REFLUX TO TRAYS CORRELATION FOR MULTICOMPONENT DISTILLATION SYSTEMS

By

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REFLUX TO TRAYS CORRELATION FOR MULTICOMPONENT

DISTILLATION SYSTEMS

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PREFACE

A correlation has been developed which relates operating reflux ratio and number of stages to the minimum reflux ratio and number of stages for multicomponent systems.

A comparison of results from the correlation was made with results from plate to plate calculations.

I am grateful for the guidance given me by my adviser, Professor Robert N. Maddox. I also appreciate the assistance give me by Mr. Don DuBois.

I wish to thank Phillips Petroleum Company for the use of its computer.

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CHAPTER I

INTRODUCTION

A few years ago, short cut techniques for distillation calculations were a matter of necessity. The complexity of most distillation problems would not permit solution by rigorous methods in a reasonable period of time with hand calculations. In that era considerable effort was devoted to developing short cut methods. Then came development and widespread use of the digital computer which made the application of rigorous methods not only possible, but practical. The result was a decreased emphasis on short cut techniques. While it is true that short cut methods for distillation calculations are no longer a matter of necessity, they do remain attractive tools in certain areas of engineering work, even when a digital computer is available. In the area of design, answers sufficiently reliable for preliminary cost estimates may be obtained considerably cheaper by short cut methods. In the area of plant simulation by computer, the limitation of computer storage space may dictate the use of a short cut method.

A frequently used approach to short cut distillation calculations involves calculation of minimum values for the reflux ratio and number of stages required for a specified separation and the estimation of operating values based on the calculated minimum values. This approach requires a means of relating the operating values to the minimum values. Many correlations have been presented in the literature which relate these variables with varying degrees of accuracy. Errors up to and even exceeding 100 percent may be noted between results from these correlations and plate to plate calculations. Such errors 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. Other reasons for poor results may be that poor enthalpy or vapor-liquid equilibrium data were used to develop the correlation or the data were plotted on a single curve when a family of lines may have represented that data more accurately.

Of the many correlations that have been presented, the correlation of Erbar (6) appears to be particularly useful. Erbar plotted reflux ratios, L/V, against ratios of minimum trays to operating trays for separations representing various minimum reflux ratios. Such a plot results in a family of curves, each passing through the points L/V=1 at Sm/S=1 and the minimum L/V at Sm/S=0. Although the Erbar correlations represents a considerable advance in correlations of this type, it does have several limitations. The first limitation involves the conclusion by Erbar that the enthalpy and equilibrium data used in the development of the correlation left something to be desired. The second limitation is based on the possibility of errors caused by development of the correlation from data representing only relatively high minimum reflux ratios.

While the Erbar correlation offered many advantages over the correlations which preceded it, it appeared that an even more useful correlation would result, if a similiar correlation could be developed using better, or at least more consistent, enthalpy and equilibrium data. An additional objective of the study was to check the reliability of the correlation for separations representing lower values of minimum L/V ratios.

Limitations of the Study

The study was limited to multicomponent systems which contained paraffin hydrocarbons between methane and decane. The various systems used in the study are presented in Table I. In addition, only cases pertaining to the simple fractionator with a bubble point feed were considered. A correlation relating the minimum and operating reflux ratio and the minimum and operating number of stages was developed.

TABLE I

FEED COMPOSITIONS

	Feed Composition - Moles								
Component	1	2	3	4	5	7	8	11	12
C_1					1				
C_2				5	5	5			
C_3			10	20	24	15		20	25
iC_4		20	20	15	15	10		20	25
nC_4	25	20	20	15	15	10	1	20	
iC_5	25	20	20	15	15	10	4		
nC_5	25	20	20	15	15	10	45	20	25
C_6	25	20	10	15	10	10	50	20	25
C_7						10			
C_{10}						20			
Totals	100	100	100	100	100	100	100	100	100

CHAPTER II

SURVEY OF LITERATURE

To achieve a specified separation between two components of a given feed stream, a fractionator must be operated between two limits, which are: (1) the minimum reflux which occurs at an infinite number of stages, and (2) the minimum number of stages which occurs at infinite reflux. The operating stages and reflux must lie between these limits.

One short cut technique frequently used to solve distillation problems involves calculation of the minimum reflux ratio and the minimum number of stages required to make a desired separation, selection of a practical number of operating stages above the minimum, and estimation of the operating reflux ratio needed at the chosen number of operating stages. Such an approach is strongly dependent on the correlation relating the operating and minimum values for its reliability. A number of correlations relating these variables have been presented in the literature. Most of these correlations are inadequate for many distillation problems and will result in reflux rates which differ by 100 percent or more from values calculated by plate to plate methods. Such errors may result because a consistent basis was not used to determine the correlation parameters, but in most of the presentations no mention of the sources of equilibrium and enthalpy data or the methods of determining the parameters is given. Other possible explanations for errors of this magnitude include: (1) unreliable equilibrium and/or enthalpy data were used in the development of the correlations, and (2) the data were correlated with a single curve when a family of curves would have been more suitable.

A typical plot of the number of stages versus reflux ratio for a given separation is shown in Figure 1 (14). The curve in Figure 1 may be represented by an equation of the form

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

Underwood (14) has suggested the form

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

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

Brown and Martin (2) presented a correlation in 1939 that was based primarily on binary systems. Brown and Martin checked this correlation for multicomponent systems and found it to have nearly the same degree of accuracy for multicomponent systems as was noted for binary systems. The Brown and Martin correlation appears in Figure 2. The quantities V and L refer to vapor and liquid rates in the entire rectifying or stripping section of the fractionator. Usually, the assumption of constant molal overflow is applied to facilitate the choice of the vapor and liquid rates.

Gilliland (9) has presented a correlation based on multicomponent systems as well as binary systems. This correlation appears in Figure 3. Gilliland presents the correlation as a distinct line, but suggests that perhaps a better correlation would be a series of lines having approximately the same shape as the line presented. The assumption of constant molal overflow is made by Gilliland also.

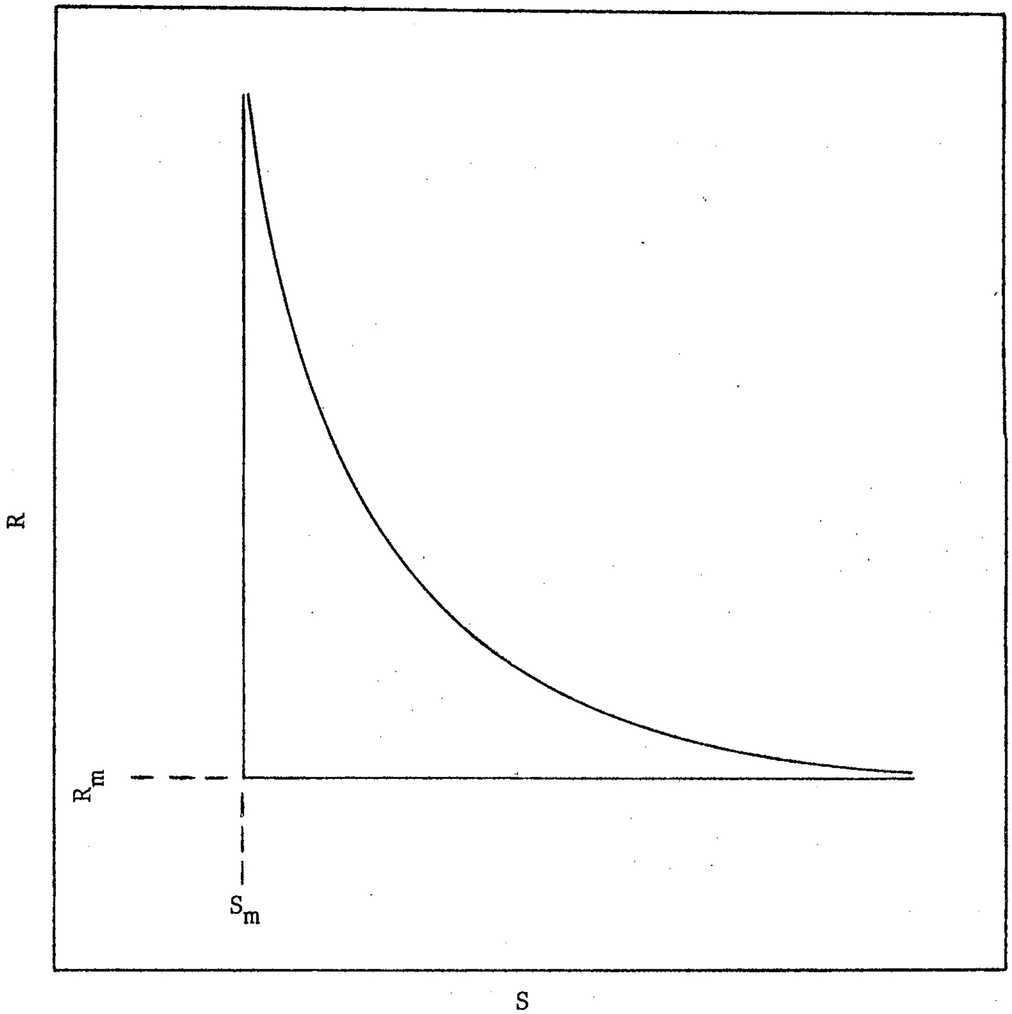

Figure 1. Relation of Operating Stages and Reflux Ratio to Minimum Stages and Reflux Ratio for a Given Separation

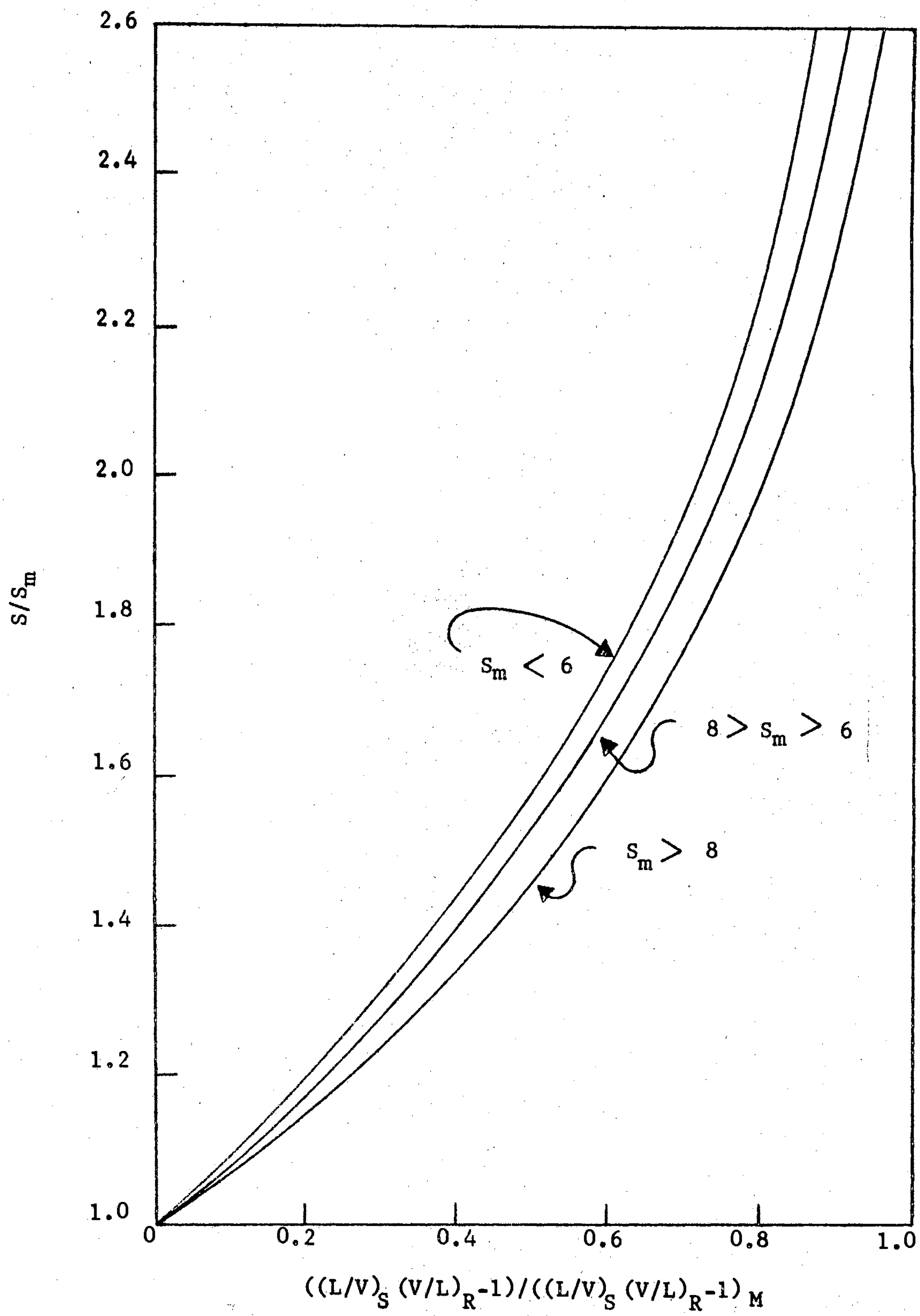

Figure 2. Brown and Martin Correlation of Minimum and Operating Reflux Ratio and Stages

