CORRELATIONS FOR MULTICOMPONENT DISTILLATION CALCULATIONS

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PREFACE

New and improved correlations of minimum and operating reflux ratios and stages for multicomponent distillation calculations have been developed. An equation relating the reflux rate required to make a similar distillate product and feed condition has also been developed.

Comparisons of the results of this study and those of previous investigators were made.

I sincerely appreciate the guidance and constructive criticism given by my advisory committee: Dr. R. N. Maddox, Dr. J. B. West, Prof. W. C. Edmister, Prof. J. E. Norton, and Dr. F. E. Jewett. Special thanks are due to Dr. Maddox for his advice and patient guidance.

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CHAPTER I

INTRODUCTION

Short cut calculations coupled with correlations, empirical or otherwise, have long held a place of prime importance in the field of distillation calculations. These techniques have found wide application because the more rigorous methods of distillation calculation require considerable time for solution. With the advent of the digital computer, emphasis has shifted from short cut techniques to the longer, more rigorous calculations. However, short cut techniques have not lost their attractiveness in the area of preliminary design. By means of these calculations, answers which are sufficiently reliable for preliminary cost estimates may be obtained.

A number of correlations relating the reflux ratio as a function of the number of stages, the minimum reflux ratio, and the minimum number of stages are available in the literature. Use of one has indicated that these relationships are not adequate for existing techniques in the field of distillation calculations. One case stands out in that a difference between correlation results and plate to plate results of over 100% was found in the reflux rate when using existing correlations as a basis for the starting values for plate to plate calculations. This error may stem from the fact that a consistent basis was not used for the determination of the correlation parameters. However, in most cases, sufficient data were not given with the original presentation of the various methods to allow one to determine the sources of data or the methods used in determining the parameters. In other areas of distillation calculations no correlations exist which adequately describe certain relationships that are often desired.

The objectives of this study were two fold:

1. To develop a correlation relating minimum and operating reflux ratio as a function of minimum and operating number of stages using published data sources.
2. To develop an expression which would allow the prediction of the change in reflux ratio necessary to make the same distillate product if the feed vaporization were changed.

Such correlations would have value to both the process design engineer and to the operating engineer. Correlation 1 is of the type previously mentioned but would be based on more rigorous methods than used in previous correlations. In addition, various methods of determining the parameters could be used which would allow the process engineer considerable flexibility in the basis which he may use to carry out his own calculations. Correlation 2 would allow the process engineer to give the better estimate of fractionator cost for various feed conditions. The operating engineer could use Correlation 2 to better control the fractionator in cases of upset. This correlation will also provide the instrumentation engineer with a mathematical expression for predicting changes in reflux ratio resulting from changes in feed condition. Such an expression can easily be used with control devices such as the analog computer.

Limitations of the Study

The study was limited to multicomponent systems which contained the lighter hydrocarbons. These were all the normal paraffin hydrocarbons between methane and decane. Fairly reliable thermodynamic data are available for these compounds. In addition, only the cases pertaining to the simple fractionator were studied. The various systems used in this study are presented in Table I. Correlations relating the minimum and operating reflux ratio and the minimum and operating number of stages for two different methods of computing the minimum reflux ratio were studied.

CHAPTER II

THEORY

Operation of a fractionator to perform a specified separation on a given feed stream must lie between two limits. These limits are: (1) the minimum reflux ratio which occurs at an infinite number of stages, and (2) the minimum number of stages which occurs at an infinite reflux ratio. These two minimum quantities define the limits of fractionator operation and the operating number of stages and reflux ratio must lie somewhere between these two limits. Typical relations between the number of stages and reflux ratio are shown by Figure 1 (19). The curve in Figure 1 may be represented by an equation of the form

$$(g)(z)^{c} = C \qquad (1)$$

Underwood (19) has suggested the form

$$(R - R_m)(S - S_m) = C \qquad (2)$$

for purposes of correlating minimum and operating reflux ratio and minimum and operating number of stages.

Various investigators have correlated minimum and operating reflux ratio as a function of the minimum and operating number of stages. Brown and Martin's (3) correlation which appeared in 1939 was based principally on binary mixtures. This correlation is shown in Figure 2. The quantities, V and L, refer to vapor and liquid rates in an entire section of the fractionator. When the assumption

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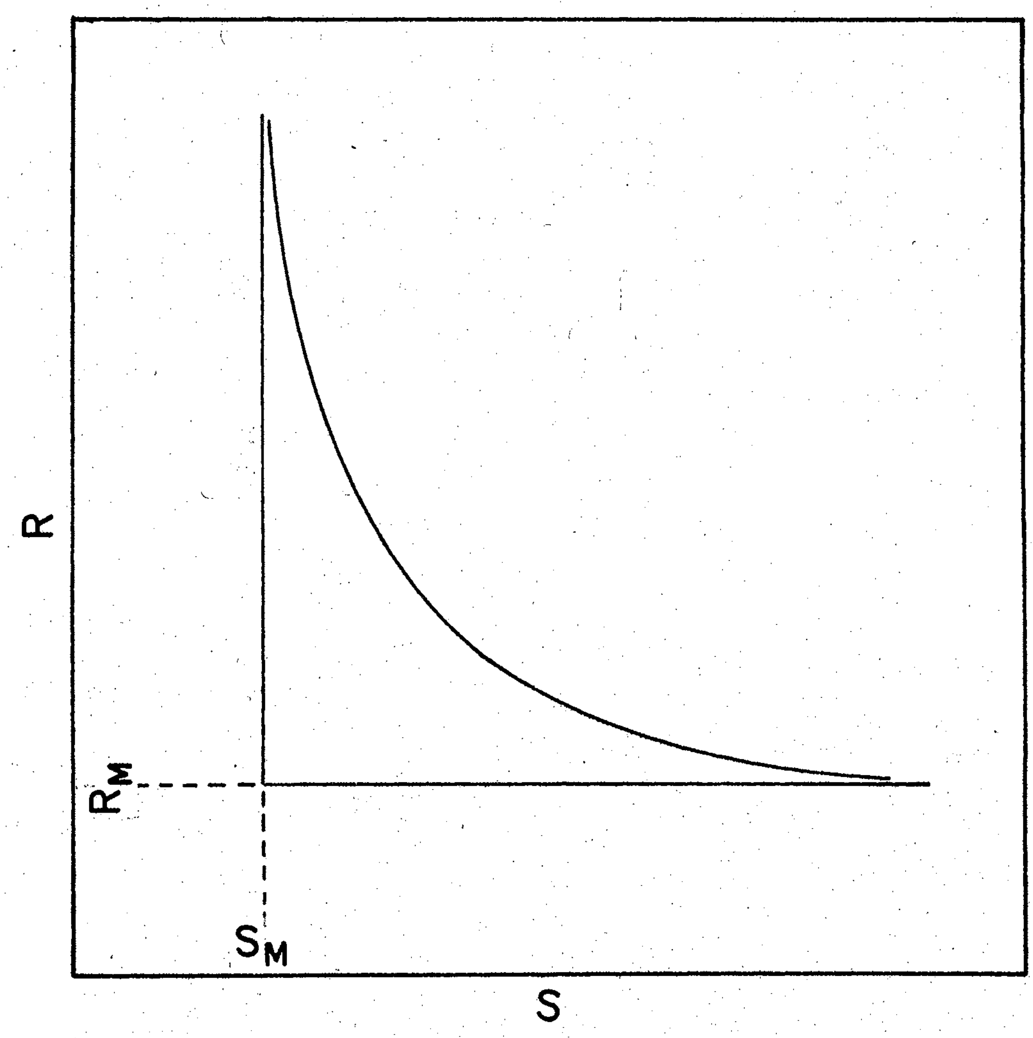


FIGURE 1

RELATION OF OPERATING STAGES AND REFLUX RATIO TO MINIMUM STAGES AND REFLUX RATIO

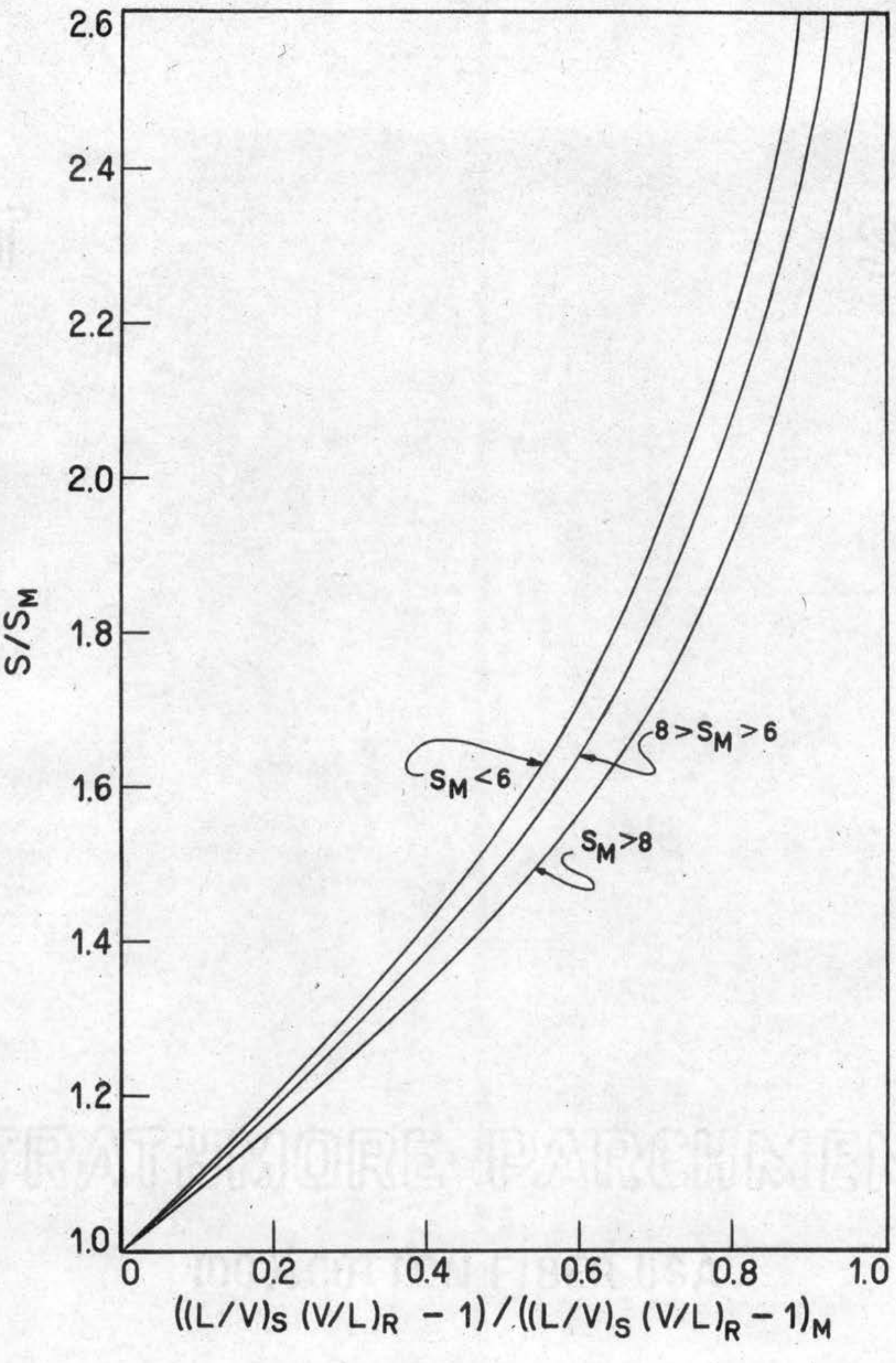


FIGURE 2
BROWN AND MARTIN'S CORRELATION OF MINIMUM AND OPERATING REFLUX RATIO AND STAGES

of constant molal overflow is not applied, use of the Brown and Martin method becomes somewhat difficult for there is a question of what vapor rate is to be used. In addition, parameters for the operating curves were shown and make the problem of interpolation for the minimum number of stages somewhat difficult. The correlation was checked by Brown and Martin for multicomponent mixtures and found to have approximately the same degree of accuracy as was noted for binary mixtures.

Gilliland (7) has also presented a correlation which included multicomponent systems in addition to binary systems, but also made the assumption of constant molal overflow. Gilliland's correlation is shown in Figure 3. Although the correlation is presented as a distinct line, Gilliland states that a better correlation would perhaps be a series of lines having approximately the same shape as the line presented.

Donnell and Cooper (4) have presented a correlation which relates the number of plates to the boilup vapor. In this case, the authors were looking for the optimum steam requirement rather than a finite reflux ratio. Modifications of this method have been used to determine the reflux ratio from the minimum parameters. The systems studied in this method were both binary and multicomponent systems. The analytical method of Underwood (18) was used to determine the minimum number of stages. No indication of the systems studied was given in the presentation of the original article but, in sample calculations accompanying the article, constant molal overflow was used as a basis of calculations.

Recently, Mason (14) has presented another correlation having

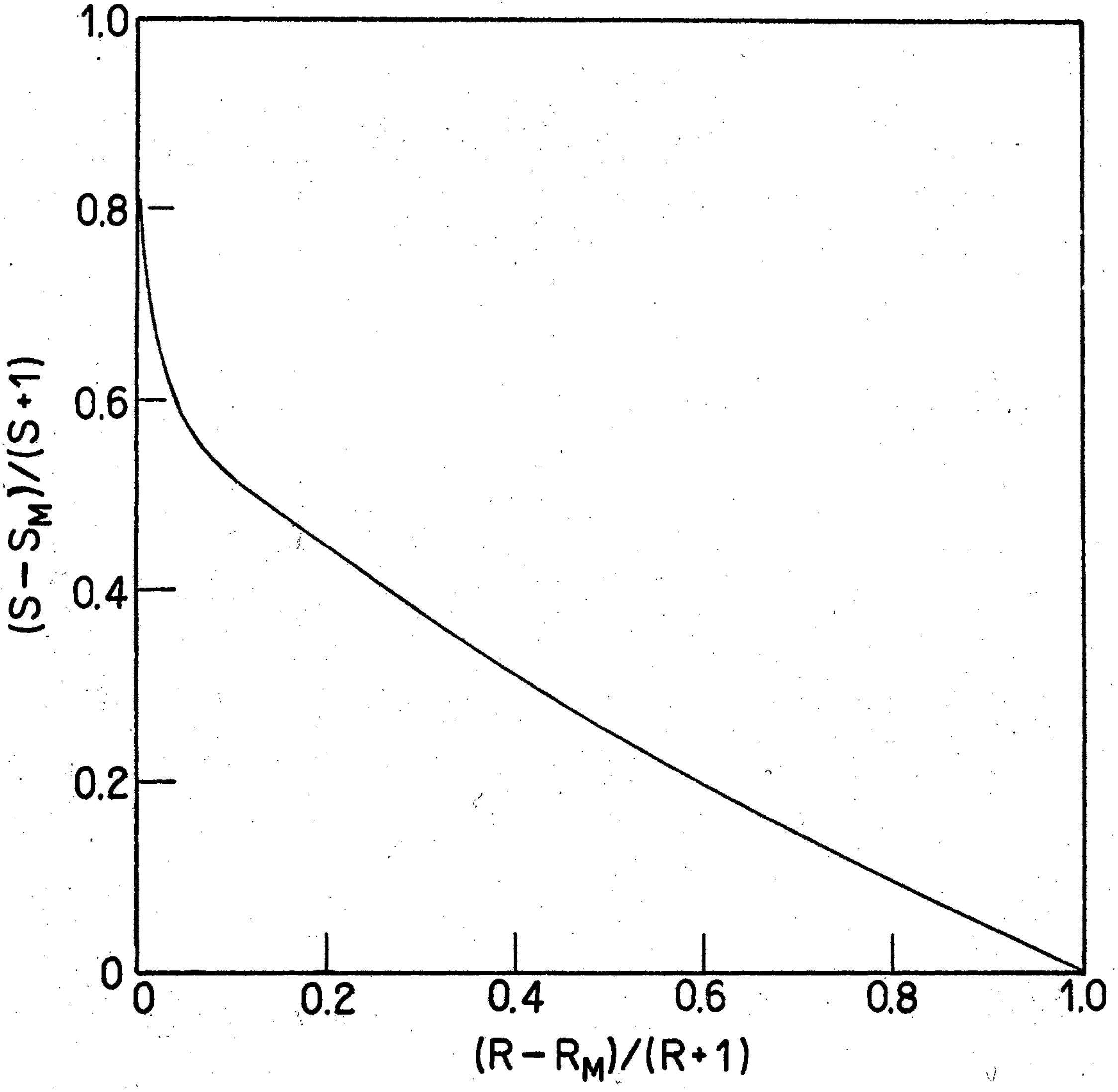


FIGURE 3

GILLILAND'S CORRELATION OF MINIMUM AND OPERATING REFLUX RATIO AND STAGES a completely different form than any of the preceding authors. Mason recognized the fact that the curve shown in Figure 1 had a hyperbolic form and correlated his data on this basis. The resulting correlation is shown in Figure 4. Here again, no mention of the method of determination of the various variables was given.

Determination of the minimum number of stages is most conveniently done by use of one of two methods. These methods are presented by Fenske (6) and Winn (20). The analytical expression for Fenske's method is

$$\alpha^{S_m} = \left(\frac{X_D}{X_W}\right)_{LK} \left(\frac{X_W}{X_D}\right)_{HK}^{b} \qquad (3)$$

In the derivation of the above equation, assumptions of constant molal overflow and constant relative volatility were used. These assumptions somewhat limit the validity of the expression but for the most part are not bad assumptions. Winn's expression has a slightly modified form from that of Fenske, and is

$$\beta^{S_m} = \left(\frac{X_D}{X_W}\right)_{LK} \left(\frac{X_W}{X_D}\right)_{HK}^{b} \left(\frac{B}{D}\right)^{1-b} \qquad (4)$$

This relationship also involves the assumption of constant molal overflow but does not make the assumption of constant relative volatility. The terms, β and b, are used to relate the K values of the key components at the distillate and bottoms temperatures. If a plot of K of the heavy key as a function of K of the light key is a straight line and the assumption of constant molal overflow is valid, Equation 4 is rigorous.

Morrison (16) performed a study of the minimum number of stages as calculated by both the Fenske equation and the Winn

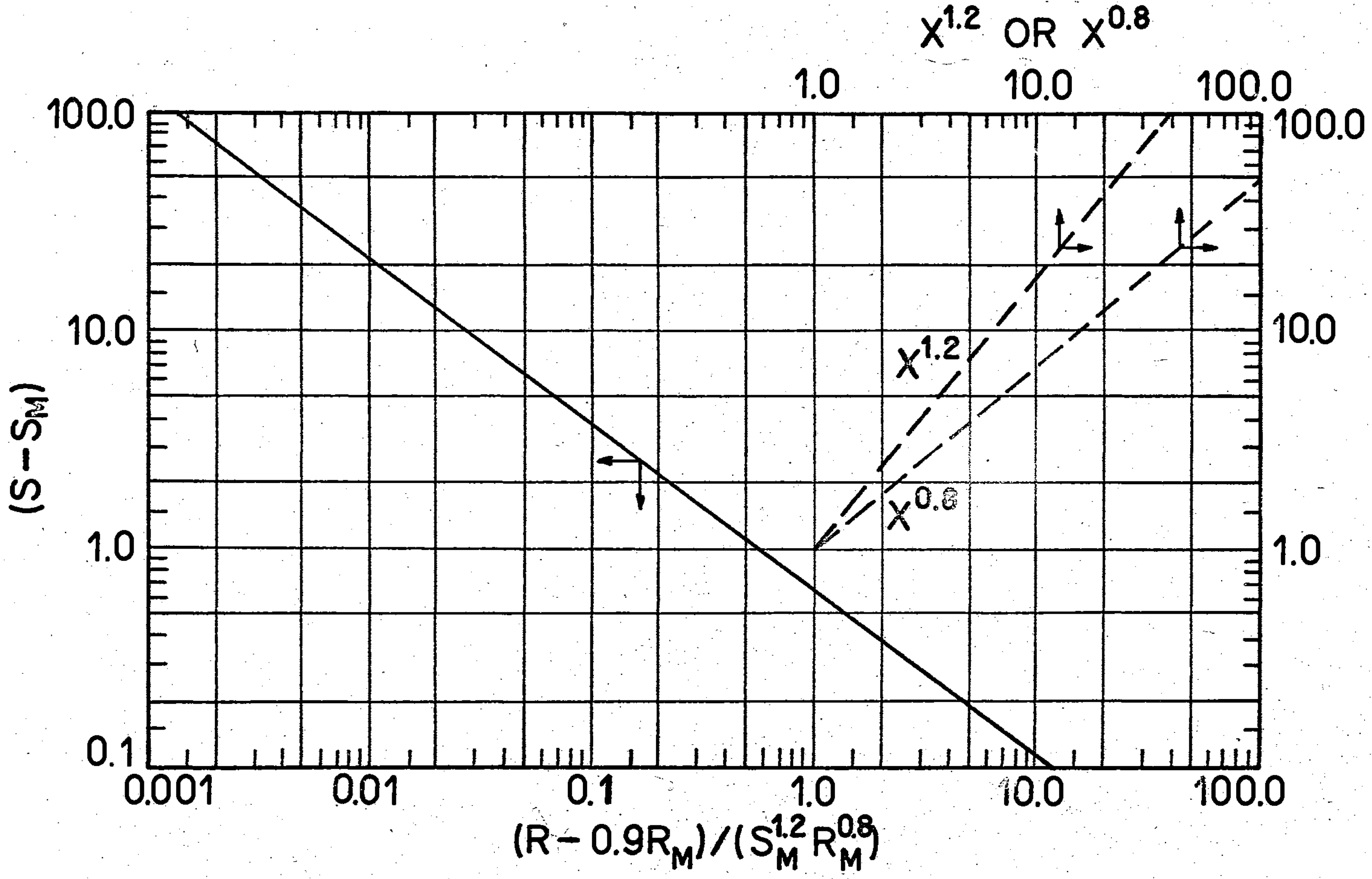


FIGURE 4

MASON'S CORRELATION OF MINIMUM AND OPERATING REFLUX RATIO AND STAGES equation. The results of this study indicated that the minimum number of stages as calculated by both methods were approximately the same. For over forty different cases, an average difference of approximately 5% was noted for the two methods. All calculations were performed on the IBM 650 Digital Computer using programs developed by the author of this thesis.

