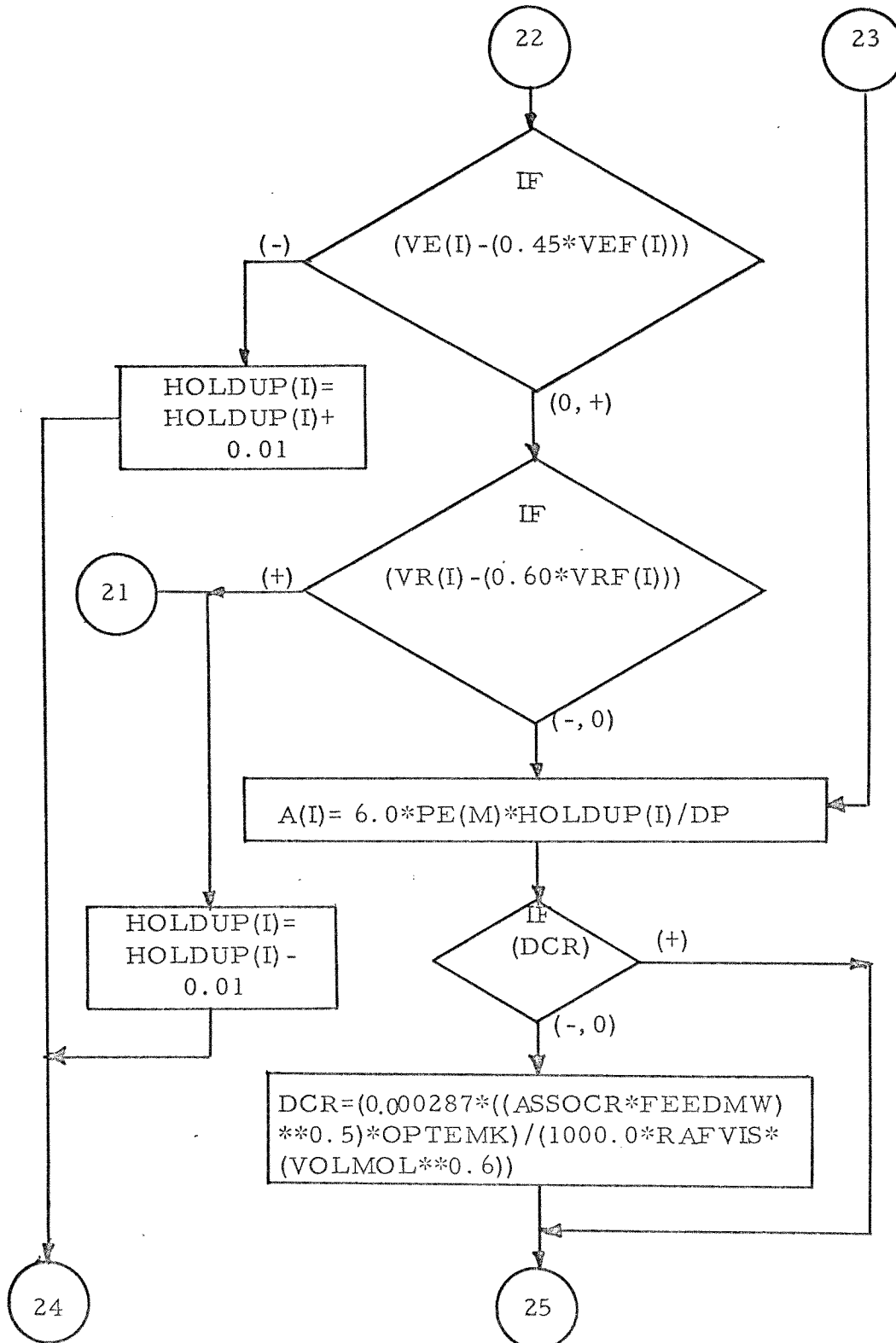
## Block Diagram 16

Block Diagram 17

Block Diagram 18

25

$$X19=((DP*(1.0-HOLDUP(I))*RAFDEN)/(2.42*RAFVIS))**0.43$$

$$X20=(2.42*RAFVIS/(RAFDEN*DCR))**0.58$$

$$XKR=(0.725*VK*(1.0-HOLDUP(I))**2.0)/(X19*X20$$

$$XKRA(I)=XKR*A(I)$$

$$HTR(I)=VR(I)*XKRA(I)$$

$$F(I)=SLOPE1*P(I)$$

IF

$(HTR(I)-HTE(I))$

(+)

(-,0)