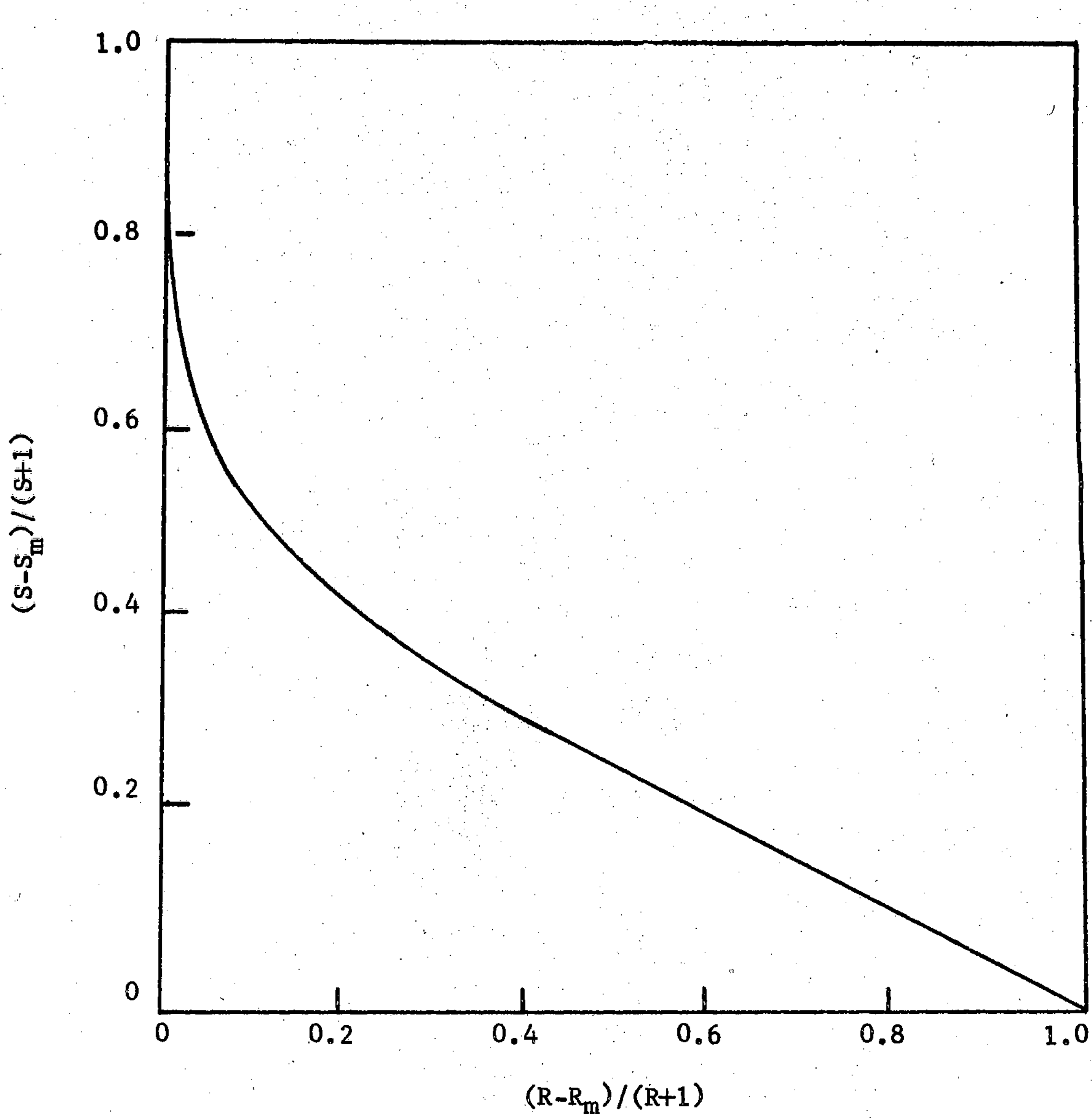

Figure 3. Gilliland Correlation of Minimum and Operating Reflux Ratio and Stages

Donnell and Cooper (4) have presented a correlation relating the number of stages to the boilup vapor, which was intended for use in determining the optimum steam requirement. With modifications, this correlation has been used to determine the reflux ratio from the minimum parameters. The correlation was based on binary and multicomponent systems, but what systems were studied was not specified. The assumption of constant molal overflow was not stated as a basis of the correlation, but it was used as a basis for solving sample problems presented in the article.

Mason (11) has presented the correlation shown in Figure 4. This curve has a hyperbolic form, which is entirely different from the forms presented by preceding authors. The method of determining the different variables was not mentioned in the presentation.

Erbar (6) has presented the correlation shown in Figure 5. This correlation was based on multicomponent systems containing paraffin hydrocarbons between methane and decane. In addition only cases pertaining to the simple fractionator were studied. Actually two separate correlations were presented. In one correlation the method of Underwood (13) was used to determine the minimum reflux ratio. In the other correlation the method of Erbar (7) was used to determine the minimum reflux ratio. In both correlations the minimum number of stages was determined by the method of Winn (15) and operating values were deter- by plate to plate calculations.

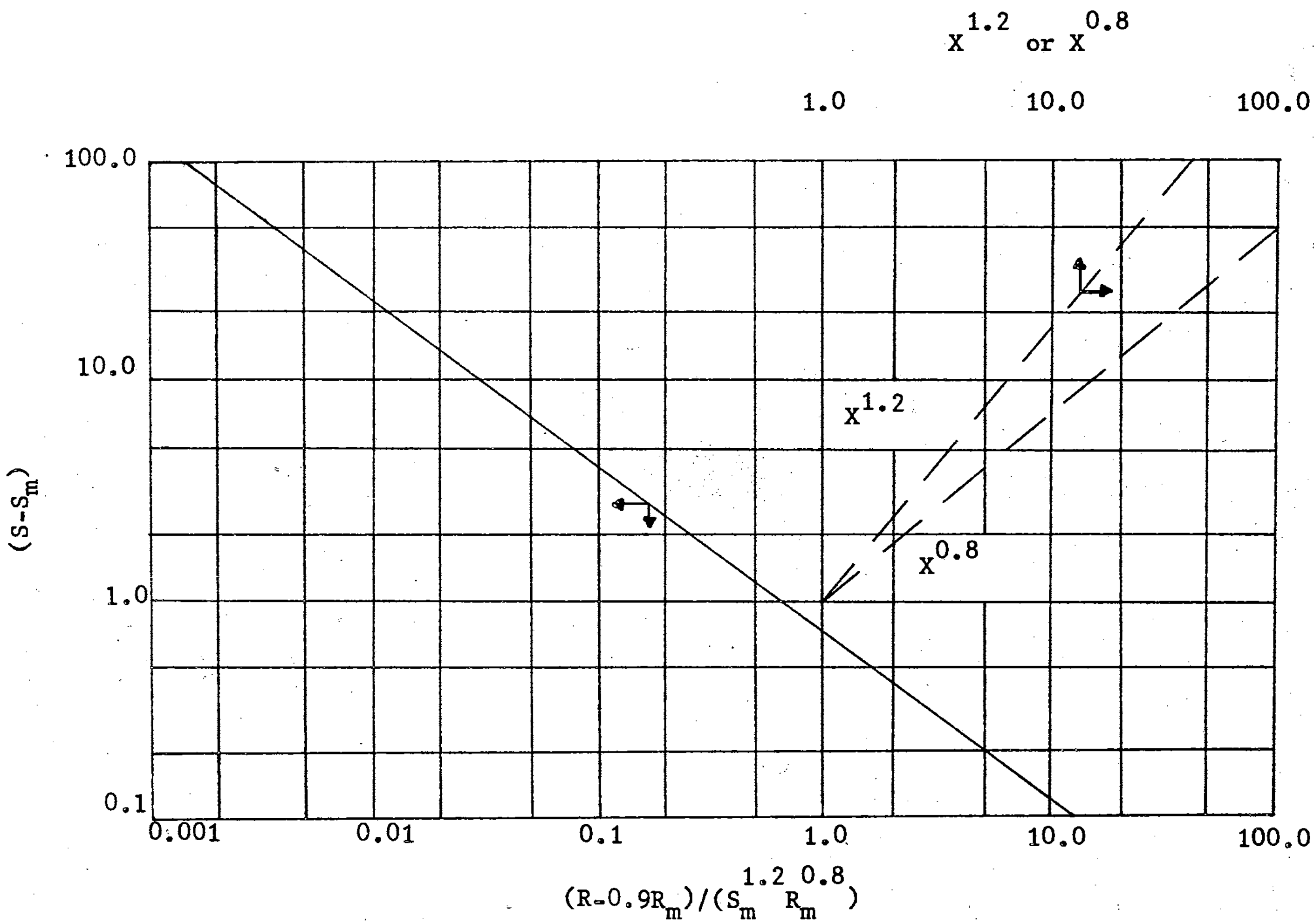

Figure 4. Mason Correlation of Minimum and Operating Reflux Ratio and Stages

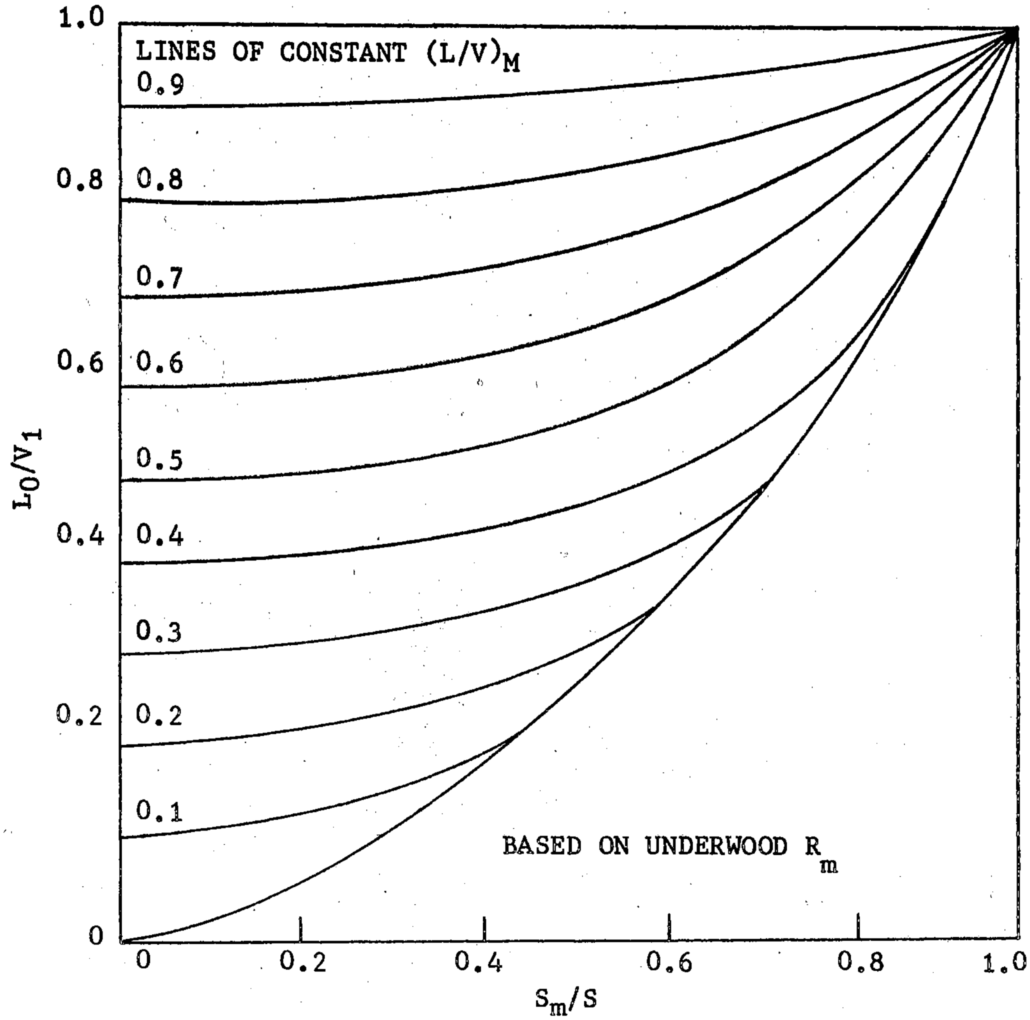

Figure 5. Erbar Correlation of Minimum and Operating Reflux Ratio and Stages

CHAPTER III

METHODS

All calculations used as a basis for the correlation presented in this thesis were carried out on an IBM 7094 Digital Computer.

Plate to plate calculations were made with an available program based on the principles of the Thiele-Geddes (12) approach using conventional Lewis and Matheson (10) tray calculations. In each problem the number of stages, the feed location, and the separation between two adjacent key components were specified and the plate to plate program computed the reflux rate required to make the specified separation between the key components.

Two methods were available for the minimum tray calculations. These were the short cut methods which have been presented by Fenske (8) and Winn (15). The analytical expression for Fenske's method is

$$\alpha^{Sm} = (X_D/X_B)_{LK}(X_B/X_D)_{HK} \tag{3}$$

The Fenske equation is based on the assumption of average relative volatility. Winn's method is expressed similiarly. It is

$$B_e^{Sm} = (X_D/X_B)_{LK}(X_B/X_D)_{HK}^{b}(B/D)^{1-b} \tag{4}$$

The terms B_e and b are used to relate the equilibrium K values of the key components at the distillate and bottoms temperatures.

Erbar (6) indicates that the minimum number of stages as calculated by the Fenske and Winn methods are approximately the same. The Fenske method was chosen arbitrarily for use in this study.

Many methods have been presented for calculating the minimum reflux ratio. In most of these methods, constant molal overflow and constant relative volatility were assumed. A few investigators have made a third assumption, namely, that the distillate composition that would be obtained at an infinite number of stages and the minimum reflux ratio can be obtained at a finite reflux ratio and number of stages. This third assumption has been shown to be in error (7).

Bachelor (1) presented the first method which did not rest upon the classical assumptions. R. Erbar (7) modified Bachelor's approach to obtain a plate to plate calculation for the determination of the minimum reflux ratio. R. Erbar also presents a comparison of results between her method and several frequently used short cut methods. The comparison indicates that the method of Underwood (13) agrees best with the theoretically correct values of R. Erbar. The average difference between the results of these two methods was about 10 percent. R. Erbar also presents evidence that results of calculations by the method of Underwood (13) are improved if the calculations are performed at the higher temperature of the feed temperature and the average column temperature.

DuBois (5) has proposed a modification of the Underwood minimum reflux correlation, which attempts to correct for the assumption of constant molal overflow.

In this study both the traditional Underwood method and the Underwood method as modified by DuBois were used to make minimum reflux calculations.

The vapor-liquid equilibria data used in this study were calculated from the correlation presented by Chao and Seader (3). Enthalpy data were obtained by the method of Yen and Alexander (16).

All calculations were performed on the feed systems presented in Table I. The results of the calculations are presented in the appendices of this thesis.

To facilitate problem interpretation and identification, a unique problem numbering system was employed. Each problem number consisted of nine digits which may be broken down as follows:

FFPPP.RRRR

where: FF - refers to the feed composition from Table I

PPP - refers to the number of operating stages exclusive of the reboiler and partial condenser, if present

RRRR - refers to the minimum reflux ratio, L/V, computed at the average column temperature

For example, problem number 01038.6337 means that:

1. Feed composition number 1 was used.
2. There were 38 operating stages in the fractionator excluding the reboiler.
3. The specified separation required a minimum reflux ratio of .6337.

CHAPTER IV

RESULTS AND DISCUSSION OF RESULTS

The results of this investigation are presented on the following pages. The data from which the results were determined are presented in the appendices. Results are presented in both tabular and graphical form.

A total of one hundred and forty-six tray by tray calculations were made. These calculations represented nine different feed compositions and thirty-seven distinct separations. Minimum reflux and minimum tray computations were made for each of the separations. Minimum tray calculations were made at the average column temperature. Minimum reflux calculations were performed at both the feed temperature and the average column temperature. Plots of the raw data from these computations are presented in Figures 6 through 9. For the purpose of plotting Figures 6 through 9, the data from the tray by tray calculations were combined into nineteen groups with each group having the same, or nearly the same L/V ratio. Each of these groups of data is represented by a minimum L/V line in Figures 6 through 9.