In addition, modified plate to plate calculations were carried out to determine the validity of both short cut methods. The calculations were performed in the following fashion:

1. A plate to plate calculation was set up as if to be run for the normal fractionation problem.
2. After the first trial, the vapor rate leaving the top tray was arbitrarily set to a value of approximately 10^{45}.
3. Computations were carried out until feed plate matching was achieved.
4. Component distributions from this calculation were then used with the short cut minimum number of stages calculations to determine the minimum number of stages.

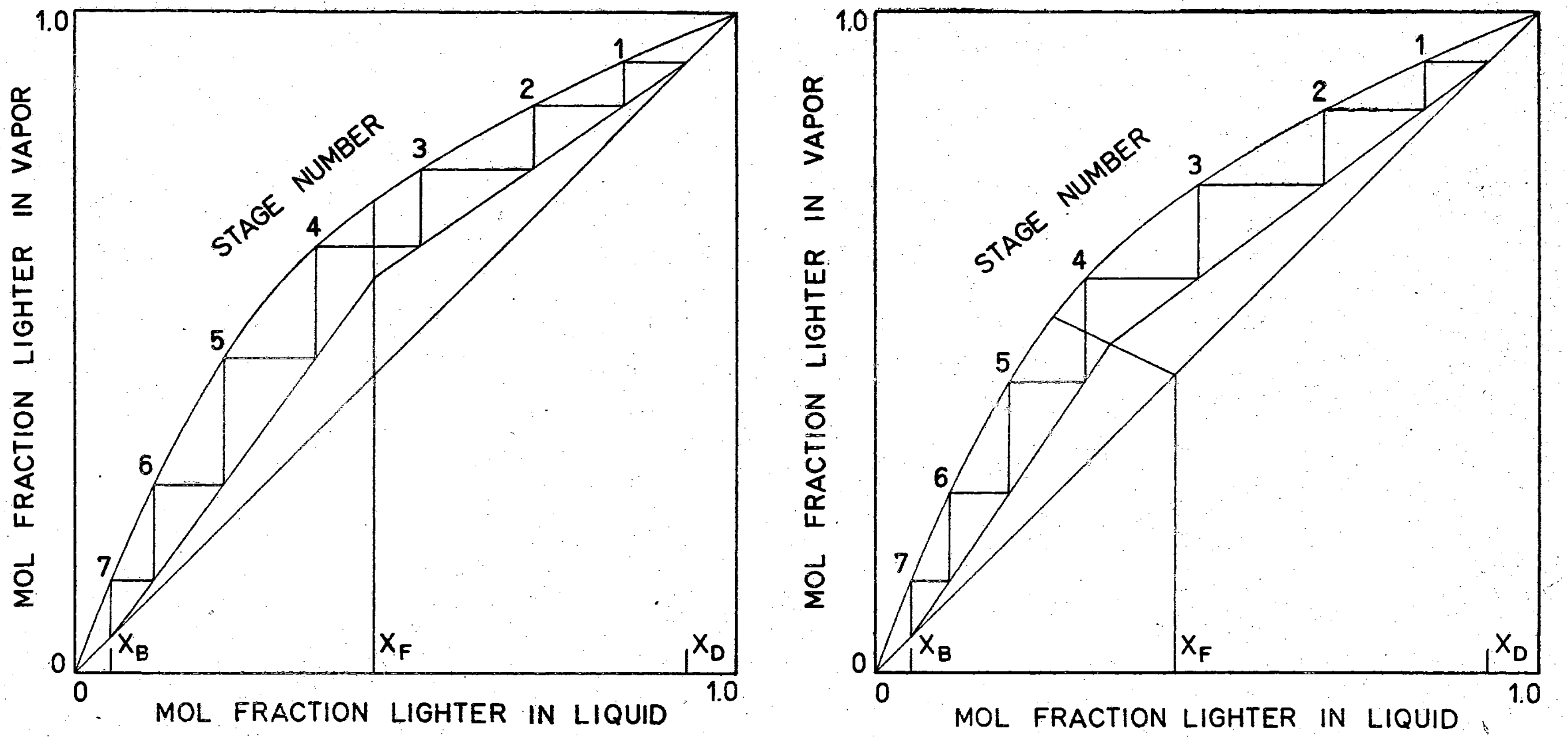
Plate to plate calculations carried out in this manner should provide data regarding the minimum number of stages. The minimum number of stages occurs at an infinite reflux ratio, or stated another way, when the interstage vapor and liquid traffics are equal. In the method Morrison used, the L/V ratios are, effectively, unity. In addition, the reflux ratio was approximately 10^{45} which approaches the criterion of an infinite reflux ratio. Several calculations of the nature mentioned above were carried out and the average deviation was found to be approximately 5% for both the

Fenske and the Winn methods.

In the opinion of the author, no adequate rigorous method for the determination of the minimum number of stages for any separation has been presented. This is due to the fact that an adequate method for the determination of fractional stages has yet to be found. Until this problem can be overcome, the so-called short cut techniques of Fenske and Winn are the most reliable methods for the determination of the minimum number of stages.

Many investigators have presented methods for calculation of the minimum reflux ratio. In the great majority of these, the simplifying assumptions of constant molal overflow and constant relative volatility were applied. An additional assumption occasionally made is that the distillate composition at a finite reflux ratio and number of stages is identical to the composition that would be obtained at an infinite number of stages and the minimum reflux ratio. This last assumption has been shown to be in error (5). The methods of Bachelor (1) and R. Erbar (5) do not make the usual simplifying assumptions and are perhaps the most rigorous methods available for the determination of the minimum reflux ratio. Bachelor's work was the first which did not make the classical assumptions of constant molal overflow and/or relative volatility. R. Erbar has modified Bachelor's method to a rigorous plate by plate tray calculation for the determination of the minimum reflux ratio. This method has been programmed for computer solution. R. Erbar also presents a comparison between her rigorous method and some short cut methods for determination of the minimum reflux ratio. Underwood's (18) method was found to agree best with the theoretically correct values of R. Erbar. The average difference between the results of the Underwood method and the results of the Erbar method was about 10%. This is excellent agreement considering the fact that Underwood assumes constant molal overflow and constant relative volatility.

The qualitative statement can be made that holding the number of stages constant, an increase in the percentage feed vaporization or increase in the feed temperature will require an increase in the reflux ratio to make the same distillate product. This statement may be proved rather simply for the case of binary mixtures by examining a McCabe-Thiele (15) diagram as shown in Figure 5. Figure 5a shows the fractionator operating with a bubble point feed and a given number of stages. Figure 5b shows the same fractionator operating with a partially vaporized feed and the same number of stages as Figure 5a. The reflux ratio in Figure 5a is less than the reflux ratio in Figure 5b. An analogous relationship holds for multicomponent systems. However, such a system cannot be conveniently shown schematically.



BUBBLEPOINT FEED

5a

TWO PHASE FEED

5b

FIGURE 5

FRACTIONATOR OPERATING AT VARIOUS FEED CONDITIONS

CHAPTER III

METHODS

Calculations used as a basis for the correlations to be presented later in this thesis were carried out on the IBM 650 Digital Computer located on the Oklahoma State University campus. This computer is equipped with immediate access storage, indexing registers, and floating decimal device. Although several programs were available for carrying out the calculations, in most instances these programs were not specifically suited to the needs of this problem and had to be either revised or completely re-programmed.

Bonner's (2) plate to plate program for the IBM 650 was available for use. However, Bonner's program has been found to be somewhat unreliable for "broad range" problems. The term "broad range" describes systems containing components whose boiling points vary widely. A typical example of such a system would be the feed stream to a de-ethanizer. A stream of this nature could contain all the normal paraffin hydrocarbons between methane and n-decane. Such problems have been run with the Bonner program, but for only a few cases has a final solution been obtained. This necessitated the writing of a plate to plate program which would be more reliable and practically guarantee solution to the problem. The program developed is based on the principles of the Thiele-Geddes (17) method and uses conventional Lewis and Matheson (8) tray calculations. This program has been adequately described in the literature (9,10) and no further description will be repeated in this thesis.

A program for the calculation of the minimum number of stages was developed by the author (11) using both the methods of Fenske and Winn. R. Erbar (12) developed a method and program for the computation of the minimum reflux ratio. In addition, a program utilizing the Underwood method for the determination of the minimum reflux ratio was developed by R. Erbar (13). These programs were used to compute the data necessary for the correlations to be presented.

The data used in this study were taken from the NGSMA Handbook (23). The vapor-liquid equilibria data were made available to the NGSMA by the Natural Gasoline Association of America. The enthalpy data are from the M. W. Kellogg Company. Although it is recognized that the enthalpy data are not the best available for certain hydrocarbons it does, at least, present a set of data for the entire range of compounds studied in this thesis. These data offer the additional advantage that they are available to engineers at large.

A number of plate to plate calculations were carried out on six different feed streams at varying conditions of reflux ratio and stages. The feed streams used in this investigation are presented in Table I. Pertinent operating data are presented in Tables XVI through LVI. In each case the pressure was specified so that the condenser temperature would be in the range of 80°F to 120°F. Distillate products expressed as fractions of the feed

TABLE I

FEED COMPOSITIONS

	Feed Composition - Mols					
Component	1	2	3	4	5	7
C_1					1	
C_2				5	5	5
C_3			10	20	24	15
iC_4		20	20	15	15	10
nC_4	25	20	20	15	15	10
iC_5	25	20	20	15	15	10
nC_5	25	20	20	15	15	10
C_6	25	20	10	15	10	10
C_7						10
C_{10}						10
Totals	100	100	100	100	100	100

TABLE II

DISTILLATE RATES

Feed Stream Number	Fraction of Feed Removed As Distillate (D/F)			
1	0.25000	0.500		
2	0.20000	0.400	0.60	
3	0.15761	0.300	0.50	
4	0.08266	0.245	0.40	0.55080
5	0.30000	0.600		
7	0.08600	0.210	0.40	

removed as distillate (D/F) for each feed stream are presented in Table II. The resulting component distributions were then used with the minimum number of stages program and the minimum reflux ratio programs to determine the operating limits for the calculated separations.

The resulting data were correlated by means of additional programs using known statistical correlations. These programs are included in the Beaton correlation program (21) for reduction of the data to a matrix form and the computation of certain statistical terms. Selected output data of the Beaton program were then used with a multiple regression analysis program (22) for the final determination of the relationship correlating minimum and operating reflux ratio and minimum and operating number of stages.

To facilitate problem interpretation and identification, a unique problem numbering system was used. Each problem number consists of ten digits and may be broken down as follows:

FFVPP.DDDDD

where: FF - refers to the feed composition number
V - refers to feed condition (0 - bubble point feed; 1 - partially or totally vaporized)
PP - refers to the number of plates in the tower (does not include the effect of the reboiler or partial condenser)
DDDDD - refers to the fraction of the feed removed as distillate product

For example, problem number 01018.25200 means that:

1. Feed composition number one was used.
2. The feed to the fractionator is a bubble point liquid.
3. There are 18 plates in the fractionator not counting the

reboiler.

4. The total distillate product represents 25.2% of the total feed to the fractionator.

CHAPTER IV

RESULTS

The following pages contain the results of this investigation. The data from which these values were determined are presented in Appendices A and B. Data are presented in both tabular and graphical form.

Several methods of correlating the minimum and operating reflux ratio and minimum and operating number of stages were tried. The results of three of these methods of correlation will be presented and discussed below. The correlations will be presented in two different forms. One form will be used to describe the reflux ratio-plates relationship when using values of minimum reflux calculated by the Erbar-Maddox rigorous method. Because of the lengthy time consuming calculations involved in this method, a second correlation is presented based on the minimum reflux ratio as calculated by Underwood's method. Thirty-two different problems were used in developing the correlations based on rigorous values of minimum reflux. Forty-one different problems were used in developing the correlations based on Underwood's values of minimum reflux ratio.

Gilliland's Method

Figure 6 shows a comparison between Gilliland's correlation and the results used in this research. Figure 6 shows a comparison of values based on the Erbar-Maddox rigorous minimum reflux

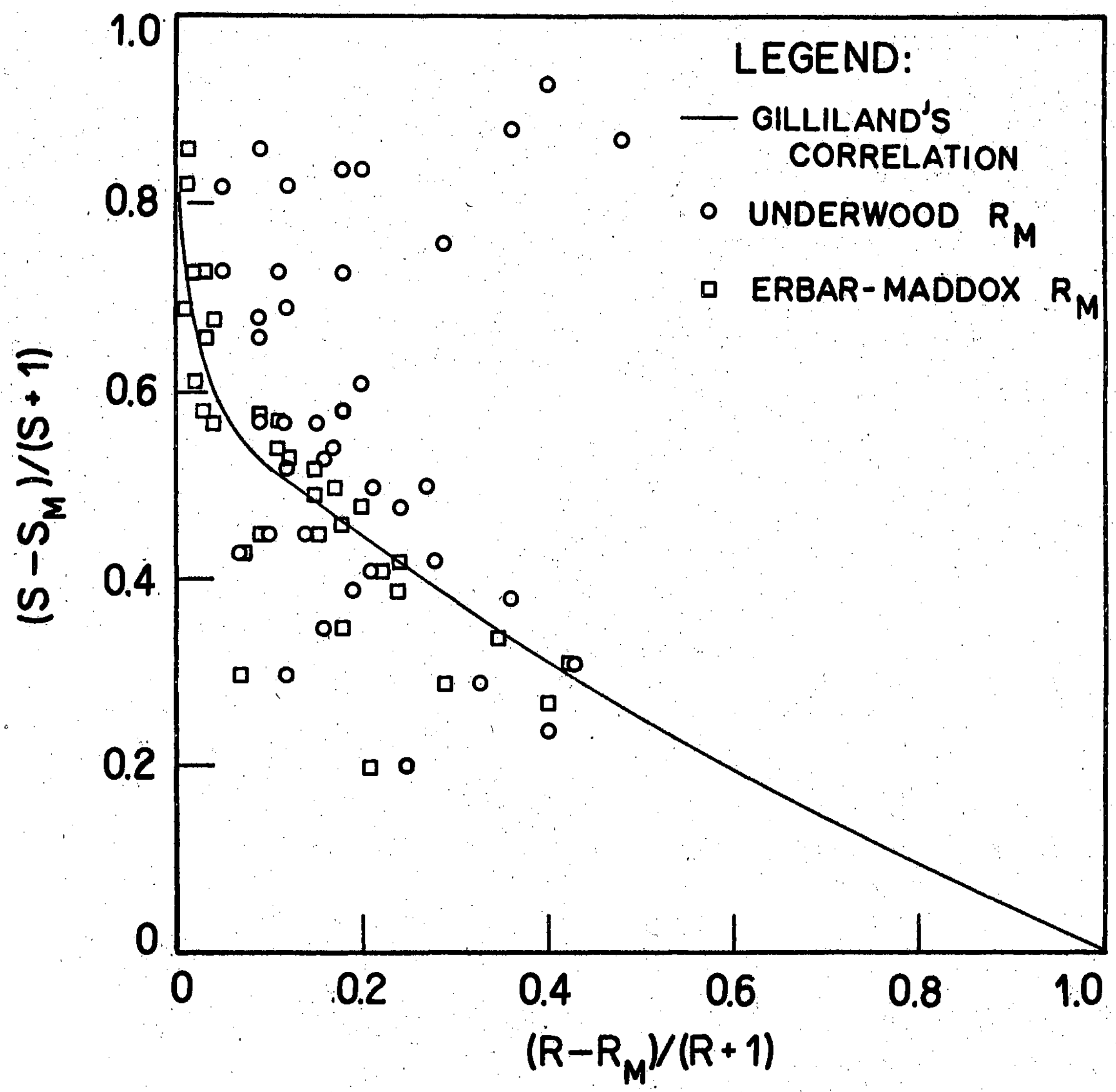


FIGURE 6

COMPARISON OF CALCULATED DATA WITH GILLILAND'S CORRELATION calculation and also the comparison based on Underwood's value of minimum reflux. Tables III, IV, V and VI compare actual values with values calculated from Gilliland's correlation and give the percentage error for each point. Table III compares the results of plate-to-plate calculations and Gilliland's correlation using rigorous minimum reflux values and considering reflux ratio as the independent variable and operating number of theoretical stages as the dependent variable. Table V shows the same comparison based on Underwood values of minimum reflux ratio. Table IV compares plate-to-plate results with Gilliland's correlation using rigorous values of minimum reflux and considering the operating number of stages to be the independent variable and reflux rate to be the dependent variable. Table VI shows the same comparison using Underwood values for minimum reflux.

Mason's Method

Equations 5 and 6, Figures 7, 8, 9 and 10, and Tables III, IV, V and VI compare the calculated data of this research with two modified forms of Mason's correlation.

$$(S - S_m) = \frac{(2.22)R_m^{0.365} S_m^{0.479}}{(R - R_m)^{0.381}} \qquad (5a)$$

$$(R - R_m) = \frac{(0.308)S_m^{1.317} R_m^{0.767}}{(S - S_m)^{1.424}} \qquad (5b)$$

Equation 5, Figures 7 and 9, and Tables III and V are based on the Erbar-Maddox rigorous minimum reflux values. Equation 5a, Figure 7, and Table III consider the reflux rate to be the independent variable and operating number of stages to be the dependent variable.