27

28

Block Diagram 19

$$XNTU(I)=(ALOG(X13*(1.0-1.0/F(I))+1.0/F(I)))/(1.0-1.0/F(I))$$

$$HTU(I)=HTR(I)+VR(I)*HTE(I)/(SLOPE1*VE(I))$$

$$X13A=(XCE(I)-(XCR2*SLOPE1))/(XCE2-(XCR2*SLOPE1))$$

$$XNTU(I)=(ALOG(X13A*(1.0-F(I))+F(I)))/(1.0-F(I))$$

$$HTU(I)=HTE(I)+(SLOPE1*VE(I)*HTR(I)/VR(I))$$

$$HOP(I)=HTU(I)*XNTU(I)$$

$$PV=0.785*HOP(I)*T(I)**2.0$$

28

27

29

Block Diagram 20

Block Diagram 21

# PROGRAM LISTING

```
      1            PROGRAM COLDES
      2  C         DATA INPUT
      3            READ (97,1) EXVIS,RAFVIS,EXDEN,RAFDEN,SOLVMW,SOLUMS,VOLMEE
      4       1 FORMAT (7F10.0)
      5            READ (97,2) SURTEN,SLOPE,R1,OPTEMF,CR1,CR2,CE2
      6       2 FORMAT (7F10.0)
      7  C         A-B MUTUAL SOLUBILITY DATA
      8            READ (97,3) XAA1,XBA,XBB1,XAB
      9  C         B-C MUTUAL SOLUBILTY DATA
     10            READ (97,3) XBC,XCC1,XCB,XBB2
     11  C         C-A MUTUAL SOLUBILTY DATA
     12            READ (97,3) XAC,XCC2,XCA,XAA2
     13       3 FORMAT (4F10.0)
     14  C         DISTRIBUTION COEFFICIENT AND HEIGHT OF TRANSFER UNIT DATA
     15            READ (97,85) DCR,DCE,FEEDMW,ASSOCR,ASSOCE
     16      85 FORMAT (5F10.0)
     17  C         INPUT OF RASCHIG RING (OR OTHER ) PACKING DATA
     18            DIMENSION PD(10),PE(10),PA(10),PDEN(10),PCOST1(10)
     19            DO 11 J=1,6,1
     20            READ (97,12) PD(J),PE(J),PA(J),PDEN(J),PCOST1(J)
     21      12 FORMAT (5F10.0)
     22      11 CONTINUE
     23            IF (SLOPE) 4,6,7
     24       4 WRITE (99,5)
     25       5 FORMAT (21H ERROR NEGATIVE SLOPE)
     26            GO TO 64
     27  C         CALCULATION OF EQUILIBRIUM SLOPE USING TWO SUFFIX VAN LAAR EQN'S
     28  C         CALCULATION OF VAN LAAR CONSTANTS FOR A-B BINARY
     29       6 X1=XAA1/XBA+XAB/XBB1
     30            X2=ALOG10(XAB/XAA1)
     31            X3=ALOG10(XBA/XBB1)
     32            X4=2.0*XAA1*XAB*X2
     33            X5=XBA*XBB1*X3
     34            A1AB=(X1*X2/X3-2.0)/(X1-(X4/X5))
     35            X6=(1.0+(A1AB*XAA1/XBA))**2.0
     36            X7=(1.0+(A1AB*XAB/XBB1))**2.0
     37            A2AB=X2/(1.0/X6-1.0/X7)
     38  C         CALCULATION OF VAN LAAR CONSTANTS FOR B-C BINARY
     39            X1=XBB2/XCB+XBC/XCC1
     40            X2=ALOG10(XBC/XBB2)
     41            X3=ALOG10(XCB/XCC1)
     42            X4=2.0*XBB2*XBC*X2
     43            X5=XCB*XCC1*X3
     44            A1BC=(X1*X2/X3-2.0)/(X1-(X4/X5))
     45            X6=(1.0+(A1BC*XBB2/XCB))**2.0
     46            X7=(1.0+(A1BC*XBC/XCC1))**2.0
     47            A2BC=X2/(1.0/X6-1.0/X7)
     48  C         CALCULATION OF VAN LAAR CONSTANTS FOR C-A BINARY
     49            X1=XCC2/XAC+XCA/XAA2
     50            X2=ALOG10(XCA/XCC2)
```

```
FORTRAN IV024 SOURCE PROGRAM  COLDES   PROGRAM                      03/30/70   PAGE

    51          X3=ALOG10(XAC/XAA2)
    52          X4=2.0**XCC2*XCA*X2
    53          X5=XAC*XAA2*X3
    54          A1CA=(X1*X2/X3-2.0)/(X1-(X4/X5))
    55          X6=(1.0+(A1CA*XCC2/XAC))**2.0
    56          X7=(1.0+(A1CA*XCA/XAA2))**2.0
    57          A2CA=X2/(1.0/X6-1.0/X7)
    58  C       CALCULATE SOLUTE ACTIVITY COEFFICIENT IN A RICH LAYER
    59          X8=(XAA1**2.0)*A2CA*(1.0/A1CA)**2.0
    60          X9=XBA**2.0*(1.0/A1BC)*A2BC*A1BC**2.0
    61          X10=XAA1*XBA*(1.0/A1CA)*A1BC
    62          X11=A2CA+(1.0/A1BC)*A2BC-(1.0/A1AB)*A2AB*(1.0/A1BC)
    63          X12=(XAA1*(1.0/A1CA)+XBA*A1BC)**2.0
    64          GAMMA1=(X8+X9+X10*X11)/X12
    65  C       CALCULATE SOLUTE ACTIVITY COEFFICIENT IN B RICH LAYER
    66          X8=(XAB**2.0)*A2CA*(1.0/A1CA)**2.0
    67          X9=XBB1**2.0*(1.0/A1BC)*A2BC*A1BC**2.0
    68          X10=XAB*XBB1*(1.0/A1CA)*A1BC
    69          X12=(XAB*(1.0/A1CA)+XBB1*A1BC)**2.0
    70          GAMMA2=(X8+X9+X10*X11)/X12
    71  C       CALCULATION OF EQUILIBRIUM SLOPE
    72          SLOPE=10.0**(GAMMA1-GAMMA2)
    73  C       CONVERT MOLE FRACTIONS TO WEIGHT FRACTIONS
    74        7 XCR1=(CR1*SOLUMW)/(CR1*SOLUMW+FEEDMW*(1.0-CR1))
    75          XCR2=(CR2*SOLUMW)/(CR2*SOLUMW+FEEDMW*(1.0-CR2))
    76          XCE2=(CE2*SOLUMW)/(CE2*SOLUMW+SOLVMW*(1.0-CE2))
    77  C       CONVERT EQUILIBRIUM SLOPE TO WEIGHT FRACTION BASIS
    78          SLOPE1=FEEDMW*SLOPE/SOLVMW
    79  C       CHECK SOLUTE CONCENTRATION IN SOLVENT FEED
    80          IF (SLOPE1*XCR2-XCE2)8,8,10
    81        8 WRITE (99,9)
    82        9 FORMAT (50H ERROR,SOLVENT FEED IN EQUILIBRIUM WITH RAFFINATE )
    83          GO TO 64
    84  C       CALCULATION OF MINIMUM SOLVENT FEED RATE
    85       10 X14=R1*(XCR1-XCR2)
    86          R2=R1-X14
    87          E2=THERO/((SLOPE1*XCR1-XCE2)/(XCR1-XCR2))
    88          X13=(XCR1-XCE2/SLOPE1)/(XCR2-XCE2/SLOPE1)
    89  C       CALCULATION OF CRITICAL PACKING SIZE
    90          X15=ABS(RAFDEN-EXDEN)
    91          PDC=0.24*(SURTEN/X15)**0.5
    92  C       DETERMINATION OF PACKING SIZE
    93          DO 14 J=1,6,1
    94          K=J
    95          IF (PDC-PD(J))22,14,14
    96       14 CONTINUE
    97       62 WRITE (99,63) PDC
    98       63 FORMAT (43H CRITICAL PACKING DIAMETER TOO LARGE  PDC=,F10.4)
    99          GO TO 64
   100       22 VRAV=(R1+R2)/(2.0*RAFDEN)
```

```
   101 C        CONVERT OPERATING TEMPERATURE TO KELVIN SCALE
   102          OPTEMK=(0.556*(OPTEMF-32.0))+273.0
   103          DIMENSION G1(30),P(30),F(30),XNTU(30),XCE1(30),E1(30),E2(30)
   104          DIMENSION VEAV(30),VRF(30),VEF(30),HOLDUP(30),VE(30),VR(30)
   105          DIMENSION T(30),A(30),XKEA(30),HTE(30),XKRA(30),HTR(30),HTU(30)
   106          DIMENSION HOP(30),PCOST2(30),FCOST(30),TCOST(30),P5(30),P6(30)
   107          DO 67 M=K,6,1
   108          WRITE (99,49) PD(M)
   109    49 FORMAT (23H1PACKING DIAMETER (IN)=,F6.3)
   110          DO 61 I=12,30,2
   111          G=I
   112          G1(I)=G/10.0
   113          F(I)=G1(I)*F2MIN/R2
   114 C        CALCULATION OF EXIT SOLVENT CONCENTRATION
   115          XCE1(I)=(X14+R2*P(I)*XCE2)/(X14+R2*P(I))
   116 C        CALCULATION OF SOLVENT FEED RATE
   117          E2(I)=R2*P(I)
   118 C        CALCULATION OF EXTRACT FLOW RATE
   119    13 E1(I)=E2(I)+X14
   120          VEAV(I)=(E1(I)+E2(I))/(2.0*EXDEN)
   121          P1=VEAV(I)/VRAV
   122 C        CALCULATION OF FLOODING VELOCITIES
   123    33 FO=((28700.0*SURTEN/RAFDEN)**0.2)*(2.42*RAFVIS/X15)*
   124       1 ((PA(M)/PE(M))**1.5)
   125          IF (FO-160.0)19,15,15
   126    15 IF (3800.0-FO)17,16,16
   127    16 FA=(140000.0/FO)**1.02
   128          GO TO 21
   129    17 IF (54000.0-FO)19,18,18
   130    18 FA=(54000.0/FO)**1.39
   131          GO TO 21
   132    19 WRITE (99,20)
   133    20 FORMAT (54H FLOODING VELOCITY ORDINATE OUTSIDE RANGE OF EQUATIONS)
   134          WRITE (99,65) FO
   135    65 FORMAT (4H FO=,F12.1)
   136          GO TO 86
   137    21 VRF(I)=(PA(M)*2.42*RAFVIS*FA)/(((1.0+P1**0.5)**2.0)*RAFDEN)
   138          VEF(I)=VRF(I)*P1
   139 C        CALCULATION OF TOWER DIAMETER AND DISPERSED PHASE HOLDUP
   140          HOLDUP(I)=0.15
   141    39 P2=(1.0/(PE(M)*HOLDUP(I)*(1.0-HOLDUP(I))))+(1.0/(P1*PE(M))*
   142       1 ((1.0-HOLDUP(I))**2.0)))
   143 C        CALCULATION OF DROP DIAMETER(DP)
   144          DP=0.00762*((SURTEN/X15)**0.5)*P2*PE(M)*HOLDUP(I)
   145 C        CALCULATION OF TERMINAL DROP VELOCITY
   146          P3=(1644.0*(RAFDEN**2.0)*(SURTEN**3.0))/((RAFVIS**4.0)*X15)
   147          TVO=19400.0*X15*DP**2.0*P3**0.15/SURTEN
   148          IF (TVO-1.0)26,28,23
   149    23 IF (TVO-7.2)28,29,24
   150    24 IF (TVO-78.0)29,30,25
```

```
 151        25 IF (TVO-2000.0)30,30,26
 152        26 WRITE (99,27)
 153        27 FORMAT (45H TERMINAL VELOCITY OUTSIDE RANGE OF EQUATIONS)
 154        86 WRITE (99,72) A1AB,A2AB,A1BC
 155        72 FORMAT (6HOA1AB=,F10.5,6H A2AB=,F10.5,6H A1BC=,F10.5)
 156           WRITE (99,73) A2BC,A1CA,A2CA
 157        73 FORMAT (6HOA2BC=,F10.5,6H A1CA=,F10.5,6H A2CA=,F10.5)
 158           WRITE (99,74) GAMMA1,GAMMA2
 159        74 FORMAT (6HOGAMMA1=,F10.5,8H GAMMA2=,F10.5)
 160           WRITE (99,71) SLOPE1,P2,VRAV
 161        71 FORMAT (9HOSLOPE1 =,F10.5,5H P2 =,F10.4,9H VRAV   =,F8.1)
 162           WRITE (99,68) HOLDUP(I),F1,VEAV(I)
 163        68 FORMAT (11HOHOLDUP(I)=,F6.3,4H P1=,F8.3,9H VEAV(I)=,F8.1)
 164           WRITE (99,66) TVO,DP,P3
 165        66 FORMAT (5HOTVO=,F12.1,4H DP=,F14.8,4H P3=,E12.6)
 166           GO TO 64
 167        28 TVA=0.26*TVO**1.25
 168           GO TO 31
 169        29 TVA=0.6*TVO**0.8
 170           GO TO 31
 171        30 TVA=3.4*TVO**0.424
 172        31 VT=(2.42*TVA*RAFVIS*(P3**0.15))/(DP*RAFDEN)
 173 C        CALCULATION OF CHARACTERISTIC DROP VELOCITY(VK)
 174           X16=(418000000.0*X15)/(EXDEN*(VT**2.0))
 175           X17=(0.35*PD(M)/12.0)-(0.00762*(SURTEN/X15)**0.5)
 176           VKO=X16*X17
 177           VKA=(ALOG(VKO/0.023))/6.42
 178           VK=VT*VKA
 179 C        CALCULATION OF THE TOWER DIAMETER
 180           VE(I)=VK/P2
 181           VR(I)=VE(I)/P1
 182           P5(I)=VE(I)*100.0/VEF(I)
 183           P6(I)= VR(I)*100.0/VRF(I)
 184       100 T(I)=1.13*(VRAV/VR(I))**0.5
 185 C        COMPARE HOLD-UP TO HOLD-UP AT TRANSITION
 186           HOLDTP=(((P1**2.0)+(8.0*P1))**0.5)-3.0*P1)/(4.0*(1.0-P1))
 187           IF (HOLDUP(I)-0.05)40,40,84
 188        84 IF (HOLDUP(I)-HOLDTP)34,40,40
 189 C        COMPARISON OF OPERATING AND FLOODING SUPERFICIAL VELOCITIES
 190        39 IF (VE(I)-(0.60*VEF(I)))35,35,38
 191        35 IF (VE(I)-(0.45*VEF(I)))37,36,36
 192        36 IF (VR(I)-(0.60*VRF(I)))40,40,38
 193        37 HOLDUP(I)=HOLDUP(I)+0.01
 194           GO TO 39
 195        38 HOLDUP(I)=HOLDUP(I)-0.01
 196           GO TO 39
 197 C        CALCULATION OF INTERFACIAL AREA
 198        40 A(I)=6.0*PE(M)*HOLDUP(I)/DP
 199 C        CALCULATION OF DIFFUSION COEFFICIENT FOR SOLUTE IN RAFFINATE
 200           IF (OCR) 41,41,42
```

```
201      41 DCR=(0.000287*((ASSOCR*FEEDMW)**0.5)*OPTEMK)/(1000.0*RAFVIS*
202       1(VOLMOL**0.6))
203 C         CALCULATION OF DIFFUSION COEFFICIENT FOR SOLUTE IN EXTRACT
204      42 IF (DCE) 43,43,44
205      43 DCE=(0.000287*((ASSOCE*SOLVMW)**0.5)*OPTEMK)/(1000.0*EXVIS*
206       1(VOLMOL**0.6))
207 C         CALCULATION OF HEIGHT OF EXTRACT TRANSFER UNIT
208      44 DP1=0.006*(SURTEN/(X15*P3**0.15))**0.5
209         IF (DP-DP1)45,45,46
210      45 XKE=17.9*DCE/DP
211         GO TO 47
212      46 XKE=(0.00375*VK*(1.0-HOLDUP(I)))/(1.0+(EXVIS/RAFVIS))
213      47 XKEA(I)=A(I)*XKE
214         HTE(I)=VE(I)/XKEA(I)
215 C         CALCULATION OF HEIGHT OF RAFFINATE TRANSFER UNIT
216         X19=((DP*(1.0-HOLDUP(I))*RAFDEN)/(2.42*RAFVIS))**0.43
217         X20=(2.42*RAFVIS/(RAFDEN*DCR))**0.58
218         XKR=(0.725*VK*(1.0-HOLDUP(I))**2.0)/(X19*X20)
219         XKRA(I)=XKR*A(I)
220         HTR(I)=VR(I)/XKRA(I)
221 C         CALCULATION OF HEIGHT OF OVERALL TRANSFER UNIT AND PACKED HEIGHT
222 C         CALCULATION OF THE NUMBER OF TRANSFER UNITS
223         F(I)=SLOPE1*P(I)
224         IF (HTR(I)-HTE(I))90,90,91
225      90 XNTU(I)=(ALOG(X13*(1.0-1.0/F(I))+1.0/F(I)))/(1.0-1.0/F(I))
226         HTU(I)=HTR(I)+VR(I)*HTE(I)/(SLOPE1*VE(I))
227         GO TO 92
228      91 X13A=(XCE1(I)-(XCR2*SLOPE1))/(XCE2-(XCR2*SLOPE1))
229         XNTU(I)=(ALOG(X13A*(1.0-F(I))+F(I)))/(1.0-F(I))
230         HTU(I)=HTE(I)+(SLOPE1*VE(I)*HTR(I)/VR(I))
231      92 HOP(I)=HTU(I)*XNTU(I)
232 C         CALCULATION OF THE COST OF THE COLUMN
233         PV=0.785*HOP(I)*T(I)**2.0
234         PCOST2(I)=PV*PCOST1(M)
235         X21=(T(I)+0.0313)**2.0-T(I)**2.0
236         TW=26.4*T(I)**2.0+(421.0*(HOP(I)+6.0)*X21)
237         FCOST(I)=19.1*TW**0.607
238      48 TCOST(I)=PCOST2(I)+FCOST(I)
239      61 CONTINUE
240         WRITE (99,78)
241      78 FORMAT (13H0   HOLDUP  ,5X,2HP5,10X,2HP6,10X,2HG1,9X,3HXCE1)
242         DO 79 I=12,30,2
243      79 WRITE (99,80) HOLDUP(I),P5(I),P6(I),G1(I),XCE1(I)
244      80 FORMAT (1H ,3X,F6.2,7X,F5.1,7X,F5.1,7X,F4.1,7X,F9.6)
245         WRITE (99,81)
246      81 FORMAT (13H0     E2     ,4X,4HNTU ,8X,4HHTU ,8X,4HDIAM,9X,3HHOP,
247       18X,5HTCOST)
248         DO 83 I=12,30,2
249      83 WRITE (99,82) E2(I),XNTU(I),HTU(I),T(I),HOP(I),TCOST(I)
250      82 FORMAT (1H ,3X,F6.0,6X,F6.2,6X,F6.2,7X,F4.1,7X,F6.1,5X,F6.0)
```

```
251    67 CONTINUE
252    64 CONTINUE
253       STOP
254       END
```