Figure 10 is the correlation recommended for use. A comparison of results from Figure 10 and results of tray by tray calculations is presented in Table II. Percent deviations and absolute deviations between estimated and calculated L/V ratios are given. Results estimated from Figure 10 and presented in Table II are based on standard Under-

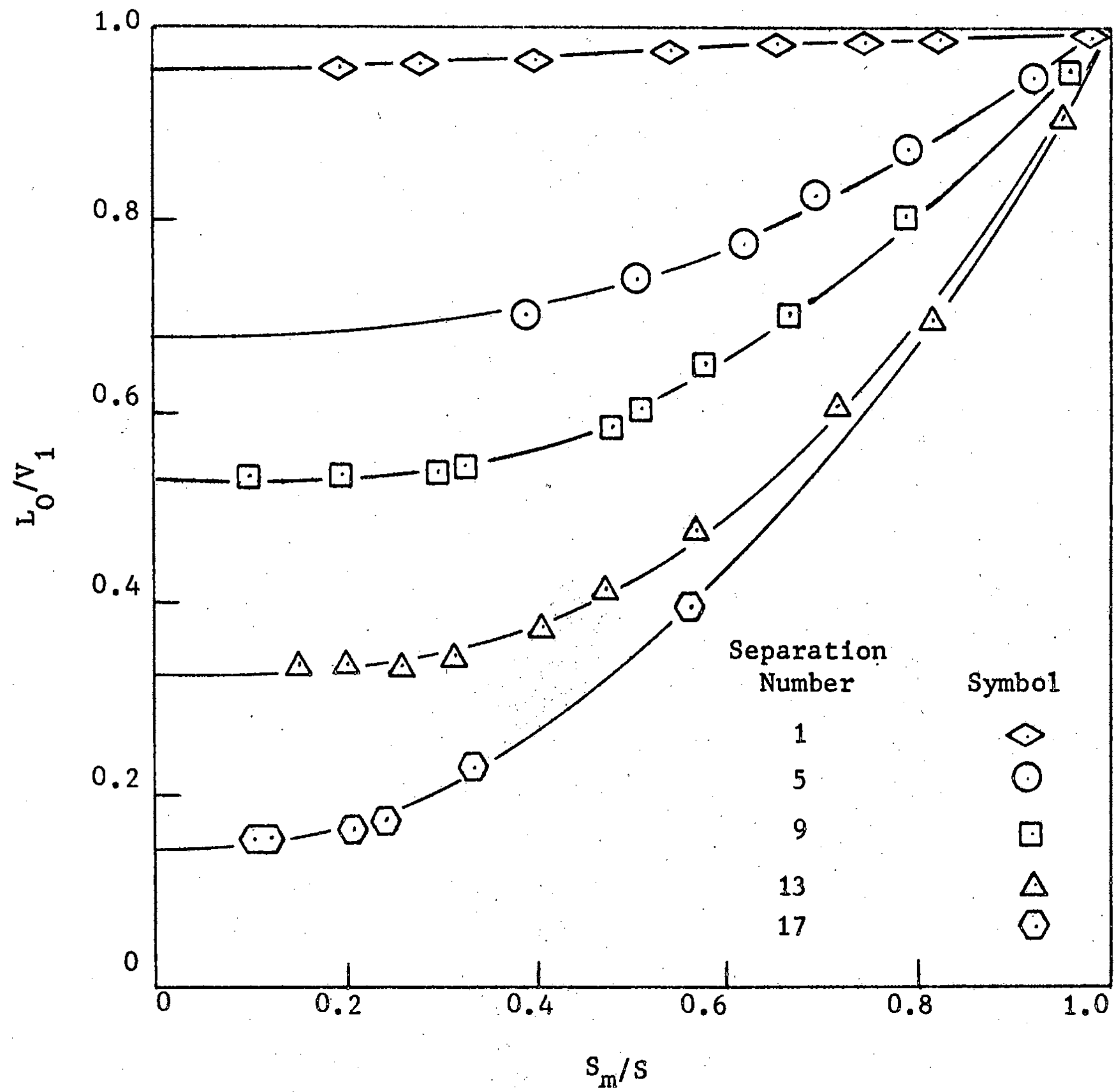

Figure 6. Data for Separations 1, 5, 9, 13, and 17 of Table XI Plotted in the Form of the Proposed Correlation.

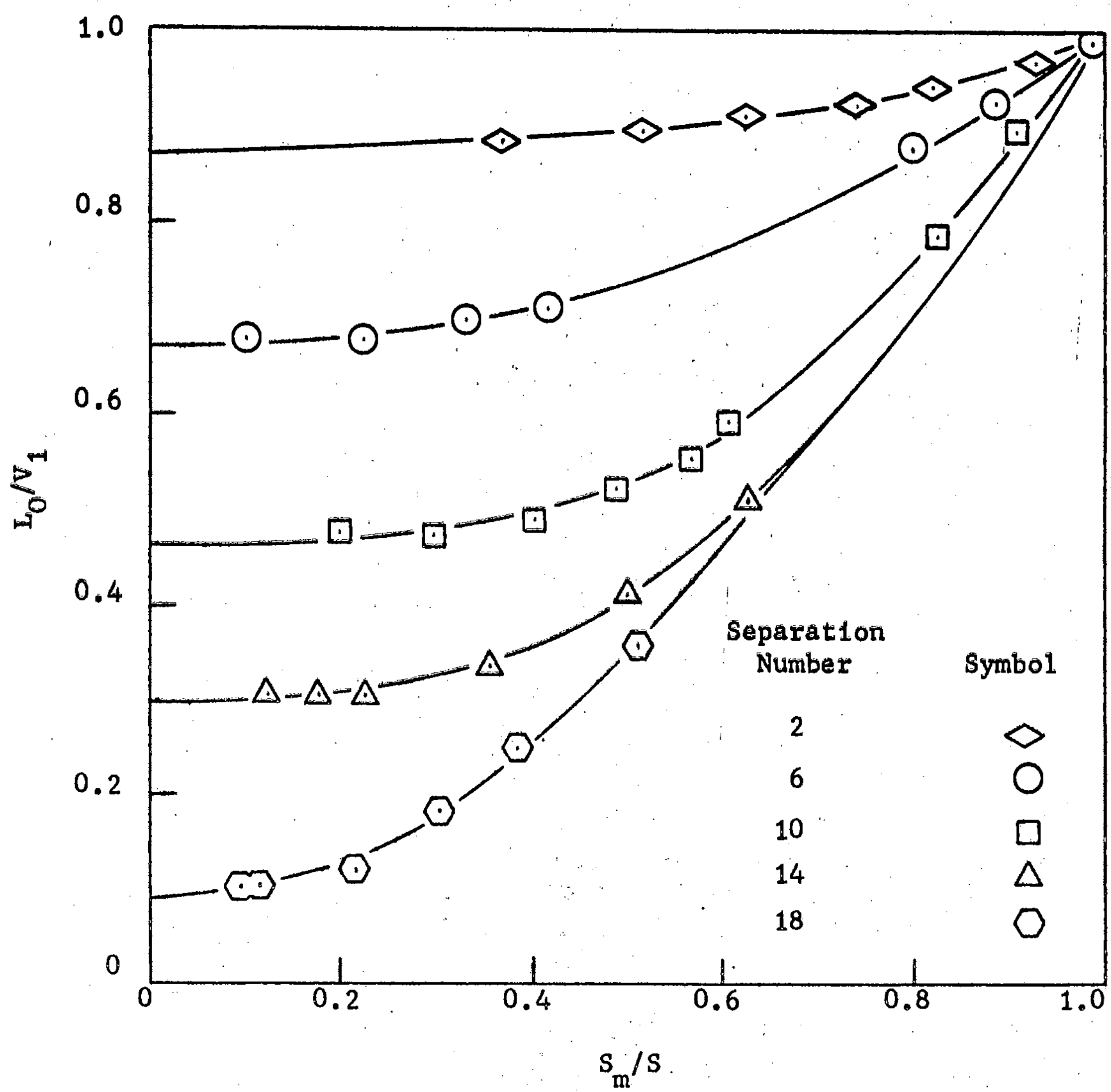

Figure 7. Data for Separations 2, 6, 10, 14, and 18 of Table XI Plotted in the Form of the Proposed Correlation.

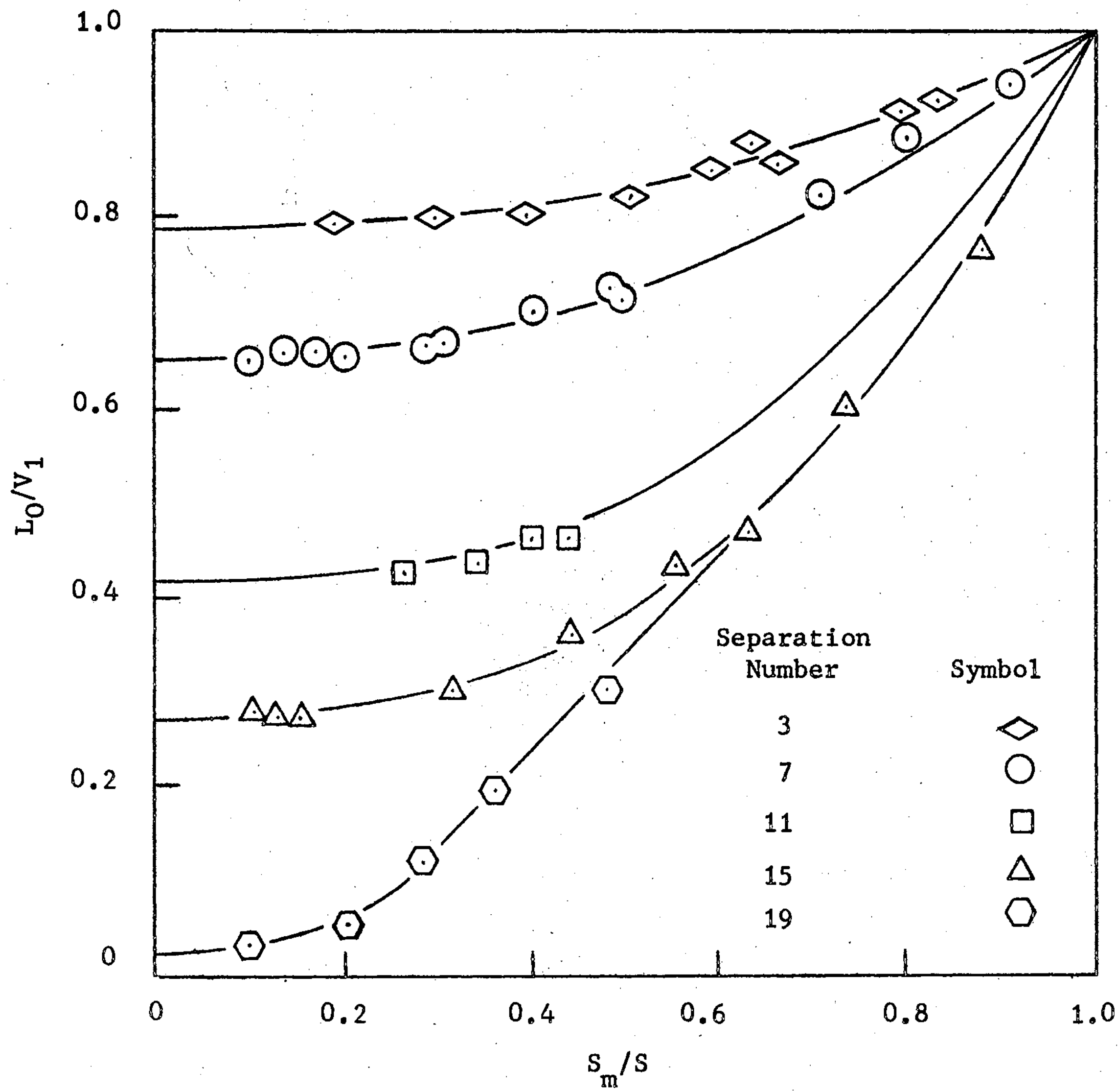

Figure 8. Data for Separations 3, 7, 11, 15, and 19 of Table XI Plotted in the Form of the Proposed Correlation.

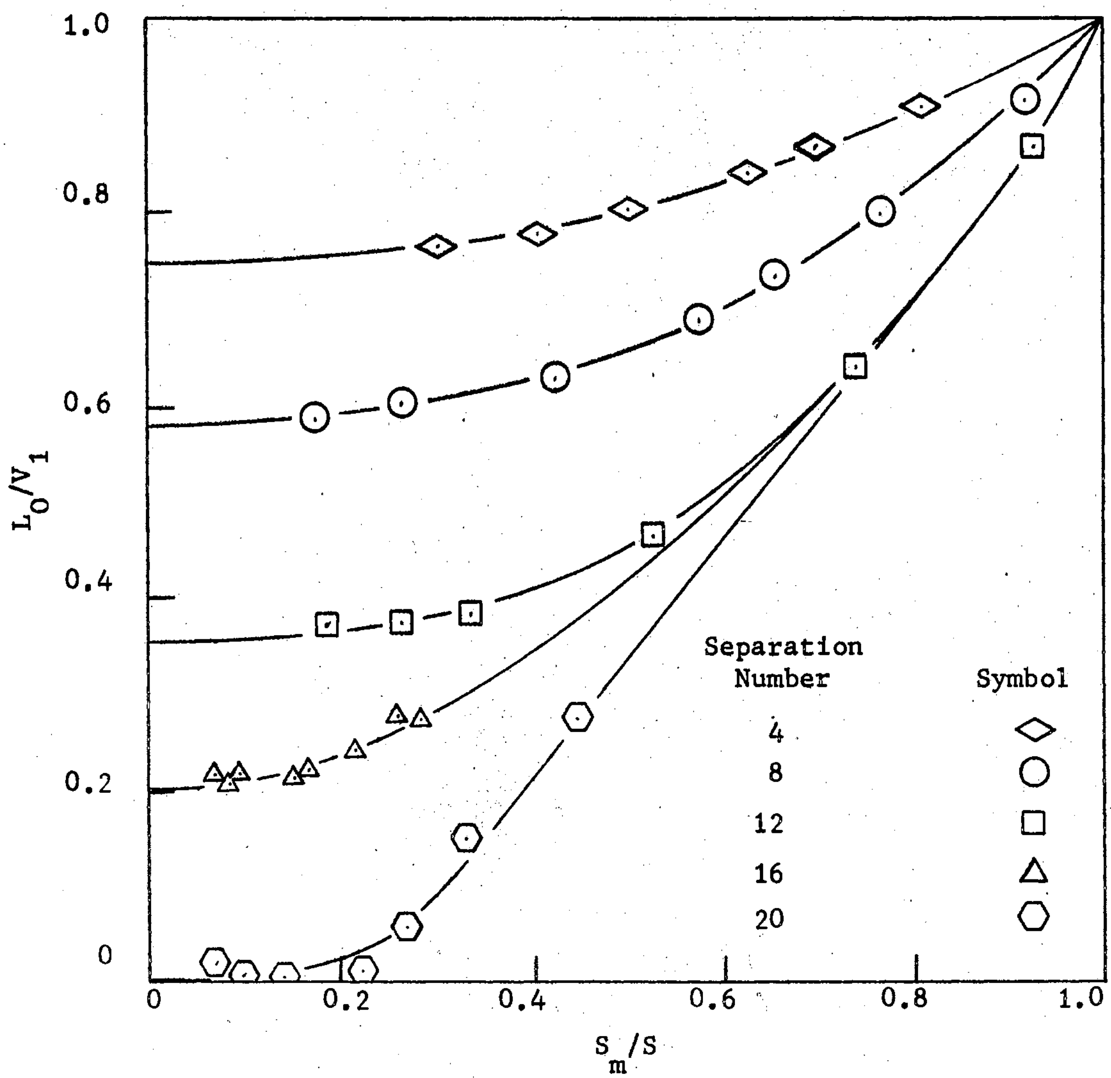

Figure 9. Data for Separations 4, 8, 12, 16, and 20 of Table XI Plotted in the Form of the Proposed Correlation.