TABLE III

COMPARISON OF THE RESULTS OF EQUATION 5a, GILLILAND CORRELATION AND DATA FROM PLATE-TO-PLATE CALCULATIONS

Problem	Plate to	Modified Mason		Gilliland	
Number	Plate	S	% Error	S	% Error
01018.25200	19.0	19.040	2.116	18.677	1.700
01028.25200	29.0	29.530	1.828	25.692	11.407
01038.25200	39.0	32.382	16.969	23.491	39.767
01038.50000	39.0	37.291	4.382	38.508	1.262
01048.50000	49.0	43.090	12.061	48.811	0.386
01058.50000	59.0	49.003	16.944	60.929	3.270
01068.50000	69.0	53.793	22.039	70.464	2.122
02026.20000	27.0	27.517	1.915	26.064	3.467
02041.20000	42.0	36.399	13.336	40.274	4.110
02058.20000	59.0	45.940	22.136	57.075	3.263
02024.40000	25.0	31.125	24.500	31.451	25.804
02040.60000	41.0	49.841	21.566	59.644	45.471
02050.60000	51.0	64.536	26.541	90.877	78.190
03016.15761	17.0	17.856	5.035	13.486	20.671
03021.30000	22.0	25.697	16.805	25.155	14.341
03031.30000	32.0	35.679	11.497	41.536	29.800
03017.50000	18.0	17.480	2.889	18.321	1.783
03027.50000	28.0	23.755	23.583	25.077	10.439
04015.24500	17.0	17.344	2.024	16.538	2.718
04025.24500	27.0	32.561	20.596	28.098	4.067
04025.40000	27.0	28.513	5.604	27.987	3.656
04035.40000	37.0	35.247	4.738	38.904	5.146
04019.55080	21.0	20.105	4.262	21.948	4.514
04029.55080	31.0	25.184	18.761	30.488	1.652
05016.30000	18.0	18.200	5.111	18.448	2.489
05026.30000	28.0	30.453	8.761	28.596	2.129
05020.60000	22.0	24.044	9.291	27.192	23.600
05030.60000	32.0	35.162	9.881	46.007	43.772
07019.40000	21.0	20.808	0.914	23.431	11.576
07033.40000	35.0	34.715	0.814	43.200	23.429
Average absolute difference			11.230%		14.102%

TABLE IV

COMPARISON OF THE RESULTS OF EQUATION 5b, GILLILAND CORRELATION AND DATA FROM PLATE TO PLATE CALCULATIONS

Problem Number	Plate to Plate	Modified Mason		Gilliland	
		R	% Error	R	% Error
01018.25200	2.254	2.169	3.741	2.186	3.016
01028.25200	1.891	1.922	1.616	1.869	1.194
01038.25200	1.802	1.812	0.559	1.777	1.371
01038.50000	6.259	5.148	17.753	6.253	0.105
01048.50000	5.300	4.686	11.587	5.254	0.859
01058.50000	4.789	4.525	5.513	4.803	0.278
01068.50000	4.520	4.358	3.578	4.473	1.041
02026.20000	9.686	7.614	22.426	9.272	4.276
02041.20000	9.005	6.249	10.750	6.687	4.532
02058.20000	6.343	6.050	4.623	6.128	3.389
02024.40000	1.426	1.529	7.240	1.553	8.960
02040.60000	4.166	6.538	56.925	8.939	114.561
02050.60000	3.471	4.764	37.232	6.053	74.380
03016.15761	2.100	2.093	0.319	2.017	3.948
03021.30000	6.005	6.115	1.836	7.713	28.439
03031.30000	4.623	4.909	6.183	5.343	15.572
03017.50000	1.179	1.075	8.843	1.158	1.803
03027.50000	1.013	0.998	1.502	0.977	3.540
04015.24500	2.627	2.357	10.287	2.517	4.180
04025.24500	2.003	2.071	3.388	2.017	0.706
04025.40000	4.295	3.682	14.270	4.847	1.287
04035.40000	3.236	2.936	9.272	3.454	6.711
04019.55080	1.056	0.839	20.509	1.124	6.495
04029.55080	0.870	0.719	17.338	0.823	5.386
05016.30000	2.705	2.475	8.499	2.721	0.566
05026.30000	2.064	2.124	2.953	2.088	1.197
05020.60000	1.199	1.209	0.826	1.674	39.656
05030.60000	0.999	1.129	12.998	1.393	39.467
07019.40000	1.0153	0.921	9.330	1.139	11.387
07033.40000	0.791	0.836	5.705	0.881	11.406
Average absolute difference			10.588		13.327

TABLE V

COMPARISON OF THE RESULTS OF EQUATION 6a, GILLILAND CORRELATION AND DATA FROM PLATE TO PLATE CALCULATIONS

Problem	Plate to	Modified Mason		Gilliland	
Number	Plate	S	% Error	S	% Error
01018.25200	19.0	25.276	33.033	14.887	21.648
01028.25200	29.0	27.472	5.269	17.155	40.857
01038.25200	39.0	26.513	32.018	14.945	61.681
01048.25200	49.0	27.729	43.410	15.441	68.486
01038.50000	39.0	37.311	4.331	36.883	5.428
01048.50000	49.0	40.690	16.660	45.321	7.495
01058.50000	59.0	43.316	26.583	53.632	9.148
01068.50000	69.0	45.576	33.948	61.500	10.869
02026.20000	27.0	30.297	62.209	25.799	4.451
02041.20000	42.0	35.945	14.417	39.348	6.312
02058.20000	59.0	41.107	30.327	55.103	6.606
02024.40000	25.0	29.858	19.433	24.799	0.804
02034.40000	35.0	31.740	9.314	24.890	28.881
02044.40000	45.0	31.448	30.115	21.642	31.907
02040.60000	41.0	45.689	11.437	55.681	35.809
02050.60000	51.0	50.852	0.289	78.492	53.905
02060.60000	61.0	57.726	5.368	108.908	78.338
03016.15761	17.0	23.678	39.284	8.387	50.666
03026.15761	27.0	23.822	11.771	7.946	70.569
03021.30000	22.0	28.906	31.390	23.963	8.922
03031.30000	32.0	33.925	6.015	36.836	15.110
03017.50000	18.0	25.652	42.512	16.598	7.787
03027.50000	28.0	28.841	3.003	21.448	23.401
04013.08266	15.0	21.186	41.237	5.183	65.446
04023.08266	25.0	19.787	20.851	3.811	84.756
04015.24500	17.0	24.042	41.424	14.038	17.424
04025.24500	27.0	27.335	1.241	17.989	33.371
04025.40000	27.0	51.181	91.800	29.550	9.450
04035.40000	37.0	37.124	0.335	42.232	14.140
04019.55080	21.0	27.183	29.443	22.239	5.900
04029.55080	31.0	30.912	0.285	31.215	0.694
05016.30000	18.0	25.402	41.122	16.703	7.207
05026.30000	28.0	29.724	6.158	22.840	18.430
05020.60000	22.0	30.123	36.924	28.386	29.028
05030.60000	32.0	36.949	15.465	46.684	45.889
07016.08600	18.0	13.974	22.365	2.370	86.833
07031.08600	33.0	16.286	50.648	2.511	92.392
07017.21000	19.0	24.393	28.384	13.135	30.868
07032.21000	34.0	23.229	31.680	9.310	72.619
07019.40000	21.0	29.851	42.147	2.665	26.885
07033.40000	35.0	30.535	12.758	30.684	12.331
Average absolute difference			23.123%		32.837%

TABLE VI

COMPARISON OF THE RESULTS OF EQUATION 6b, GILLILAND CORRELATION AND DATA FROM PLATE TO PLATE CALCULATIONS

Problem Number	Plate to Plate	Modified Mason R	Modified Mason % Error	Gilliland R	Gilliland % Error
01018.25200	2.254	2.468	9.507	1.871	16.997
01028.25200	1.891	2.127	12.480	1.607	15.336
01038.25200	1.802	1.896	5.199	1.463	8.722
01048.25200	1.700	1.830	7.635	1.457	14.314
01038.50000	6.259	4.123	34.131	5.768	7.851
01048.50000	5.300	4.052	23.542	4.835	8.762
01058.50000	4.789	4.011	16.252	4.362	8.926
01068.50000	4.520	3.991	11.204	4.121	8.838
02026.20000	9.686	6.437	33.540	9.067	6.383
02041.20000	7.005	6.069	13.360	6.562	6.321
02058.20000	6.343	6.001	5.388	6.021	5.077
02024.40000	1.426	1.733	21.497	1.382	3.117
02034.40000	1.292	1.569	21.401	1.171	9.394
02044.40000	1.212	1.442	18.440	1.021	16.159
02040.60000	4.166	3.679	11.690	8.400	91.639
02050.60000	3.471	3.514	1.236	5.645	62.601
02060.60000	3.133	3.430	9.497	4.642	48.170
03016.15761	2.100	2.412	14.889	1.542	26.552
03026.15761	1.918	2.026	5.661	1.414	26.269
03021.30000	6.005	5.043	16.015	7.225	20.315
03031.30000	4.623	4.707	1.823	5.032	8.856
03017.50000	1.179	1.412	19.762	1.058	10.239
03027.50000	1.013	1.238	22.199	0.887	12.488
04013.08266	2.520	2.505	0.619	1.524	39.553
04023.08266	2.014	1.524	24.352	0.946	53.062
04015.24500	2.627	2.576	1.921	2.126	19.049
04025.24500	2.003	2.226	11.105	1.680	15.640
04025.40000	4.295	7.792	81.446	4.530	5.465
04035.40000	3.236	3.029	6.414	3.733	15.349
04019.55080	1.006	1.092	3.434	1.145	8.412
04029.55080	0.870	0.923	6.104	0.844	2.930
05016.30000	2.705	2.759	1.977	2.474	8.557
05026.30000	2.064	2.395	16.042	1.896	8.116
05020.60000	1.199	1.405	17.203	1.742	45.301
05030.60000	0.999	1.244	24.572	1.405	40.608
07016.08600	1.008	0.223	77.929	0.055	94.539
07031.08600	0.831	0.286	65.564	0.111	86.599
07017.21000	2.344	2.468	5.290	1.813	22.676
07032.21000	1.562	1.486	4.866	1.061	32.100
07019.40000	1.015	1.337	31.697	1.257	23.801
07033.40000	0.791	0.780	1.438	0.663	16.177
Average absolute difference			17.934%		24.895%

