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CORRELATION OF THE NUMBER

OF

THEORETICAL PLATES

vs.

REFLUX RATIO

by

George L. Parisi

Submitted in Partial Fulfillment
of the Requirements
for the Degree of
MASTER OF SCIENCE
in Chemical Engineering
in the
Graduate Division
at the
Newark College of Engineering

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SUMMARY

A correlation is presented from which the number of theoretical plates for a given separation by distillation can be estimated as a function of the reflux ratio. The effects of relative volatility and feed composition upon such a correlation are also studied. Smoker's (1) equation was used in calculating the data. The results were obtained by varying the several parameters which have to be given for any separation desired. These include feed compositions of 0.25, 0.50, and 0.75; relative volatilities of 1.1, 1.2, 1.5, and 2.0; and various reflux ratios. The overhead product and bottoms product compositions were kept constant at 0.95 and 0.05 respectively.

To present and use the correlation, the calculation of S_m and R_m is necessary. Graphs relating the number of theoretical plates to reflux ratio are presented. The effects of relative volatility and feed composition are shown.

Three presentations of the results are made from the same data, primarily for purposes of comparing with the results of other authors. The coordinate groups used in each case are the same as those used by the author with whom the results are being compared. Comparison with Gilliland (2) and Donnell and Cooper (4) show close agreement, but comparison with Hachmuth (3) shows disagreement. Nevertheless, if average results are compared, the present data agree with those of Hachmuth (3) but not as well as with those of Gilliland (2) and Donnell and Cooper (4).

A similar type of correlation by Brown and Martin (5) also does not agree too well with that of Hachmuth (3). No comparison was made between the results of this paper and those of Brown and Martin (5).

INTRODUCTION

There have been numberless investigations of the unit operation of distillation. Many of these have been connected with methods by which the number of theoretical plates for a given separation can be found. McCabe and Thiele developed a graphical method of accomplishing this for a binary mixture.

This paper presents a correlation of the number of theoretical plates vs. reflux ratio, and, therefore, gives a convenient method by which the number of plates for a given separation can be estimated as a function of the reflux ratio.

The results were found analytically using Smoker's (1) equation and are based on binary mixtures. However, the excellent agreement of these results with those of Gilliland (2) and Donnell and Cooper (4) who include all types of systems in their correlations, indicates that the present correlation can also be used for multicomponent systems. With multicomponent systems it is only necessary to consider the key components as constituting a binary mixture.

The only assumptions made in this correlation are those inherent in Smoker's (1) equation which require, that the vapor-liquid relationships of the solutions can be represented accurately over wide concentration ranges by a constant value of α, and a constant molal overflow.

The relative volatility α charactizes the vapor-liquid equilibrium curve. As the value of α increases, the equilibrium curve tends to deviate further from the $X = Y$ diagonal where X is the mole fraction of the more volatile component in the liquid phase and Y is the mole fraction of the same component in the vapor phase. Consequently, as α increases, the separation becomes less difficult and the number of required steps decreases. Also, minimum reflux ratio and minimum number of plates for a given separation are functions of several variables including the relative volatility.

Reflux ratio is the ratio of the amount of liquid down-flow to the rectifying column to that drawn off as product. The minimum reflux ratio is the least reflux that can be used with an unlimited number of plates to attain a given separation. Minimum number of plates is the least number of steps that can be used with an unlimited reflux ratio ($R = \infty$) to attain a given separation.

As has been stated before, an analytical method of distillation calculations has been devised by Smoker (1). By a systematic procedure employing his equation, a correlation has been established whereby the number of theoretical plates for any separation can be estimated as a function of the reflux ratio. This eliminates the necessity of either the conventional graphical calculation (McCabe and Thiele) or the necessity of going through the aforementioned analytical procedure.

The final results of this paper, found in Figures 10, 21, and 32, are in close agreement respectively with those of Gilliland (2) who used experimental data of binary and multicomponent systems; Hachmuth (3) who used calculated data of binary systems; and Donnell and Cooper (4) who used over one hundred analytical and experimental data of all type systems.

In obtaining the data for this paper the calculations were somewhat simplified by considering the feed to be a liquid at its boiling point. However, such a condition is not necessary to use the correlation which is presented here. During the course of attaining the master curves, the effects of relative volatility and feed composition upon the correlation were found and are subsequently discussed and presented in the severa figures.