FIGURES

FIGURE 6

EFFECT OF EXTRACT DENSITY ON COLUMN COST
AND THE HEIGHT OF A TRANSFER UNIT
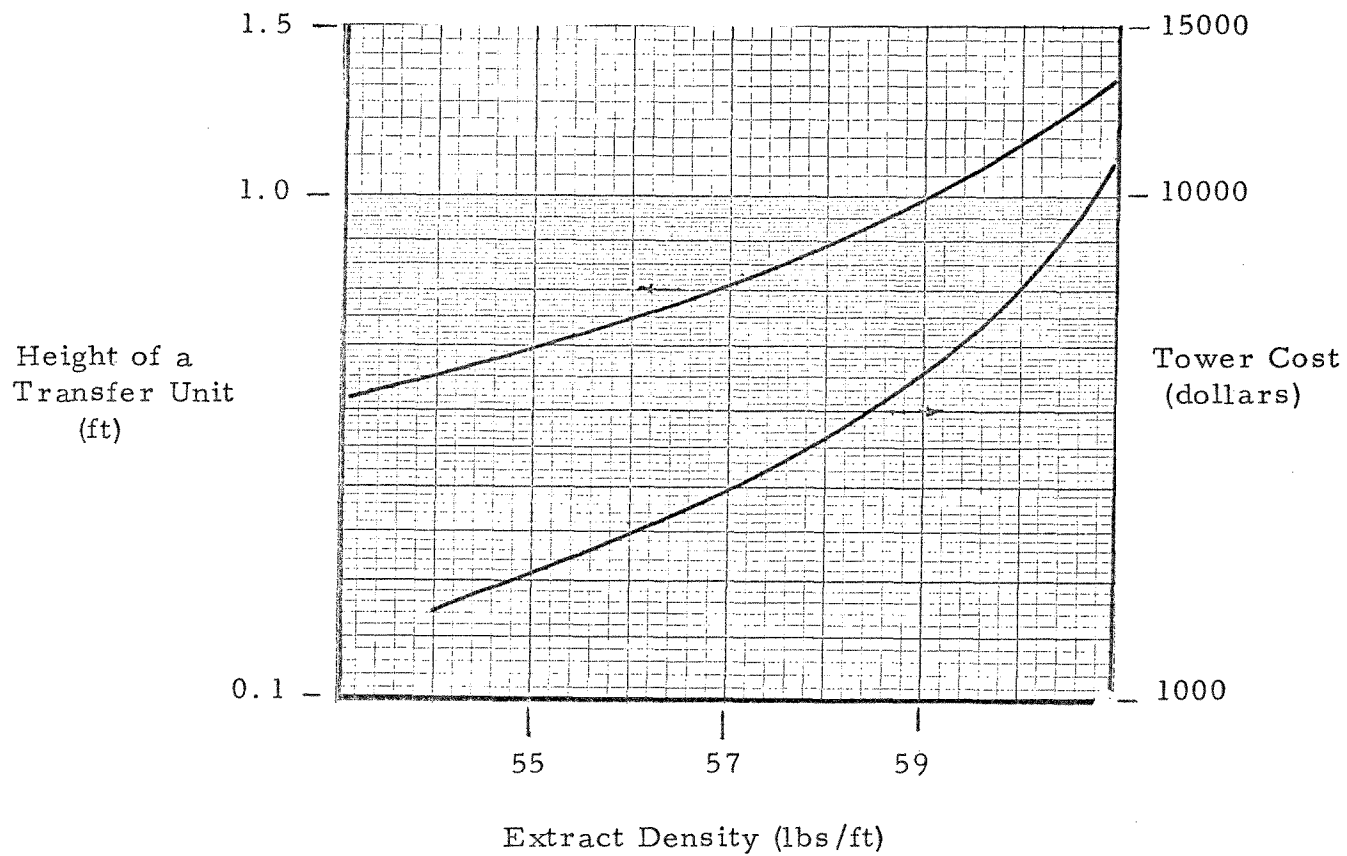
## FIGURE 7

### EFFECT OF EXTRACT DENSITY ON TOWER DIAMETER



Tower Diameter (ft) vs Extract Density (lbs/cu ft)
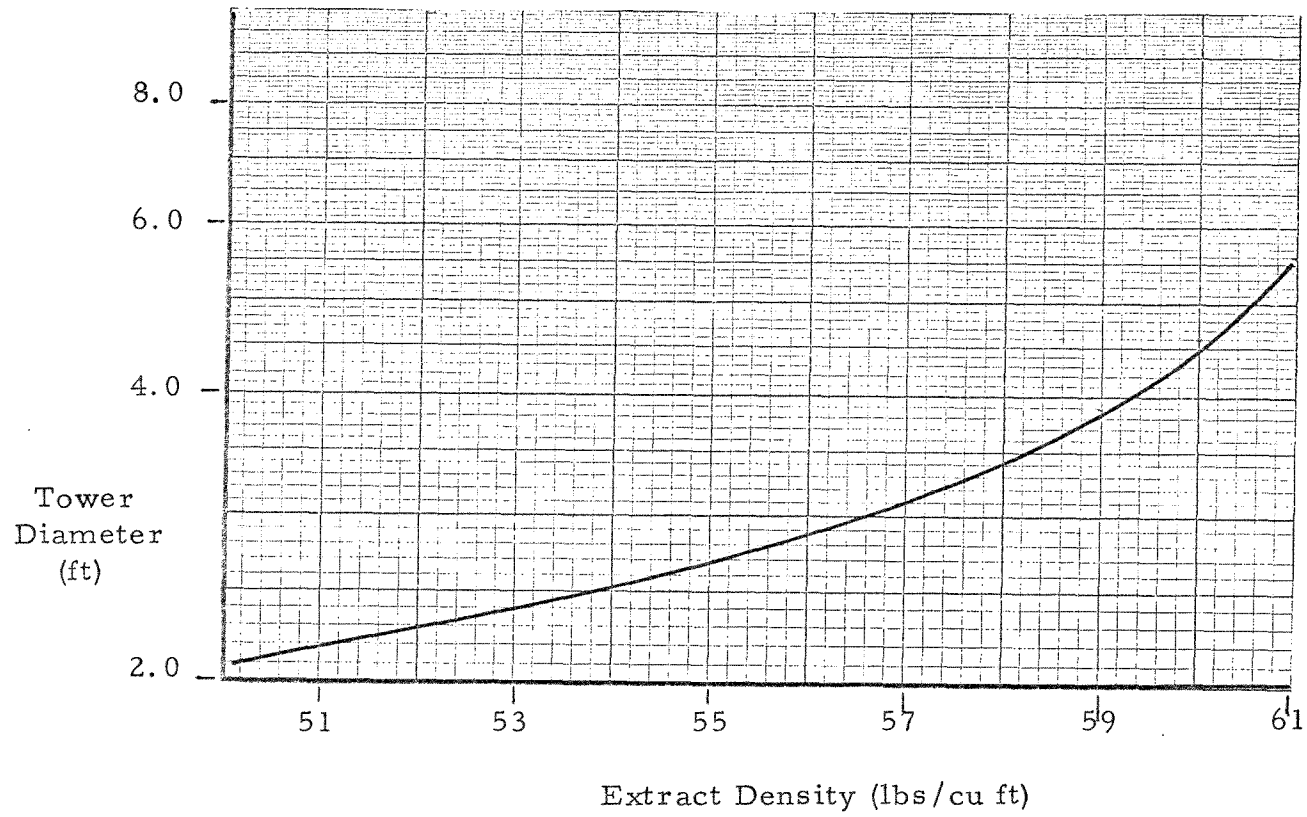
## FIGURE 8