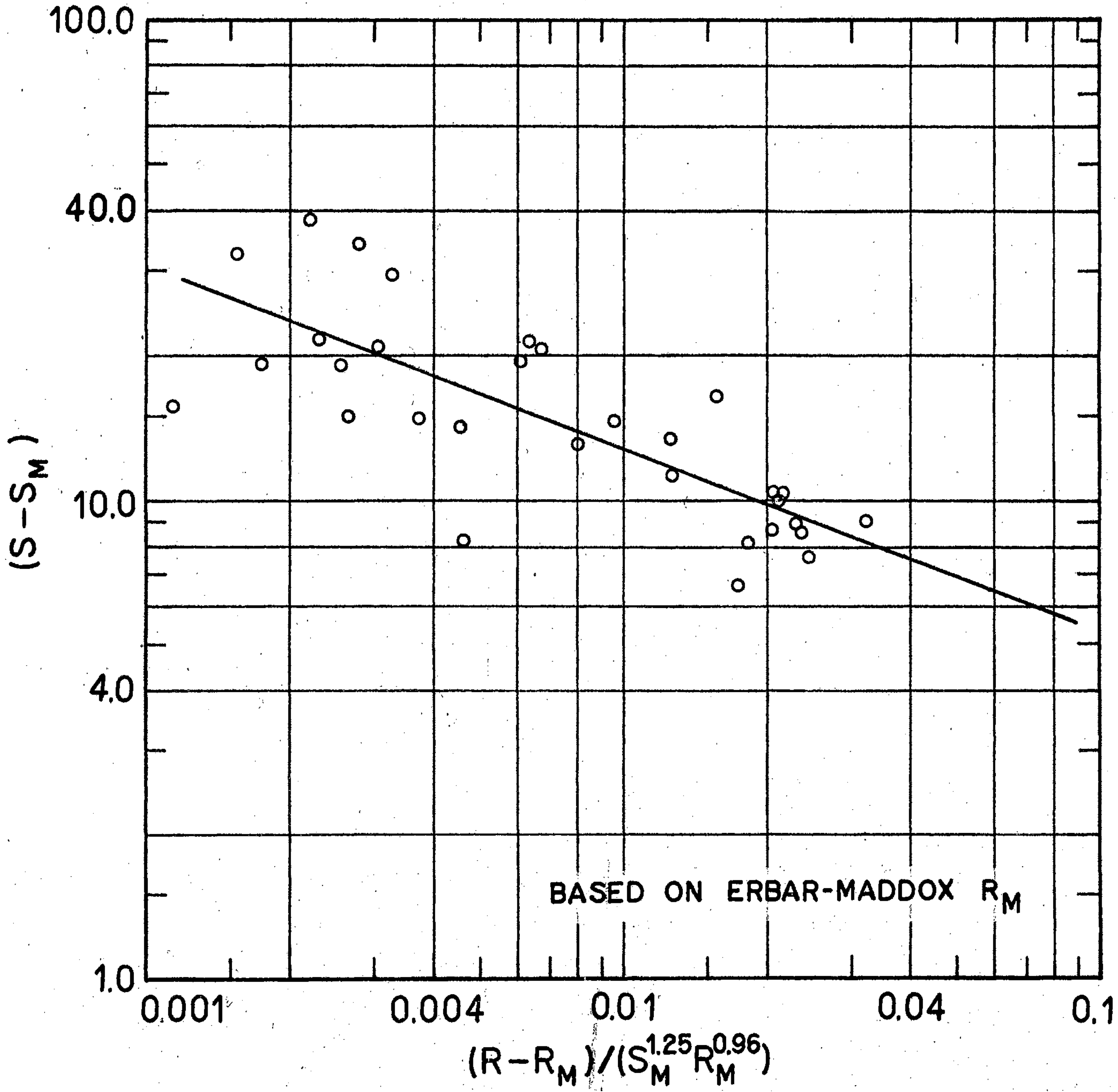


FIGURE 7

GRAPHICAL SOLUTION OF EQUATION 5a

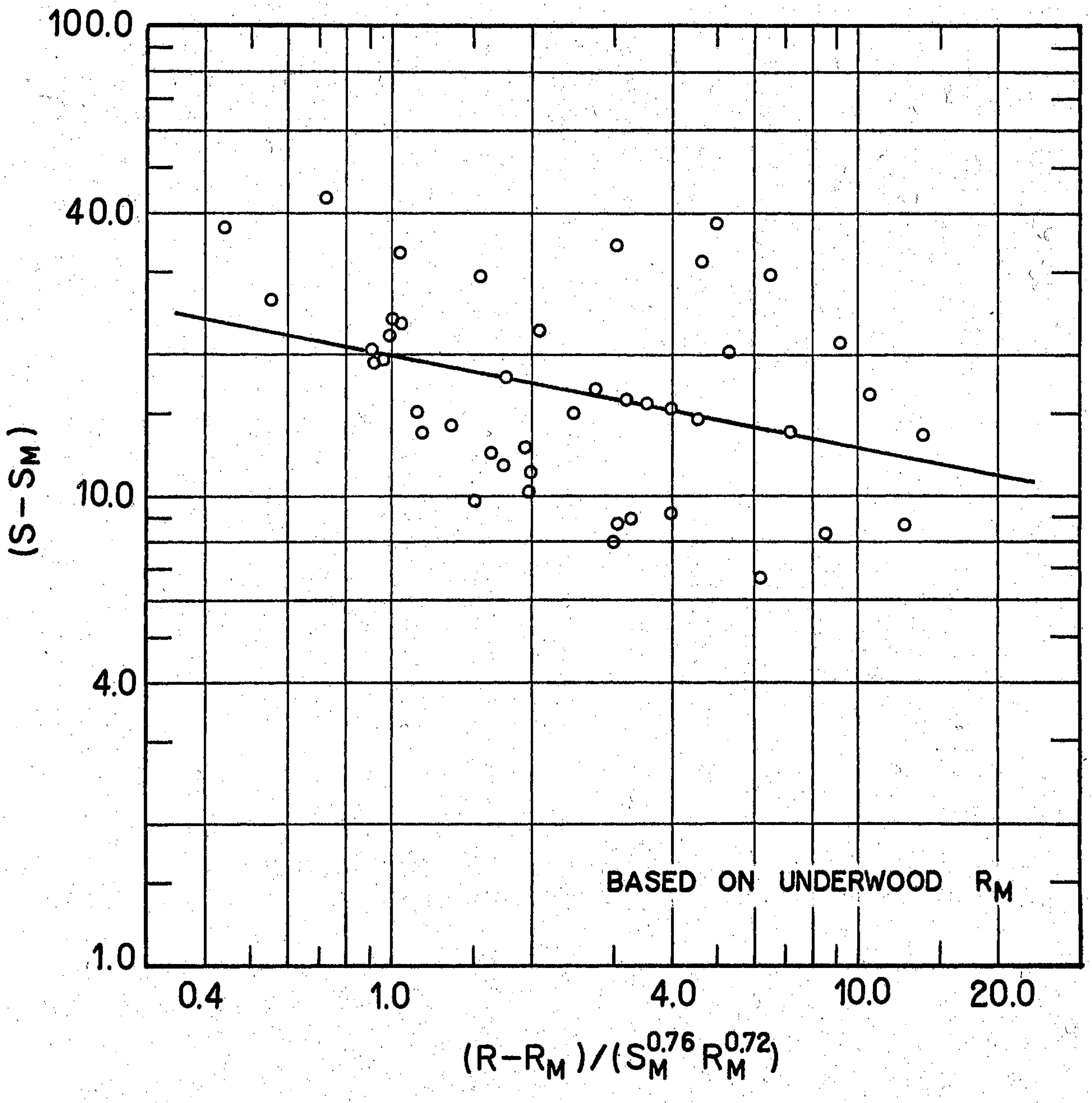


FIGURE 8

GRAPHICAL SOLUTION OF EQUATION 6a

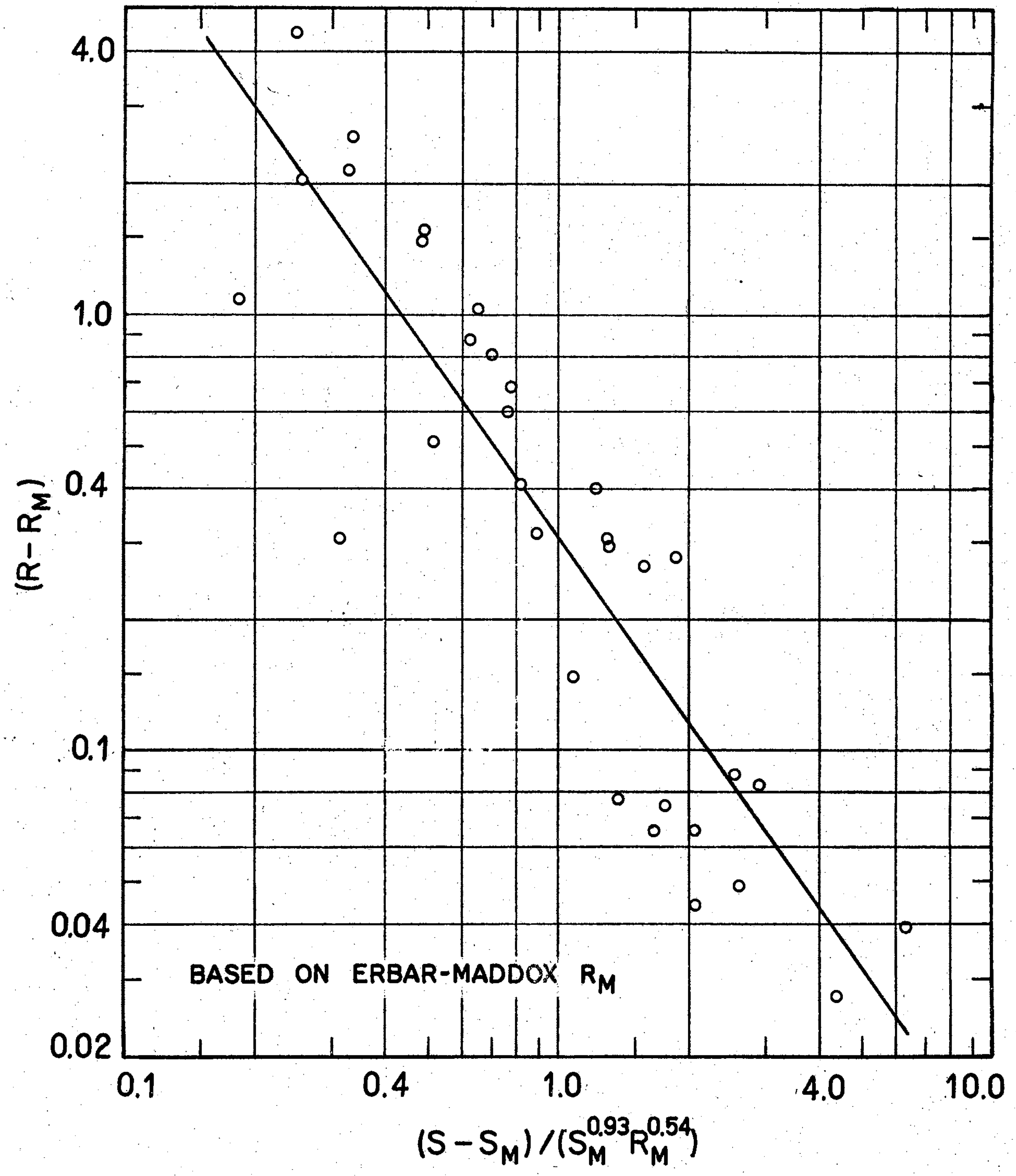


FIGURE 9

GRAPHICAL SOLUTION OF EQUATION 5b

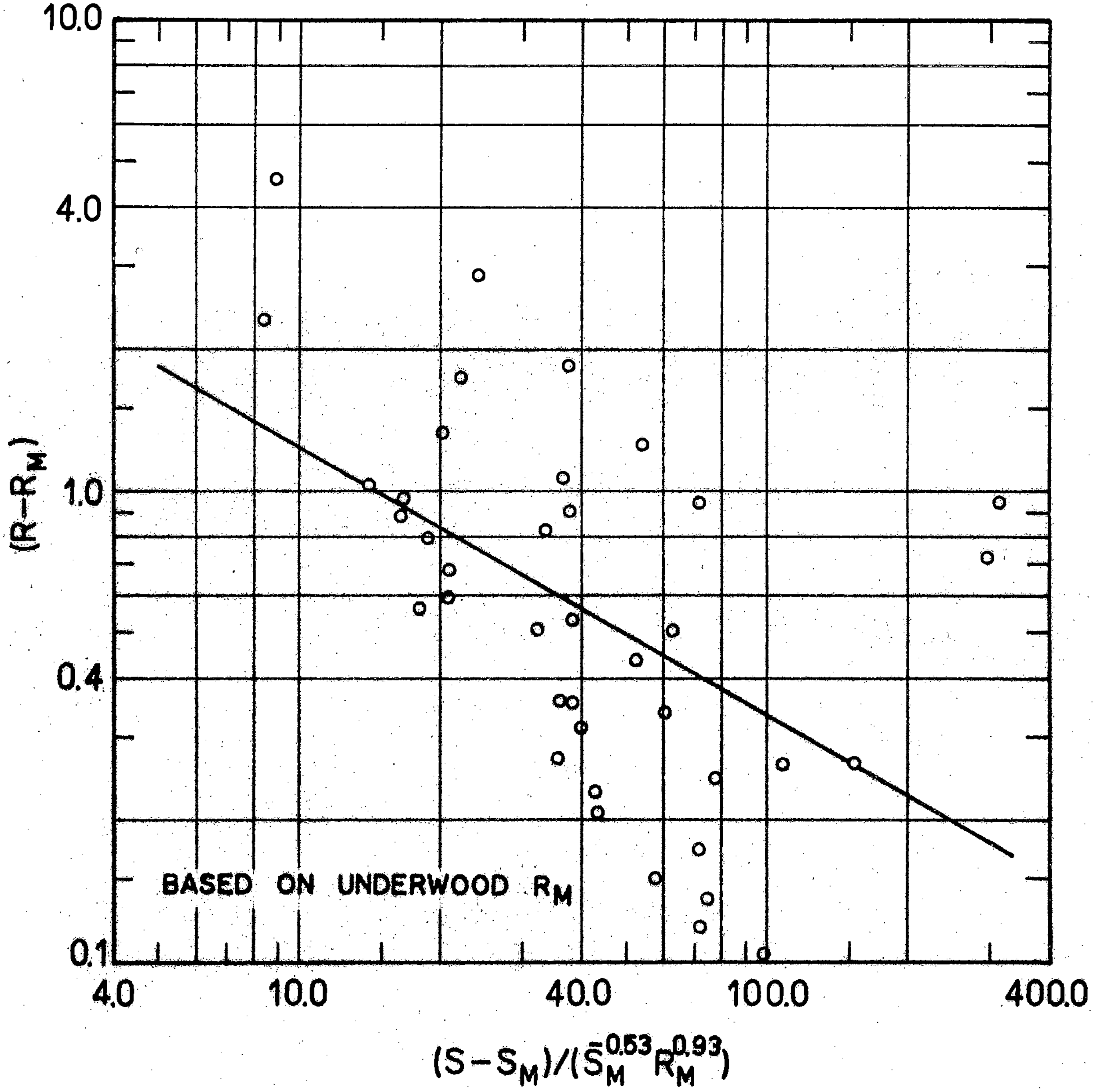


FIGURE 10

GRAPHICAL SOLUTION OF EQUATION 6b

Equation 5b, Figure 9, and Table V consider operating number of stages the independent variable and reflux rate the dependent variable.

Equation 6, Figures 8 and 10, and Tables IV and VI compare the modified Mason equation with the calculated data when using Underwood's values for minimum reflux ratio.

$$(S - S_m) = \frac{(20.35)R_m^{0.149}\ S_m^{0.157}}{(R - R_m)^{0.206}} \qquad (6a)$$

$$(R - R_m) = \frac{(4.65)S_m^{-0.306}\ R_m^{0.539}}{(S - S_m)^{0.577}} \qquad (6b)$$

Equation 6a, Figure 8, and Table IV consider reflux rate the independent variable and operating number of stages the dependent variable. Equation 6b, Figure 10, and Table VI consider operating number of stages the independent variable and reflux rate the dependent variable.

New Method of Correlation

Figures 11, 11a, 12, 12a, along with Tables VII and VIII show the proposed new correlation method. Figure 11a and 12a are raw data plots based on calculated data. Figures 11 and 12 are the smoothed and generalized plots recommended for use. Examination of the errors in Tables VII and VIII shows that the new correlation of reflux ratio and plates offers great advantage over the other correlation attempts.

Feed Flash Correlation

Twenty-five plate-to plate calculations were made to investithe effect of feed flash on reflux ratio. The results of these

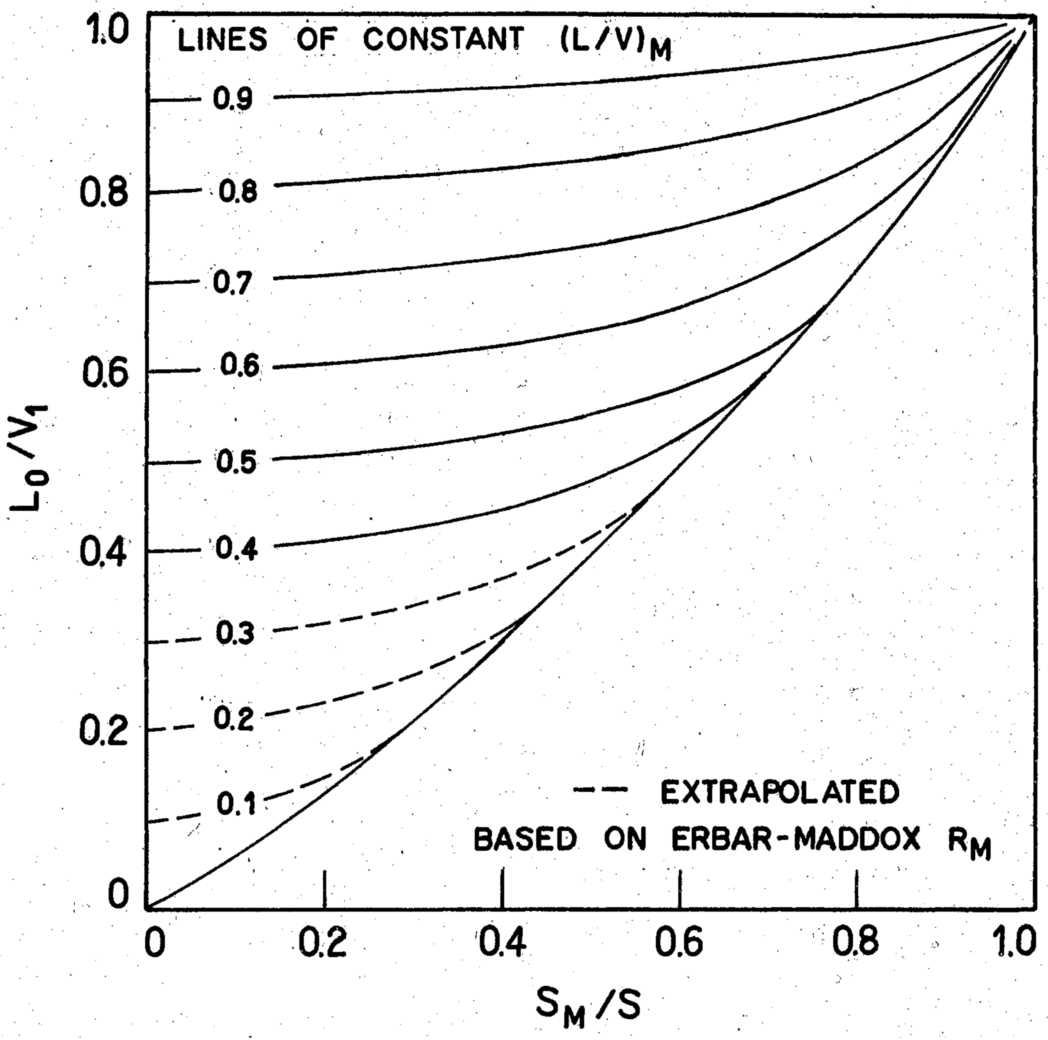


FIGURE 11

PROPOSED CORRELATION OF MINIMUM AND OPERATING REFLUX RATIO AND STAGES

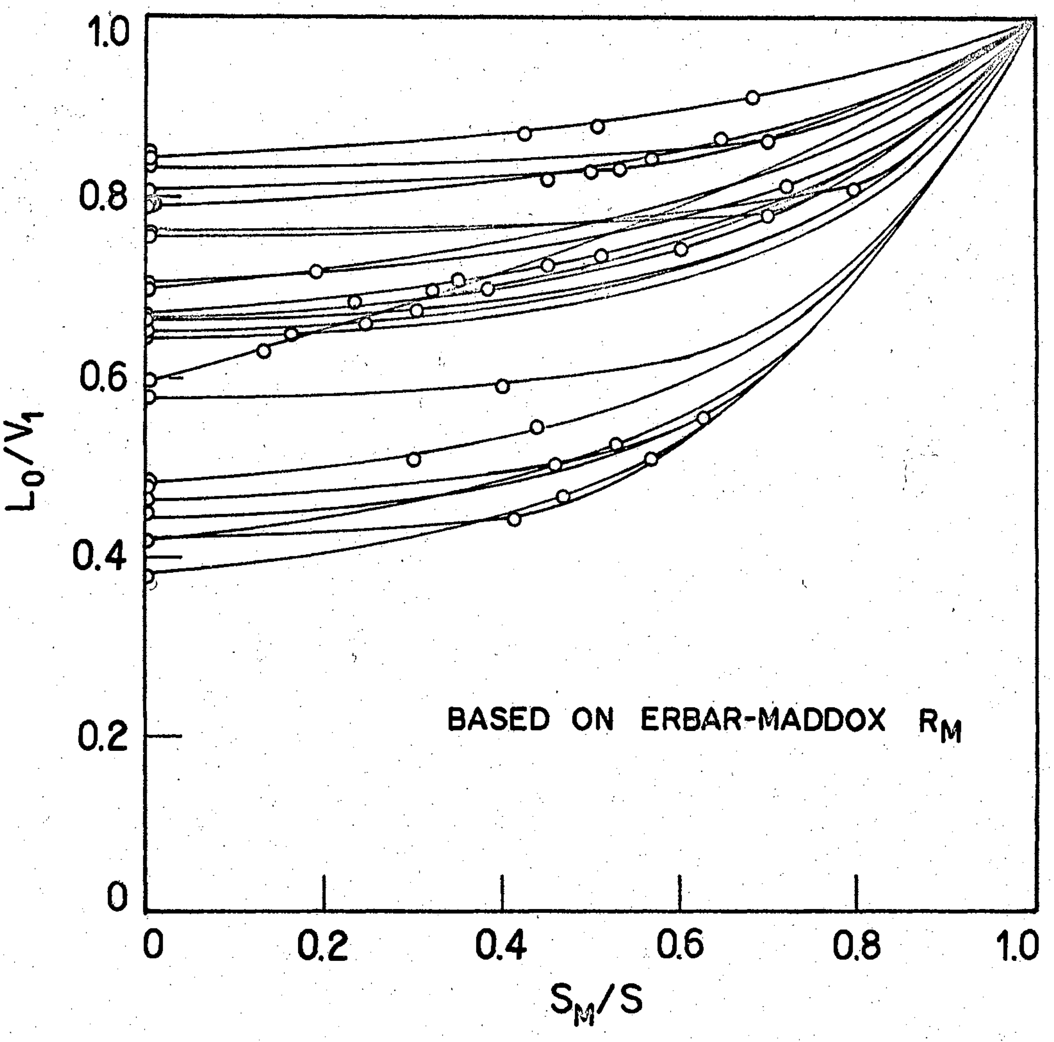


FIGURE 11a

RAW DATA PLOTTED IN THE FORM OF THE PROPOSED CORRELATION

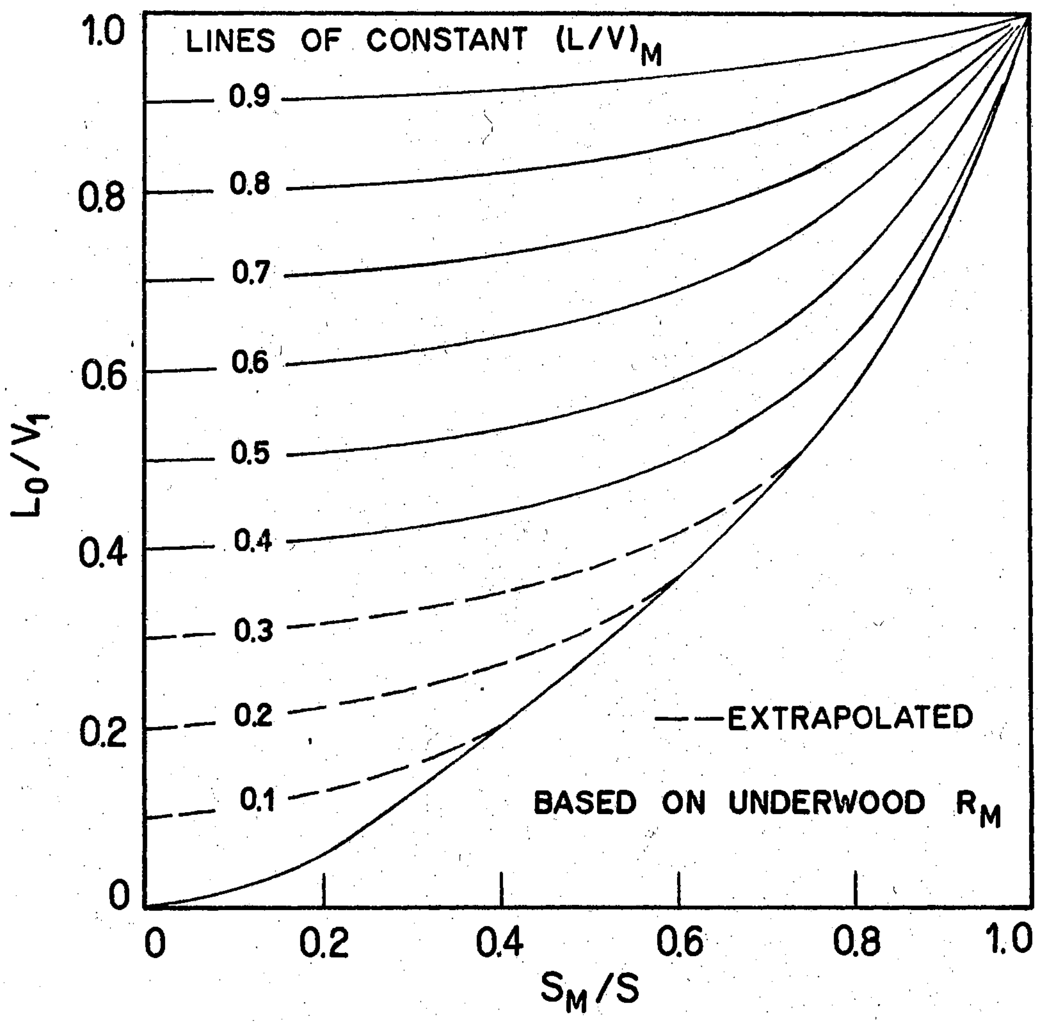


FIGURE 12

PROPOSED CORRELATION OF MINIMUM AND OPERATING REFLUX RATIO AND STAGES

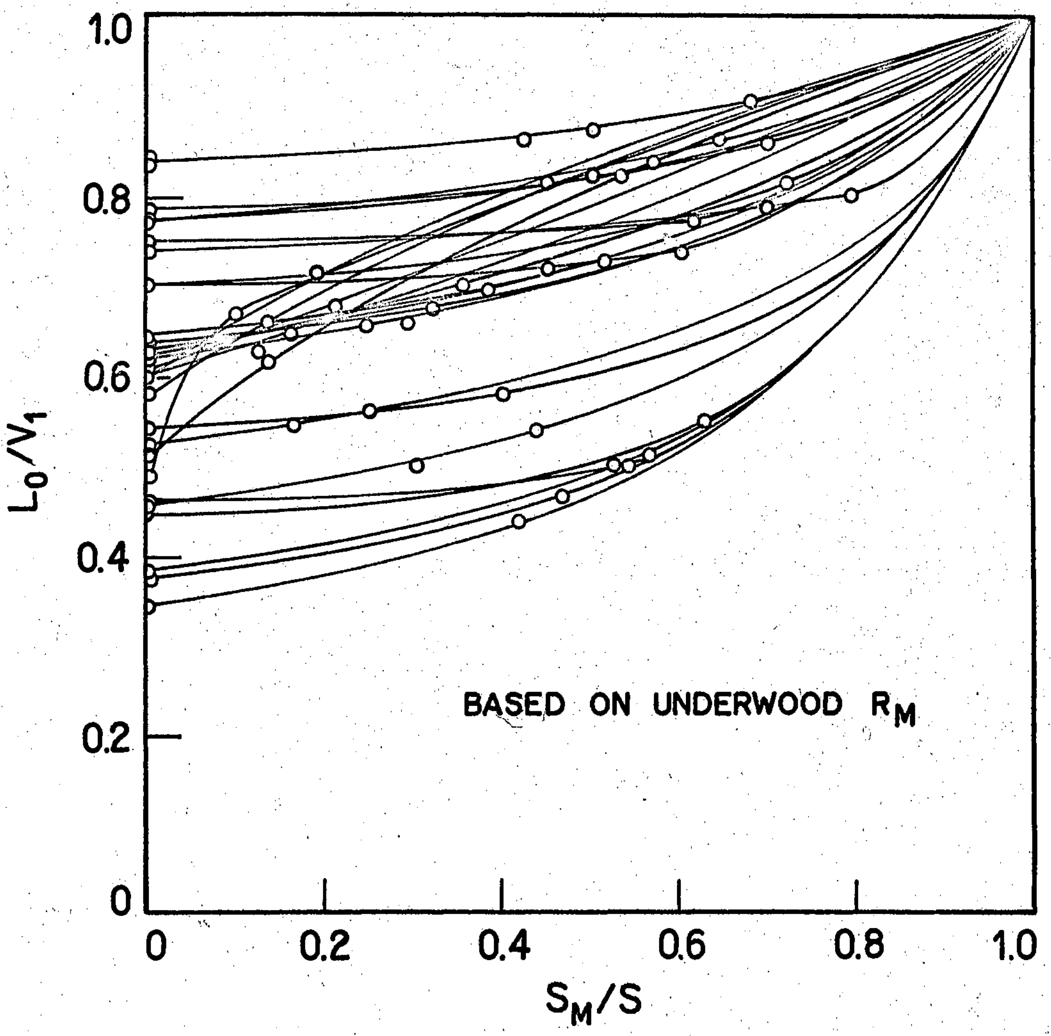


FIGURE 12a

RAW DATA PLOTTED IN THE FORM OF THE PROPOSED CORRELATION

TABLE VII

COMPARISON OF THE RESULTS OF FIGURE 11 AND DATA FROM PLATE TO PLATE CALCULATIONS

Problem Number	$(S_m / S)_{op}$	$(L/V)_{min}$ E-M	$(L/V)_{op}$ CALC	$(L/V)_{op}$ CORR	% Error
01018.25200	0.386	0.664	0.692	0.692	0.00
01028.25200	0.244	0.648	0.655	0.655	0.00
01038.25200	0.162	0.640	0.645	0.645	0.00
01048.25200	0.122	0.594	0.630	0.597	5.24
01038.50000	0.645	0.787	0.862	0.848	1.62
01048.50000	0.516	0.792	0.840	0.840	0.00
01058.50000	0.500	0.797	0.826	0.830	0.48
01068.50000	0.450	0.797	0.820	0.825	0.61
02026.20000	0.680	0.840	0.907	0.898	0.99
02041.20000	0.502	0.840	0.875	0.865	1.14
02058.20000	0.423	0.847	0.865	0.865	0.00
02024.40000	0.399	0.576	0.586	0.605	3.24
02040.60000	0.795	0.755	0.805	0.810	0.62
02050.60000	0.692	0.760	0.780	0.782	0.26
03016.15761	0.231	0.666	0.678	0.675	0.44
03021.30000	0.698	0.831	0.858	0.890	3.73
03031.30000	0.531	0.805	0.825	0.833	0.97
03017.50000	0.438	0.476	0.540	0.540	0.00
03027.50000	0.298	0.482	0.505	0.505	0.00
04013.08266	0.190	0.693	0.717	0.700	2.37
04015.24500	0.447	0.667	0.725	0.705	2.76
04025.24500	0.288	0.663	0.667	0.671	0.60
04025.40000	0.717	0.685	0.810	0.785	3.09
04035.40000	0.600	0.658	0.740	0.725	2.03
04019.55080	0.566	0.378	0.513	0.500	2.54
04029.55080	0.465	0.372	0.465	0.450	3.22
05016.30000	0.512	0.670	0.730	0.720	1.37
05026.30000	0.320	0.665	0.675	0.685	1.48
05020.60000	0.630	0.443	0.550	0.550	0.00
05030.60000	0.558	0.460	0.500	0.535	7.00
07017.21000	0.354	0.665	0.701	0.690	1.57
07019.40000	0.528	0.415	0.505	0.500	0.99
07033.40000	0.415	0.421	0.440	0.420	4.55
Average absolute difference					1.60%