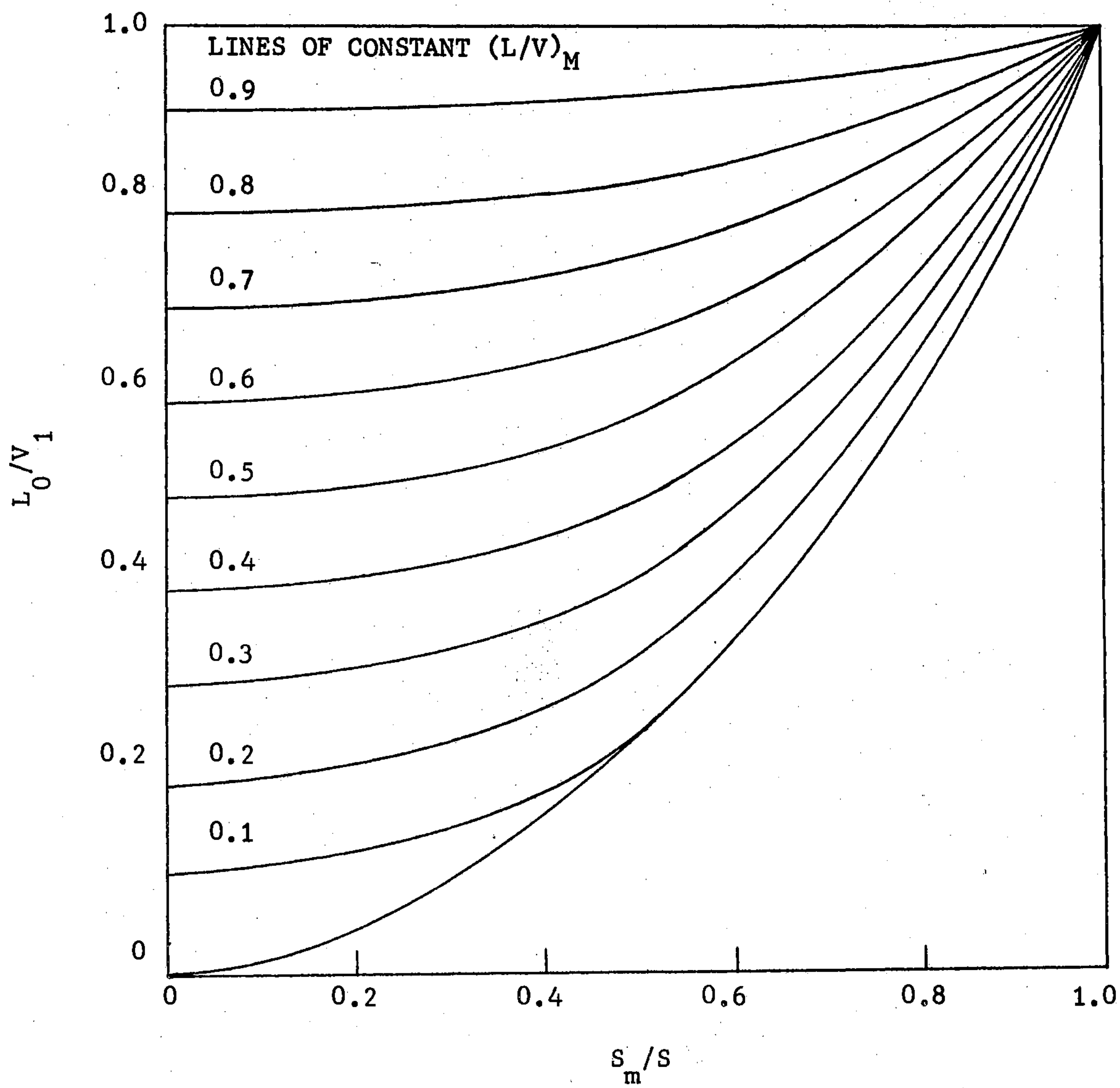

Figure 10. Proposed Correlation of Minimum and Operating Reflux Ratio and Stages

TABLE II

COMPARISON OF RESULTS FROM FIGURE 10 WITH RESULTS FROM TRAY BY TRAY CALCULATIONS BASED ON MINIMUM L/V RATIOS AT THE AVERAGE COLUMN TEMPERATURE

PROBLEM NUMBER	$\frac{S_m}{S}$ op	$\frac{L}{V}$ min	(L/V)op CALC	(L/V)op CORR	ABS. DEV.	Percent Dev.
08157.9523	.1991	.9523	.9590	.9531	.0059	- .62
08111.9523	.2809	.9523	.9630	.9542	.0088	- .91
08077.9523	.4034	.9523	.9688	.9570	.0118	- 1.22
08057.9523	.5425	.9523	.9754	.9622	.0132	- 1.36
08047.9523	.6555	.9523	.9804	.9682	.0122	- 1.25
08041.9523	.7492	.9523	.9861	.9746	.0115	- 1.17
08037.9523	.8280	.9523	.9884	.9811	.0073	- .74
08031.9523	.9893	.9523	.9961	.9977	.0016	.16
02059.8630	.3702	.8630	.8815	.8738	.0077	- .87
02029.8630	.7403	.8630	.9283	.9251	.0032	- .34
02026.8630	.8226	.8630	.9432	.9444	.0012	.12
02023.8630	.9254	.8630	.9647	.9735	.0088	.92
02041.8667	.6225	.8667	.9110	.9057	.0053	- .59
02058.8697	.5142	.8697	.8993	.8932	.0061	- .68
03021.8121	.8398	.8121	.9298	.9298	.0000	- .01
01109.7952	.3037	.7952	.8013	.8051	.0038	.47
01055.7952	.5966	.7952	.8551	.8490	.0061	- .72
01041.7952	.7955	.7952	.9177	.9068	.0109	- 1.19
01038.7844	.6643	.7844	.8664	.8587	.0077	- .89
03031.8189	.6403	.8189	.8807	.8757	.0050	- .56
01151.7922	.1972	.7922	.7949	.7956	.0007	.09
01074.7922	.3997	.7922	.8092	.8121	.0029	.36
01058.7922	.5081	.7922	.8293	.8286	.0007	- .08
02109.7481	.2992	.7481	.7647	.7598	.0049	- .64
02081.7481	.4014	.7481	.7794	.7725	.0069	- .88
02065.7481	.4987	.7481	.8017	.7902	.0115	- 1.43
02040.7481	.8028	.7481	.9095	.8886	.0209	- 2.30
02050.7540	.6981	.7540	.8678	.8501	.0177	- 2.04
02060.7562	.6211	.7562	.8427	.8270	.0157	- 1.86
05026.6993	.3972	.6993	.7001	.7277	.0276	3.94
05020.6993	.5056	.6993	.7374	.7513	.0139	1.89
05016.6993	.6179	.6993	.7733	.7855	.0122	1.58
05014.6993	.6952	.6993	.8246	.8155	.0091	- 1.10
05012.6993	.7945	.6993	.8762	.8626	.0136	- 1.55
05010.6993	.9269	.6993	.9487	.9430	.0057	- .60
01079.6503	.0993	.6503	.6779	.6513	.0266	- 3.92
01035.6503	.2208	.6503	.6795	.6579	.0216	- 3.18
01023.6503	.3312	.6503	.6942	.6712	.0230	- 3.31
01018.6503	.4183	.6503	.7064	.6879	.0185	- 2.62
01009.6503	.7948	.6503	.8794	.8404	.0390	- 4.43
01008.6503	.8831	.6503	.9225	.8998	.0227	- 2.46
01007.6503	.9935	.6503	.9897	.9930	.0033	.33

TABLE II (Continued)

PROBLEM NUMBER	$\frac{S_m}{S}$ op	$\frac{L}{V}$ min	(L/V)op CALC	(L/V)op CORR	ABS. DEV.	Percent Dev.
01065.6223	.0972	.6223	.6488	.6234	.0254	- 3.92
01048.6223	.1310	.6223	.6529	.6245	.0284	- 4.35
01031.6223	.2006	.6223	.6539	.6288	.0251	- 3.85
01020.6223	.3056	.6223	.6668	.6408	.0260	- 3.90
01015.6223	.4011	.6223	.7008	.6589	.0419	- 5.99
01012.6223	.4937	.6223	.7266	.6839	.0427	- 5.88
01008.6223	.7131	.6223	.8274	.7780	.0494	- 5.97
01007.6223	.8022	.6223	.8862	.8326	.0536	- 6.05
01006.6223	.9169	.6223	.9446	.9197	.0249	- 2.63
04015.6351	.4932	.6351	.7113	.6944	.0169	- 2.37
04025.6316	.2973	.6316	.6680	.6484	.0196	- 2.93
01038.6337	.1751	.6337	.6604	.6382	.0222	- 3.37
02034.5613	.2613	.5613	.6022	.5758	.0264	- 4.38
02015.5613	.5715	.5613	.6895	.6646	.0249	- 3.61
02013.5613	.6531	.5613	.7361	.7060	.0301	- 4.08
02011.5613	.7620	.5613	.7999	.7754	.0245	- 3.06
02009.5613	.9144	.5613	.9153	.9043	.0110	- 1.20
02024.5668	.4217	.5668	.6300	.6143	.0157	- 2.49
02044.5493	.1708	.5493	.5883	.5544	.0339	- 5.75
03085.5098	.1009	.5098	.5325	.5113	.0212	- 3.98
03043.5098	.1972	.5098	.5352	.5178	.0174	- 3.25
03028.5098	.2992	.5098	.5381	.5326	.0055	- 1.03
03017.5098	.4821	.5098	.5893	.5851	.0042	- .72
03014.5098	.5785	.5098	.6525	.6289	.0236	- 3.62
03012.5098	.6675	.5098	.7037	.6807	.0230	- 3.27
03010.5098	.7888	.5098	.8010	.7712	.0298	- 3.72
03008.5098	.9641	.5098	.9668	.9513	.0155	- 1.60
03027.5137	.3272	.5137	.5453	.5420	.0033	- .61
03017.5137	.5091	.5137	.6054	.5993	.0061	- 1.00
05089.4874	.1995	.4874	.4749	.4960	.0211	4.45
05059.4874	.2976	.4874	.4761	.5109	.0348	7.31
05043.4874	.4034	.4874	.4886	.5377	.0491	10.05
05035.4874	.4906	.4874	.5223	.5696	.0473	9.06
05030.4874	.5673	.4874	.5539	.6059	.0520	9.39
05023.4874	.6051	.4874	.5928	.6269	.0341	5.74
05020.4874	.8251	.4874	.7893	.7942	.0049	.62
05018.4874	.9076	.4874	.8990	.8804	.0186	- 2.07
07033.4676	.4446	.4676	.4651	.5343	.0692	14.88
04045.4284	.2641	.4284	.4292	.4478	.0186	4.34
04029.4284	.4005	.4284	.4663	.4835	.0172	3.69
04041.4248	.3460	.4248	.4383	.4632	.0249	5.69
11039.3659	.1849	.3659	.3716	.3747	.0031	.84
11027.3659	.2641	.3659	.3734	.3874	.0140	3.76
11021.3659	.3362	.3659	.3815	.4053	.0238	6.25
11013.3659	.5283	.3659	.4634	.4885	.0251	5.41
11009.3659	.7396	.3659	.6393	.6527	.0134	2.10
11007.3659	.9245	.3659	.8665	.8762	.0097	1.12

TABLE II (Continued)

PROBLEM NUMBER	$\frac{S_m}{S}$ op	$\frac{L}{V}$ min	(L/V) op CALC	(L/V) op CORR	ABS. DEV.	Percent Dev.
11039.3313	.1434	.3313	.3344	.3362	.0018	.55
11027.3313	.2049	.3313	.3349	.3433	.0084	2.52
11021.3313	.2608	.3313	.3383	.3533	.0150	4.44
11017.3313	.3187	.3313	.3477	.3677	.0120	5.75
11013.3313	.4098	.3313	.3789	.3996	.0207	5.46
11011.3313	.4781	.3313	.4151	.4319	.0168	4.04
11009.3313	.5737	.3313	.4799	.4903	.0104	2.18
11007.3313	.7171	.3313	.6041	.6109	.0068	1.13
11006.3313	.8196	.3313	.6953	.7247	.0294	4.23
11005.3313	.9562	.3313	.9059	.9203	.0144	1.58
11039.3061	.1254	.3061	.3075	.3098	.0023	.74
11027.3061	.1791	.3061	.3075	.3150	.0075	2.45
11021.3061	.2280	.3061	.3096	.3224	.0128	4.14
11013.3061	.3583	.3061	.3387	.3567	.0180	5.32
11009.3061	.5016	.3061	.4153	.4238	.0085	2.05
11007.3061	.6270	.3061	.5110	.5126	.0016	.31
11039.2784	.1110	.2784	.2789	.2817	.0028	1.01
11033.2784	.1306	.2784	.2788	.2831	.0043	1.55
11027.2784	.1586	.2784	.2787	.2857	.0070	2.53
11013.2784	.3172	.2784	.3012	.3177	.0165	5.47
11009.2734	.4441	.2784	.3620	.3690	.0070	1.93
11007.2784	.5551	.2784	.4388	.4367	.0021	- .47
11006.2784	.6344	.2784	.4712	.5000	.0288	6.10
11005.2784	.7402	.2784	.6080	.6058	.0022	.37
11004.2784	.8882	.2784	.7714	.8013	.0299	3.87
12033.2017	.0767	.2017	.2181	.2029	.0152	- 6.95
12031.2017	.0815	.2017	.2177	.2031	.0146	- 6.69
12027.2017	.0931	.2017	.2175	.2037	.0138	- 6.34
12016.2017	.1534	.2017	.2175	.2087	.0088	- 4.06
12015.2017	.1629	.2017	.2217	.2098	.0119	- 5.37
12011.2017	.2172	.2017	.2450	.2183	.0267	-10.88
12009.2017	.2607	.2017	.2772	.2280	.0492	-17.76
12008.2017	.2897	.2017	.2754	.2359	.0395	-14.34
12031.1725	.1054	.1725	.1539	.1764	.0225	13.92
12027.1725	.1204	.1725	.1540	.1753	.0213	14.57
12015.1725	.2108	.1725	.1646	.1885	.0239	14.52
12013.1725	.2409	.1725	.1761	.1948	.0187	10.64
12009.1725	.3372	.1725	.2296	.2243	.0053	- 2.29
12005.1725	.5620	.1725	.3981	.3594	.0387	- 9.73
12029.1508	.1026	.1508	.1003	.1535	.0532	53.05
12025.1508	.1184	.1508	.1005	.1547	.0542	53.91
12013.1508	.2199	.1508	.1218	.1691	.0473	38.79
12009.1508	.3078	.1508	.1876	.1931	.0055	2.95
12007.1508	.3848	.1508	.2501	.2249	.0252	-10.09
12005.1508	.5130	.1508	.3563	.3032	.0531	-14.90
12017.1244	.1032	.1244	.0373	.1272	.0899	241.12
12013.1244	.2065	.1244	.0557	.1405	.0848	152.21

TABLE II (Continued)

PROBLEM NUMBER	$\frac{S_m}{S}$ op	$\frac{L}{V}$ min	(L/V)op CALC	(L/V)op CORR	ABS. DEV.	Percent Dev.
12009.1244	.2891	.1244	.1228	.1617	.0389	31.69
12007.1244	.3614	.1244	.1995	.1897	.0098	- 4.93
12005.1244	.4818	.1244	.3084	.2586	.0498	-16.14
12025.0769	.1036	.0769	.0010	.0799	.0789	7892.
12017.0769	.1496	.0769	.0013	.0845	.0832	6498.
12011.0769	.2244	.0769	.0137	.0978	.0841	613.65
12009.0769	.2693	.0769	.0553	.1098	.0545	98.63
12007.0769	.3366	.0769	.1482	.1345	.0137	- 9.26
12005.0769	.4488	.0769	.2757	.1953	.0804	-29.15
07016.0001	.0757	.0001	.0150	.0783	.0633	421.86

Total absolute difference 2.225

Average absolute difference .017

Average percent deviation 3.438

wood (13) minimum reflux ratios computed at the average column temperature.