### EFFECT OF EXTRACT VISCOSITY ON TOWER COST
### AND THE HEIGHT OF A TRANSFER UNIT



Height of a
Transfer Unit
(ft)

Tower Cost
(dollars)

Extract Viscosity (centipoise)
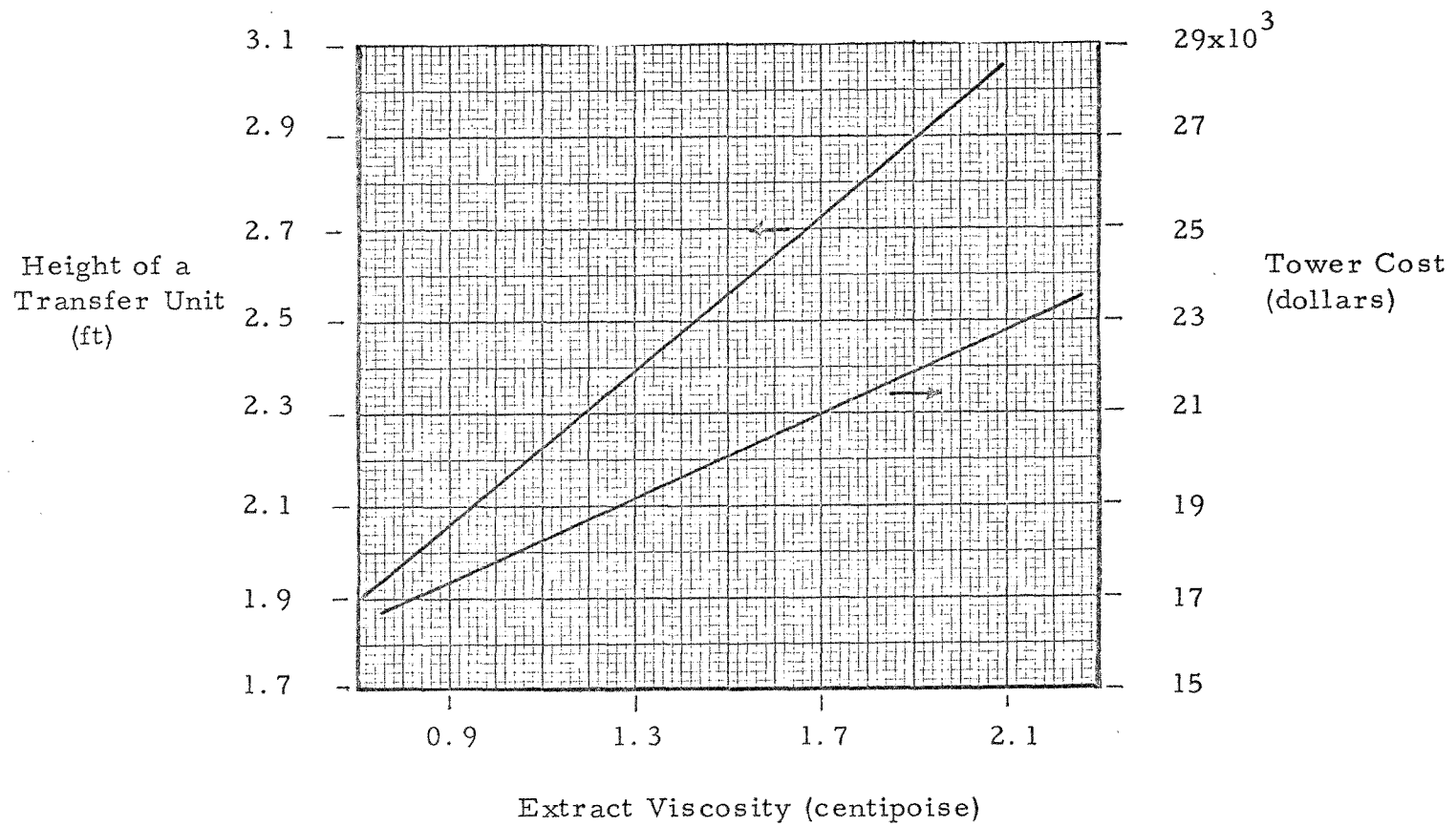
FIGURE 9

EFFECT OF RAFFINATE DENSITY ON TOWER COST
AND THE HEIGHT OF A TRANSFER UNIT
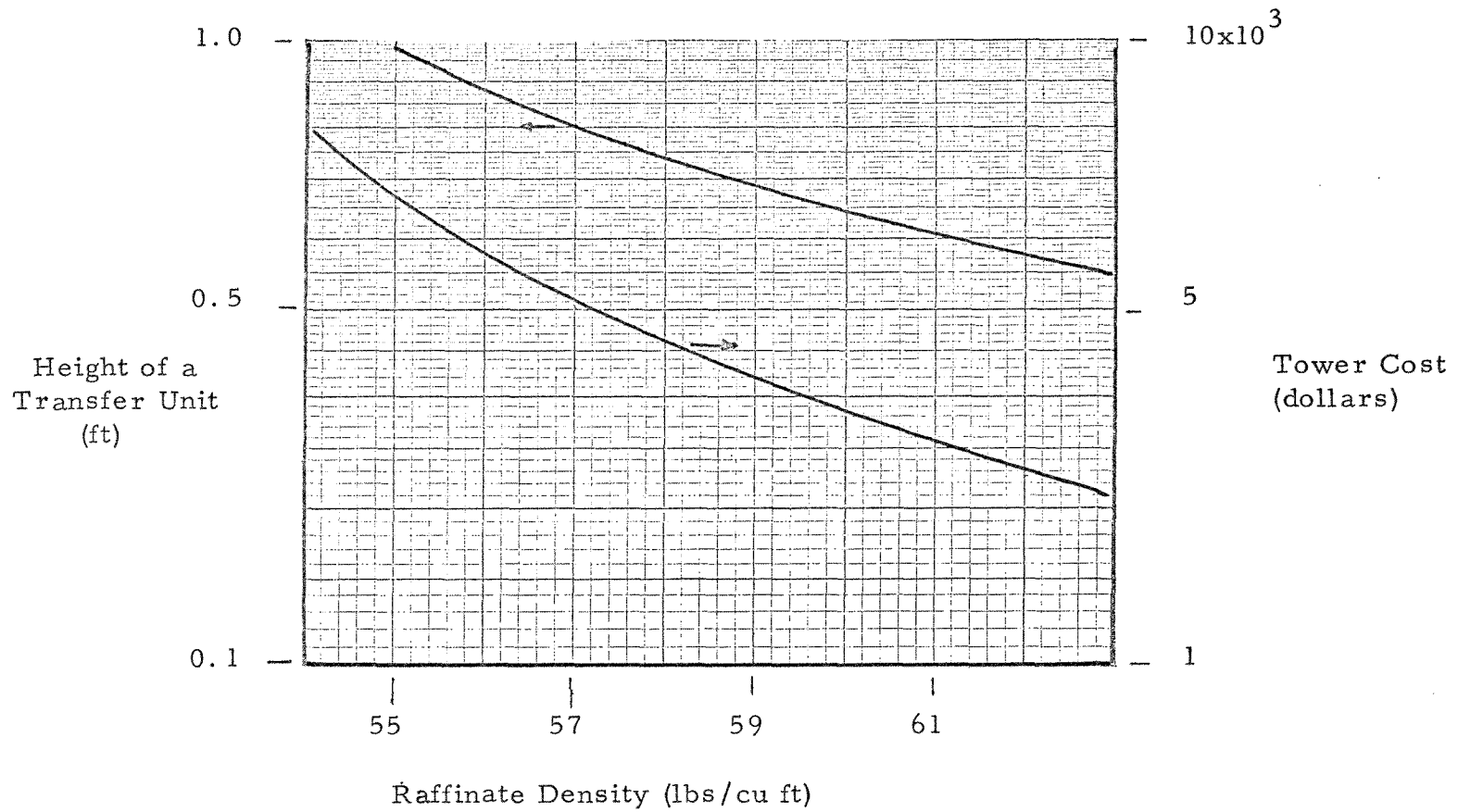
FIGURE 10