TABLE VIII

COMPARISON OF THE RESULTS OF FIGURE 12 AND DATA FROM PLATE TO PLATE CALCULATIONS

Problem Number	(S_m / S)	$(L/V)_{min}$ UW	$(L/V)_{op}$ CALC	$(L/V)_{op}$ CORR	% Error
01018.25200	0.386	0.625	0.692	0.655	5.35
01028.25200	0.244	0.617	0.655	0.635	3.06
01038.25200	0.162	0.595	0.645	0.600	6.98
01048.25200	0.122	0.592	0.630	0.598	5.08
01038.50000	0.645	0.770	0.862	0.845	1.97
01048.50000	0.566	0.779	0.840	0.835	0.60
01058.50000	0.500	0.780	0.826	0.830	0.49
01068.50000	0.450	0.782	0.820	0.819	0.12
02026.20000	0.680	0.837	0.907	0.895	1.32
02041.20000	0.502	0.845	0.875	0.875	0.00
02058.20000	0.423	0.845	0.865	0.865	0.00
02024.40000	0.399	0.545	0.576	0.576	0.00
02034.40000	0.248	0.545	0.565	0.555	1.77
02044.40000	0.162	0.527	0.555	0.532	4.15
02040.60000	0.795	0.740	0.805	0.875	8.70
02050.60000	0.692	0.750	0.780	0.840	7.70
02060.60000	0.617	0.750	0.760	0.817	7.50
03016.15761	0.231	0.610	0.678	0.620	8.55
03026.15761	0.134	0.580	0.655	0.590	9.93
03021.30000	0.698	0.783	0.858	0.858	0.00
03031.30000	0.531	0.775	0.825	0.825	0.00
03017.50000	0.438	0.453	0.540	0.505	6.48
03027.50000	0.298	0.456	0.505	0.480	4.95
04015.24500	0.447	0.625	0.725	0.667	8.28
04025.24500	0.288	0.621	0.667	0.640	4.22
04025.40000	0.717	0.700	0.810	0.810	0.00
04035.40000	0.600	0.707	0.740	0.770	4.05
04019.55080	0.566	0.382	0.513	0.470	8.39
04029.55080	0.465	0.379	0.465	0.440	5.38
05016.30000	0.512	0.645	0.730	0.701	3.98
05026.30000	0.320	0.642	0.675	0.661	2.07
05020.60000	0.630	0.456	0.550	0.555	0.91
05030.60000	0.558	0.462	0.500	0.531	6.20
07017.21000	0.354	0.625	0.701	0.650	7.27
07032.21000	0.135	0.515	0.615	0.520	15.45
07019.40000	0.528	0.447	0.505	0.510	0.99
07033.40000	0.415	0.345	0.440	0.400	9.10
Average absolute difference					4.35

calculations are summarized in Table IX. In order to obtain these data, it was necessary to modify slightly the basic plate-to-plate program. Through these modifications it was possible to specify the composition of the key components in the overhead and bottom streams. With a specified number of plates, the program would adjust the reflux ratio until a value of reflux was found which would give essentially the same distillate composition as had been derived from another solution of the same problem.

Figure 13 shows a typical curve relating reflux ratio and percentage feed vaporization. The proposed correlation to represent this change is shown in Equation 7.

$$V_{1u} = V_{1k} + \frac{\left(1 - \frac{D}{F}\right)\left(H^{f}F_{u} - H^{f}F_{k}\right)}{\left(\frac{Q_{c}}{L_{CT}}\right)_{k}} \tag{7}$$

The degree to which this equation represents the calculated data is also shown in Figure 13 and Table IX.

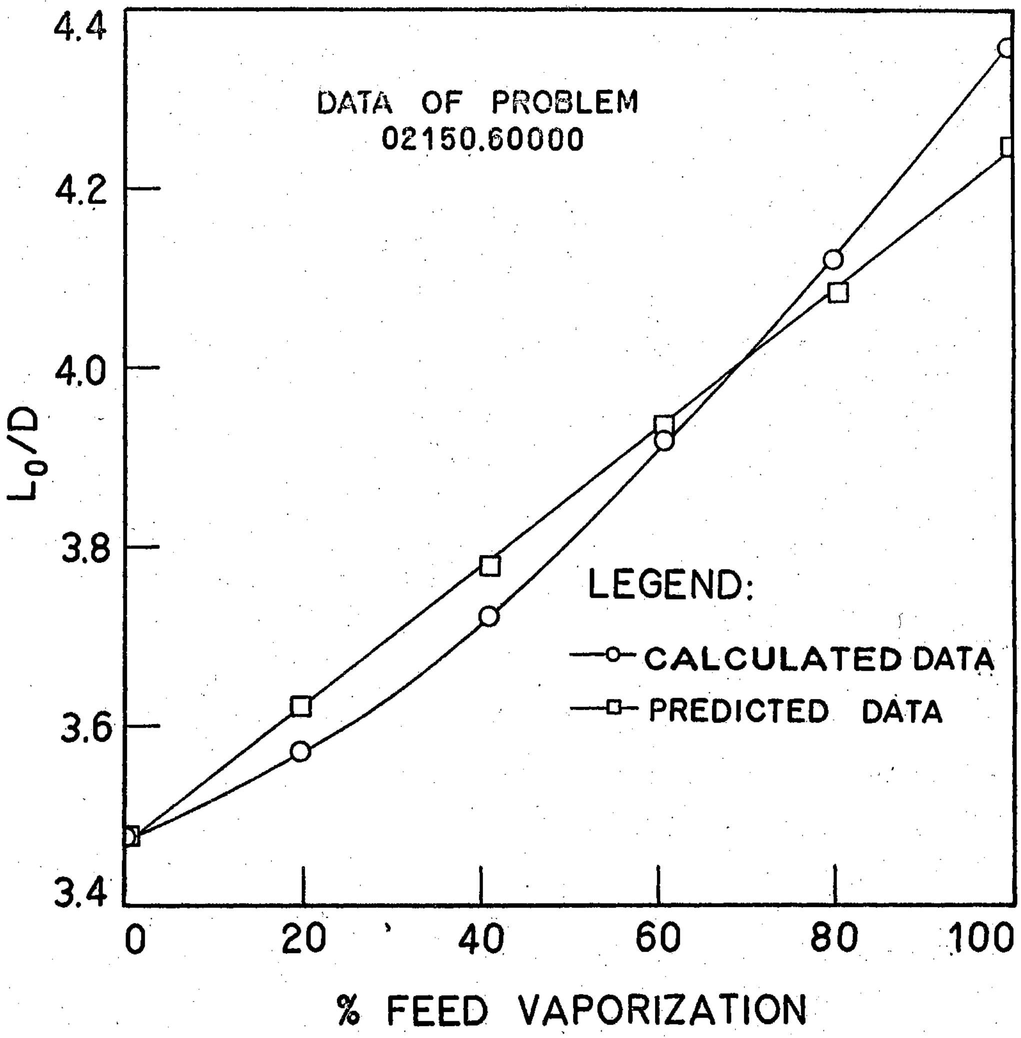


FIGURE 13

A TYPICAL CURVE RELATING REFLUX RATIO AND PERCENTAGE FEED VAPORIZATION

TABLE IX

COMPARISON OF THE RESULTS OF EQUATION 7 AND CALCULATED DATA

Problem Number	% Feed Vaporization	Calculated L_o/D	Predicted L_o/D	% Error
02126.20000	19.6	10.547	10.733	1.76
	41.0	11.592	11.793	1.75
	60.2	12.463	12.777	2.52
	79.7	13.474	13.799	2.41
	100.0	14.653	14.923	1.84
02124.40000	25.7	1.807	1.924	6.47
	50.8	2.299	2.406	4.79
	75.2	2.846	2.884	1.34
	100.0	3.540	3.398	4.01
02150.60000	19.6	3.571	3.627	1.23
	41.0	3.737	3.787	1.34
	60.2	3.920	3.931	0.28
	79.7	4.123	4.083	0.97
	100.0	4.380	4.250	2.97
03116.15761	25.8	3.230	4.070	23.10
	49.9	4.411	5.781	31.10
	100.0	7.277	9.406	28.90
03121.30000	25.4	6.790	6.883	1.65
	50.0	7.426	7.614	2.55
	72.3	8.108	8.290	2.23
	100.0	9.137	9.099	0.41
04125.40000	24.8	4.685	4.870	3.94
	50.4	5.306	5.399	1.75
	68.8	5.631	5.783	2.70
	100.0	6.448	6.461	0.82

Average absolute difference	5.31%
Average absolute difference omitting data of Problem 03116.15761	2.26%
Average absolute difference Problem 03116.15761	27.70%

CHAPTER V

DISCUSSION OF RESULTS

Reference to Tables XVI through LVI will show that the R. Erbar method for the determination of the minimum reflux ratio was not applied to all separations. In certain cases, inconsistencies in the enthalpy data caused cycling in the tray calculations of the program developed to compute the minimum reflux ratio by the R. Erbar method. This cycling extended the time requirement from approximately two and one-half hours to ten hours per problem. Such extended time requirements made impractical the solution of some problems by this method. For this reason, plus the fact that two correlations were desired, calculations were carried out based on the Underwood method. This method has also been programmed for computer solution and is much shorter than the Erbar method.

In several cases, the R. Erbar method predicted a minimum reflux ratio that was greater than the reflux ratio used in the plate-to-plate solution of the problem. This inconsistency stems from a lack of a consistent set of enthalpy and equilibrium data. Problems exhibiting this characteristic were not included in any of the correlations.

The location of the feed plate in the original plate-to-plate calculations was determined in the following manner:

1. The minimum number of stages was calculated by the Fenske equation.

2. Using the relative volatility data calculated in Step 1, a Fenske calculation was carried out substituting the feed composition for the bottoms composition.
3. The ratio of the minimum number of stages in the enriching section to the total minimum number of stages was multiplied by the operating number of stages to determine the final feed plate location.

Although it is recognized that this method may not give the optimum feed location with respect to operating conditions, it is a good approximation (3). Determination of the optimum feed location would be a long, arduous task if attempted using the J. Erbar-Maddox plate-to-plate program. Although no comparisons were carried out, it is the opinion of the author that no significant difference would result in the product distributions from the feed plate located in the above manner and located optimumly.

As mentioned previously, the correlation of the minimum and operating reflux ratio and the minimum and operating number of stages were based on bubble point feeds in every case. This restriction was placed on the feed condition in the hope that a more consistent set of data would be obtained. No attempt was made to include in the reflux ratio-plates correlations any feed which was partially vaporized at tower conditions.

In calculating the data for the various correlations, the same thermodynamic data sources were used in all problems. For the plate-to-plate calculation, the vapor-liquid equilibria data had to be converted to relative volatilities before the calculation could be carried out. For the determination of the minimum parameters, the thermodynamic data for each problem were simply transferred from one program deck to another. Here again the purpose was to be as consistent as possible.

Correlation of the data for the minimum and operating reflux ratio and minimum and operating number of stages was accomplished by use of statistical methods and empirical curve fitting. The statistical methods have been programmed for computer solution and are available through International Business Machines Corporation. Two separate methods of correlating the minimum and operating parameters are presented. Within each of these methods, two relationships based on different methods of calculation of the minimum reflux rate are given. The reasons for presenting the data for different sources of minimum reflux ratio data are:

1. The Erbar-Maddox method for the determination of the minimum reflux ratio is an extremely long, time consuming calculation even on the digital computer. This method is not suited to hand computation.
2. To point out that consistent methods for the determination of the minimum parameters must be used if a correlation is to be expected to give reliable results.
3. To allow the design engineer some flexibility in the choice of calculation methods he wishes to use.

Based on the results of a comparison of different methods of computing the minimum reflux ratio carried out by R. Erbar, the decision was made to use the Underwood method as an alternative method for the prediction of minimum reflux ratios. This method gave the smallest deviation of any of the methods compared by

R. Erbar. The results of Morrison's work indicated the Winn method of computing the minimum number of stages was the better of the two short cut methods available.

The major problem in the correlation of the minimum and operating number of stages was that of determining the form to be used. Here again, several alternative methods were tried and, one by one, eliminated. The data were plotted in the form originally used by Gilliland. The results of this plotting are shown in Figure 6. As found by Gilliland, considerable scatter around the central line was noted. The method suggested by Underwood and later modified by Mason was also used. Statistical methods for the determination of the constants of Equations 5 and 6 were used. The results of these computations are shown in Figures 7, 8, 9, and 10. As with the Gilliland method of correlation, considerable scatter around the computed line was found.

Dissatisfaction with the ability of these correlations to adequately represent the data of this investigation prompted the development of a new method for correlating the minimum and operating reflux ratio and the minimum and operating number of stages. This development is based on the two limits of fractionator operation. These limits are the minimum reflux ratio which occurs at an infinite number of stages and the minimum number of stages which occurs at an infinite reflux ratio. Consideration of the number of stages between these two limits showed that the ratio (S_m / S) would vary between zero and unity for all cases of fractionator operation. Further consideration of the limiting conditions indicated that the reflux ratio could not be so conveniently handled. Another way of expressing the reflux ratio is by the term (L_o / V_1) which is related to the reflux ratio by

$$\frac{L_o}{V_1} = \frac{R}{1 + R} \tag{8}$$

Examination of the ratio (L_o / V_1) at the limiting conditions showed that it reached a maximum value of one at the minimum number of stages. This ratio, while never zero, can then vary between zero and one. Based on the above reasoning, a good assumption would be that points between the limiting conditions could be connected with minimum values $\left[(L_o / V_1)_m, S_m / S = 0; L_o / V_1 = S_m / S = 1)\right]$ by a smooth curve. Rather than a single curve pertaining to all separations, the proposed method would have a family of curves each for a particular minimum (L_o / V_1) ratio. Such curves could be interpolated to determine the conditions of operating stages and (L_o / V_1) ratio.

Plots of the data of this investigation have verified the reasonableness of the assumption regarding the curves connecting the minimum conditions and operating conditions. As a general rule the shape of such curves is of the exponential form:

$$g^c = z \tag{9}$$

where: $c > 1$

In certain cases, plots of the data indicated that the exponent, c, should be between zero and unity. This occurred in only three or four cases and was presumed to indicate that the points were in error.

Two generalized plots (Figures 11 and 12) correlating $(L_o / V_1)_{op}$, $(L_o / V_1)_m$, and S_m / S were developed from the data of this investigation. The parameters $(L_o / V_1)_m$ were adjusted to give the best correlation possible from this data. Use of these charts is quite simple:

1. Compute the minimum parameters, S_m, R_m
2. Compute the ratios S_m / S and $(L_o / V_1)_m$
3. Locate the point S_m / S and $(L_o / V_1)_m$ by use of the abscissa and the parameters of the chart
4. Read $(L_o / V_1)_{op}$ from the ordinate
5. Convert $(L_o / V_1)_{op}$ to R_{op} if necessary (Equation 8)

Although it is recognized that the proposed correlations may be difficult to use in the region $0 > S_m / S > 0.1$, this is not a serious limitation in that seldom does fractionator operation fall within this area. If values of S_m / S less than 0.1 are encountered and $(L_o / V_1)_m$ is greater than 0.7 a good approximation of the curve can be made by a straight line connecting $\left[S_m / S = 0,\ (L_o / V_1)_m\right]$ and $\left[S_m / S = 1,\ (L_o / V_1) = 1\right]$. Unless an unusual situation is encountered values of $(L_o / V_1)_{op}$ or S determined in this fashion will always be high.

Other authors (4,7,14) have pointed out that their correlation of minimum and operating reflux ratio and minimum and operating number of stages may not adequately represent the data of a particular problem. For these cases they recommend the construction of a line through a known point parallel to their correlating line. A similar situation may be encountered with the proposed correlation. In these instances the recommended procedure is to simply draw a smooth curve through the minimum points $\left[0,\ (L_o / V_1)_m;\ 1,\ 1\right]$ and the known point $\left[(S_m / S)_{op},\ (L_o / V_1)_{op}\right]$. The resulting curve should establish combinations of S and L/V for other operating conditions.

The data of this investigation were plotted in the form suggested by Underwood, that is, $\log(S-S_m)$ as a function of $\log(R-R_m)$. Two items of interest were found from these plots. The first was that the slope of the lines connecting similar separations was almost constant for all the data plotted. This fact indicates that previously mentioned methods of handling data removed from the correlation line are valid. The second item of interest is that the constant, C, of Underwood is not a constant but some function of the minimum number of stages and reflux ratio. Mason has assumed that the functional relationship of C, R_m, and S_m is $C = C' R_m^a \cdot S_m^c$. The accuracy of this assumption can neither be refuted nor verified from the results of this investigation.

As stated previously an expression of correlation similar to that presented by Mason was developed. These expressions did not satisfactorily represent the data of this investigation. This fault may be attributed to several items. Among these are:

1. Lack of an adequate mathematical expression relating C, R_m, and S_m
2. Inadequate statistical methods
3. Poor or unreliable data

In the opinion of the author the principal source of difficulty was in the expression C as a function of C', R_m, and S_m. Working plots of Figure 7 have shown that the slope of the lines connecting similar separations have almost the same slope as the correlating line. These lines of similar separation are, however, displaced from the correlating line. This indicates that the relation $C = C' R_m^a S_m^c$ is not adequate to represent the data. Figure 8 presents an even worse picture for this method of correlation. Not only are the lines of similar separation removed from the correlating line but the slope of these lines is quite different from that of the correlating line. These differences may be attributed in part to the lack of proper statistical method and to the fact that the minimum reflux ratios used in this correlation were not rigorous values.

The correlations based on Mason's method were compared with one of the existing correlations (Gilliland's). The data for the comparison were obtained by:

1. Calculating ϕ_S and ϕ_R from the experimental data
2. Reading from Gilliland's curve values of ϕ'_R and ϕ'_S corresponding to the calculated values of ϕ_R and ϕ_S
3. Using resulting data to calculate S and R based on the experimental minimum quantity

As shown by Tables III through VIII, in each case the average deviation between the experimental and predicted data was smaller for the proposed correlations. Further checking reveals that maximum deviation between the data is less for the proposed equations.

A comparison of results of developed correlations and the experimental data was made. This comparison indicates the proposed method reproduces the experimental data within $\pm 2.0\%$ for the minimum (L_0 / V_1) based on the Erbar-Maddox minimum reflux ratio method. The average error for the proposed method when using Underwood's method of determining the minimum reflux is approximately $\pm 5.0\%$. Percentage differences between the experimental data and values predicted by Equations 5a and 5b are approximately $\pm 10\%$ to 12%.

These differences for Equations 6a and 6b are ± 15% to 20%. Equations 6a and 6b are based on data from the Underwood method of computing the minimum reflux ratio.

The derivation of Equation 7 was empirical. Tables X through XV and Figure 13 show nearly a uniform increase in the reflux ratio and condenser duty with increasing percentage feed vaporization. Various methods of predicting this increase were tried and Equation 7 was found to fit the data best. Two assumptions were made in the derivation of Equation 7. They are:

1. The latent heat of condensation of the vapor leaving the top tray of a fractionator will not vary appreciably for different reflux ratios.
2. The sensible heat effects in the condenser are negligible when compared with the latent heat effects.

The first assumption implies that there will be a small change in the composition of the vapor leaving the top tray for varied reflux ratios. In the case of a total condenser where the reflux and the distillate have the same composition, this assumption is valid unless there is more than a negligible change in the composition of the distillate product. For the case of a partial condenser with a vapor distillate product, the first assumption may or may not be valid. Consider, for example, the case where the reflux ratio is very small for a bubble point feed and the slope of the line relating the reflux ratio and percentage feed vaporization is large. Significant increases in the percentage feed vaporization would cause rather large changes in the reflux ratio and therefore, cause rather large changes in the composition of the vapor leaving the top tray. In these cases, Equation 7 could not be expected to predict the reflux ratio for varying percentage feed vaporizations adequately. Furthermore, Equation 7 has been tested only between the bubble point and the dew point of the various feed streams and may not be reliable outside this range. Tentative results, based on only three cases indicate that Equation 7 cannot be used to predict the changes in the minimum reflux ratio for varying feed conditions.