To use the correlation for estimating the number of plates required for a given separation, it is necessary to compute S_m and R_m from α, X_F, X_D, and X_W using the relationships shown in the next section. When dealing with multicomponent systems, the key components are considered to be the constituents of a binary mixture. The desired value of the reflux ratio is then used to evaluate either $R - R_m/R + 1$, R_m/R, or $R + 1/R_m + 1$ depending upon whether Figure 10, 21, or 32 is to be used. The corresponding coordinate value is then obtained from the curve and the required number of theoretical plates is calculated from either $S - S_m/S + 1$, S_m/S, or S/S_m using S_m.

Figures 10 and 21 have the advantage of having the curves terminate at values of 1 for both coordinates, whereas Figure 32 has a curve asymptotic to the ordinate. Figure 21 has the further advantage of having the simplest ordinate and abscissa groups.

METHOD OF CALCULATION

Smoker (1) has derived an equation for determining analytically the number of plates required for the separation of a binary mixture (as Mc Cabe and Thiele do graphically). This is done with the assumptions of constant molal overflow and that the relative volatility α remains constant throughout the separation.

Smoker's (1) equation is:

$$n = \frac{\log \dfrac{x_0\left(1 - \dfrac{MC(\alpha-1)}{\alpha - MC^2}\, x_n\right)}{x_n\left(1 - \dfrac{MC(\alpha-1)}{\alpha - MC^2}\, x_0\right)}}{\log \dfrac{\alpha}{MC^2}}$$

which gives the number of theoretical plates necessary to effect a separation between any pair of concentrations for any reflux ratio.

The terms in Smoker's (1) equation are obtained as follows: In the rectifying section,

$$M = \frac{R}{R+1}$$

and

$$b = \frac{X_D}{R+1}$$

Also

$$M(\alpha-1)k^2 + [M + b(\alpha-1) - \alpha]k + b = 0$$

k is the root of the quadratic equation between 0 and 1.

$$x_0 = X_D - k$$

$$x_n = X_F - k$$

$$C = 1 + (\alpha-1)k$$

In the stripping section,

$$M = \frac{RX_F + X_D - (R+1)X_W}{(R+1)(X_F - X_W)}$$

and

$$b = \frac{(X_F - X_D)\,X_W}{(R+1)(X_F - X_W)}$$

Also $$M(\alpha - 1)k^2 + [M + b(\alpha - 1) - \alpha]k + b = 0$$

k is the root between 0 and 1.

$$x_0 = X_F - k$$

$$x_n = X_W - k$$

$$c = 1 + (\alpha - 1)k$$

The calculations were performed in a systematic manner. In all the systems investigated, the overhead product and bottom product compositions were kept constant at $X_D = 0.95$ and $X_W = 0.05$. The following procedure was adhered to:

1. The feed composition X_F was set equal to 0.25 and the relative volatility $\alpha = 1.1$. For these conditions, Smoker's (1) equation was applied for five different reflux ratios over the rectifying section and secondly over the stripping section. The number of plates obtained from each section was added to give the total plates required at each of the reflux ratios used.
2. The same procedure was followed as above except that α was varied from 1.2 to 1.5 and to 2.0.
3. The feed composition was then changed to 0.50 and the calculations repeated for α's of 1.1, 1.2, 1.5 and 2.0

at five different reflux ratios for each value of α.

4. The feed composition was again changed to 0.75 and the calculations repeated for α's of 1.1, 1.2, 1.5 and 2.0 at five different reflux ratios for each α.

In all instances, the feed was assumed to be at the boiling point so that X_F could be used directly in Smoker's (1) equation.

Minimum reflux ratio and minimum number of plates were calculated for each system investigated, not only for purposes of plotting the data, but because these are important factors to know about any separation. The minimum reflux can be calculated for a binary mixture from:

$$R_m = \frac{1}{\alpha - 1}\left[\frac{X_D}{X_F} - \alpha \frac{1 - X_D}{1 - X_F}\right]$$

The minimum number of steps can be calculated from:

$$S_m = \frac{\log \left(\frac{X_D}{1 - X_D}\right)\left(\frac{1 - X_W}{X_W}\right)}{\log \alpha}$$

which is essentially Fenske's (7) or Underwood's (6) equation, or a reduction of Smoker's (1) equation for $R = \infty$.

The various coordinate groups used in the graphical presentations were then calculated from the values of R, S, S_m, and R_m.