EFFECT OF RAFFINATE DENSITY ON TOWER DIAMETER



Raffinate Density (lbs/cu ft)
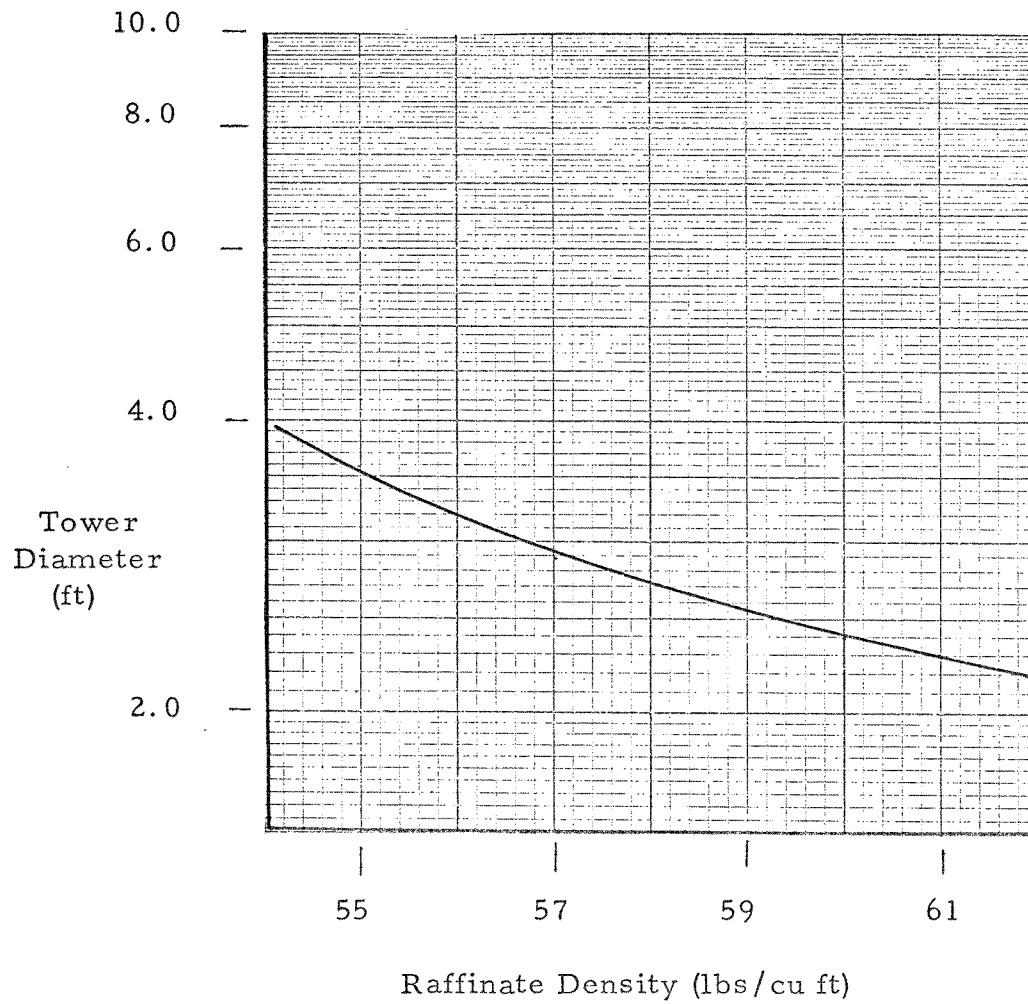
FIGURE 11

EFFECT OF INTERFACIAL TENSION ON TOWER COST
AND THE HEIGHT OF A TRANSFER UNIT



Height of a
Transfer Unit
(ft)

Tower Cost
(dollars)

Interfacial Tension (dynes/cm)
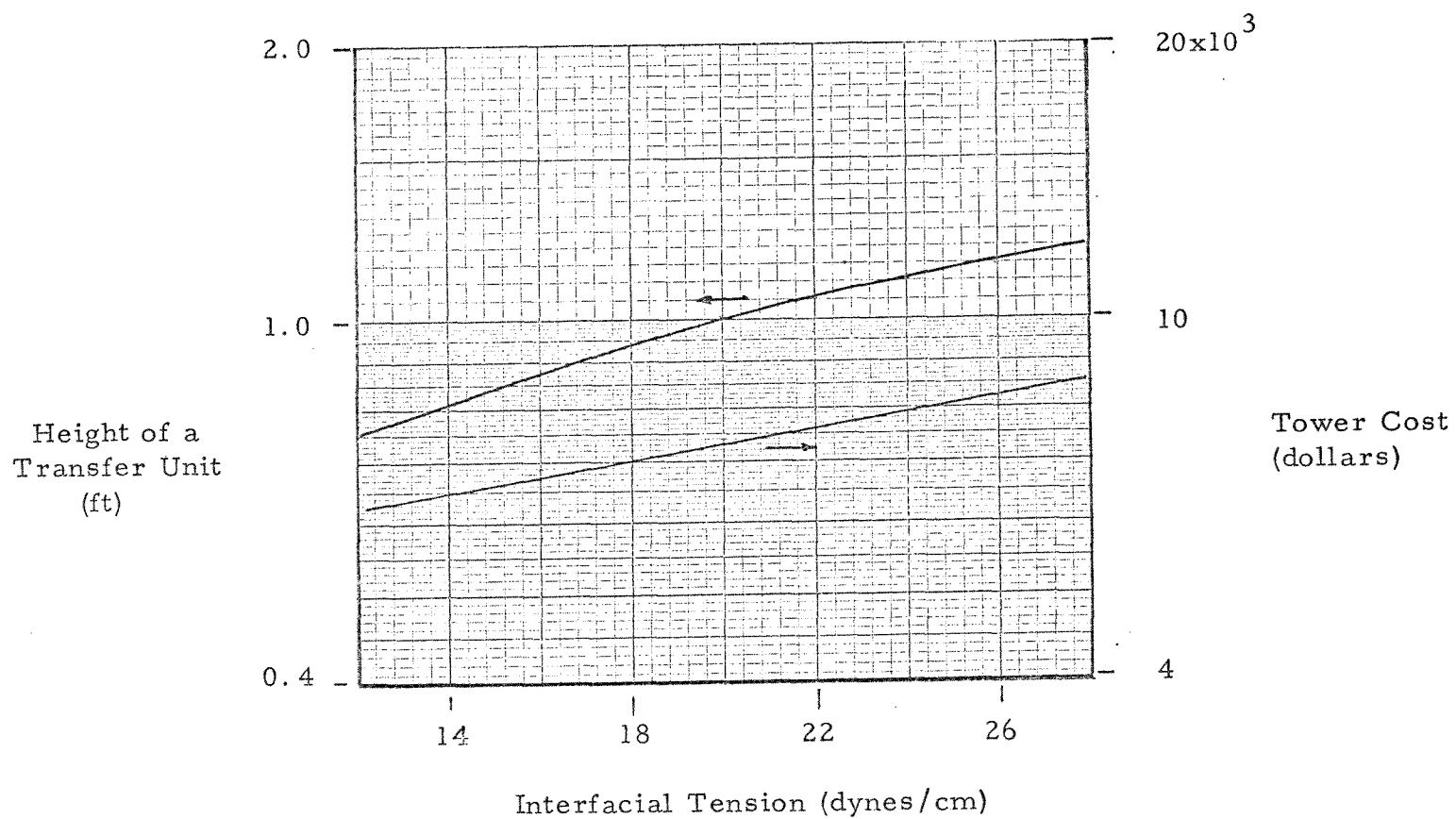
## FIGURE 12

### EFFECT OF SOLVENT RATE ON THE NUMBER OF TRANSFER UNITS
### AND THE HEIGHT OF A TRANSFER UNIT



Number of Transfer Units

Height of a Transfer Unit (ft)

Ratio of Actual to Minimum Solvent Rate
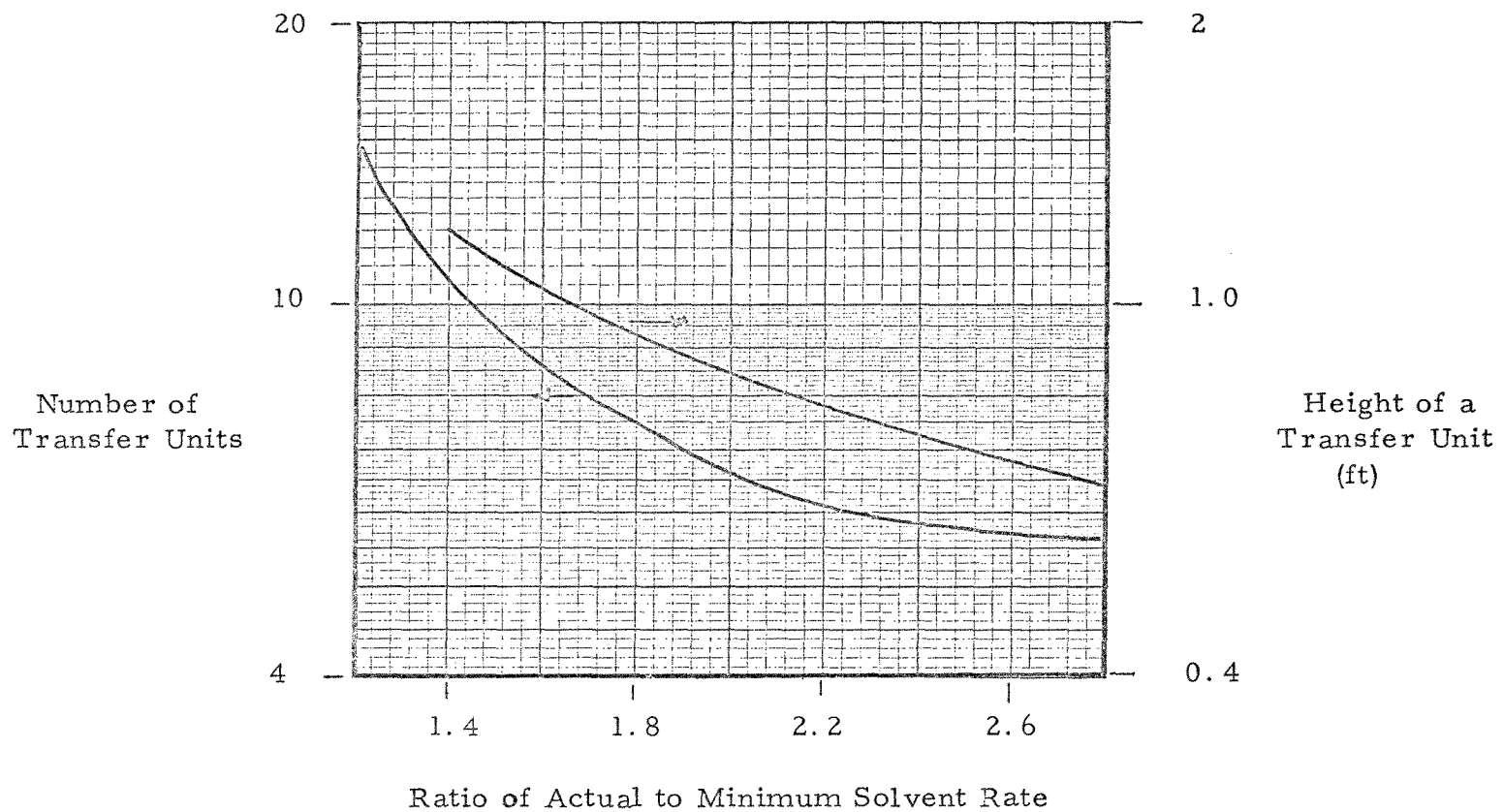
FIGURE 13