The data of Table IX and Tables X through XV tend to indicate that Equation 7 is more reliable for "sharp separations." A "sharp separation" may be thought of as a separation wherein no component heavier than the heavy key appears in the distillate and no component lighter than the light key appears in the bottoms product from a fractionator. All of the data presented in Table IX, with the exception of the data from Problem 03116.15761, are for sharp separations. This problem results in a fairly "sloppy" separation, for considerable quantities of both the light and heavy keys appear in both the distillate and bottoms product. Also, there is a considerable quantity of the lightest component in the feed in the bottoms product.

Equation 7 points out very clearly that the assumptions that all of the increase in feed enthalpy will go either to the condenser or to the reboiler are invalid. In effect, Equation 7 says that any increase in the feed enthalpy will be distributed to the condenser and reboiler heat duties by the relationships:

$(B/F)(\Delta H^{f}F) \approx Q_c$ - an increase in the condenser load

$(D/F)(\Delta H^{f}F) \approx -Q_r$ - a decrease in the reboiler load

Knowledge of these distributions will allow better preliminary cost estimations for fractionating columns and auxiliary equipment. For example, consider the case where the design engineer has a fair idea of the overhead product composition. He wishes to determine the optimum combination of condenser cost, fractionator cost, and reboiler cost. Increasing the percentage feed vaporization may increase the fractionator cost through the requirement of a larger column. There will be an increase in the condenser cost because a larger condenser is required to handle the increased heat duty. A smaller reboiler will be required. To design the optimum fractionator, both from an initial investment cost standpoint and the operating cost standpoint, the optimum combination of fractionator and accessory equipment must be found. Application of Equation 7 will allow the process engineer to rapidly make such a determination.

Equation 7 is also intended for use with the developed correlations of minimum and operating reflux ratio and minimum and operating stages. All correlations of minimum and operating reflux ratio, and minimum and operating stages are based on bubble point feeds. If the feed condition is known to be a partially vaporized feed, short cut calculations may be carried out using conventional calculations for the determination of the various parameters for a bubble point feed. The operating reflux ratio for the bubble point feed may be determined. Equation 7 may then be applied to determine the reflux ratio for the particular feed condition at hand. As stated previously, Equation 7 has been derived and checked for operating reflux ratios and cannot be used with minimum reflux ratios.

The relationship developed for the correlation of the reflux ratio and percentage feed vaporization should not be affected appreciably by changing the source of enthalpy data. For the case of the total condenser where the distillate, reflux, and the top tray vapor have the same composition, no noticeable effect should be found. In the case of the partial condenser, more error will probably be encountered. If enthalpy data which are composition dependent are employed, the effect will be somewhat greater. However, even in this case, a great effect should not be noticed.

Either of the proposed correlations, the proposed method or the form of Mason, can be used to predict operating reflux ratio and plates. Since the proposed method appears to give better results, its use is of course, recommended. In the application of these correlations, the basis on which they were derived must be remembered. These are:

1. A specific set of thermodynamic data (NGAA K values and M. W. Kellogg enthalpy data).
2. The manner in which the minimum parameters were determined.
3. A feed condition corresponding to a bubble point feed at tower conditions.

If these conditions are not satisfied neither of the correlations can be expected to give reliable results. If the feed is partially vaporized at tower conditions calculations for minimum parameters should be carried out for a bubble point feed. The operating conditions for the fractionator at a bubble point feed can then be determined by use of one of the proposed correlations. The reflux ratio then can be adjusted to account for the partially vaporized feed by means of Equation 7.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Lack of adequate correlations in the area of short distillation calculations has prompted the development of new and better correlations. The correlations developed in this investigation are based on data which are easily available to the average engineer. In addition, the relationships are presented in such a form that they may be applied to either hand calculation or machine computation.

The correlations presented are:

1. Correlations relating minimum and operating stages and minimum and operating reflux ratio.
2. A relationship expressing the change in reflux ratio necessary to make approximately the same separation as a function of percentage feed vaporization.

Correlations relating the operating and minimum parameters are presented using the methods of previous investigators. A new method for the correlation of these parameters was developed and is presented. These relationships are based on 30 or more plate-to-plate calculations and rigorous or approximate methods for the determination of the minimum parameters.

These correlations should be extremely useful to the process engineer in any preliminary design calculation involving fractionation problems. Based upon separations predicted by the Winn method or the Fenske method, and the minimum number of stages computed by the previously mentioned methods, and the minimum reflux ratio calculated by the Underwood method, the engineer may rapidly and more accurately determine the ultimate fractionator to be used to perform a given separation. In addition, one of the relationships presented may offer some use to the instrumentation engineer in control of fractionation columns. The relationship of feed vaporization and reflux ratio is not intended to be a final correlation but merely to serve to indicate that such a correlation exists and to stimulate interest in the betterment and further development of similar expressions.

Based on some of the results of this thesis, it can be concluded that the engineer today sorely needs a better set of enthalpy and equilibrium data. It is hoped that the results of this thesis will provide some stimulus for research in this area.

APPENDIX A

TABLE X

RESULTS OF PROBLEM NUMBER 02126.20000

FEED COMPOSITION NO. 2

Component	Distillate Composition (mol fraction)					
	Percent Feed Vaporized					
	0%	19.6%	41.0%	60.2%	79.7%	100%
iC_4	0.95852	0.95888	0.95942	0.95893	0.95888	0.95863
nC_4	0.04148	0.04112	0.04058	0.04107	0.04112	0.04137
iC_5	0	0	0	0	0	0
nC_5	0	0	0	0	0	0
C_6	0	0	0	0	0	0
Total Mols Distillate	19.83965	19.83114	19.83374	19.83314	19.82602	19.83992
N_s	26	26	26	26	26	26
N_{fp}	13	13	13	13	13	13
L/D	9.68567	10.54749	11.59156	12.46299	13.47432	14.65321
Q_c	1.90×10^7	2.05×10^7	2.24×10^7	2.39×10^7	2.57×10^7	2.78×10^7
Q_r	1.96×10^7	1.88×10^7	1.83×10^7	1.77×10^7	1.72×10^7	1.70×10^7
Q_f	1.11×10^7	1.35×10^7	1.58×10^7	1.80×10^7	2.03×10^7	2.28×10^7
Q_d	1.59×10^6	1.59×10^6	1.59×10^6	1.59×10^6	1.59×10^6	1.59×10^6
Q_b	1.01×10^7	1.01×10^7	1.01×10^7	1.01×10^7	1.01×10^7	1.01×10^7
T_f	122	135	143	152	160	172

Type of Condenser - Total
Pressure 50 psia

TABLE XI

RESULTS OF PROBLEM NUMBER 02124.40000

FEED COMPOSITION NO. 2

Comp.	Distillate Composition (mol fraction)				
	Percent Feed Vaporized				
	0%	25.2%	50.8%	75.2%	100%
iC_4	0.50301	0.50361	0.50331	0.50332	0.50312
nC_4	0.49024	0.49068	0.49114	0.49000	0.48987
iC_5	0.00650	0.00549	0.00534	0.00638	0.00668
nC_5	0.00026	0.00022	0.00022	0.00029	0.00033
C_6	0	0	0	0	0
Total Mols Distillate	39.73431	39.68578	39.70922	39.70072	39.71190
N_s	25	25	25	25	25
N_{fp}	12	12	12	12	12
L/D	1.42611	1.80705	2.29945	2.84588	3.54011
Q_c	8.62×10^6	9.96×10^6	1.17×10^7	1.37×10^7	1.61×10^7
Q_r	9.79×10^6	8.19×10^6	7.09×10^6	6.22×10^6	5.67×10^6
Q_f	1.11×10^7	1.41×10^7	1.69×10^7	1.97×10^7	2.28×10^7
Q_d	3.28×10^6	3.27×10^6	3.28×10^6	3.28×10^6	3.28×10^6
Q_b	9.04×10^6	9.04×10^6	9.04×10^6	9.04×10^6	9.04×10^6
T_f	122	137	148	158	172

Type of Condenser - Total

Pressure - 50 psia

TABLE XII

RESULTS OF PROBLEM NUMBER 02150.60000

FEED COMPOSITION NO. 2

Component	Distillate Composition (mol fraction)					
	Percent Feed Vaporized					
	0%	19.6%	41.0%	60.2%	79.7%	100%
iC_4	0.33245	0.33243	0.33242	0.33245	0.33245	0.33248
nC_4	0.33245	0.33243	0.33242	0.33245	0.33245	0.33248
iC_5	0.32201	0.32149	0.32133	0.32126	0.32119	0.32116
nC_5	0.01310	0.01364	0.01383	0.01385	0.01392	0.01388
C_6	0	0	0	0	0	0
Total Mols Distillate	60.16021	60.16238	60.16433	60.16000	60.16001	60.15455
N_s	51	51	51	51	51	51
N_{fp}	25	25	25	25	25	25
L/D	3.47139	3.57096	3.73702	3.91958	4.12296	4.37983
Q_c	2.67×10^7	2.73×10^7	2.83×10^7	2.94×10^7	3.06×10^7	3.21×10^7
Q_r	2.67×10^7	2.59×10^7	2.46×10^7	2.35×10^7	2.24×10^7	2.14×10^7
Q_f	1.11×10^7	1.35×10^7	1.58×10^7	1.80×10^7	2.03×10^7	2.28×10^7
Q_d	5.58×10^6	5.58×10^6	5.58×10^6	5.58×10^6	5.58×10^6	5.58×10^6
Q_b	6.50×10^6	6.50×10^6	6.50×10^6	6.50×10^6	6.50×10^6	6.50×10^6
T_f	122	135	143	152	160	172

Type of Condenser - Total
Pressure 50 psia

TABLE XIII

RESULTS OF PROBLEM NUMBER 03116.15761

FEED COMPOSITION NO. 3

Comp.	Distillate Composition (mol fraction)			
	Percent Feed Vaporized			
	0%	25.8%	49.9%	100%
C_3	0.52170	0.49263	0.47889	0.47000
iC_4	0.33233	0.36219	0.37604	0.38377
nC_4	0.14311	0.14261	0.14226	0.14233
iC_5	0.00234	0.00209	0.00225	0.00302
nC_5	0.00052	0.00049	0.00056	0.00087
C_6	0	0	0	0
Total Mols Distillate	15.74031	15.65425	15.70198	15.74000

N_s	17	17	17	17
N_{fp}	7	7	7	7
L/D	2.09962	3.23044	4.41133	7.27688
Q_c	3.46×10^6	4.73×10^6	6.09×10^6	9.37×10^6
Q_r	4.13×10^6	2.75×10^6	1.84×10^6	3.14×10^5
Q_f	1.30×10^7	1.56×10^7	1.78×10^7	2.26×10^7
Q_d	1.33×10^6	1.34×10^6	1.35×10^6	1.35×10^6
Q_b	1.23×10^7	1.23×10^7	1.22×10^7	1.22×10^7
T_f	176	194	205	230

Type of Condenser - Total
Pressure - 150 psia

TABLE XIV

RESULTS OF PROBLEM NUMBER 03121.30000

FEED COMPOSITION NO. 3

Comp.	Distillate Composition (mol fraction)				
	Percent Feed Vaporized				
	0%	25.4%	50%	72.3%	100%
C_3	0.33497	0.33508	0.33459	0.33508	0.33550
iC_4	0.59977	0.60046	0.59924	0.59903	0.59994
nC_4	0.06526	0.06445	0.06616	0.06588	0.06455
iC_5	0.00001	0.00001	0.00001	0.00001	0.00001
nC_5	0	0	0	0	0
C_6	0	0	0	0	0
Total Mols Distillate	29.85348	29.84333	29.88698	29.84338	29.80653

	0%	25.4%	50%	72.3%	100%
N_s	22	22	22	22	22
N_{fp}	11	11	11	11	11
L/D	6.00497	6.79047	7.42566	8.10811	9.13747
Q_c	1.63×10^7	1.82×10^7	1.97×10^7	2.12×10^7	2.36×10^7
Q_r	1.74×10^7	1.63×10^7	1.54×10^7	1.47×10^7	1.44×10^7
Q_f	1.14×10^7	1.43×10^7	1.67×10^7	1.90×10^7	2.17×10^7
Q_d	2.48×10^6	2.48×10^6	2.49×10^6	2.48×10^6	2.48×10^6
Q_b	9.94×10^6	9.94×10^6	9.94×10^7	9.94×10^6	9.95×10^6
T_f	138	160	171	179	185

Type of Condenser - Total

Pressure - 100 psia

TABLE XV

RESULTS OF PROBLEM NUMBER 04125.40000

FEED COMPOSITION NO. 4

Comp.	Distillate Composition (mol fraction)				
	Percent Feed Vaporized				
	0%	24.8%	50.4%	68.8%	100%
C_2	0.12521	0.12553	0.12541	0.12556	0.12535
C_3	0.50085	0.50211	0.50163	0.50225	0.50139
iC_4	0.35492	0.35419	0.35488	0.35409	0.35421
nC_4	0.01902	0.01817	0.01808	0.01810	0.01905
iC_5	0	0	0	0	0
nC_5	0	0	0	0	0
C_6	0	0	0	0	0
Total Mols Distillate	39.93211	39.83158	39.87023	39.82116	39.88878
N_s	27	27	27	27	27
N_{fp}	13	13	13	13	13
L/D	4.29461	4.68536	5.30600	5.63111	6.44750
Q_c	1.37×10^7	1.49×10^7	1.69×10^7	1.79×10^7	2.05×10^7
Q_r	1.89×10^7	1.70×10^7	1.62×10^7	1.52×10^7	1.42×10^7
Q_f	9.68×10^6	1.27×10^7	1.55×10^7	1.76×10^7	2.12×10^7
Q_d	5.65×10^6	5.63×10^6	5.64×10^6	5.63×10^6	5.64×10^6
Q_b	9.22×10^6	9.23×10^6	9.23×10^6	9.23×10^6	9.23×10^6
T_f	103	138	160	174	199

Type of Condenser - Partial

Pressure - 100 psia

APPENDIX B

TABLE XVI

RESULTS OF PROBLEM NUMBER 01018.25200

FEED COMPOSITION NO. 1

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min. Stages	At Min. Reflux	At Op. Cond.
nC_4	25.00000	24.19612	24.19614	24.19612
iC_5	25.00000	0.91698	0.91698	0.91698
nC_5	25.00000	0.13763	0	0.08917
C_6	25.00000	0.00003	0	0
Totals	100.00000	25.25076	25.11312	25.20227

Operating Conditions:

Number of Stages	19.0
Feed Point	10.0
Reflux Ratio	2.25367
Type of Condenser	Total
Feed Condition	BP
Pressure psia	25.0

Heat Loads Btu/Hr

Condenser	7.40×10^6
Reboiler	8.01×10^6
Feed	1.05×10^7
Distillate	2.07×10^6
Bottoms	9.05×10^6

Minimum Number of Stages	7.34655
Minimum Reflux Ratio	
Erbar - Maddox	1.95567
Underwood	1.66332

TABLE XVII

RESULTS OF PROBLEM NUMBER 01028.25200

FEED COMPOSITION NO. 1

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min. Stages	At Min. Reflux	At Op. Cond.
nC_4	25.00000	24.32715	24.32713	24.32715
iC_5	25.00000	1.43859	1.43859	1.43859
nC_5	25.00000	0.24498	0	0.06927
C_6	25.00000	0.00008	0	0
Totals	100.00000	26.01081	25.76572	25.83501

Operating Conditions:

Number of Stages	29.0
Feed Point	15.0
Reflux Ratio	1.89142
Type of Condenser	Total
Feed Condition	BP
Pressure psia	25.0

Heat Loads Btu/Hr

Condenser	6.77×10^6
Reboiler	7.39×10^6
Feed	1.05×10^7
Distillate	2.13×10^6
Bottoms	8.99×10^6

Minimum Number of Stages	7.07308
Minimum Reflux Ratio	
Erbar - Maddox	1.84303
Underwood	1.57794

TABLE XVIII

RESULTS OF PROBLEM NUMBER 01038.25200

FEED COMPOSITION NO. 1

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min.Stages	At Min.Reflux	At Op. Cond.
nC_4	25.00000	23.89377	23.89377	23.89377
iC_5	25.00000	1.65478	1.65478	1.65478
nC_5	25.00000	0.34180	0	0.03874
C_6	25.00000	0.00026	0	0
Totals	100.00000	25.89061	25.54855	25.58729

Operating Conditions:

Number of Stages	39.0
Feed Point	20.0
Reflux Ratio	1.80217
Type of Condenser	Total
Feed Condition	BP
Pressure psia	25.0

<u>Heat Loads Btu/Hr</u>

Condenser	6.52×10^6
Reboiler	7.11×10^6
Feed	1.05×10^7
Distillate	2.11×10^6
Bottoms	8.99×10^6

Minimum Number of Stages	6.33219
Minimum Reflux Ratio	
Erbar - Maddox	1.77467
Underwood	1.46230

TABLE XIX

RESULTS OF PROBLEM NUMBER 01048.25200

FEED COMPOSITION NO. 1

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min.Stages	At Min.Reflux	At Op. Cond.
nC_4	25.00000	23.81699	23.81698	23.81699
iC_5	25.00000	2.14663	2.14663	2.14663
nC_5	25.00000	0.50327	0	0.03600
C_6	25.00000	0.00062	0	0
Totals	100.00000	26.46752	25.96361	25.99962

Operating Conditions:

Number of Stages	49.0
Feed Point	25.0
Reflux Ratio	1.70003
Type of Condenser	Total
Feed Condition	BP
Pressure psia	25.0

Heat Loads Btu/Hr	
Condenser	6.41×10^6
Reboiler	7.01×10^6
Feed	1.05×10^7
Distillate	2.16×10^6
Bottoms	8.94×10^6

Minimum Number of Stages	5.96255
Minimum Reflux Ratio	
Erbar - Maddox	1.66055
Underwood	1.45424

TABLE XX

RESULTS OF PROBLEM NUMBER 01038.50000

FEED COMPOSITION NO. 1

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min.Stages	At Min.Reflux	At Op. Cond.
nC_4	25.00000	25.00000	25.00000	25.00000
iC_5	25.00000	23.64628	23.64628	23.64628
nC_5	25.00000	1.35838	1.35840	1.35838
C_6	25.00000	0	0	0
Totals	100.00000	50.00466	50.00468	50.00466

Operating Conditions:

Number of Stages	39.0
Feed Point	19.0
Reflux Ratio	6.25932
Type of Condenser	Total
Feed Condition	BP
Pressure psia	25.0

Heat Loads	Btu/Hr
Condenser	3.69×10^7
Reboiler	3.75×10^7
Feed	1.05×10^7
Distillate	4.58×10^6
Bottoms	6.61×10^6

Minimum Number of Stages 25.48928

Minimum Reflux Ratio

Erbar - Maddox	3.69706
Underwood	3.38304

TABLE XXI

RESULTS OF PROBLEM NUMBER 01048.50000

FEED COMPOSITION NO. 1

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min.Stages	At Min.Reflux	At Op. Cond.
nC_4	25.00000	25.00000	25.00000	25.00000
iC_5	25.00000	23.94205	23.94205	23.94205
nC_5	25.00000	1.06070	1.06070	1.06070
C_6	25.00000	0	0	0
Totals	100.00000	50.00275	50.00275	50.00275

Operating Conditions:

Number of Stages	49.0
Feed Point	24.0
Reflux Ratio	5.29965
Type of Condenser	Total
Feed Condition	BP
Pressure psia	25.0

Heat Loads	Btu/Hr
Condenser	3.20×10^7
Reboiler	3.27×10^7
Feed	1.05×10^7
Distillate	4.58×10^2
Bottoms	6.62×10^6

Minimum Number of Stages 27.80072

Minimum Reflux Ratio

Erbar - Maddox	3.80928
Underwood	3.48721

TABLE XXII

RESULTS OF PROBLEM NUMBER 01058.50000

FEED COMPOSITION NO. 1

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min. Stages	At Min. Reflux	At Op. Cond.
nC_4	25.00000	25.00000	25.00000	25.00000
iC_5	25.00000	24.11807	24.11807	24.11807
nC_5	25.00000	0.88637	0.88637	0.88307
C_6	25.00000	0	0	0
Totals	100.00000	50.00444	50.00444	50.00444

Operating Conditions:

Number of Stages	59.0
Feed Point	29.0
Reflux Ratio	4.78948
Type of Condenser	Total
Feed Condition	BP
Pressure psia	25.0