DISCUSSION OF RESULTS

As previously mentioned the results of this paper are presented in three forms to facilitate comparison with the work of Gilliland (2), Hachmuth (3), and Donnell and Cooper (4). The data have also been plotted in several ways to note the effect of various parameters on the correlation. Several articles pertaining to this type of correlation have appeared in the literature, although the results in each case have been obtained by different methods.

For purposes of comparison with Gilliland (2) the curves are plotted on square section paper using $S - S_m/S + 1$ as the ordinate and $R - R_m/R + 1$ as the abscissa. These were chosen by Gilliland (2) so that the range of both axes is from 0 to 1.

The effects of relative volatility and feed composition in the ranges investigated are self-evident from observation of Figures 1-10. It will be observed from Figure 1, where the feed composition is 0.25, that the effect of relative volatility is negligible. Although, the relative volatility is a measure of the ease of separation, it is apparent that at such a low value of X_F it has little influence on the correlation. In Figure 2 where X_F is 0.50 the effect of relative volatility is appreciable and in Figure 3 where X_F is 0.75, it becomes more pronounced. It can be concluded, therefore, that on this type of plot the influence of relative volatility increases with increasing mole fractions of the more volatile component in the feed. To note the effect of feed composition, whatever the relative volatility may be, Figure 4 has been constructed from averages of Figures 1, 2, and 3. Here it is seen that the ordinate which involves the number of plates required for a separation passes through a maximum as X_F increases.

To note the effect of feed composition for each individual relative volatility investigated, Figures 5, 6, 7, and 8 have been plotted. Here again the ordinate passes through a maximum as X_F increases. However, when $\alpha = 2.0$ (Figure 8) the ordinate decreases as X_F becomes greater. In plotting a relation of number of plates vs. feed composition at constant values of relative volatility a curve is obtained which passes through a maximum. For larger values of relative volatility the maximum tends to flatten out and no longer exists at an α of 2.0 or greater.

Figure 9 contains averages of Figures 5, 6, 7, and 8 to compare the effect of relative volatility whatever the feed composition may be (0.25, 0.50, or 0.75). From these curves it can be concluded that for any separation the number of plates decreases as α increases, which is as expected since α is a measure of the ease or difficulty of separation.

The final result of all the calculated data is presented in Figure 10, which is a master curve and the objective of the correlation inherent in this thesis. The plot is an average curve of the correlation of the number of theoretical plates vs. reflux ratio regardless of feed composition or relative volatility. Figure 10 can be used for any problem within the ranges investigated and it will give results of sufficient accuracy for most engineering uses. Should a problem arise where α, X_F, X_D, and X_W are the same as those of one of the curves presented here, that particular curve should be used in preference to the master correlation to give somewhat better results.

Comparison of the present data with those of Gilliland (2) in Figure 11 shows excellent agreement in spite of the fact that Gilliland (2) obtained his data from actual experimental runs and includes multicomponent systems, whereas the writer's data were obtained analytically and for binary mixtures. The good agreement, therefore, would seem to indicate that the present data hold equally well for multicomponent mixtures. A slight difference between the two curves is that at higher reflux ratios corresponding to values of $R - R_m/R + 1 > 0.155$, Gilliland's (2) curve indicates a larger value for the number of plates. At lower values of reflux ratio where $R - R_m/R + 1 < 0.155$, the writer's curve yields a larger value for the number of plates.

The second method of presenting the results is analogous to the first. For purposes of comparison with Hachmuth (3) the data are plotted on square section paper with R_m/R as the ordinate group and S_m/S as the abscissa group.

Figures 12, 13, and 14 show the effect of relative volatility upon the correlation and regardless of feed composition the influence of relative volatility is appreciable. The different influence of α here as compared to that when using Gilliland's (2) coordinates is due to the different coordinates used. It appears from these families of curves that as α increases the number of actual plates required would also increase, which is contrary to what was found using Gilliland's (2) coordinates in Figures 1, 2, and 3, and which is contrary to distillation theory. However, this is not the case, since the minimum reflux and minimum number of plates are also a function of the relative volatility and they tend to decrease with increasing α. This latter relationship compensates for the increase in the S_m/S ratio that might be inferred from Figures 12, 13, and 14, so that the total number of plates actually decreases as α increases.