EFFECT OF SOLVENT RATE ON TOWER COST AND TOWER DIAMETER



Ratio of Actual to Minimum Solvent Rate
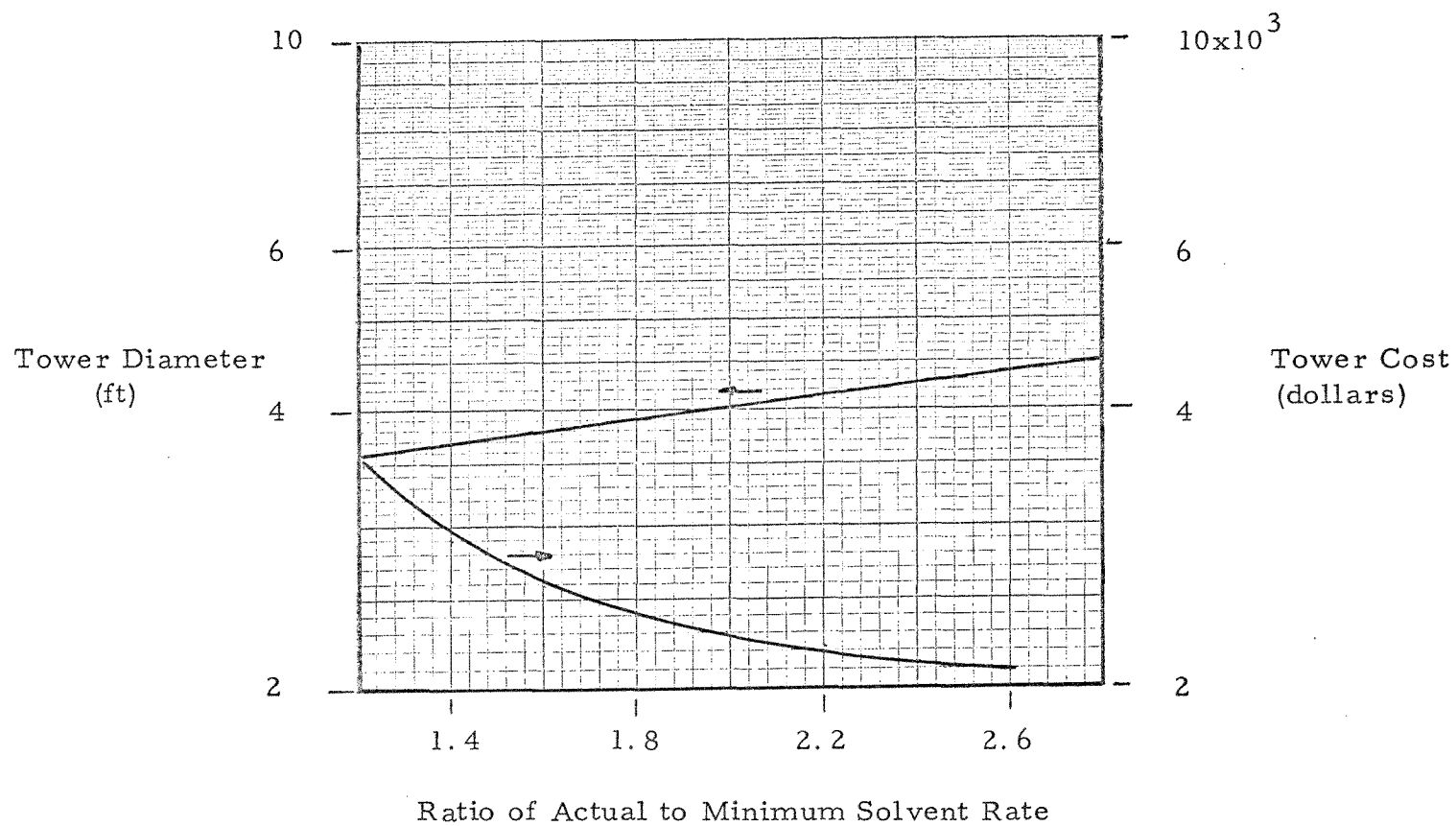
# FIGURE 14

## EFFECT OF PACKING DIAMETER ON TOWER COST AND THE HEIGHT OF A TRANSFER UNIT
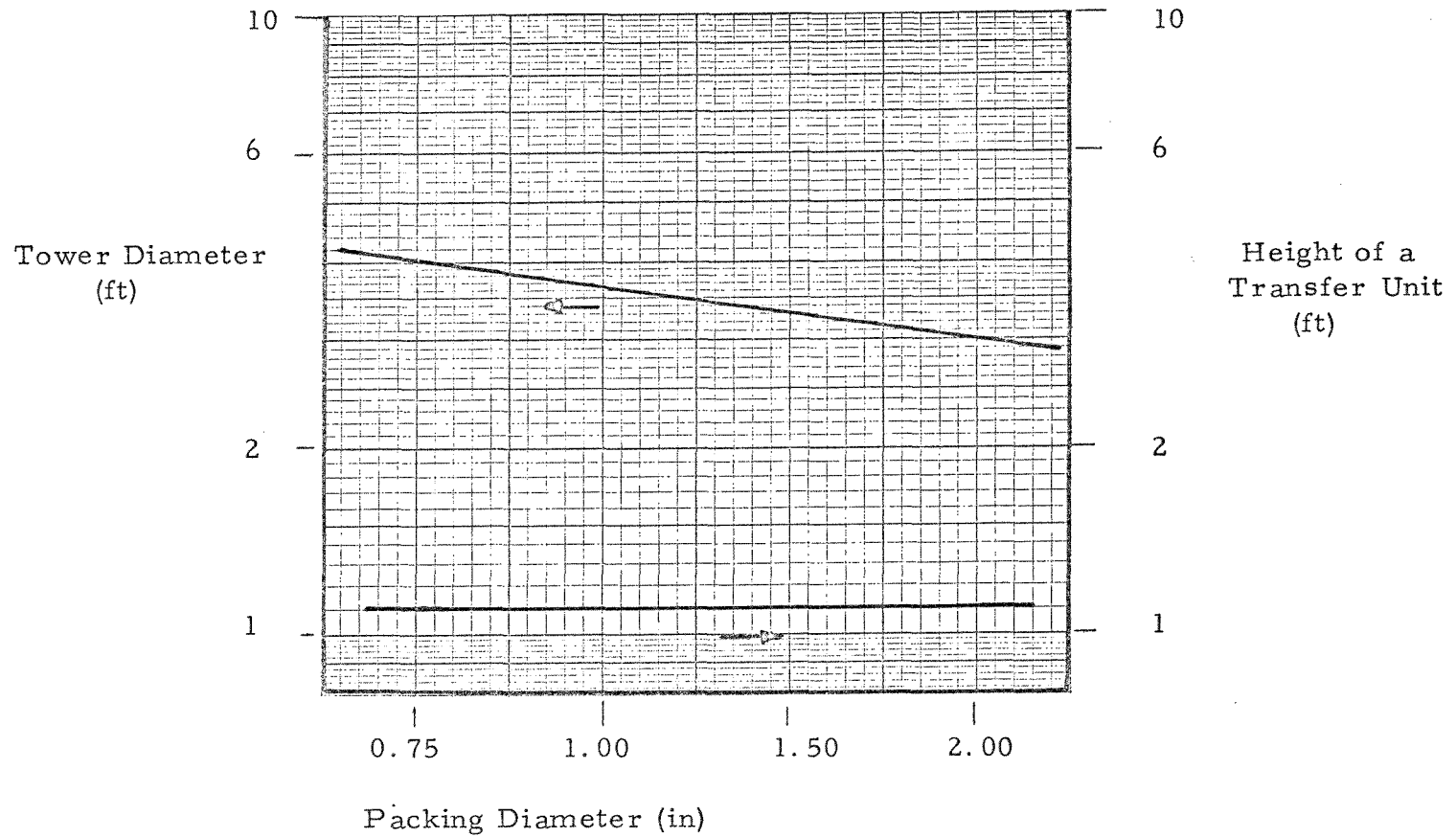
# TABLES

## TABLE 4

### EFFECT OF EXTRACT DENSITY ON COLUMN DESIGN

| | | |
|---|---|---|
| Packing | = | 1.0 inch Raschig Rings |
| Ratio of Actual to Minimum Solvent Flow Rate | = | 1.5 |
| Number of Transfer Units | = | 9.23 |
| Raffinate Density | = | 64.0 lbs/cu ft |

| Extract Density (lbs/cu ft) | Dispersed Phase Holdup | Height of Overall Transfer Unit (ft) | Tower Diameter (ft) | Tower Cost (dollars) |
|---|---|---|---|---|
| 50.0 | 0.13 | 0.53 | 2.0 | 2963 |
| 51.0 | 0.12 | 0.55 | 2.1 | 3134 |
| 52.0 | 0.11 | 0.58 | 2.2 | 3339 |
| 53.0 | 0.10 | 0.61 | 2.3 | 3585 |
| 54.0 | 0.10 | 0.66 | 2.4 | 3751 |
| 55.0 | 0.09 | 0.70 | 2.5 | 4093 |
| 57.0 | 0.07 | 0.81 | 2.9 | 5110 |
| 58.0 | 0.07 | 0.90 | 3.0 | 5565 |
| 59.0 | 0.06 | 0.99 | 3.4 | 6586 |
| 60.0 | 0.05 | 1.13 | 4.0 | 8220 |
| 61.0 | 0.05 | 1.34 | 4.4 | 10248 |
| 62.0 | 0.05 | 1.74 | 5.6 | 15659 |