R. Erbar (7) reports some improvement in minimum reflux values by the Underwood method using the higher of the feed temperature and the average column temperature. Estimated results from Figure 10 using the feed and the average column temperature are compared with results of tray by tray calculations in Table III.

Table IV is a presentation of results estimated from Figure 10 using the Underwood method as modified by DuBois (5). Table IV results are based on minimum reflux ratios calculated at the average column temperature.

Some of the problems used in this study are identical to problems used by Erbar (6). A comparison of results for these common problems from Erbar's work and Table II are presented in Table V.

Table II shows the results of one hundred and forty-six problems used in this study. Calculations are based on the standard Underwood method and the average column temperature. The percentage deviation for $(L/V)_{min}$ values greater than .20 are very low. Between $(L/V)_{min}$ values of .15 and .20, the percentage deviations are reasonable. Below $(L/V)_{min}$ equal to .15, the percentage deviations are very high. A comparison of the $(L/V)_{min}$ values and the calculated $(L/V)_{op}$ values of Table II shows many points where the $(L/V)_{op}$ value is much less than the predicted $(L/V)_{min}$ value. The $(L/V)_{min}$ values are incorrect for these points and cannot be used with Figure 10 to calculate reliable $(L/V)_{op}$ values. Therefore, deviations for problems below $(L/V)_{min}$ equal to .15 are not included in total and average deviations presented. The total absolute deviation for Table II is 2.225. The average

TABLE III

COMPARISON OF RESULTS FROM FIGURE 10 WITH RESULTS FROM TRAY BY TRAY CALCULATIONS BASED ON MINIMUM L/V RATIOS AT THE HIGHER OF THE FEED AND THE AVERAGE COLUMN TEMPERATURE

PROBLEM NUMBER	$\frac{S_m}{S}$ op	$\frac{L}{V}$ min	(L/V)op CALC	(L/V)op CORR	ABS. DEV.	Percent Dev.
08157.9523	.1991	.9551	.9590	.9559	.0031	- .33
08111.9523	.2807	.9551	.9630	.9569	.0061	- .64
08077.9523	.4034	.9551	.9688	.9595	.0093	- .96
08057.9523	.5425	.9551	.9754	.9644	.0110	- 1.13
08047.9523	.6555	.9551	.9804	.9701	.0103	- 1.06
08041.9523	.7492	.9551	.9861	.9761	.0100	- 1.02
08037.9523	.8280	.9551	.9884	.9822	.0062	- .63
08031.9523	.9893	.9551	.9961	.9978	.0017	.17
02059.8630	.3702	.8699	.8815	.8802	.0013	- .15
02029.8630	.7403	.8699	.9283	.9289	.0006	.06
02026.8630	.8226	.8699	.9432	.9472	.0040	.42
02023.8630	.9254	.8699	.9647	.9749	.0102	1.05
02041.8667	.6225	.8734	.9110	.9104	.0006	- .07
02058.8697	.5142	.8763	.8993	.8986	.0007	- .07
03021.8121	.8398	.8131	.9298	.9302	.0004	.04
01109.7952	.3037	.7952	.8013	.8051	.0038	.47
01055.7952	.5966	.7952	.8551	.8490	.0061	- .72
01041.7952	.7955	.7952	.9177	.9068	.0109	- 1.19
01038.7844	.6643	.7844	.8664	.8587	.0077	- .89
03031.8189	.6403	.8199	.8807	.8764	.0043	- .49
01151.7922	.1972	.7922	.7949	.7956	.0007	.09
01074.7922	.3997	.7922	.8092	.8121	.0029	.36
01058.7922	.5081	.7922	.8293	.8286	.0007	- .08
02109.7581	.2992	.7481	.7647	.7598	.0049	- .64
02081.7481	.4014	.7481	.7794	.7725	.0069	- .88
02065.7481	.4987	.7481	.8017	.7902	.0115	- 1.43
02040.7481	.8028	.7481	.9095	.8886	.0209	- 2.30
02050.7540	.6981	.7540	.8678	.8501	.0177	- 2.04
02060.7562	.6211	.7562	.8427	.8270	.0157	- 1.86
05026.6993	.3972	.6993	.7001	.7277	.0276	3.94
05020.6993	.5056	.6993	.7374	.7513	.0139	1.89
05016.6993	.6179	.6993	.7733	.7855	.0122	1.58
05014.6993	.6952	.6993	.8246	.8155	.0091	- 1.10
05012.6993	.7945	.6993	.8762	.8626	.0136	- 1.55
05010.6993	.9269	.6993	.9487	.9430	.0057	- .60
01079.6503	.0993	.6573	.6779	.6583	.0196	- 2.89
01035.6503	.2208	.6573	.6795	.6647	.0148	- 2.17
01023.6503	.3312	.6573	.6942	.6778	.0164	- 2.36
01018.6503	.4183	.6573	.7064	.6941	.0123	- 1.73
01009.6503	.7948	.6573	.8794	.8436	.0358	- 4.07
01008.6503	.8831	.6573	.9225	.9018	.0207	- 2.24
01007.6503	.9935	.6573	.9897	.9931	.0034	.34

TABLE III (Continued)

PROBLEM NUMBER	$\frac{S_m}{S}$ op	$\frac{L}{V}$ min	(L/V)op CALC	(L/V)op CORR	ABS. DEV.	Percent Dev.
01065.6223	.0972	.6283	.6488	.6293	.0195	- 3.00
01048.6223	.1310	.6283	.6529	.6305	.0224	- 3.43
01031.6223	.2006	.6283	.6539	.6346	.0193	- 2.94
01020.6223	.3056	.6283	.6668	.6465	.0203	- 3.04
01015.6223	.4011	.6283	.7008	.6643	.0365	- 5.21
01012.6223	.4937	.6283	.7266	.6889	.0377	- 5.19
01008.6223	.7131	.6283	.8274	.7815	.0459	- 5.54
01007.6223	.8022	.6283	.8862	.8352	.0510	- 5.75
01006.6223	.9169	.6283	.9446	.9210	.0236	- 2.50
04015.6351	.4932	.6371	.7113	.6961	.0152	- 2.14
04025.6316	.2973	.6335	.6680	.6503	.0177	- 2.66
01038.6337	.1751	.6401	.6604	.6445	.0159	- 2.41
02034.5615	.2613	.5613	.6022	.5758	.0264	- 4.38
02015.5613	.5715	.5613	.6895	.6646	.0249	- 3.61
02013.5613	.6531	.5613	.7361	.7060	.0301	- 4.08
02011.5613	.7620	.5613	.7999	.7754	.0245	- 3.06
02009.5613	.9144	.5613	.9153	.9043	.0110	- 1.20
02024.5668	.4217	.5668	.6300	.6143	.0157	- 2.49
02044.5493	.1708	.5493	.5883	.5544	.0339	- 5.75
03085.5098	.1009	.5098	.5325	.5113	.0212	- 3.98
03043.5098	.1972	.5098	.5352	.5178	.0174	- 3.25
03028.5098	.2992	.5098	.5381	.5326	.0055	- 1.03
03017.5098	.4821	.5098	.5893	.5851	.0042	- .72
03014.5098	.5785	.5098	.6525	.6289	.0236	- 3.62
03012.5098	.6675	.5098	.7037	.6807	.0230	- 3.27
03010.5098	.7888	.5098	.8010	.7712	.0298	- 3.72
03008.5098	.9641	.5098	.9668	.9513	.0155	- 1.60
03027.5137	.3272	.5137	.5453	.5420	.0033	- .61
03017.5137	.5091	.5137	.6054	.5993	.0061	- 1.00
05089.4874	.1995	.4874	.4749	.4960	.0211	4.45
05059.4874	.2976	.4874	.4761	.5109	.0348	7.31
05043.4874	.4034	.4874	.4886	.5377	.0491	10.05
05035.4874	.4906	.4874	.5223	.5696	.0473	9.06
05030.4874	.5673	.4874	.5539	.6099	.0520	9.39
05028.4874	.6051	.4874	.5928	.6269	.0341	5.74
05020.4874	.8251	.4874	.7893	.7942	.0049	.62
05018.4874	.9076	.4874	.8990	.8804	.0186	- 2.07
07033.4676	.4446	.4676	.4651	.5343	.0692	14.88
04045.4284	.2641	.4284	.4292	.4478	.0186	4.34
04029.4284	.4005	.4284	.4663	.4835	.0172	3.69
04041.4248	.3460	.4248	.4383	.4632	.0249	5.69
11039.3659	.1849	.3659	.3716	.3747	.0031	.84
11027.3659	.2641	.3659	.3734	.3874	.0140	3.76
11021.3659	.3362	.3659	.3815	.4053	.0238	6.25
11013.3659	.5283	.3659	.4634	.4885	.0251	5.41
11009.3659	.7396	.3659	.6393	.6527	.0134	2.10

TABLE III (Continued)

PROBLEM NUMBER	$\frac{S_m}{S}$ op	$\frac{L}{V}$ min	(L/V)op CALC	CORR	ABS. DEV.	Percent Dev.
11007.3659	.9245	.3659	.8665	.8762	.0097	1.12
11039.3313	.1434	.3313	.3344	.3362	.0018	.55
11027.3313	.2049	.3313	.3349	.3433	.0084	2.52
11021.3313	.2608	.3313	.3383	.3533	.0150	4.44
11017.3313	.3187	.3313	.3477	.3677	.0120	5.75
11013.3313	.4098	.3313	.3789	.3996	.0207	5.46
11011.3313	.4781	.3313	.4151	.4319	.0168	4.04
11009.3313	.5737	.3313	.4799	.4903	.0104	2.18
11007.3313	.7171	.3313	.6041	.6109	.0068	1.13
11006.3313	.8196	.3313	.6953	.7247	.0294	4.23
11005.3313	.9562	.3313	.9059	.9203	.0144	1.58
11039.3061	.1254	.3061	.3075	.3098	.0023	.74
11027.3061	.1791	.3061	.3075	.3150	.0075	2.45
11021.3061	.2280	.3061	.3096	.3224	.0128	4.14
11013.3061	.3583	.3061	.3387	.3567	.0180	5.32
11009.3061	.5016	.3061	.4153	.4238	.0085	2.05
11007.3061	.6270	.3061	.5110	.5127	.0016	.31
11039.2784	.1110	.2784	.2789	.2817	.0028	1.01
11033.2784	.1306	.2784	.2788	.2831	.0043	1.55
11027.1784	.1586	.2784	.2787	.2857	.0070	2.53
11013.2784	.3172	.2784	.3012	.3177	.0165	5.47
11007.2784	.5551	.2784	.4388	.4367	.0021	- .47
11006.2784	.6344	.2784	.4712	.5000	.0288	6.10
11005.2784	.7402	.2784	.6080	.6058	.0022	- .37
11004.2784	.8882	.2784	.7714	.8013	.0299	3.87
12033.2017	.0767	.2017	.2181	.2029	.0152	- 6.95
12031.2017	.0815	.0217	.2177	.2031	.0146	- 6.69
12027.2017	.0931	.2017	.2175	.2037	.0138	- 6.34
12016.2017	.1534	.2017	.2175	.2087	.0088	- 4.06
12015.2017	.1629	.2017	.2217	.2098	.0119	- 5.37
12011.2017	.2172	.2017	.2450	.2183	.0267	-10.88
12009.2017	.2607	.2017	.2772	.2280	.0492	-17.76
12008.2017	.2897	.2017	.2754	.2359	.0395	-14.34
12031.1725	.1054	.1725	.1539	.1753	.0214	13.92
12027.1725	.1204	.1725	.1540	.1764	.0024	14.57
12015.1725	.2108	.1725	.1646	.1885	.0239	14.52
12013.1725	.2409	.1725	.1761	.1948	.0187	10.64
12009.1725	.3372	.1725	.2296	.2243	.0053	- 2.29
12005.1725	.5620	.1725	.3981	.3594	.0387	- 9.73
12029.1508	.1026	.1508	.1003	.1535	.0532	53.05
12025.1508	.1184	.1508	.1005	.1547	.0542	53.91
12013.1508	.2199	.1508	.1218	.1691	.0473	38.79
12009.1508	.3078	.1508	.1876	.1931	.0055	2.95
12007.1508	.3848	.1508	.2501	.2249	.0252	-10.09
12005.1508	.5130	.1508	.3563	.3032	.0531	-14.90
12017.1244	.1032	.1244	.0373	.1272	.0899	241.12

TABLE III (Continued)

PROBLEM NUMBER	$\frac{S_m}{S}$ op	$\frac{L}{V}$ min	(L/V)op		ABS. DEV.	Percent Dev.
			CALC	CORR		
12013.1244	.2065	.1244	.0557	.1405	.0848	152.21
12009.1244	.2891	.1244	.1228	.1617	.0389	31.69
12007.1244	.3614	.1244	.1995	.1897	.0098	- 4.93
12005.1244	.4818	.1244	.3084	.2586	.0498	-16.14
12025.0769	.1036	.0769	.0010	.0799	.0789	7892.
12017.0769	.1496	.0769	.0013	.0845	.0832	6398.
12011.0769	.2244	.0769	.0137	.0978	.0841	613.65
12009.0769	.2693	.0769	.0553	.1098	.0545	98.63
12007.0769	.3366	.0769	.1482	.1345	.0137	- 9.26
12005.0769	.4488	.0769	.2757	.1953	.0804	-29.15
07016.0001	.0757	.0355	.0150	.0783	.0633	421.86
11009.2784	.4441	.2784	.3620	.3690	.0070	1.93

Total absolute difference	2.112
Average absolute difference	.0165
Average percent deviation	3.313