Hachmuth (3) has presented curves calculated for α's ranging from 1.1 to 1.5 which he indicates are difficult separations. In order to make a more valid comparison of the present data with those of Hachmuth (3) average curves of the correlation were obtained for X_F of 0.25, 0.50, and 0.75 from Figures 12, 13, and 14 respectively, for α's of 1.1, 1.2, and 1.5 excluding $\alpha = 2.0$. These are shown in Figure 15. For feed compositions of 0.25 and 0.75, the curves are nearly completely superimposed and constitute the upper edge of the band, whereas for $X_F = .50$ the curve obtained represents the lower edge of the band.

Hachmuth's (3) curve for equal molal concentrations of the two components in the feed is in agreement with the X_F = .50 curve. However, his curve which represents equal concentrations in the feed comprises the upper edge of his band whereas the lower edge applies when there are four parts of one component to one part of the other component in the feed. Exactly the contrary was found to be true in the present study.

Checks were made using the experimental data of Gilliland (2) which proved to be in agreement with the results of this thesis and not in agreement with the results of Hachmuth (3). Since Hachmuth's (3) results are also calculated, it is possible that a misstatement was made in his article when he referred to the upper and lower edges of the band.

Figures 16, 17, 18, and 19 show the effect of feed composition on the correlation for individual values of relative volatility. These also show upper and lower edges of a band defined by the various feed compositions. Only when α = 2.0 (Figure 19) or greater is a different tendency exhibited.

To note the effect of relative volatility on the correlation, regardless of feed composition, Figure 20 is plotted which contains average curves of Figures 16, 17, 18, and 19.

Figure 21 is the master curve for all of the parameters investigated, with the exclusion of α = 2.0, for the correlation of the number of theoretical plates vs. reflux ratio. Agreement of this curve with the master curve using Gilliland's (2) coordinates (Figure 10) is good and would be perfect had the curves of α = 2.0 been included here.

To compare the master curve with Hachmuth's (3) data, an average of the latter's band was taken, thereby eliminating the contradiction found between the two, concerning which edge of the band corresponds to the stated feed composition. Figure 22 shows the deviation between the present data and Hachmuth's (3) average data. This difference is greater than the divergency found between the present data and those of Gilliland (3).

The final presentation of the results found in this paper is made on semi-logarithmic paper with the values $R + 1/R_m + 1$ as ordinate and S/S_m as abscissa, to facilitate comparison with the work of Donnell and Cooper (4).

The same general tendencies are exhibited on these coordinates by the various parameters as were observed previously. However, due to the different coordinates used the influences of α and X_F are not as pronounced since the curves lie closer to each other in these figures.

Figures 23, 24, and 25 show the effect of relative volatility on the correlation for feed compositions of 0.25, 0.50, and 0.75 respectively. Figures 27, 28, 29, and 30 indicate the effect of feed composition for relative volatilities of 1.1, 1.2, 1.5, and 2.0.

Averages of these plots, namely Figure 26, for the effect of feed composition regardless of α and Figure 31, for the effect of relative volatility regardless of X_F show that the feed composition has a much greater influence than relative volatility.

The average curve of all of the various parameters is the master curve (Figure 32) of the correlation of the number of theoretical plates vs. reflux ratio. This curve agrees with the master curves presented heretofore when using Gilliland's (2) coordinates (Figure 10) and Hachmuth's (3) coordinates (Figure 21). It can be used with equally good results.

Comparison of the present data is made with those of Donnell and Cooper (4) in Figure 33. The agreement between the average curves is close when consideration is taken of how differently the data were obtained. The data in this thesis form a systematic analytical investigation of binary systems, whereas Donnel and Cooper (4) cover the work of over one hundred investigations and those of previous authors including experimental and analytical data of binary, multicomponent, ideal and non-ideal systems.

Based upon the close agreement between these curves, the thesis results can be assumed to yield good estimates of the number of theoretical plates as a function of the reflux ratio.

The upper and lower limits of Donnell and Cooper's (4) data are spread over a much wider range than the thesis data, because the results of a greater number of systems were used in plotting. Nevertheless, the average curves are very close.

In comparing the three methods of plotting with each other, it was found that not one alone gives the best results in all cases, when the data are represented by a single master curve. When the separation is difficult ($\alpha < 1.5$) and the components in the feed are in unequal concentrations, the most accurate results may be obtained from the master curve using Gilliland's (2) coordinates (Figure 10). If the relative volatility is greater than 1.5 and for a feed composition near equal molal concentrations of the two components Figure 10 should also be used.