# TABLE 5

## EFFECT OF EXTRACT VISCOSITY ON COLUMN DESIGN

| | | |
|---|---|---|
| Packing | = | 1.0 inch Raschig Rings |
| Ratio of Actual to Minimum Solvent Flow Rate | = | 1.5 |
| Number of Transfer Units | = | 9.23 |
| Raffinate Viscosity | = | 1.0 centipoise |
| Extract Density | = | 62.0 lbs/cu ft |

| Extract Viscosity (centipoise) | Dispersed Phase Holdup | Height of Overall Transfer Unit (ft) | Tower Diameter (ft) | Tower Cost (dollars) |
|---|---|---|---|---|
| 0.5 | 0.06 | 1.74 | 5.6 | 15659 |
| 0.7 | 0.06 | 1.90 | 5.6 | 16583 |
| 0.9 | 0.06 | 2.07 | 5.6 | 17499 |
| 1.1 | 0.06 | 2.24 | 5.6 | 18409 |
| 1.3 | 0.06 | 2.40 | 5.6 | 19312 |
| 1.5 | 0.06 | 2.57 | 5.6 | 20210 |
| 1.7 | 0.06 | 2.73 | 5.6 | 21102 |
| 1.9 | 0.06 | 2.90 | 5.6 | 21989 |
| 2.1 | 0.06 | 3.06 | 5.6 | 22871 |
| 2.3 | 0.06 | 3.23 | 5.6 | 23748 |
| 2.5 | 0.06 | 3.40 | 5.6 | 24620 |
| 2.7 | 0.06 | 3.56 | 5.6 | 25489 |
| 2.9 | 0.06 | 3.73 | 5.6 | 26353 |

# TABLE 6

## EFFECT OF RAFFINATE DENSITY ON COLUMN DESIGN

| | | | |
|---|---|---|---|
| Packing | = | 1.0 inch Raschig Rings | |
| Ratio of Actual to Minimum Solvent Flow Rate | = | 1.5 | |
| Number of Transfer Units | = | 9.23 | |
| Extract Density | = | 50 lbs/cu ft | |

| Raffinate Density (lbs/cu ft) | Dispersed Phase Holdup | Height of Overall Transfer Unit (ft) | Tower Diameter (ft) | Tower Cost (dollars) |
|---|---|---|---|---|
| 54 | 0.06 | 1.13 | 3.8 | 7993 |
| 55 | 0.06 | 0.98 | 3.6 | 6876 |
| 56 | 0.07 | 0.88 | 3.2 | 5775 |
| 57 | 0.08 | 0.81 | 2.9 | 5018 |
| 58 | 0.08 | 0.74 | 2.8 | 4656 |
| 59 | 0.09 | 0.69 | 2.6 | 4187 |
| 60 | 0.10 | 0.65 | 2.4 | 3820 |
| 61 | 0.11 | 0.62 | 2.3 | 3525 |
| 62 | 0.11 | 0.58 | 2.2 | 3373 |
| 63 | 0.12 | 0.55 | 2.1 | 3154 |

## TABLE 7

### EFFECT OF RAFFINATE VISCOSITY ON COLUMN DESIGN

| | | |
|---|---|---|
| Packing | = | 1.0 inch Raschig Rings |
| Ratio of Actual to Minimum Solvent Flow Rate | = | 1.5 |
| Number of Transfer Units | = | 9.23 |
| Extract Viscosity | = | 0.5 centipoise |
| Extract Density | = | 50.0 lbs/cu ft |
| Raffinate Density | = | 63.0 lbs/cu ft |

| Raffinate Viscosity (centipoise) | Dispersed Phase Holdup | Height of Overall Transfer Unit (ft) | Tower Diameter (ft) | Tower Cost (dollars) |
|---|---|---|---|---|
| 1.0 | 0.12 | 0.55 | 2.1 | 3154 |
| 1.2 | 0.12 | 0.53 | 2.1 | 3119 |
| 1.4 | 0.12 | 0.52 | 2.1 | 3096 |
| 1.6 | 0.12 | 0.51 | 2.1 | 3081 |
| 1.8 | 0.12 | 0.50 | 2.1 | 3071 |
| 2.0 | 0.12 | 0.49 | 2.2 | 3063 |
| 2.2 | 0.12 | 0.49 | 2.2 | 3059 |
| 2.4 | 0.12 | 0.49 | 2.2 | 3056 |

## TABLE 8

### EFFECT OF INTERFACIAL TENSION ON COLUMN DESIGN

Packing                                          =    1.0 inch Raschig Rings
Ratio of Actual to Minimum Solvent Flow Rate     =    1.5
Number of Transfer Units                         =    9.23

| Interfacial Tension (dynes/cm) | Dispersed Phase Holdup | Height of Overall Transfer Unit (ft) | Tower Diameter (ft) | Tower Cost (dollars) |
|---|---|---|---|---|
| 10 | 0.07 | 0.69 | 3.5 | 5764 |
| 12 | 0.07 | 0.77 | 3.5 | 6001 |
| 14 | 0.06 | 0.82 | 3.8 | 6641 |
| 16 | 0.06 | 0.89 | 3.8 | 6883 |
| 18 | 0.06 | 0.94 | 3.8 | 7125 |
| 20 | 0.06 | 1.00 | 3.8 | 7368 |
| 22 | 0.06 | 1.06 | 3.8 | 7614 |
| 24 | 0.06 | 1.11 | 3.8 | 7865 |
| 26 | 0.06 | 1.16 | 3.9 | 8124 |
| 28 | 0.06 | 1.21 | 3.9 | 8391 |
| 30 | 0.06 | 1.25 | 3.9 | 8669 |

## TABLE 9

### EFFECT OF SOLVENT-FEED SOLUBILITY ON COLUMN DESIGN

Packing                                       =    1.0 inch Raschig Rings
Ratio of Actual to Minimum Solvent Flow Rate  =    1.5
Number of Transfer Units                      =    9.23
Extract Density                               =    50.0 lbs/cu ft
Raffinate Viscosity                           =    3.2 centipoise

Mutual Solubilities
(Mole Fractions)

| $X_{ba}, X_{ab}$ | $X_{aa}, X_{bb}$ | Dispersed Phase Holdup | Height of Overall Transfer Unit (ft) | Tower Diameter (ft) | Tower Cost (dollars) |
|---|---|---|---|---|---|
| 0.001 | 0.999 | 0.12 | 0.48 | 2.2 | 3053 |
| 0.003 | 0.997 | 0.12 | 0.47 | 2.2 | 3067 |
| 0.005 | 0.995 | 0.12 | 0.47 | 2.2 | 3082 |
| 0.007 | 0.993 | 0.13 | 0.48 | 2.1 | 3023 |
| 0.009 | 0.991 | 0.13 | 0.48 | 2.2 | 3036 |
| 0.011 | 0.989 | 0.13 | 0.47 | 2.2 | 3050 |
| 0.013 | 0.987 | 0.13 | 0.47 | 2.2 | 3063 |
| 0.015 | 0.985 | 0.13 | 0.47 | 2.2 | 3076 |
| 0.017 | 0.983 | 0.13 | 0.47 | 2.2 | 3090 |

# TABLE 10

## COMPUTER OUTPUT FOR 0.75 INCH RASCHIG RINGS

PACKING DIAMETER (IN)= 0.750

| HOLDUP | P5 | P6 | G1 | XCE1 |
|---|---|---|---|---|
| 0.07 | 58.5 | 58.8 | 1.2 | 0.062352 |
| 0.07 | 55.0 | 55.0 | 1.4 | 0.053925 |
| 0.08 | 57.7 | 57.7 | 1.6 | 0.047505 |
| 0.08 | 55.0 | 55.0 | 1.8 | 0.042450 |
| 0.09 | 57.8 | 57.8 | 2.0 | 0.038368 |
| 0.09 | 55.7 | 55.7 | 2.2 | 0.035002 |
| 0.10 | 58.3 | 58.3 | 2.4 | 0.032179 |
| 0.10 | 56.6 | 56.6 | 2.6 | 0.029778 |
| 0.11 | 59.1 | 59.1 | 2.8 | 0.027710 |
| 0.11 | 57.7 | 57.7 | 3.0 | 0.025910 |

| E2 | NTU | HTU | DIAM | HDP | TCOST |
|---|---|---|---|---|---|
| 7194. | 14.95 | 1.46 | 4.0 | 21.8 | 4543. |
| 8393. | 10.70 | 1.25 | 4.2 | 12.9 | 3544. |
| 9592. | 8.40 | 1.11 | 4.2 | 9.4 | 3006. |
| 10790. | 7.49 | 0.99 | 4.5 | 7.4 | 2826. |
| 11989. | 6.87 | 0.91 | 4.5 | 6.2 | 2611. |
| 13188. | 6.44 | 0.82 | 4.7 | 5.3 | 2556. |
| 14387. | 6.13 | 0.77 | 4.6 | 4.7 | 2432. |
| 15586. | 5.89 | 0.71 | 4.8 | 4.2 | 2417. |
| 16785. | 5.70 | 0.67 | 4.8 | 3.8 | 2334. |
| 17984. | 5.54 | 0.62 | 4.9 | 3.5 | 2330. |