Heat Loads	Btu/Hr
Condenser	2.94×10^7
Reboiler	3.01×10^7
Feed	1.05×10^7
Distillate	4.58×10^6
Bottoms	6.62×10^6

Minimum Number of Stages 29.47674

Minimum Reflux Ratio

Erbar - Maddox	3.92154
Underwood	3.54851

TABLE XXIII

RESULTS OF PROBLEM NUMBER 01068.50000

FEED COMPOSITION NO. 1

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min.Stages	At Min.Reflux	At Op. Cond.
nC_4	25.00000	25.00000	25.00000	25.00000
iC_5	25.00000	24.24574	24.24573	24.24574
nC_5	25.00000	0.75336	0.75336	0.75336
C_6	25.00000	0	0	0
Totals	100.00000	49.99910	49.99909	49.99910

Operating Conditions:

Number of Stages	69.0
Feed Point	34.0
Reflux Ratio	4.52009
Type of Condenser	Total
Feed Condition	BP
Pressure psia	25.0

<u>Heat Loads Btu/Hr</u>

Condenser	2.80×10^7
Reboiler	2.87×10^7
Feed	1.05×10^7
Distillate	4.58×10^6
Bottoms	6.62×10^6

Minimum Number of Stages 30.94494

Minimum Reflux Ratio

Erbar - Maddox	3.91084
Underwood	3.59461

TABLE XXIV

RESULTS OF PROBLEM NUMBER 02026.20000

FEED COMPOSITION NO. 2

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min.Stages	At Min.Reflux	At Op. Cond.
iC_4	20.00000	19.01669	19.01668	19.01669
nC_4	20.00000	0.82296	0.82294	0.82296
iC_5	20.00000	0	0	0
nC_5	20.00000	0	0	0
C_6	20.00000	0	0	0
Totals	100.00000	19.83965	19.83962	19.83965

Operating Conditions:

Number of Stages	27.0
Feed Point	13.0
Reflux Ratio	9.68567
Type of Condenser	Total
Feed Condition	BP
Pressure psia	50.0

Heat Loads Btu/Hr	
Condenser	1.90×10^7
Reboiler	1.96×10^7
Feed	1.11×10^7
Distillate	1.59×10^6
Bottoms	1.01×10^7

Minimum Number of Stages 18.25116

Minimum Reflux Ratio

Erbar - Maddox	5.24447
Underwood	5.12040

TABLE XXV

RESULTS OF PROBLEM NUMBER 02041.20000

FEED COMPOSITION NO. 2

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min. Stages	At Min. Reflux	At Op. Cond.
iC_4	20.00000	19.49084	19.49084	19.49084
nC_4	20.00000	0.55977	0.55977	0.55977
iC_5	20.00000	0	0	0
nC_5	20.00000	0	0	0
C_6	20.00000	0	0	0
Totals	100.00000	20.05061	20.05061	20.05061

Operating Conditions:

Number of Stages	42.0
Feed Point	21.0
Reflux Ratio	7.00474
Type of Condenser	Total
Feed Condition	BP
Pressure	50.0

Heat Loads	Btu/Hr
Condenser	1.44×10^7
Reboiler	1.50×10^7
Feed	1.11×10^7
Distillate	1.60×10^6
Bottoms	1.01×10^7

Minimum Number of Stages 21.50100

Minimum Reflux Ratio

Erbar - Maddox	5.39333
Underwood	5.28909

TABLE XXVI

RESULTS OF PROBLEM NUMBER 02058.20000

FEED COMPOSITION NO. 2

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min.Stages	At Min.Reflux	At Op. Cond.
iC_4	20.00000	19.70639	19.70647	19.70639
nC_4	20.00000	0.31303	0.31303	0.31303
iC_5	20.00000	0	0	0
nC_5	20.00000	0	0	0
C_6	20.00000	0	0	0
Totals	100.00000	20.01942	20.01950	20.01942

Operating Conditions:

Number of Stages	59.0
Feed Point	29.0
Reflux Ratio	6.34287
Type of Condenser	Total
Feed Condition	BP
Pressure psia	50.0

Heat Loads	Btu/Hr
Condenser	1.32×10^7
Reboiler	1.38×10^7
Feed	1.11×10^7
Distillate	1.60×10^6
Bottoms	1.01×10^7

Minimum Number of Stages 24.93632

Minimum Reflux Ratio

Erbar - Maddox	5.53495
Underwood	5.43679

TABLE XXVII

RESULTS OF PROBLEM NUMBER 02024.40000

FEED COMPOSITION NO. 2

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min. Stages	At Min. Reflux	At Op. Cond.
iC_4	20.00000	19.97134	20.00000	19.98668
nC_4	20.00000	19.47924	19.47923	19.47924
iC_5	20.00000	0.25811	0.25811	0.25811
nC_5	20.00000	0.02910	0	0.01028
C_6	20.00000	0	0	0
Totals	100.00000	39.73779	39.73735	39.73431

Operating Conditions:

Number of Stages	25.0
Feed Point	12.0
Reflux Ratio	1.42611
Type of Condenser	Total
Feed Condition	BP
Pressure psia	50.0

Heat Loads Btu/Hr	
Condenser	8.62×10^6
Reboiler	9.79×10^6
Feed	1.11×10^7
Distillate	3.28×10^6
Bottoms	9.04×10^6

Minimum Number of Stages 9.97330

Minimum Reflux Ratio

Erbar - Maddox	1.36086
Underwood	1.20164

TABLE XXVIII

RESULTS OF PROBLEM NUMBER 02034.40000

FEED COMPOSITION NO. 2

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min. Stages	At Min. Reflux	At Op. Cond.
iC_4	20.00000	19.93132	20.00000	19.99401
nC_4	20.00000	19.16387	19.16387	19.16387
iC_5	20.00000	0.44979	0.44979	0.44979
nC_5	20.00000	0.06856	0	0.00602
C_6	20.00000	0.00001	0	0
Totals	100.00000	39.61355	39.61366	39.61370

Operating Conditions:

Number of Stages	35.0
Feed Point	17.0
Reflux Ratio	1.29213
Type of Condenser	Total
Feed Condition	BP
Pressure psia	50.0

Heat Loads Btu/Hr	
Condenser	8.13×10^6
Reboiler	9.29×10^6
Feed	1.11×10^7
Distillate	3.27×10^6
Bottoms	9.03×10^6

Minimum Number of Stages 8.65903

Minimum Reflux Ratio

Erbar - Maddox	1.313603
Underwood	1.172700

TABLE XXIX

RESULTS OF PROBLEM NUMBER 02044.40000

FEED COMPOSITION NO. 2

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min.Stages	At Min.Reflux	At Op. Cond.
iC_4	20.00000	19.84754	20.00000	19.99742
nC_4	20.00000	18.78370	18.78370	18.78370
iC_5	20.00000	0.89316	0.89316	0.89316
nC_5	20.00000	0.18904	0	0.00516
C_6	20.00000	0.00011	0	0
Totals	100.00000	39.71356	39.67686	39.67990

Operating Conditions:

Number of Stages	45.0
Feed Point	22.0
Reflux Ratio	1.21774
Type of Condenser	Total
Feed Condition	BP
Pressure psia	50.0

Heat Loads Btu/Hr

Condenser	7.92×10^6
Reboiler	9.05×10^6
Feed	1.11×10^7
Distillate	3.29×10^6
Bottoms	8.99×10^6

Minimum Number of Stages 7.30405

Minimum Reflux Ratio

Erbar - Maddox	1.22570
Underwood	1.11253

TABLE XXX

RESULTS OF PROBLEM NUMBER 02040.60000

FEED COMPOSITION NO. 2

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min.Stages	At Min.Reflux	At Op. Cond.
iC_4	20.00000	20.00000	20.00000	20.00000
nC_4	20.00000	20.00000	20.00000	20.00000
iC_5	20.00000	19.27975	19.27975	19.27975
nC_5	20.00000	1.11441	1.11443	1.11441
C_6	20.00000	0	0	0
Totals	100.00000	60.39416	60.39418	60.39416

Operating Conditions:

Number of Stages	41.0	**Heat Loads Btu/Hr**	
Feed Point	20.0	Condenser	3.10×10^7
Reflux Ratio	4.16606	Reboiler	3.19×10^7
Type of Condenser	Total	Feed	1.11×10^7
Feed Condition	BP	Distillate	5.61×10^6
Pressure psia	50.0	Bottoms	6.47×10^6

Minimum Number of Stages	32.65133
Minimum Reflux Ratio	
Erbar - Maddox	3.07384
Underwood	2.85318

TABLE XXXI

RESULTS OF PROBLEM NUMBER 02050.60000

FEED COMPOSITION NO. 2

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min. Stages	At Min. Reflux	At Op. Cond.
iC_4	20.00000	20.00000	20.00000	20.00000
nC_4	20.00000	20.00000	20.00000	20.00000
iC_5	20.00000	19.37218	19.37217	19.37218
nC_5	20.00000	0.78803	0.78802	0.78803
C_6	20.00000	0	0	0
Totals	100.00000	60.16021	60.16019	60.16021

Operating Conditions:

Number of Stages	51.0
Feed Point	25.0
Reflux Ratio	3.47139
Type of Condenser	Total
Feed Condition	BP
Pressure psia	50.0

<u>Heat Loads Btu/Hr</u>

Condenser	2.67×10^7
Reboiler	2.76×10^7
Feed	1.11×10^7
Distillate	5.58×10^6
Bottoms	6.50×10^6

Minimum Number of Stages 35.32062

Minimum Reflux Ratio

Erbar - Maddox	3.16341
Underwood	2.94585

TABLE XXXII

RESULTS OF PROBLEM NUMBER 02060.60000

FEED COMPOSITION NO. 2

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min.Stages	At Min.Reflux	At Op. Cond.
iC_4	20.00000	20.00000	20.00000	20.00000
nC_4	20.00000	20.00000	20.00000	20.00000
iC_5	20.00000	19.53892	19.53892	19.53892
nC_5	20.00000	0.71201	0.71201	0.71201
C_6	20.00000	0	0	0
Totals	100.00000	60.25093	60.25093	60.25093

Operating Conditions:

Number of Stages	61.0
Feed Point	30.0
Reflux Ratio	3.13271
Type of Condenser	Total
Feed Condition	BP
Pressure psia	50.0

<u>Heat Loads Btu/Hr</u>

Condenser	2.47×10^7
Reboiler	2.57×10^7
Feed	1.11×10^7
Distillate	5.59×10^6
Bottoms	6.49×10^6

Minimum Number of Stages 37.60846

Minimum Reflux Ratio

Erbar - Maddox	3.20286
Underwood	2.98305

TABLE XXXIII

RESULTS OF PROBLEM NUMBER 03016.15761

FEED COMPOSITION NO. 3

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min.Stages	At Min.Reflux	At Op. Cond.
C_3	10.00000	8.21174	8.21174	8.21174
iC_4	20.00000	5.23097	5.70542	5.23096
nC_4	20.00000	2.25486	2.25254	2.25254
iC_5	20.00000	0.17539	0	0.03681
nC_5	20.00000	0.07743	0	0.00825
C_6	10.00000	0.00117	0	0.00001
Totals	100.00000	15.95156	16.16970	15.74031

Operating Conditions:

Number of Stages	17.0
Feed Point	7.0
Reflux Ratio	2.09962
Type of Condenser	Total
Feed Condition	BP
Pressure psia	150.0

Heat Loads Btu/Hr	
Condenser	3.46×10^6
Reboiler	4.13×10^6
Feed	1.30×10^7
Distillate	1.33×10^6
Bottoms	1.23×10^7

Minimum Number of Stages 3.92982

Minimum Reflux Ratio

Erbar - Maddox	2.01155
Underwood	1.53777

TABLE XXXIV

RESULTS OF PROBLEM NUMBER 03026.15761

FEED COMPOSITION NO. 3

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min. Stages	At Min. Reflux	At Op. Cond.
C_3	10.00000	7.89727	7.89727	7.89727
iC_4	20.00000	5.26751	5.57643	5.26751
nC_4	20.00000	2.44812	2.31478	2.31478
iC_5	20.00000	0.23924	0	0.00830
nC_5	20.00000	0.11359	0	0.00096
C_6	10.00000	0.00233	0	0
Totals	100.00000	15.96806	15.78848	15.48882

Operating Conditions:

Number of Stages	27.0
Feed Point	10.0
Reflux Ratio	1.91771
Type of Condenser	Total
Feed Condition	BP
Pressure psia	150.0

Heat Loads Btu/Hr	
Condenser	3.21×10^{6}
Reboiler	3.85×10^{6}
Feed	1.30×10^{7}
Distillate	1.31×10^{6}
Bottoms	1.23×10^{7}

Minimum Number of Stages 3.62074

Minimum Reflux Ratio

Erbar - Maddox	1.94343
Underwood	1.41353

TABLE XXXV

RESULTS OF PROBLEM NUMBER 03021.30000

FEED COMPOSITION NO. 3

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min.Stages	At min.Reflux	At Op. Cond.
C_3	10.00000	9.99998	10.00000	9.99989
iC_4	20.00000	17.90530	17.90530	17.90530
nC_4	20.00000	1.94810	1.94810	1.94810
iC_5	20.00000	0.00001	0	0.00018
nC_5	20.00000	0	0	0.00001
C_6	10.00000	0	0	0
Totals	100.00000	29.85339	29.85340	29.85348

Operating Conditions:

Number of Stages	22.0
Feed Point	11.0
Reflux Ratio	6.00497
Type of Condenser	Total
Feed Condition	BP
Pressure psia	100.0

Heat Loads	Btu/Hr
Condenser	1.63×10^7
Reboiler	1.74×10^7
Feed	1.14×10^7
Distillate	2.48×10^6
Bottoms	9.94×10^6

Minimum Number of Stages 15.36873

Minimum Reflux Ratio

Erbar - Maddox	3.95318
Underwood	3.68106

TABLE XXXVI

RESULTS OF PROBLEM NUMBER 03031.30000

FEED COMPOSITION NO. 3

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min. Stages	At Min. Reflux	At Op. Cond.
C_3	10.00000	10.00000	10.00000	10.00000
iC_4	20.00000	18.36573	18.36573	18.36573
nC_4	20.00000	1.61940	1.61941	1.61940
iC_5	20.00000	0	0	0
nC_5	20.00000	0	0	0
C_6	10.00000	0	0	0
Totals	100.00000	29.98513	29.98514	29.98513

Operating Conditions:

Number of Stages	32.0
Feed Point	16.0
Reflux Ratio	4.62285
Type of Condenser	Total
Feed Condition	BP
Pressure psia	100.0

<u>Heat Loads Btu/Hr</u>

Condenser	1.32×10^7
Reboiler	1.42×10^7
Feed	1.14×10^7
Distillate	2.49×10^6
Bottoms	9.94×10^6

Minimum Number of Stages 17.02173

Minimum Reflux Ratio

Erbar - Maddox	4.11013
Underwood	3.86000

TABLE XXXVII

RESULTS OF PROBLEM NUMBER 03017.50000

FEED COMPOSITION NO. 3

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min.Stages	At Min.Reflux	At Op. Cond.
C_3	10.00000	9.99982	10.00000	9.99998
iC_4	20.00000	19.90560	20.00000	19.94847
nC_4	20.00000	19.27919	19.27919	19.27919
iC_5	20.00000	1.10445	1.10445	1.10445
nC_5	20.00000	0.22726	0	0.14539
C_6	10.00000	0.00003	0	0.00001
Totals	100.00000	50.51634	50.38364	50.47748

Operating Conditions:

Number of Stages	18.0
Feed Point	9.0
Reflux Ratio	1.17918
Type of Condenser	Total
Feed Condition	BP
Pressure psia	75.0

Heat Loads	Btu/Hr
Condenser	9.41×10^6
Reboiler	1.08×10^7
Feed	1.06×10^7
Distillate	4.28×10^6
Bottoms	7.70×10^6

Minimum Number of Stages	7.88900
Minimum Reflux Ratio	
Erbar - Maddox	.91448
Underwood	.82623

TABLE XXXVIII

RESULTS OF PROBLEM NUMBER 03027.50000

FEED COMPOSITION NO. 3

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min.Stages	At Min.Reflux	At Op. Cond.
C_3	10.00000	9.99990	10.00000	10.00000
iC_4	20.00000	19.93165	20.00000	19.98880
nC_4	20.00000	19.40874	19.40874	19.40874
iC_5	20.00000	0.96838	0.96838	0.96838
nC_5	20.00000	0.18038	0	0.05419
C_6	10.00000	0.00002	0	0
Totals	100.00000	50.48907	50.37712	50.42010

Operating Conditions:

Number of Stages	28.0
Feed Point	14.0
Reflux Ratio	1.01308
Type of Condenser	Total
Feed Condition	BP
Pressure psia	75.0

<u>Heat Loads Btu/Hr</u>

Condenser	8.67×10^6
Reboiler	1.01×10^7
Feed	1.06×10^7
Distillate	4.27×10^6
Bottoms	7.72×10^6

Minimum Number of Stages	8.34376
Minimum Reflux Ratio	
Erbar - Maddox	.92998
Underwood	.84150

TABLE XXXIX

RESULTS OF PROBLEM NUMBER 04013.08266

FEED COMPOSITION NO. 4

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min. Stages	At Min. Reflux	At Op. Cond.
C_2	5.00000	3.62115	3.62115	3.62115
C_3	20.00000	4.10628	5.16585	4.10628
iC_4	15.00000	0.74901	0.37154	0.37154
nC_4	15.00000	0.38855	0	0.09775
iC_5	15.00000	0.07651	0	0.00279
nC_5	15.00000	0.45560	0	0.00094
C_6	15.00000	0.00612	0	0.00001
Totals	100.00000	8.99319	9.15854	8.20046

Operating Conditions:

Number of Stages	15.0
Feed Point	5.0
Reflux Ratio	2.52041
Type of Condenser	Partial
Feed Condition	BP
Pressure psia	300.0

<u>Heat Loads Btu/Hr</u>

Condenser	1.20×10^6
Reboiler	2.13×10^6
Feed	1.45×10^7
Distillate	9.61×10^5
Bottoms	1.44×10^7

Minimum Number of Stages	2.84273
Minimum Reflux Ratio	
Erbar - Maddox	2.24655
Underwood	1.50838

TABLE XL

RESULTS OF PROBLEM NUMBER 04023.08266

FEED COMPOSITION NO. 4

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min.Stages	At Min.Reflux	At Op. Cond.
C_2	5.00000	3.19791	3.19791	3.19791
C_3	20.00000	4.38611	4.67504	4.38610
iC_4	15.00000	0.73873	0.53009	0.53009
nC_4	15.00000	0.44282	0	0.07930
iC_5	15.00000	0.12454	0	0.00026
nC_5	15.00000	0.08251	0	0.00004
C_6	15.00000	0.01704	0	0
Totals	100.00000	8.98967	8.40304	8.19370

Operating Conditions:

Number of Stages	25.0
Feed Point	9.0
Reflux Ratio	2.01438
Type of Condenser	Partial
Feed Condition	BP
Pressure psia	300.0

Heat Loads Btu/Hr	
Condenser	9.54×10^5
Reboiler	1.84×10^6
Feed	1.45×10^7
Distillate	9.89×10^5
Bottoms	1.44×10^7

Minimum Number of Stages	2.23330
Minimum Reflux Ratio	
Erbar - Maddox	2.03658
Underwood	0.94357

TABLE XLI

RESULTS OF PROBLEM NUMBER 04015.24500

FEED COMPOSITION NO. 4

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min.Stages	At Min.Reflux	At Op. Cond.
C_2	5.00000	4.99994	5.00000	4.99979
C_3	20.00000	18.66793	18.66793	18.66793
iC_4	15.00000	0.66297	0.66297	0.66297
nC_4	15.00000	0.07558	0	0.03691
iC_5	15.00000	0.00021	0	0.00001
nC_5	15.00000	0.00003	0	0
C_6	15.00000	0	0	0
Totals	100.00000	24.40666	24.33090	24.36762

Operating Conditions:

Number of Stages	17.0	<u>Heat Loads/Hr</u>	
Feed point	9.0	Condenser	4.09×10^6
Reflux Ratio	2.6278	Reboiler	7.37×10^7
Type of Condenser	Partial	Feed	1.12×10^7
Feed Condition	BP	Distillate	3.00×10^6
Pressure psia	150.0	Bottoms	1.15×10^7

Minimum Number of Stages	8.07183
Minimum Reflux Ratio	
Erbar - Maddox	1.99731
Underwood	1.66446