TABLE IV

COMPARISON OF RESULTS FROM FIGURE 10 WITH RESULTS FROM TRAY BY TRAY CALCULATIONS BASED ON MINIMUM L/V RATIOS CALCULATED BY THE MODIFIED UNDERWOOD METHOD

PROBLEM NUMBER	$\frac{S_m}{S}$ op	$\frac{L}{V}$ min	(L/V)op CALC	(L/V)op CORR	ABS. DEV.	Percent Dev.
08157.9523	.1991	.9566	.9590	.9573	.0017	- .17
08111.9523	.2807	.9566	.9630	.9583	.0047	- .49
08077.9523	.4034	.9566	.9688	.9609	.0079	- .82
08057.9523	.5425	.9566	.9754	.9656	.0098	- 1.01
08047.9523	.6555	.9566	.9804	.9711	.0093	- .95
08041.9523	.7492	.9566	.9861	.9769	.0092	- .93
08037.9523	.8280	.9566	.9884	.9828	.0056	- .57
08031.9523	.9893	.9566	.9961	.9979	.0018	.18
02059.8630	.3702	.8946	.8815	.9029	.0214	2.43
02029.8630	.7403	.8946	.9283	.9424	.0141	1.52
02026.8630	.8226	.8946	.9432	.9572	.0140	1.48
02023.8630	.9254	.8946	.9647	.9796	.0149	1.55
02041.8667	.6225	.8978	.9110	.9277	.0167	1.83
02058.8697	.5142	.9006	.8993	.9185	.0192	2.14
03021.8121	.8398	.8489	.9298	.9435	.0137	1.48
01109.7952	.3037	.8353	.8013	.8432	.0419	5.23
01055.7952	.5966	.8353	.8551	.8785	.0234	2.74
01041.7952	.7955	.8353	.9177	.9250	.0073	.80
01038.7844	.6643	.8264	.8664	.8862	.0198	2.28
03031.8189	.6403	.8548	.8807	.9004	.0197	2.23
01151.7922	.1972	.8329	.7949	.8356	.0407	5.12
01074.7922	.3997	.8329	.8092	.8489	.0397	4.91
01058.7922	.5081	.8329	.8293	.8622	.0329	3.96
02109.7481	.2992	.7987	.7647	.8080	.0433	5.67
02081.7482	.4014	.7987	.7794	.8182	.0388	4.98
02065.7481	.4987	.7987	.8017	.8323	.0306	3.82
02040.7481	.8028	.7987	.9095	.9110	.0291	3.20
02050.7540	.6981	.8038	.8678	.8804	.0126	1.46
02060.7562	.6211	.8056	.8427	.8621	.0194	2.30
05026.6993	.3972	.7267	.7001	.7525	.0524	7.49
05020.6993	.5056	.7267	.7374	.7740	.0366	4.96
05016.6993	.6179	.7267	.7733	.8051	.0318	4.11
05014.6993	.6952	.7267	.8246	.8323	.0077	.94
05012.6993	.7945	.7267	.8762	.8751	.0011	- .12
05010.6993	.9269	.7267	.9487	.9482	.0005	- .06
01079.6703	.0993	.7255	.6779	.7263	.0484	7.14
01035.6503	.2208	.7255	.6795	.7315	.0520	7.65
01023.6503	.3312	.7255	.6942	.7419	.0477	6.88
01018.6503	.4183	.7255	.7064	.7550	.0486	6.88
01009.6503	.7948	.7255	.8794	.8747	.0047	- .53
01008.6503	.8831	.7255	.9225	.9214	.0011	- .12

TABLE IV (Continued)

PROBLEM NUMBER	$\frac{S_m}{S}$ op	$\frac{L}{V}$ min	(L/V)op CALC	(L/V)op CORR	ABS. DEV.	Percent Dev.
01007.6503	.9935	.7255	.9897	.9945	.0048	.48
01065.6223	.9072	.6994	.6488	.7002	.0514	7.93
01048.6223	.1310	.6994	.6529	.7012	.0483	7.40
01031.6223	.2006	.6994	.6539	.7046	.0507	7.75
01020.6223	.3056	.6994	.6668	.7141	.0473	7.09
01015.6223	.4011	.6994	.7008	.7285	.0277	3.95
01012.6223	.4937	.6994	.7266	.7485	.0219	3.01
01008.6223	.7131	.6994	.8274	.8233	.0041	- .50
01007.6223	.8022	.6994	.8862	.8668	.0194	- 2.19
01006.6223	.9169	.6994	.9446	.9020	.0426	- 4.51
04015.6351	.4932	.6918	.7113	.7419	.0306	4.30
04025.6316	.2973	.6888	.6680	.7030	.0350	5.24
01038.6337	.1751	.7099	.6604	.7134	.0530	8.03
02034.5613	.2613	.6585	.6022	.6698	.0676	11.23
02015.5613	.5715	.6585	.6895	.7389	.0494	7.17
02013.5613	.6531	.6585	.7361	.7711	.0351	4.76
02011.5613	.7620	.6585	.7999	.8252	.0253	3.16
02009.5613	.9144	.6585	.9153	.9255	.0102	1.11
02024.5668	.4217	.6631	.6300	.7001	.0701	11.12
02044.5493	.1708	.6480	.5883	.6520	.0637	10.83
03085.5098	.1009	.6380	.5325	.6391	.1066	20.02
03043.5098	.1972	.6380	.5352	.6439	.1087	20.31
03028.5098	.2992	.6380	.5581	.6548	.1167	21.69
03017.5098	.4821	.6380	.5893	.6936	.1043	17.70
03014.5098	.5785	.6380	.6525	.7259	.0734	11.25
03012.5098	.6675	.6380	.7037	.7642	.0605	8.60
03010.5098	.7888	.6380	.8010	.8310	.0300	3.75
03008.5098	.9641	.6380	.9668	.9640	.0028	- .29
03027.5137	.3272	.6413	.5453	.6621	.1168	21.43
03017.5137	.5091	.6413	.6054	.7045	.0991	16.36
05089.4874	.1995	.6085	.4749	.6151	.1402	29.52
05059.4874	.2976	.6085	.4761	,6269	.1503	31.58
05043.4874	.4034	.6085	.4886	.6469	.1583	32.41
05035.4874	.4906	.6085	.5223	.6713	.1490	28.53
05030.4874	.5673	.6085	.5539	.6990	.1451	26.20
05028.4874	.6051	.6085	.5928	.7150	.1222	20.62
05020.4874	.8251	.6085	.7893	.8428	.0535	6.78
05018.4874	.9076	.6085	.8990	.9086	.0096	1.07
07033.4676	.4446	.6085	.4651	.6576	.1925	41.38
04045.4284	.2641	.5992	.4292	.6128	.1836	42.78
04029.4284	.4005	.5992	.4663	.6378	.1715	36.79
04041.4248	.3460	.5960	.4383	.6230	.1847	42.14
11039.3659	.1849	.5474	.3716	.5537	.1821	49.01
11027.3659	.2641	.5474	.3734	.5628	.1894	50.72
11021.3659	.3362	.5474	.3815	.5755	.1940	50.86
11013.3659	.5283	.5474	.4634	.6349	.1715	37.00

TABLE IV (Continued)

PROBLEM NUMBER	$\frac{S_m}{S}$ op	$\frac{L}{V}$ min	(L/V) op CALC	(L/V) op CORR	ABS. DEV.	Percent Dev.
11009.3659	.7396	.5474	.6393	.7521	.1128	17.65
11007.3659	.9245	.5474	.8665	.9117	.0452	5.21
11039.3313	.1434	.5198	.3344	.5233	.1889	56.50
11027.3313	.2049	.5198	.3349	.5284	.1935	57.79
11021.3313	.2608	.5198	.3383	.5356	.1973	58.33
11017.3313	.3187	.5198	.3477	.5459	.1982	57.01
11013.3313	.4098	.5198	.3789	.5688	.1899	50.13
11011.3313	.4781	.5198	.4151	.5920	.1769	42.62
11009.3313	.5737	.5198	.4799	.6340	.1541	32.11
11007.3313	.7171	.5198	.6041	.7206	.1165	19.29
11006.3313	.8196	.5198	.6853	.8023	.1070	15.39
11005.3313	.9562	.5198	.9059	.9427	.0368	4.07
11039.3061	.1254	.4997	.3075	.5023	.1948	63.36
11027.3061	.1791	.4997	.3075	.5061	.1986	64.60
11021.3061	.2280	.4997	.3096	.5115	.2019	65.20
11013.3061	.3583	.4997	.3387	.5362	.1975	58.31
11009.3061	.5016	.4997	.4153	.5846	.1693	40.76
11007.3061	.6270	.4997	.5110	.6486	.1376	26.93
11039.2784	.1110	.4780	.2789	.4800	.2011	72.12
11033.2784	.1306	.4780	.2788	.4810	.2022	72.54
11027.2784	.1586	.4780	.2787	.4830	.2043	73.29
11013.2784	.3172	.4780	.3012	.5061	.2049	68.02
11009.2784	.4441	.4780	.3620	.5432	.1812	50.06
11007.2784	.5551	.4780	.4388	.5922	.1535	34.97
11006.2784	.6344	.4870	.4712	.6380	.1668	35.40
11005.2784	.7402	.4780	.6080	.7146	.1066	17.54
11004.2784	.8882	.4780	.7714	.8561	.0847	10.98
12033.2017	.0767	.4452	.2181	.4461	.2280	104.52
12031.2017	.0815	.4452	.2177	.4462	.2285	104.96
12027.2017	.0931	.4452	.2175	.4466	.2291	105.33
12016.2017	.1534	.4452	.2175	.4500	.2325	106.92
12015.2017	.1629	.4452	.2217	.4508	.2291	103.35
12011.2017	.2172	.4452	.2450	.4568	.2118	86.43
12009.2017	.2607	.4452	.2772	.4635	.1863	67.19
12008.2017	.1897	.4452	.2754	.4690	.1936	70.29

Total absolute difference	11.780
Average absolute difference	.097
Average percent deviation	22.211

TABLE V

RESULTS FROM THIS WORK COMPARED WITH RESULTS FROM ERBAR'S WORK

	ERBAR'S WORK			THIS WORK		
PROBLEM NUMBER	$(L/V)_{op}$ CALC	$(L/V)_{op}$ CORR	DEV.	$(L/V)_{op}$ CALC	$(L/V)_{op}$ CORR	DEV.
01018.6503	.692	.655	-.037	.706	.694	-.012
01038.7844	.645	.600	-.045	.660	.644	-.016
01048.6223	.630	.598	-.032	.653	.630	-.023
01038.7844	.862	.845	-.017	.866	.859	-.007
01058.7922	.826	.830	.004	.829	.829	.000
02026.8630	.907	.895	-.012	.943	.947	.004
02041.8667	.875	.875	.000	.911	.910	-.001
02058.8697	.865	.865	.000	.899	.899	.000
02024.5668	.576	.576	.000	.630	.614	-.016
02034.5613	.565	.555	-.010	.602	.576	.026
02044.5493	.555	.532	-.023	.588	.554	-.034
02040.7481	.805	.875	.070	.910	.889	-.021
02050.7540	.780	.840	.060	.868	.850	-.018
02060.7562	.760	.817	.057	.843	.827	-.016
03021.8121	.858	.858	.000	.930	.930	.000
03031.8189	.825	.825	.000	.881	.876	-.005
03017.5137	.540	.505	-.035	.605	.599	-.006
03027.5137	.505	.480	-.025	.545	.542	-.003
04015.6351	.725	.667	-.058	.711	.694	-.017
04025.6316	.667	.640	-.027	.668	.648	-.020
04029.4284	.465	.440	-.025	.466	.484	.018
05016.6993	.730	.701	-.029	.773	.786	.013
05026.6993	.675	.661	-.014	.700	.728	.028
05020.4874	.550	.555	.005	.789	.794	.005
05030.4874	.500	.531	.031	.554	.606	.052
07033.4676	.440	.400	-.040	.465	.534	.069
Total absolute difference			.656			.430
Average absolute difference			.025			.016

absolute deviation is .017. The average percent deviation is 3.438.

Table III results are based on standard Underwood minimum reflux ratios calculated at the higher of the feed temperature and the average column temperature. Absolute and average percent deviations are presented for all one hundred and forty-six problems studied, but values for problems below $(L/V)_{min}$ equal to .15, where calculated $(L/V)_{op}$ values are less than corresponding $(L/V)_{min}$ values, are omitted from total and average deviations presented. The total absolute deviation is 2.112 and the corresponding average absolute deviation is .0165. The average percent deviation is 3.313.

Results based on the Underwood method as modified by DuBois are presented in Table IV. The modified method failed to converage on minimum reflux rates for problems where $(L/V)_{min}$ was less than .15, therefore, total and average deviations include all values presented in Table IV. The total absolute deviation is 11.78. The average absolute deviation is .097 and the average percent deviation is 22.11.

For the twenty-six problems common to this work and Erbar's (6) investigation, the average absolute deviation for Erbar's results is .0252. The results from this work, taken from Table III, show an average absolute deviation of .0165 for these twenty-six problems.

The purpose of this study was to develop a correlation identical in form to the Erbar (6) correlation. The primary objectives of the study were three in number. These were:

1. To base the new correlation on more consistent enthalpy and equilibrium data than the Erbar correlation was based upon.

2. To test the reliability of the new correlation in the region of low minimum reflux ratios.

3. To see if results from the correlation would be improved by using the Underwood minimum reflux method as modified by DuBois.

The degree to which the first objective was achieved can not be measured directly or accurately, however an examination of Figures 6-9 gives a good indication of the degree of success that was achieved with respect to the first objective. As shown by Figures 6-9, the raw data obtained from the tray by tray calculations plots with only nominal scatter. Since the enthalpy and equilibrium data exert a strong influence on the results of tray by tray calculations, the general smoothness and consistency of the raw data are good indications that the enthalpy and equilibrium data also possess a high degree of consistency. Thus, success is indicated in the first objectives of the study.

To assure success in reaching the second goal of the study, a large number of problems were selected for use in the study, which represented all regions of the $(L/V)_{min}$ parameter. A total of one hundred and forty-six tray by tray calculations were performed. The data from these calculations are presented in the appendices. Results of the tray by tray calculations have been compared with results from the proposed correlation in Tables II through IV. Table III represents the better results, which were obtained using the minimum reflux ratio calculated at the higher of the feed and average column temperatures. The results of Table III indicate three distinct regions of reliability for the correlation presented in Figure 10. For problems with an $(L/V)_{min}$ greater than .2, an average error of only 2.7 percent was noted for one hundred and forteen data points. In comparison, Erbar obtained an average error of 4.35 percent for thirty-nine points in the same region. For problems with an $(L/V)_{min}$ between .15 and .2, an average error of approximately 10 percent was obtained for fourteen data points using the correlation presented in Figure 10. In the region of $(L/V)_{min}$ below .15, eighteen data points indicated the new correlation was completely unreliable in that region with many errors exceeding 100 percent. Erbar did not present any data with an $(L/V)_{min}$ less than .2, so no comparisons can be made.