The master curve using Hachmuth's (3) coordinates (Figure 21) gives best results under the following conditions; α's less than 1.5 and equal molal concentrations of components in the feed; also, α's greater than 1.5 and unequal concentration of components in the feed.

In spite of this, the most consistent narrowest band is given when the method of Donnell and Cooper (4) is used. The master curve using Donnell and Cooper's (4) coordinates (Figure 32) gives results which are consistently reliable over the entire range of parameters investigated in this presentation. This method of plotting is, therefore, recommended.

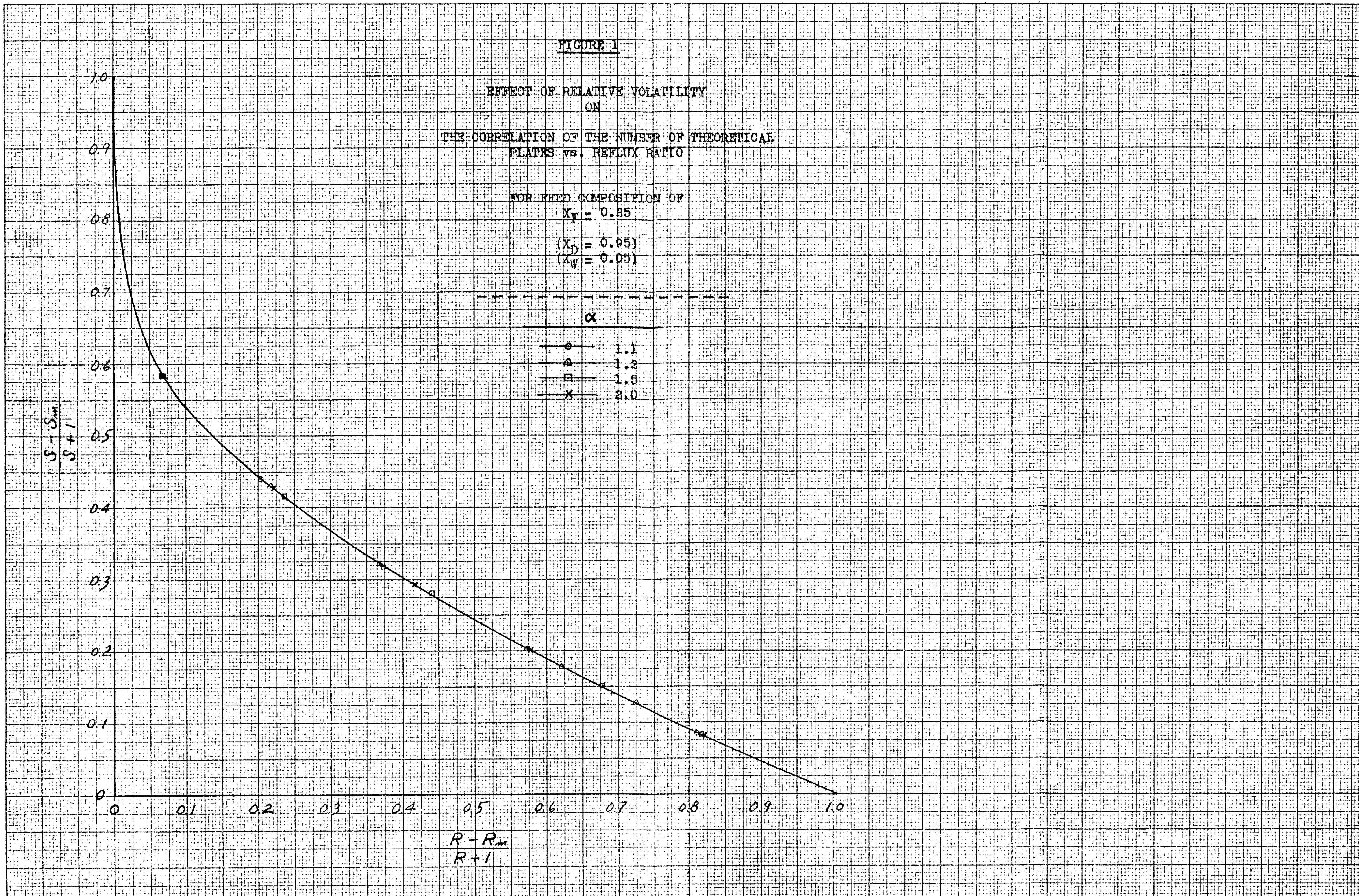

FIGURE 1

EFFECT OF RELATIVE VOLATILITY
ON
THE CORRELATION OF THE NUMBER OF THEORETICAL
PLATES vs. REFLUX RATIO

FOR FEED COMPOSITION OF
$X_F = 0.25$

$(X_D = 0.95)$
$(X_W = 0.05)$

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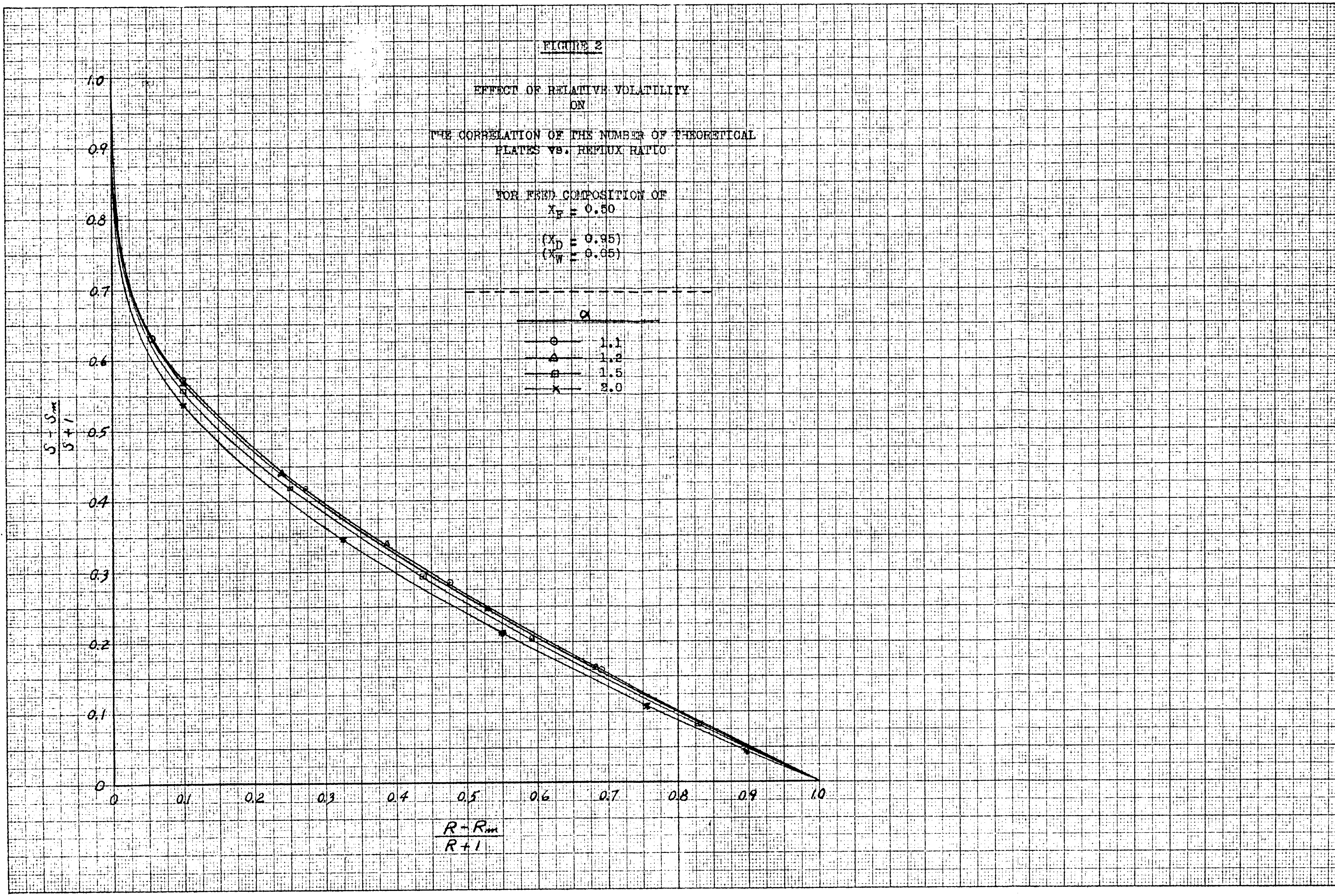