# TABLE 11

## COMPUTER OUTPUT FOR 1.00 INCH RASCHIG RINGS

PACKING DIAMETER (IN)= 1.000

| HOLDUP | P5 | P6 | G1 | XCEI |
|--------|------|------|-----|----------|
| 0.05 | 57.0 | 57.0 | 1.2 | 0.062352 |
| 0.05 | 52.9 | 52.9 | 1.4 | 0.053925 |
| 0.06 | 58.3 | 58.3 | 1.6 | 0.047505 |
| 0.06 | 55.3 | 55.3 | 1.8 | 0.042450 |
| 0.06 | 52.7 | 52.7 | 2.0 | 0.038368 |
| 0.07 | 57.8 | 57.8 | 2.2 | 0.035002 |
| 0.07 | 55.7 | 55.7 | 2.4 | 0.032179 |
| 0.07 | 53.8 | 53.8 | 2.6 | 0.029778 |
| 0.08 | 58.6 | 58.6 | 2.8 | 0.027710 |
| 0.08 | 57.0 | 57.0 | 3.0 | 0.025910 |

| EZ | NTU | HTU | DIAM | HDP | TCOST |
|-------|-------|------|------|------|-------|
| 7194. | 14.96 | 1.41 | 3.6 | 21.1 | 3815. |
| 8393. | 10.30 | 1.21 | 3.9 | 12.5 | 3032. |
| 9592. | 8.43 | 1.08 | 3.8 | 9.2 | 2531. |
| 10790. | 7.49 | 0.96 | 4.0 | 7.2 | 2400. |
| 11989. | 6.87 | 0.87 | 4.2 | 6.0 | 2331. |
| 13168. | 6.44 | 0.80 | 4.1 | 5.2 | 2152. |
| 14387. | 6.13 | 0.73 | 4.3 | 4.5 | 2136. |
| 15586. | 5.89 | 0.68 | 4.4 | 4.0 | 2132. |
| 16785. | 5.70 | 0.64 | 4.3 | 3.6 | 2023. |
| 17984. | 5.54 | 0.60 | 4.5 | 3.3 | 2031. |

# TABLE 12

## COMPUTER OUTPUT FOR 1.50 INCH RASCHIG RINGS

PACKING DIAMETER (IN)= 1.500

| HOLDUP | P5 | P6 | GI | XCEI |
|--------|------|------|-----|----------|
| 0.05 | 60.3 | 60.3 | 1.2 | 0.062352 |
| 0.05 | 55.9 | 55.9 | 1.4 | 0.053925 |
| 0.05 | 52.4 | 52.4 | 1.6 | 0.047505 |
| 0.06 | 58.4 | 58.4 | 1.8 | 0.042450 |
| 0.06 | 55.6 | 55.6 | 2.0 | 0.038368 |
| 0.06 | 53.3 | 53.3 | 2.2 | 0.035002 |
| 0.07 | 58.9 | 58.9 | 2.4 | 0.032179 |
| 0.07 | 56.9 | 56.9 | 2.6 | 0.029778 |
| 0.07 | 55.1 | 55.1 | 2.8 | 0.027710 |
| 0.07 | 53.5 | 53.5 | 3.0 | 0.025910 |

| E2 | NTU | HTU | DIAM | HUP | TCOST |
|--------|-------|------|------|------|-------|
| 7193. | 14.96 | 1.41 | 3.2 | 21.1 | 3091. |
| 8392. | 10.30 | 1.21 | 3.4 | 12.5 | 2500. |
| 9592. | 8.48 | 1.06 | 3.6 | 9.0 | 2280. |
| 10790. | 7.49 | 0.96 | 3.5 | 7.2 | 2021. |
| 11989. | 6.87 | 0.87 | 3.7 | 6.0 | 1972. |
| 13189. | 6.44 | 0.79 | 3.9 | 5.1 | 1948. |
| 14387. | 6.13 | 0.73 | 3.8 | 4.5 | 1825. |
| 15586. | 5.89 | 0.68 | 3.9 | 4.0 | 1825. |
| 16785. | 5.70 | 0.63 | 4.1 | 3.6 | 1831. |
| 17984. | 5.54 | 0.59 | 4.2 | 3.3 | 1842. |

# TABLE 13

## COMPUTER OUTPUT FOR 2.00 INCH RASCHIG RINGS

PACKING DIAMETER (IN)= 2.000

| HOLDUP | P5 | P6 | G1 | XCE1 |
|--------|------|------|-----|----------|
| 0.05 | 56.5 | 55.5 | 1.2 | 0.062352 |
| 0.05 | 52.4 | 52.4 | 1.4 | 0.053925 |
| 0.06 | 57.9 | 57.9 | 1.6 | 0.047505 |
| 0.06 | 54.7 | 54.7 | 1.8 | 0.042450 |
| 0.07 | 59.9 | 59.9 | 2.0 | 0.038368 |
| 0.07 | 57.4 | 57.4 | 2.2 | 0.035002 |
| 0.07 | 55.2 | 55.2 | 2.4 | 0.032179 |
| 0.07 | 53.3 | 53.3 | 2.6 | 0.029778 |
| 0.08 | 58.2 | 58.2 | 2.8 | 0.027710 |
| 0.08 | 56.5 | 56.5 | 3.0 | 0.025910 |

| E2 | NTU | HTU | DIAM | HOP | TCOST |
|-------|-------|------|------|------|-------|
| 7194. | 14.96 | 1.41 | 2.9 | 21.1 | 2819. |
| 8393. | 10.30 | 1.21 | 3.2 | 12.5 | 2290. |
| 9592. | 8.48 | 1.03 | 3.1 | 9.2 | 1949. |
| 10790. | 7.49 | 0.96 | 3.3 | 7.2 | 1861. |
| 11989. | 6.87 | 0.89 | 3.2 | 6.0 | 1714. |
| 13188. | 6.44 | 0.80 | 3.3 | 5.2 | 1693. |
| 14387. | 6.13 | 0.73 | 3.5 | 4.5 | 1685. |
| 15586. | 5.89 | 0.68 | 3.6 | 4.0 | 1686. |
| 16785. | 5.70 | 0.64 | 3.5 | 3.6 | 1608. |
| 17984. | 5.54 | 0.60 | 3.6 | 3.3 | 1617. |

# TABLE 14

## COMPUTER OUTPUT FOR 3.00 INCH RASCHIG RINGS

PACKING DIAMETER (IN)= 3.000

| HOLDUP | P5 | P6 | G1 | XCE1 |
|--------|------|------|-----|----------|
| 0.05 | 52.3 | 52.3 | 1.2 | 0.062352 |
| 0.06 | 57.1 | 57.1 | 1.4 | 0.053925 |
| 0.06 | 53.6 | 53.6 | 1.6 | 0.047505 |
| 0.07 | 58.2 | 58.2 | 1.8 | 0.042450 |
| 0.07 | 55.5 | 55.5 | 2.0 | 0.038368 |
| 0.08 | 59.8 | 59.8 | 2.2 | 0.035002 |
| 0.08 | 57.6 | 57.6 | 2.4 | 0.032179 |
| 0.08 | 55.6 | 55.6 | 2.6 | 0.029778 |
| 0.09 | 59.8 | 59.8 | 2.8 | 0.027710 |
| 0.09 | 58.1 | 58.1 | 3.0 | 0.025910 |

| E2 | NTU | HTU | DIAM | HOP | TCOST |
|-------|-------|------|------|------|-------|
| 7194. | 14.96 | 1.41 | 2.8 | 21.1 | 2577. |
| 8393. | 10.30 | 1.23 | 2.7 | 12.7 | 1969. |
| 9592. | 8.48 | 1.08 | 2.9 | 9.2 | 1804. |
| 10790. | 7.49 | 0.98 | 2.9 | 7.3 | 1633. |
| 11989. | 6.87 | 0.88 | 3.0 | 6.0 | 1595. |
| 13188. | 6.44 | 0.81 | 3.0 | 5.2 | 1504. |
| 14387. | 6.13 | 0.75 | 3.1 | 4.6 | 1495. |
| 15586. | 5.89 | 0.69 | 3.2 | 4.1 | 1495. |
| 16785. | 5.70 | 0.65 | 3.1 | 3.7 | 1446. |
| 17984. | 5.54 | 0.61 | 3.2 | 3.4 | 1447. |

## TABLE 15

### CARD FORMAT FOR DATA INPUT

Card Column Numbers

| Data Card Number | 1 - 10 | 11 - 20 | 21 - 30 | 31 - 40 | 41 - 50 | 51 - 60 | 61 - 70 |
|---|---|---|---|---|---|---|---|
| 1 | EXVIS | RAFVIS | EXDEN | RAFDEN | SOLVMW | SOLUMW | VOLMOL |
| 2 | SURTEN | SLOPE | R1 | OPTEMF | CR1 | CR2 | CE2 |
| 3 | XAA1 | XBA | XBB1 | XAB | | | |
| 4 | XBC | XCC1 | XCB | XBB2 | | | |
| 5 | XAC | XCC2 | XCA | XAA2 | | | |
| 6 | DCR | DCE | FEEDMW | ASSOCR | ASSOCE | | |
| 7 - 12 | PD(J) | PE(J) | PA(J) | PDEN(J) | PCOST1(J) | | |

Note: See Equation and Program Nomenclature for definition of program variable names.

# TABLE 16

## BASIC INPUT DATA FOR COMPUTER RUNS

Card Column Numbers

| Data Card Number | 1 – 10 | 11 – 20 | 21 – 30 | 31 – 40 | 41 – 50 | 51 – 60 | 61 – 70 |
|---|---|---|---|---|---|---|---|
| 1 | 0.5 | 1.0 | 60.0 | 64.0 | 80.0 | 100.0 | 81.0 |
| 2 | 25.0 | 0 | 15000.0 | 70.0 | 0.006 | 0.001 | 0 |
| 3 | 0.9990 | 0.0010 | 0.9990 | 0.0010 | | | |
| 4 | 0.0003 | 0.9997 | 0.1200 | 0.8800 | | | |
| 5 | 0.0002 | 0.9998 | 0.0100 | 0.9900 | | | |
| 6 | 0 | 0 | 18.0 | 2.6 | 1.0 | | |
| 7 | 0.500 | 0.74 | 114.0 | 48.0 | 13.10 | | |
| 8 | 0.750 | 0.73 | 80.0 | 44.0 | 7.20 | | |
| 9 | 1.000 | 0.73 | 58.0 | 40.0 | 6.50 | | |
| 10 | 1.500 | 0.71 | 38.0 | 42.0 | 5.05 | | |
| 11 | 2.000 | 0.74 | 28.0 | 38.0 | 4.85 | | |
| 12 | 3.000 | 0.74 | 19.0 | 40.0 | 4.30 | | |

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21.   ibid., p. 478.

22.   ibid., pp. 491-492.

23.   ibid., p. 489.

24.   ibid., p. 490.

25.   ibid., p. 182-186.

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