The failure of the correlation in Figure 10 to predict operating reflux ratios for problems with low $(L/V)_{min}$ values can be attributed to failure of the Underwood method to accurately estimate minimum reflux values in this region. This failure of the Underwood minimum reflux method in the low $(L/V)_{min}$ region is pointed out by the fact that the tray by tray calculations for many of the problems in that region indicate an operating reflux rate smaller than the minimum reflux rate predicted by the Underwood method.

To demonstrate why the correlation in Figure 10 fails to predict operating reflux ratios accurately for problems with low values of $(L/V)_{min}$, the Underwood predicted minimum reflux values are compared with minimum reflux rates estimated from Figures 6-9. The comparison is shown in Table VI. Table VI shows that on a percentage basis, the Underwood method does not predict reflux ratios accurately for lower values of $(L/V)_{min}$.

Table VI also shows why results that were obtained using the standard Underwood minimum reflux ratio calculated at the higher of the feed temperature and average column temperature are better than those that were obtained using the standard Underwood minimum reflux ratio calculated at the average column temperature or those that were obtained with the modified Underwood method. For the standard Underwood reflux

TABLE VI

COMPARISON OF MINIMUM REFLUX RATES
USED IN THIS STUDY

FIGURES 6-10		STANDARD UNDERWOOD METHOD		MODIFIED METHOD
L/V	REFLUX	AVE. TEMP.	FEED TEMP.	
.955	212.	200.	213.	221.
.864	127.	125.	133.	168.
.864	127.	130.	138.	176.
.864	127.	134.	141.	181.
.791	114.	129.	130.	168.
.791	189.	195.	181.	255.
.791	189.	182.	169.	238.
.791	114.	136.	136.	176.
.791	189.	191.	177.	249.
.752	182.	179.	155.	240.
.752	182.	184.	160.	246.
.752	182.	187.	162.	250.
.693	68.	69.	57.	79.
.670	51.	47.	48.	66.
.640	45.	43.	44.	60.
.640	44.	42.	43.	55.
.640	44.	42.	42.	54.
.640	45.	44.	45.	63.
.582	56.	51.	50.	76.
.582	56.	52.	51.	78.
.582	56.	48.	47.	73.
.530	57.	52.	48.	89.
.530	57.	53.	49.	90.
.470	53.	57.	37.	93.
.420	29.	35.	27.	62.
.420	40.	41.	32.	83.
.420	40.	41.	31.	82.
.365	35.	35.	27.	73.
.328	29.	30.	23.	65.
.300	25.	26.	20.	60.
.273	19.	23.	17.	55.
.200	13.	13.	8.	40.
.150	9.	10.	6.	
.100	6.	9.	5.	
.027	1.	7.	3.	
.001	0.	4.	0.	
.001	0.	0.	0.	

calculations, the higher value, representing the higher temperature, agrees best with the reflux rate estimated from Figures 6-9 in twenty-six of the thirty-seven cases. In almost every case the modified method calculated rates which were too high and in poor agreement with the rates estimated from Figures 6-9.

Based on the observations discussed previously, the correlation in Figure 10 is recommended for use in estimating operating reflux values for problems which have an $(L/V)_{min}$ value, calculated by the standard Underwood method of .2 or greater. The correlation may be used also in the region of $(L/V)_{min}$ between .15 and .2, but with a little less than the high degree of reliability that exists for the region of $(L/V)_{min}$ greater than .2. The correlation is not recommended for use when $(L/V)_{min}$ is less than .15. Based on the data of Tables II, III, and VI the higher of the feed temperature and the average column temperature is recommended to compute the standard Underwood value of the minimum reflux.

Best results will be obtained from the proposed correlation if it is used in a manner consistent with its development. Therefore, a definite step by step procedure will be suggested for estimating the operating reflux necessary to make a given separation. The steps are:

1. Estimate the minimum number of trays by the Fenske method.

2. Choose a reasonable number of operating trays greater than the minimum. Compute the ratio of minimum trays to operating trays.

3. Use the Underwood method to compute the minimum reflux ratio and the average column temperature. If the average column temperature is greater than the feed temperature, proceed to step 5.

4. If the feed temperature is greater than the average column

temperature, compute the Underwood minimum reflux ratio at the feed temperature.

5. Compute $(L/V)_{min}$ from equation 5, if necessary,

$$(L/V)_{min} = \frac{R}{1+R} \qquad (5)$$

6. Locate the point S_m/S and $(L_0/V_1)_{min}$ by use of the abscissa and the parameters of Figure 10. Read $(L_0/V_1)_{op}$ from the ordinate of Figure 10.

7. If necessary, convert $(L_0/V_1)_{op}$ to R_{op} by equation 6.

$$R_{op} = \frac{(L_0/V_1)_{op}}{1-(L_0/V_1)_{op}} \qquad (6)$$

In Table V the calculated L/V values were obtained from tray by tray calculations. There is considerable variation in values from Erbar's work and this work. In fact the average absolute deviation between L/V values from the two studies is .046. This is considerably more than the average deviation between the calculated and predicted results for either correlation. The differences were the result of using different vapor-liquid equilibria and enthalpy data. Table V shows why consistent data must be used in developing and using correlations of the type with which this study is concerned.

In developing the recommended correlation, every effort was made to obtain consistent data. To obtain dependable results in the application of the correlation, similar precautions must be employed. This involves using:

1. A specific set of thermodynamic data which includes K values by the Chao-Seader correlation and enthalpies by the Yen and Alexander correlation.

2. The standard Underwood minimum reflux method.

3. The Fenske method for calculating minimum trays.

4. A feed condition corresponding to a bubble point feed at the tower conditions.

5. Problems relating only to simple fractionators.

No problems were used with other than a feed condition corresponding to a bubble point feed at the tower conditions. Erbar (6) presented a correlation relating reflux ratios corresponding to partially vaporized feed conditions to reflux ratios at bubble point feed conditions.

This study was limited to systems of paraffin hydrocarbons between C_1 and C_{10}. Although it has not been checked in this study, the proposed correlation need not be limited to such systems. Since the equilibrium and enthalpy data determine the consistency of results and since both the Chao-Seader and Yen-Alexander correlations are generalized correlations, the proposed correlation should hold for all systems for which the enthalpy and equilibrium correlations are relaible. This also would mean limiting the use of the proposed correlation to problems where the operating temperatures and pressure are within the range for which the enthalpy and equilibrium correlations are recommended.

CHAPTER V

RECOMMENDATIONS AND CONCLUSIONS

An improved correlation has been developed relating operating reflux ratios and trays to minimum reflux ratios and trays. The correlation is recommended for use with problems having $(L/V)_{min}$ value of .15 or greater as calculated by the standard Underwood method.

To obtain reliable results the correlation must be applied using the same tools with which it was developed namely, the Fenske equation for minimum trays, the Chao-Seader correlation for equilibrium data, and the Yen-Alexander correlation for enthalpies.

The standard Underwood minimum reflux, calculated at the higher of the feed temperature and the average column temperature, is recommended for use with the proposed correlation to predict operating reflux ratios.

Several areas exist for future study and possible improvement of the proposed correlation. The most obvious need for improvement is in the prediction of the minimum reflux value to be used with the correlation in the area of low $(L/V)_{min}$ values. Other possibilities for further study include checking the proposed correlation for use with systems containing components other than the light paraffin hydrocarbons and basing minimum tray calculations on the Winn equation rather than the Fenske equation.

Used within the guidelines previously discussed, the proposed correlation should be a useful and convenient tool for arriving at rapid estimates of the final fractionator design required to make a given separation. The results provided by the proposed correlation should be more than adequate for making preliminary design cost estimates.

LIST OF NOMENCLATURE

B	- total moles of bottoms product per unit time
B_e	- defined by the equation $B_e = K_{LK}/K_{HK}^b$
D	- total moles of distillate per unit time
K	- vapor-liquid equilibrium constant defined as y/x
L	- total liquid rate per unit time at a given point in a fractionator
$(L/V)_{min}$	- minimum reflux ratio, related to R_m by the equation $(L/V)_{min} = R_m/(R_m + 1)$
R	- reflux ratio, defined as L_0/D
R_m	- minimum reflux ratio, defined as (L_0/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	- moles of any component in the distillate product per unit time
X_B	- moles of any component in the bottoms product per unit time
b	- exponent, defined by the equation $b = \log K_{LK}/\log B_e * K_{HK}$
c	- exponent, unknown variable
g	- algebraic variable
x	- mole fraction of any component in the liquid phase
y	- mole fraction of any component in the vapor phase
α	- relative volatility, defined by the equation $\alpha = K_1/K_2$

Subscripts

0	- pertains to reflux rate, moles
1	- pertains to stream quantities leaving the top tray of the fractionator
HK	- pertains to heavy key component
LK	- pertains to light key component
m	- pertains to minimum quantity
min	- pertains to minimum quantity
op	- pertains to operating conditions

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APPENDIX A

TABLE VII

SPECIFICATIONS FOR MINIMUM TRAY AND MINIMUM REFLUX CALCULATIONS

SEP.	FEED			COMPONENTS		MOLS TO DIST.	
NO.	NO.	TEMP.	PRESS.	LK	HK	LK	HK
1	8	149.8	25.	iC_5	nC_5	3.95	5.05
2	2	132.0	50.	iC_4	nC_5	19.0167	.8230
3	2	132.0	50.	iC_4	nC_4	19.4908	.5598
4	2	132.0	50.	iC_4	nC_4	19.7064	.3130
5	3	156.8	100.	iC_4	nC_4	17.9053	1.9481
6	1	106.8	25.	iC_5	nC_5	24.5	.75
7	1	106.8	25.	iC_5	nC_5	23.6463	1.3584
8	3	156.8	100.	iC_4	nC_4	18.3657	1.6194
9	1	106.8	25.	iC_5	nC_5	24.1181	.8831
10	2	132.0	50.	iC_5	nC_5	19.2798	1.1144
11	2	132.0	50.	iC_5	nC_5	19.3722	.7880
12	2	132.0	50.	iC_5	nC_5	19.5389	.7120
13	5	135.0	300.	C_3	iC_4	22.8894	.9587
14	1	106.8	25.	nC_4	iC_5	24.1961	.9160
15	1	106.8	25.	nC_4	iC_5	23.817	2.1466
16	4	149.6	150.	C_3	iC_4	18.668	.663
17	4	149.6	150.	C_3	iC_4	18.564	.776
18	1	106.8	25.	nC_4	iC_5	23.8938	1.6548
19	2	132.0	50.	nC_4	iC_5	19.1639	.4498
20	2	132.0	50.	nC_4	iC_5	19.4792	.2581
21	2	132.0	50.	nC_4	iC_5	18.7838	.8932
22	3	133.8	75.	nC_4	iC_5	19.2792	1.1044
23	3	133.8	75.	nC_4	iC_5	19.4087	.9684
24	5	83.6	150.	nC_4	iC_5	14.9508	.0872
25	7	131.5	100.	nC_4	iC_5	9.975	.216
26	4	89.8	75.	nC_4	iC_5	14.9143	.3658
27	4	89.8	75.	nC_4	iC_5	14.9888	.4880
28	11	117.6	75.	nC_4	nC_5	19.25	.75
29	11	117.6	75.	nC_4	nC_5	18.5	1.5
30	11	117.6	75.	nC_4	nC_5	18.	2.
31	11	117.6	75.	nC_4	nC_5	17.5	2.5
32	12	115.0	75.	iC_4	nC_5	21.75	3.25
33	12	115.0	75.	iC_4	nC_5	21.25	3.75
34	12	115.0	75.	iC_4	nC_5	20.9	4.1
35	12	115.0	75.	iC_4	nC_5	20.5	4.5
36	12	115.0	75.	iC_4	nC_5	20.5	5.
37	7	292.4	400.	C_2	iC_4	2.378	1.252

APPENDIX B

TABLE VIII

RESULTS OF MINIMUM REFLUX CALCULATIONS
AT THE AVERAGE COLUMN TEMPERATURE

SEP. NO.	AVE. COLUMN TEMPERATURE	MINIMUM VALUES REFLUX	MINIMUM VALUES VAPOR	MINIMUM VALUES L/V
1	136.7	199.7483	209.7483	.9523
2	116.8	125.0259	144.8656	.8630
3	116.8	130.3439	150.3945	.8667
4	116.7	133.6663	153.6857	.8697
5	155.1	128.9871	158.8405	.8121
6	122.2	195.1489	245.3989	.7952
7	122.0	181.9322	231.9369	.7844
8	155.1	135.5993	165.5843	.8189
9	122.0	190.6373	240.6384	.7922
10	161.3	179.4019	239.7961	.7481
11	161.1	184.3715	244.5327	.7540
12	161.2	186.9306	247.1815	.7562
13	202.9	69.4256	99.2737	.6993
14	98.7	46.7046	71.8177	.6503
15	100.4	42.7838	68.7474	.6223
16	147.2	42.3556	66.6864	.6351
17	147.4	41.7314	66.0713	.6316
18	99.7	44.1964	69.7450	.6337
19	137.3	50.6831	90.2968	.5613
20	137.4	51.9853	91.7226	.5668
21	137.6	48.3573	88.0342	.5493
22	158.2	52.3972	102.7808	.5098
23	158.2	53.2236	103.6007	.5137
24	201.8	57.0876	117.1256	.4874
25	204.7	35.3036	75.4947	.4674
26	153.4	41.4319	96.7120	.4184
27	153.8	40.9794	96.4562	.4248
28	165.0	34.6211	94.6211	.3659
29	165.8	29.7312	89.7312	.3313
30	165.7	26.4703	86.4703	.3061
31	165.6	23.2090	83.2090	.2784
32	158.8	12.6352	62.6352	.2017
33	159.0	10.4261	60.4261	.1725
34	159.1	8.8770	58.8769	.1508
35	159.2	7.1009	57.1029	.1244
36	163.6	4.2290	54.9617	.0769
37	310.3	0.	10.0537	.0000

TABLE IX

RESULTS OF MINIMUM TRAY CALCULATIONS AND MINIMUM REFLUX CALCULATIONS AT THE FEED TEMPERATURE

SEP. NO.	MINIMUM TRAYS	MINIMUM VALUES REFLUX	VAPOR	L/V
1	31.465	212.5239	222.5239	.9551
2	22.210	132.7111	152.5508	.8699
3	26.147	138.2891	158.3397	.8734
4	30.336	141.8423	161.8617	.8763
5	18.475	129.8626	159.7160	.8131
6	33.412	181.4120	231.6620	.7831
7	25.908	169.1296	219.1343	.7718
8	20.491	136.4887	166.4738	.8199
9	29.979	177.3430	227.3441	.7801
10	32.916	155.5311	215.9252	.7203
11	35.601	160.2120	220.3704	.7270
12	37.88	162.3980	222.6489	.7294
13	11.123	57.2740	87.1221	.6574
14	7.948	48.1704	73.2839	.6573
15	6.418	43.8903	69.8538	.6283
16	8.385	42.7202	67.0511	.6371
17	8.027	42.0678	66.4077	.6335
18	6.828	45.4454	70.9940	.6401
19	9.144	49.4991	89.3128	.5565
20	10.543	50.9731	90.7104	.5619
21	7.686	47.3463	87.0232	.5441
22	8.677	47.7859	98.1695	.4868
23	9.163	48.5875	98.9646	.4910
24	18.153	37.0852	97.1232	.3818
25	15.561	26.8026	66.9937	.4001
26	12.414	31.9676	87.2477	.3664
27	14.876	31.4509	86.9276	.3618
28	7.396	27.4306	87.4306	.3137
29	5.737	22.9115	82.9115	.2763
30	5.016	19.8987	79.9897	.2490
31	4.441	16.8859	76.8859	.2196
32	2.607	8.4850	58.4850	.1451
33	3.372	6.3972	56.3972	.1134
34	3.078	4.9358	54.9358	.0898
35	2.891	2.5520	53.0746	.0481
36	2.693	0.	50.7132	.0000
37	1.363	.3691	10.3887	.0355