FIGURE 2

EFFECT OF RELATIVE VOLATILITY
ON
THE CORRELATION OF THE NUMBER OF THEORETICAL
PLATES vs. REFLUX RATIO

FOR FEED COMPOSITION OF
$X_F = 0.50$

($X_D = 0.95$)
($X_W = 0.05$)

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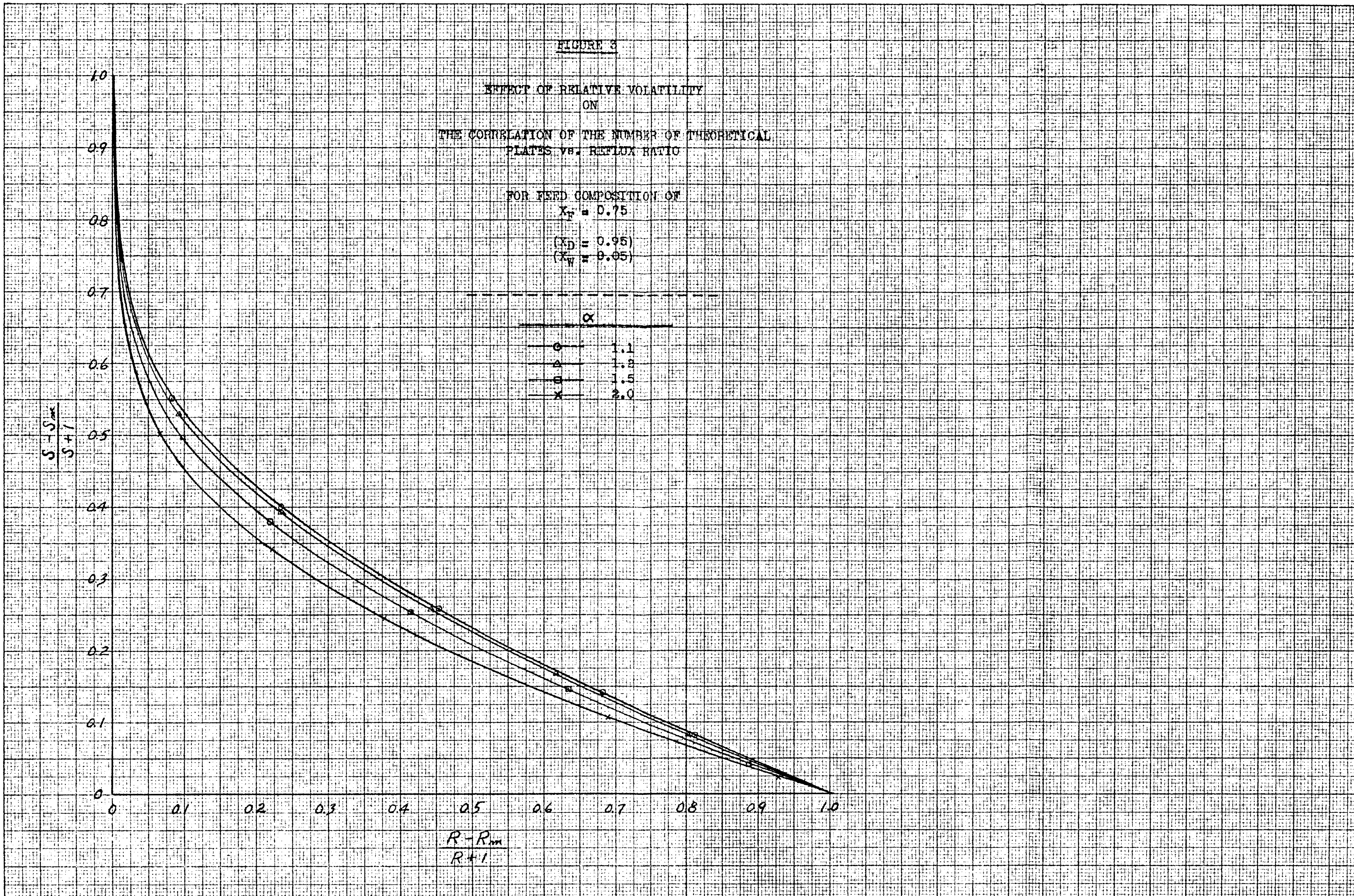