TABLE XLII

RESULTS OF PROBLEM NUMBER 04025.24500

FEED COMPOSITION NO. 4

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min. Stages	At Min. Reflux	At Op. Cond.
C_2	5.00000	4.99990	5.00000	5.00000
C_3	20.00000	18.56423	18.56424	18.56423
iC_4	15.00000	0.77572	0.77572	0.77572
nC_4	15.00000	0.09765	0	0.01585
iC_5	15.00000	0.00034	0	0
nC_5	15.00000	0.00006	0	0
C_6	15.00000	0	0	0
Totals	100.00000	24.43790	24.33996	24.35580

Operating Conditions:

Number of Stages	27.0
Feed Point	14.0
Reflux Ratio	2.00319
Type of Condenser	Partial
Feed Condition	BP
Pressure psia	150.0

Heat Loads Btu/Hr	
Condenser	3.17×10^6
Reboiler	6.44×10^6
Feed	1.12×10^7
Distillate	3.01×10^6
Bottoms	1.15×10^7

Minimum Number of Stages	7.74034
Minimum Reflux Ratio	
Erbar - Maddox	1.95900
Underwood	1.63789

TABLE XLIII

RESULTS OF PROBELM NUMBER 04025.40000

FEED COMPOSITION NO. 4

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min.Stages	At Min.Reflux	At Op. Cond.
C_2	5.00000	5.00000	5.00000	5.00000
C_3	20.00000	20.00000	20.00000	19.99997
iC_4	15.00000	14.17282	14.17280	14.17282
nC_4	15.00000	0.75932	0.75932	0.75932
iC_5	15.00000	0	0	0
nC_5	15.00000	0	0	0
C_6	15.00000	0	0	0
Totals	100.00000	39.93214	39.93212	39.93211

Operating Conditions:

Number of Stages	27.0
Feed Point	13.0
Reflux Ratio	4.29461
Type of Condenser	Partial
Feed Condition	BP
Pressure psia	100.0

Heat Loads Btu/Hr	
Condenser	1.37×10^7
Reboiler	1.89×10^7
Feed	9.68×10^6
Distillate	5.65×10^6
Bottoms	9.22×10^6

Minimum Number of Stages 19.38067

Minimum Reflux Ratio

Erbar - Maddox	2.16452
Underwood	2.32152

TABLE XLIV

RESULTS OF PROBLEM NUMBER 04035.40000

FEED COMPOSITION NO. 4

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min. Stages	At Min. Reflux	At Op. Cond.
C_2	5.00000	5.00000	5.00000	5.00000
C_3	20.00000	20.00000	20.00000	20.00000
iC_4	15.00000	14.47215	14.47215	14.47215
nC_4	15.00000	0.52592	0.52592	0.52592
iC_5	15.00000	0	0	0
nC_5	15.00000	0	0	0
C_6	15.00000	0	0	0
Totals	100.00000	39.99807	39.99807	39.99807

Operating Conditions:

Number of Stages	37.0
Feed Point	18.0
Reflux Ratio	3.23637
Type of Condenser	Partial
Feed Condition	BP
Pressure psia	100.0

<u>Heat Loads Btu/Hr</u>

Condenser	1.03×10^7
Reboiler	1.55×10^7
Feed	9.68×10^6
Distillate	5.66×10^6
Bottoms	9.23×10^6

Minimum Number of Stages	22.22961
Minimum Reflux Ratio	
Erbar - Maddox	2.21548
Underwood	2.41732

TABLE XLV

RESULTS OF PROBLEM NUMBER 04019.55080

FEED COMPOSITION NO. 4

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min. Stages	At Min. Reflux	At Op. Cond.
C_2	5.00000	5.00000	5.00000	5.00000
C_3	20.00000	20.00000	20.00000	20.00000
iC_4	15.00000	14.99648	15.00000	14.99483
nC_4	15.00000	14.91428	14.91426	14.91427
iC_5	15.00000	0.36575	0.36575	0.36575
nC_5	15.00000	0.02857	0	0.01981
C_6	15.00000	0	0	0
Totals	100.00000	55.30507	55.28001	55.29466

Operating Conditions:

Number of Stages	21.0
Feed Point	10.0
Reflux Ratio	1.05587
Type of Condenser	Partial
Feed Condition	BP
Pressure psia	75.0

Heat Loads Btu/Hr	
Condenser	5.15×10^6
Reboiler	1.21×10^7
Feed	8.91×10^6
Distillate	8.45×10^6
Bottoms	7.44×10^6

Minimum Number of Stages 11.89320

Minimum Reflux Ratio

Erbar - Maddox	0.60611
Underwood	0.62141

TABLE XLVI

RESULTS OF PROBLEM NUMBER 04029.55080

FEED COMPOSITION NO. 4

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min.Stages	At Min.Reflux	At Op. Cond.
C_2	5.00000	5.00000	5.00000	5.00000
C_3	20.00000	20.00000	20.00000	20.00000
iC_4	15.00000	14.99975	15.00000	14.99979
nC_4	15.00000	14.98883	14.98883	14.98883
iC_5	15.00000	0.48801	0.48801	0.48801
nC_5	15.00000	0.02396	0	0.01032
C_6	15.00000	0	0	0
Totals	100.00000	55.50055	55.47684	55.48695

Operating Conditions:

Number of Stages	31.0
Feed Point	15.0
Reflux Ratio	0.86982
Type of Condenser	Partial
Feed Condition	BP
Pressure psia	75.0

<u>Heat Loads Btu/Hr</u>

Condenser	4.27×10^6
Reboiler	1.13×10^7
Feed	8.91×10^6
Distillate	8.49×10^6
Bottoms	7.42×10^6

Minimum Number of Stages	14.43509
Minimum Reflux Ratio	
Erbar - Maddox	0.59280
Underwood	0.61147

TABLE XLVII

RESULTS OF PROBLEM NUMBER 05016.30000

FEED COMPOSITION NO. 5

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min. Stages	At Min. Reflux	At Op. Cond.
C_1	1.00000	1.00000	1.00000	1.00000
C_2	5.00000	4.99990	5.00000	4.99984
C_3	24.00000	22.88938	22.88938	22.88938
iC_4	15.00000	0.95873	0.95873	0.95873
nC_4	15.00000	0.13139	0	0.10799
iC_5	15.00000	0.00049	0	0.00025
nC_5	15.00000	0.00007	0	0.00004
C_6	10.00000	0	0	0
Totals	100.00000	29.97996	29.84811	29.95624

Operating Conditions:

Number of Stages	18.0
Feed Point	8.0
Reflux Ratio	2.70540
Type of Condenser	Partial
Feed Condition	BP
Pressure psia	300.0

<u>Heat Loads Btu/Hr</u>

Condenser	3.96×10^6
Reboiler	7.36×10^6
Feed	1.31×10^7
Distillate	3.72×10^6
Bottoms	1.28×10^7

Minimum Number of Stages	9.23683
Minimum Reflux Ratio	
Erbar - Maddox	2.02946
Underwood	1.82850

TABLE XLVIII

RESULTS OF PROBLEM NUMBER 05026.30000

FEED COMPOSITION NO. 5

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min. Stages	At Min. Reflux	At Op. Cond.
C_1	1.00000	1.00000	1.00000	1.00000
C_2	5.00000	4.99986	5.00000	5.00000
C_3	24.00000	22.84917	22.84916	22.84917
iC_4	15.00000	1.10660	1.10660	1.10660
nC_4	15.00000	0.16420	0	0.07497
iC_5	15.00000	0.00075	0	0.00002
nC_5	15.00000	0.00002	0	0
C_6	10.00000	0	0	0
Totals	100.00000	30.12071	29.95577	30.03076

Operating Conditions:

Number of Stages	28.0
Feed Point	12.0
Reflux Ratio	2.06352
Type of Condenser	Partial
Feed Condition	BP
Pressure psia	300.0

<u>Heat Loads Btu/Hr</u>

Condenser	3.03×10^6
Reboiler	6.44×10^6
Feed	1.31×10^7
Distillate	3.73×10^6
Bottoms	1.28×10^7

Minimum Number of Stages	8.95248
Minimum Reflux Ratio	
Erbar - Maddox	1.98516
Underwood	1.79940

TABLE XLIX

RESULTS OF PROBLEM NUMBER 05020.60000

FEED COMPOSITION NO. 5

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min. Stages	At Min. Reflux	At Op. Cond.
C_1	1.00000	1.00000	1.00000	1.00000
C_2	5.00000	5.00000	5.00000	5.00000
C_3	24.00000	24.00000	24.00000	23.99998
iC_4	15.00000	14.98974	15.00000	14.98486
nC_4	15.00000	14.80046	14.80045	14.80046
iC_5	15.00000	0.22947	0.22947	0.22947
nC_5	15.00000	0.01573	0	0.01762
C_6	10.00000	0	0	0
Totals	100.00000	60.03540	60.02992	60.03238

Operating Conditions:

Number of Stages	22.0
Feed Point	10.0
Reflux Ratio	1.19881
Type of Condenser	Partial
Feed Condition	BP
Pressure psia	150.0

Heat Loads Btu/Hr

Condenser	4.97×10^6
Reboiler	1.19×10^6
Feed	9.68×10^6
Distillate	8.92×10^6
Bottoms	7.68×10^6

Minimum Number of Stages	13.87023
Minimum Reflux Ratio	
Erbar - Maddox	0.79534
Underwood	0.84077

TABLE L

RESULTS OF PROBELM NUMBER 05030.60000

FEED COMPOSITION NO. 5

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min.Stages	At Min.Reflux	At Op. Cond.
C_1	1.00000	1.00000	1.00000	1.00000
C_2	5.00000	5.00000	5.00000	5.00000
C_3	24.00000	24.00000	24.00000	24.00000
iC_4	15.00000	14.99892	15.00000	14.99858
nC_4	15.00000	14.95079	14.95079	14.95079
iC_5	15.00000	0.08716	0.08716	0.08716
nC_5	15.00000	0.00277	0	0.00240
C_6	10.00000	0	0	0
Totals	100.00000	60.03964	60.03255	60.03393

Operating Conditions:

Number of Stages	32.0
Feed Point	15.0
Reflux Ratio	0.99888
Type of Condenser	Partial
Feed Condition	BP
Pressure psia	150.0

<u>Heat Loads Btu/Hr</u>

Condenser	4.12×10^6
Reboiler	1.10×10^6
Feed	9.68×10^6
Distillate	8.90×10^6
Bottoms	7.69×10^6

Minimum Number of Stages 17.89089

Minimum Reflux Ratio

Erbar - Maddox	0.85108
Underwood	0.85990

TABLE LI

RESULTS OF PROBLEM NUMBER 07016.08600

FEED COMPOSITION NO. 7

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min. Stages	At Min. Reflux	At Op. Cond.
C_2	5.00000	2.37826	2.37826	2.37827
C_3	15.00000	3.66685	3.66685	3.66652
iC_4	10.00000	1.50530	1.63865	1.25172
nC_4	10.00000	1.23660	1.41529	0.93673
iC_5	10.00000	0.70348	0.93394	0.21402
nC_5	10.00000	0.61583	0.84886	0.11619
C_6	10.00000	0.26478	0.45463	0.00094
C_7	10.00000	0.10713	0.22448	0
C_{10}	20.00000	0.01725	0	0
Totals	100.00000	10.49548	11.56096	8.56439

Operating Conditions:

Number of Stages	18.0
Feed Point	7.0
Reflux Ratio	1.00832
Type of Condenser	Partial
Feed Condition	BP
Pressure psia	400.0

Heat Loads Btu/Hr	
Condenser	5.20 x 10^5
Reboiler	2.23 x 10^6
Feed	2.18 x 10^7
Distillate	1.25 x 10^6
Bottoms	2.23 x 10^7

Minimum Number of Stages	1.51317
Minimum Reflux Ratio	
Erbar - Maddox	
Underwood	0.05401

TABLE LII

RESULTS OF PROBLEM NUMBER 07031.08600

FEED COMPOSITION NO. 7

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min.Stages	At Min.Reflux	At Op. Cond.
C_2	5.00000	2.24767	2.24767	2.24767
C_3	15.00000	3.52444	3.52443	3.52443
iC_4	10.00000	1.47610	1.58685	1.26234
nC_4	10.00000	1.22561	1.37274	0.99555
iC_5	10.00000	0.71820	0.90046	0.34660
nC_5	10.00000	0.63338	0.81796	0.19661
C_6	10.00000	0.28421	0.42264	0.00005
C_7	10.00000	0.12047	0.18571	0
C_{10}	20.00000	0.02218	0	0
Totals	100.00000	10.25224	11.05847	8.57326

Operating Conditions:

Number of Stages	33.0
Feed Point	14.0
Reflux Ratio	0.83128
Type of Condenser	Partial
Feed Condition	BP
Pressure psia	400.0

Heat Loads Btu/Hr	
Condenser	4.39×10^5
Reboiler	2.07×10^6
Feed	2.18×10^7
Distillate	1.30×10^6
Bottoms	2.21×10^7

Minimum Number of Stages 1.44704

Minimum Reflux Ratio

Erbar - Maddox

Underwood 0.11029

TABLE LIII

RESULTS OF PROBLEM NUMBER 07017.21000

FEED COMPOSITION NO. 7

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min.Stages	At Min.Reflux	At Op. Cond.
C_2	5.00000	4.99771	5.00000	4.99936
C_3	15.00000	13.76581	13.76581	13.76581
iC_4	10.00000	1.84454	1.84454	1.84454
nC_4	10.00000	0.46627	0	0.32026
iC_5	10.00000	0.00892	0	0.00116
nC_5	10.00000	0.00371	0	0.00029
C_6	10.00000	0.00003	0	0
C_7	10.00000	0	0	0
C_{10}	20.00000	0	0	0
Totals	100.00000	21.08699	20.61035	20.93142

Operating Conditions:

Number of Stages	19.0
Feed Point	8.0
Reflux Ratio	2.34425
Type of Condenser	Partial
Feed Condition	BP
Pressure psia	300.0

Heat Loads Btu/Hr	
Condenser	2.80×10^6
Reboiler	7.61×10^6
Feed	1.97×10^7
Distillate	2.73×10^6
Bottoms	2.18×10^7

Minimum Number of Stages 6.72900

Minimum Reflux Ratio

Erbar - Maddox	2.26792
Underwood	1.66541

TABLE LIV

RESULTS OF PROBLEM NUMBER 07032.21000

FEED COMPOSITION NO. 7

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min.Stages	At Min.Reflux	At Op. Cond.
C_2	5.00000	4.97014	5.00000	4.99999
C_3	15.00000	12.62757	12.62757	12.62757
iC_4	10.00000	2.89561	2.89561	2.89561
nC_4	10.00000	1.32431	0.84097	0.94240
iC_5	10.00000	0.11613	0	0.00028
nC_5	10.00000	0.06583	0	0.00003
C_6	10.00000	0.00280	0	0
C_7	10.00000	0.00013	0	0
C_{10}	20.00000	0	0	0
Totals	100.00000	22.00251	21.36415	21.46588

Operating Conditions:

Number of Stages	34.0
Feed Point	14.0
Reflux Ratio	1.56220
Type of Condenser	Partial
Feed Condition	BP
Pressure psia	300.0

Minimum Number of Stages 4.57201

Minimum Reflux Ratio

Erbar - Maddox	1.62159
Underwood	1.05867

Heat Loads Btu/Hr

Condenser	2.01×10^6
Reboiler	6.83×10^6
Feed	1.97×10^7
Distillate	2.91×10^6
Bottoms	2.16×10^7

TABLE LV

RESULTS OF PROBLEM NUMBER 07019.40000

FEED COMPOSITION NO. 7

Component	Feed Mols/Hr	Distillate Mols/Hr		
		At Min. Stages	At Min. Reflux	At Op. Cond.
C_2	5.00000	5.00000	5.00000	5.00000
C_3	15.00000	14.99999	15.00000	14.99998
iC_4	10.00000	9.98940	10.00000	9.98754
nC_4	10.00000	9.84604	9.84604	9.84604
iC_5	10.00000	0.32002	0.32002	0.32002
nC_5	10.00000	0.05264	0	0.03821
C_6	10.00000	0	0	0
C_7	10.00000	0	0	0
C_{10}	20.00000	0	0	0
Totals	100.00000	40.20810	40.16606	40.19179

Operating Conditions:

Number of Stages	21.0
Feed Point	10.0
Reflux Ratio	1.01533
Type of Condenser	Partial
Feed Condition	BP
Pressure psia	100.00

Heat Loads	Btu/Hr
Condenser	3.46×10^6
Reboiler	1.26×10^7
Feed	1.28×10^7
Distillate	6.05×10^6
Bottoms	1.59×10^7

Minimum Number of Stages 11.09105

Minimum Reflux Ratio

Erbar - Haddox	0.70806
Underwood	0.80909

TABLE LVI

RESULTS OF PROBLEM NUMBER 07033.40000

FEED COMPOSITION NO. 7

Component	Feed Mols/Hr	Distillate		
		At Min.Stages	At Min.Reflux	At. Op. Cond.
C_2	5.00000	5.00000	5.00000	5.00000
C_3	15.00000	15.00000	15.00000	15.00000
iC_4	10.00000	9.99924	10.00000	9.99958
nC_4	10.000000	9.97511	9.97511	9.97511
iC_5	10.00000	0.21595	0.21595	0.21595
nC_5	10.00000	0.02038	0	0.00915
C_6	10.00000	0	0	0
C_7	10.000000	0	0	0
C_{10}	20.00000	0	0	0
Totals	100.00000	40.21068	40.19107	40.19979

Operating Conditions:

Number of Stages	35.0
Feed Point	17.0
Reflux Ratio	0.79105
Type of Condenser	Partial
Feed Condition	BP
Pressure psia	100.0

Heat Loads	Btu/Hr
Condenser	2.67×10^6
Reboiler	1.18×10^7
Feed	1.28×10^7
Distillate	6.04×10^6
Bottoms	1.59×10^7

Minimum Number of Stages 14.52517

Minimum Reflux Ragio

Erbar - Maddox	0.72623
Underwood	0.52602

APPENDIX C

NOMENCLATURE

B - total mols of distillate product per unit time

C - constant

D - total mols of bottoms product per unit time

F - total mols of feed per unit time

H^f - feed enthalpy Btu per pound mol

K - vapor liquid equilibrium constant defined as y/x

L - total liquid rate per unit time at a given point in a fractionator

Q_c - condenser heat load, Btu per unit time

Q_r - reboiler heat load, Btu per unit time

R - reflux ratio, defined as L_o / D

R_m - minimum reflux ratio, defined as $(L_o / D)_m$, occurs at $S = \infty$

S - number of stages in a fractionator

S_m - minimum number of stages, occurs at $R = \infty$

V - total vapor rate per unit time at a given point in a fractionator

X_D - mols of any component in the distillate product per unit time

X_W - mols of any component in the bottoms product per unit time

a - exponent, unknown variable

b - exponent, defined by equation $b = \log K_{LK} / \log B\ K_{HK}$

c - exponent, unknown variable

g - algebraic variable

x - mol fraction of any component in the liquid phase

y - mol fraction of any component in the vapor phase

z - algebraic variable

α - relative volatility, defined by equation $\alpha = K_1/K_2$

β - defined by equation $\beta = K_{LK}/K_{HK}^{b}$

Δ - change in any quantity

ϕ_R - functional notation of Gilliland's correlation, defined by equation $\phi_R = R - R_m/R + 1$

ϕ_S - functional notation of Gilliland's correlation, defined by equation $\phi_S = S - S_m/S + 1$

Subscripts

o - pertains to reflux rate mols

1 - pertains to stream quantities leaving the top tray of fractionator

CT - pertains to total amount of liquid leaving the condenser

k - pertains to a known condition

m - pertains to minimum quantity

op - pertains to operating conditions

R - pertains to the rectifying section of a fractionator

S - pertains to the stripping section of a fractionator

u - pertains to an unknown condition

APPENDIX D

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Education: Attended elementary school in Canadian County and El Reno, graduating from Lincoln Grade School, Etta Dale Junior High School, and El Reno High School; received the Bachelor of Science degree from Oklahoma State University in May, 1954; received the Master of Science degree from Oklahoma State University in May, 1959; completed the requirements for the Doctor of Philosophy degree in August, 1960. Membership in scholarly or professional societies includes the Society of Sigma Xi, Sigma Tau, and the American Institute of Chemical Engineers.

Professional experience: Employed by the Magnolia Petroleum Company, Dallas, Texas in the Natural Gas Department from 1954 to 1956; tenure with Magnolia was interrupted for two years, while serving with the Ordnance Corps, United States Army, as a Motor Officer and Automotive Platoon Leader at Aberdeen Proving Grounds, Maryland, and in Europe; employed by Black, Sivalls and Bryson, Inc., Oklahoma City, Oklahoma, as a junior engineer, Summer of 1957