TABLE X

RESULTS OF MINIMUM REFLUX CALCULATIONS
BY THE MODIFIED UNDERWOOD METHOD

SEP. NO.	AVE. COLUMN TEMPERATURE	MINIMUM VALUES REFLUX	VAPOR	L/V
1	236.7	220.6110	230.6110	.9566
2	116.8	168.3926	188.2323	.8946
3	116.8	176.2237	196.2742	.8978
4	116.7	181.3578	201.3771	.9006
5	155.1	167.7101	197.5634	.8489
6	122.2	254.8858	305.1357	.8353
7	122.0	237.9609	287.9656	.8264
8	155.1	176.4567	206.4418	.8548
9	122.0	249.2438	299.2449	.8329
10	161.3	239.6462	300.0403	.7987
11	161.1	246.4124	306.5725	.8038
12	161.2	249.6054	309.8562	.8056
13	202.9	79.3464	109.1944	.7267
14	98.7	66.3624	91.4754	.7255
15	100.4	60.3973	86.3609	.6994
16	147.2	54.6018	78.9326	.6918
17	147.4	53.8633	78.2032	.6888
18	99.7	62.5329	88.0815	.7099
19	137.3	76.3983	116.0120	.6585
20	137.4	78.1962	117.9334	.6631
21	137.6	73.0519	112.7288	.6480
22	158.2	88.7977	139.1811	.6380
23	158.2	90.0640	140.4410	.6413
24	201.8	93.3172	153.3550	.6085
25	204.7	62.4642	102.6552	.6085
26	153.4	82.6348	137.9148	.5992
27	153.8	81.8417	137.3185	.5960
28	165.0	72.5697	132.5697	.5474
29	165.8	64.9512	124.9511	.5198
30	165.7	59.9232	119.9231	.4997
31	165.6	54.9351	114.9350	.4780
32	158.8	40.1247	90.1247	.4452

APPENDIX C

TABLE XI

RESULTS OF TRAY BY TRAY CALCULATIONS

PROBLEM NUMBER	OPERATING VALUES TRAYS	REFLUX	VAPOR	L/V	S_m/S
		SEPARATION NUMBER ONE			
08031.9523	32.	2537.49	2547.49	.9961	.9833
08037.9523	38.	853.512	863.512	.9884	.8280
08041.9523	42.	639.847	649.847	.9861	.7492
08047.9523	48.	499.75	509.75	.9804	.6555
08057.9523	58.	397.043	407.043	.9754	.5425
08077.9523	78.	259.993	320.098	.9688	.4934
08111.9523	112.	259.993	269.993	.9630	.2809
08157.9523	158.	233.819	243.819	.9590	.1991
		SEPARATION NUMBER TWO			
02023.8630	24.	541.949	561.789	.9647	.9254
02026.8630	27.	329.757	349.597	.9432	.8226
02029.8630	30.	256.786	276.626	.9283	.7403
02059.8630	60.	147.598	167.437	.8815	.3702
		SEPARATION NUMBER THREE			
02041.8667	42.	205.26	225.311	.9110	.6225
		SEPARATION NUMBER FOUR			
02058.8697	59.	178.774	198.794	.8993	.5142
		SEPARATION NUMBER FIVE			
03021.8121	22.	395.676	425.530	.9298	.8398
		SEPARATION NUMBER SIX			
01041.7952	42.	560.649	610.899	.9177	.7955
01055.7952	56.	296.478	346.728	.8551	.5966
01109.7952	110.	202.701	252.951	.8013	.3037
		SEPARATION NUMBER SEVEN			
01038.7844	39.	324.51	374.255	.8664	.6643
		SEPARATION NUMBER EIGHT			
03031.8189	32.	221.426	251.411	.8807	.6403

TABLE XI (Continued)

PROBLEM NUMBER	OPERATING VALUES TRAYS	REFLUX	VAPOR	L/V	S_m/S
		SEPARATION NUMBER NINE			
01058.7922	59.	242.951	292.952	.8293	.5081
01074.7922	75.	212.122	262.123	.8092	.3997
01151.7922	152.	193.758	243.759	.7949	.1972
		SEPARATION NUMBER TEN			
02040.7481	41.	607.130	667.524	.9095	.8028
02065.7481	66.	244.127	304.521	.8017	.4987
02081.7481	82.	213.342	273.737	.7794	.4014
02109.7481	110.	196.302	256.696	.7647	.2992
		SEPARATION NUMBER ELEVEN			
02050.7540	51.	394.981	455.141	.8678	.6981
		SEPARATION NUMBER TWELVE			
02060.7562	61.	322.75	383.001	.8427	.6211
		SEPARATION NUMBER THIRTEEN			
05010.6993	12.	554.228	584.218	.9487	.9269
05012.6993	14.	212.243	242.223	.8762	.7945
05013.6993	16.	140.853	170.822	.8246	.6952
05016.6993	18.	102.188	132.138	.7733	.6179
05020.6993	22.	84.0553	113.994	.7374	.5056
05026.6993	28.	69.8164	99.7296	.7001	.3972
		SEPARATION NUMBER FOURTEEN			
01007.6503	8.	2438.09	2463.35	.9897	.9935
01008.6503	9.	300.896	326.162	.9225	.8831
01009.6503	10.	184.157	209.406	.8794	.7948
01018.6503	19.	60.6723	85.8863	.7064	.4183
01023.6503	24.	57.1195	82.2754	.6942	.3312
01035.6503	36.	53.2799	78.4050	.6795	.2208
01079.6503	80.	52.8558	77.9690	.6779	.0993
		SEPARATION NUMBER FIFTEEN			
01006.6223	7.	451.649	478.121	.9446	.9169
01007.6223	7.	205.872	232.296	.8862	.8022
01008.6223	9.	126.863	253.319	.8274	.7131
01012.6223	13.	70.0494	96.4132	.7266	.4937

TABLE XI (Continued)

PROBLEM NUMBER	OPERATING VALUES TRAYS	REFLUX	VAPOR	L/V	S_m/S
	SEPARATION NUMBER FIFTEEN (Continued)				
01015.6223	16.	61.5118	87.7703	.7008	.4011
01020.6223	21.	52.4221	78.6227	.6668	.3056
01031.6223	32.	49.2316	75.2871	.6539	.2006
01048.6223	49.	48.8366	74.8048	.6529	.1310
01065.6223	66.	48.0254	74.0180	.6488	.0972
	SEPARATION NUMBER SIXTEEN				
04015.6351	17.	60.1383	84.5468	.7113	.4932
	SEPARATION NUMBER SEVENTEEN				
04025.6316	27.	49.0454	73.4186	.6680	.2973
	SEPARATION NUMBER EIGHTEEN				
01038.6337	39.	49.7624	75.3478	.6604	.1751
	SEPARATION NUMBER NINETEEN				
02009.5613	10.	427.382	466.950	.9153	.9144
02011.5613	12.	158.035	197.574	.7999	.7620
02013.5613	14.	110.292	149.829	.7361	.6531
02015.5613	16.	87.8118	127.360	.6895	.5715
02034.5613	35.	59.9664	99.5773	.6022	.2613
	SEPARATION NUMBER TWENTY				
02024.5668	25.	67.6525	107.379	.6300	.4217
	SEPARATION NUMBER TWENTY-ONE				
02044.5493	45.	56.6975	96.3796	.5883	.1708
	SEPARATION NUMBER TWENTY-TWO				
03008.5098	9.	1471.98	1522.49	.9668	.9641
03010.5098	11.	203.159	253.642	.8010	.7888
03012.5098	13.	119.841	170.312	.7037	.6675
03014.5098	15.	94.7783	145.248	.6525	.5785
03017.5098	18.	72.4681	122.969	.5893	.4821
03028.5098	29.	58.7836	109.234	.5381	.2992
03043.5098	44.	58.0364	108.444	.5352	.1972
03085.5098	86.	57.3916	107.776	.5325	.1009

TABLE XI (Continued)

PROBLEM NUMBER	OPERATIVE VALUES TRAYS	REFLUX	VAPOR	L/V	S_m/S
		SEPARATION NUMBER TWENTY-THREE			
03017.5237	18.	77.4325	127.907	.6054	.5091
03017.5137	28.	60.4841	110.927	.5453	.3272
		SEPARATION NUMBER TWENTY-FOUR			
05018.4874	20.	534.489	594.540	.8990	.9076
05020.4874	22.	224.058	224.998	.7893	.8251
05028.4874	30.	87.4119	147.451	.5928	.6051
05030.4874	32.	74.5371	134.579	.5539	.5673
05035.4874	37.	65.6396	125.678	.5223	.4906
05043.4874	45.	57.3694	117.408	.4886	.4034
05059.4874	61.	54.5681	114.606	.4761	.2976
05089.4874	91.	54.3054	114.343	.4749	.1995
		SEPARATION NUMBER TWENTY-FIVE			
07033.4674	35.	34.9538	75.1516	.4651	.4446
		SEPARATION NUMBER TWENTY-SIX			
04029.4284	31.	48.3141	103.603	.4663	.4005
04045.4284	47.	41.5666	96.8492	.4292	.2641
		SEPARATION NUMBER TWENTY-SEVEN			
04041.4248	43.	43.2887	98.7721	.4383	.3460
		SEPARATION NUMBER TWENTY-EIGHT			
11007.3659	8.	388.072	447.887	.8665	.9245
11009.3659	10.	105.978	165.761	.6393	.7396
11013.3659	14.	51.6777	111.513	.4634	.5283
11021.3659	22.	36.9601	96.8893	.3815	.3362
11027.3659	28.	35.7309	95.7021	.3734	.2641
11039.3659	40.	35.4773	95.4681	.3716	.1849
		SEPARATION NUMBER TWENTY-NINE			
11005.3313	6.	572.920	632.442	.9059	.9562
11006.3313	7.	135.760	195.257	.6953	.8196
11007.3313	8.	90.6759	150.096	.6041	.7171
11009.3313	10.	54.8961	114.381	.4799	.5737
11011.3313	12.	42.2749	101.843	.4151	.4781
11013.3313	14.	36.3924	96.0364	.3789	.4098
11017.3313	18.	31.8544	91.6173	.3477	.3187

TABLE XI (Continued)

PROBLEM NUMBER	OPERATING VALUES TRAYS	REFLUX	VAPOR	L/V	S_m/S
SEPARATION NUMBER TWENTY-NINE (Continued)					
11021.3313	22.	30.5920	90.4363	.3383	.2608
11027.3313	28.	30.1787	90.1124	.3349	.2049
11039.3313	40.	30.1301	90.1075	.3344	.1434
SEPARATION NUMBER THIRTY					
11007.3061	8.	61.8161	120.967	.5110	.6170
11009.3061	10.	42.1093	101.383	.4153	.5016
11013.3061	14.	30.4799	89.9804	.3387	.3583
11021.3061	22.	26.8083	86.5828	.3096	.2280
11027.3061	28.	26.5994	86.5001	.3075	.1791
11039.3061	40.	26.6235	86.5882	.3075	.1254
SEPARATION NUMBER THIRTY-ONE					
11004.2784	5.	198.900	275.854	.7714	.8882
11005.2784	6.	91.1304	149.878	.6080	.7402
11006.2784	7.	52.5111	111.451	.4712	.6344
11007.1784	8.	46.0300	104.902	.4388	.5551
11009.2784	10.	33.5060	92.5570	.3620	.4441
11013.2784	14.	25.5823	84.9259	.3012	.3172
11027.2784	28.	23.1321	82.9906	.2787	.1586
11033.2784	34.	23.1581	83.0625	.2788	.1306
11039.2784	40.	23.1810	83.1282	.2789	.1110
SEPARATION NUMBER THIRTY-TWO					
12008.2017	9.	18.9888	68.9467	.2754	.2897
12009.2017	10.	19.1473	69.0583	.2772	.2607
12011.2017	12.	16.2180	66.2007	.2450	.2172
12015.2017	16.	14.2483	64.2806	.2217	.1629
12016.2017	17.	13.9134	63.9661	.2175	.1534
12027.2017	28.	13.8981	63.9059	.2175	.0931
12031.2017	32.	13.9161	63.9194	.2177	.0815
12033.2017	34.	13.9455	63.9475	.2181	.0767
SEPARATION NUMBER THIRTY-THREE					
12005.1725	6.	32.7753	82.3217	.3981	.5620
12009.1725	10.	14.8934	64.8742	.2296	.3372
12013.1725	14.	10.7480	61.0388	.1761	.2409
12015.1725	16.	9.9250	60.3111	.1646	.2108
12017.1725	28.	9.1935	59.6788	.1540	.1204
12031.1725	32.	9.1837	59.6700	.1529	.1054

TABLE XI (Continued)

PROBLEM NUMBER	OPERATING VALUES TRAYS	REFLUX	VAPOR	L/V	S_m/S
		SEPARATION NUMBER THIRTY-FOUR			
12005.1508	6.	27.4057	76.9185	.3563	.5130
12007.2508	8.	26.6218	66.4521	.2501	.3848
12009.1508	10.	11.5815	61.7448	.1876	.3078
12013.1508	14.	7.0353	57.7644	.1218	.2199
12025.1508	26.	5.6901	56.6304	.1005	.1184
12019.1508	30.	5.6771	56.6201	.1003	.1026
		SEPARATION NUMBER THIRTY-FIVE			
12005.1244	6.	22.0701	71.5704	.3084	.4818
12007.1244	8.	12.4621	61.4515	.1995	.3614
12009.1244	10.	7.0840	57.7044	.1228	.2891
12013.1244	14.	3.0238	54.2902	.0557	.2065
12017.1244	28.	1.9959	53.4582	.0373	.1032
		SEPARATION NUMBER THIRTY-SIX			
12005.0769	6.	19.0671	69.1680	.2757	.4488
12007.0769	8.	8.8502	59.7138	.1482	.3366
12009.0769	10.	3.0278	54.7319	.0553	.2693
12011.0769	12.	.7239	52.8198	.0137	.2244
12017.0769	18.	.0689	52.3389	.0013	.1496
12015.0769	26.	.0514	52.3409	.0010	.1036
		SEPARATION NUMBER THIRTY-SEVEN			
07016.0000	18.	.1478	9.8673	.0150	.0757

VITA

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