FIGURE 3

EFFECT OF RELATIVE VOLATILITY
ON
THE CORRELATION OF THE NUMBER OF THEORETICAL
PLATES vs. REFLUX RATIO

FOR FEED COMPOSITION OF
$X_F = 0.75$

$(X_D = 0.95)$
$(X_W = 0.05)$

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Millimeters, 5 mm. lines accented, cm. lines heavy.
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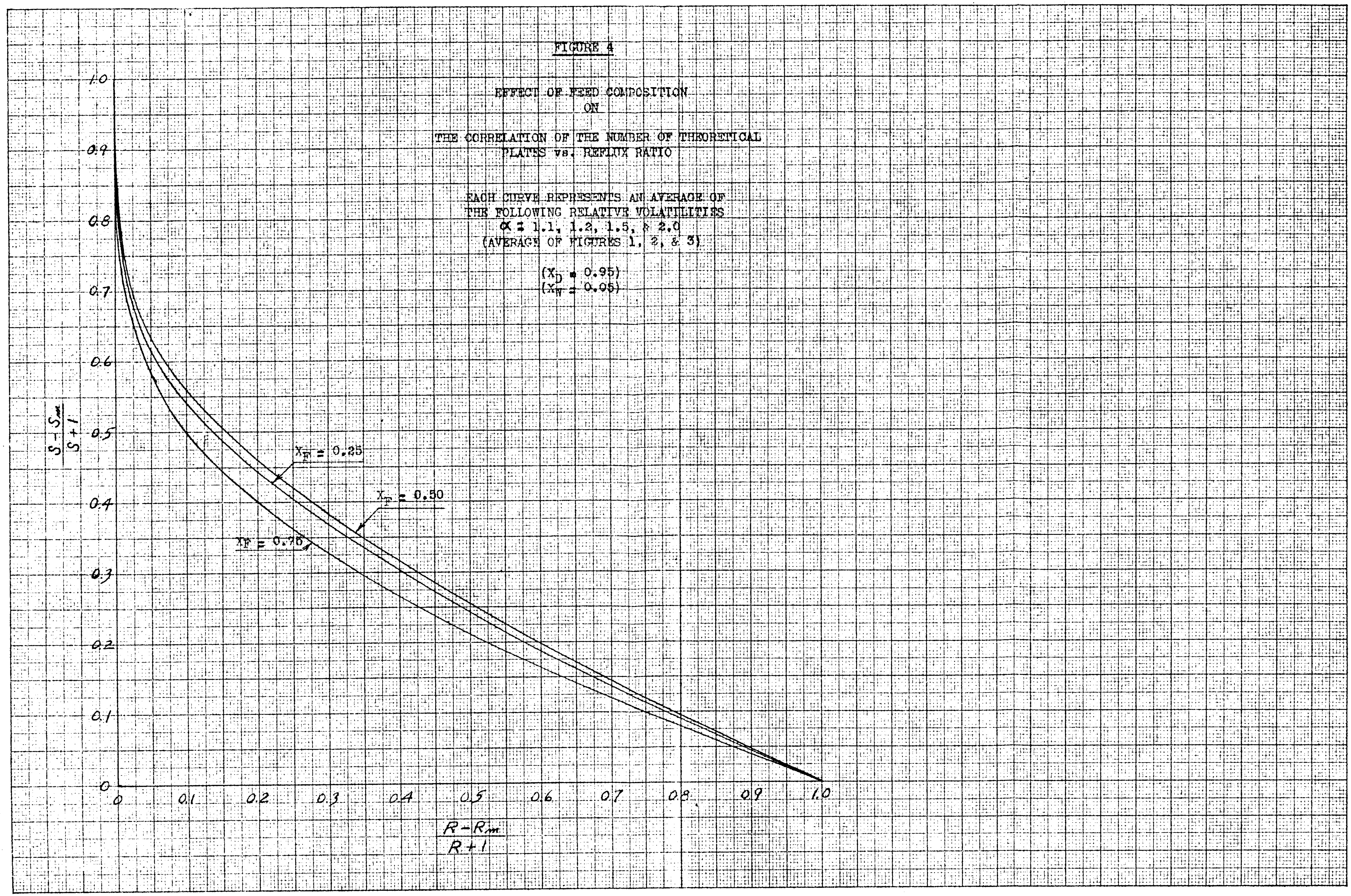
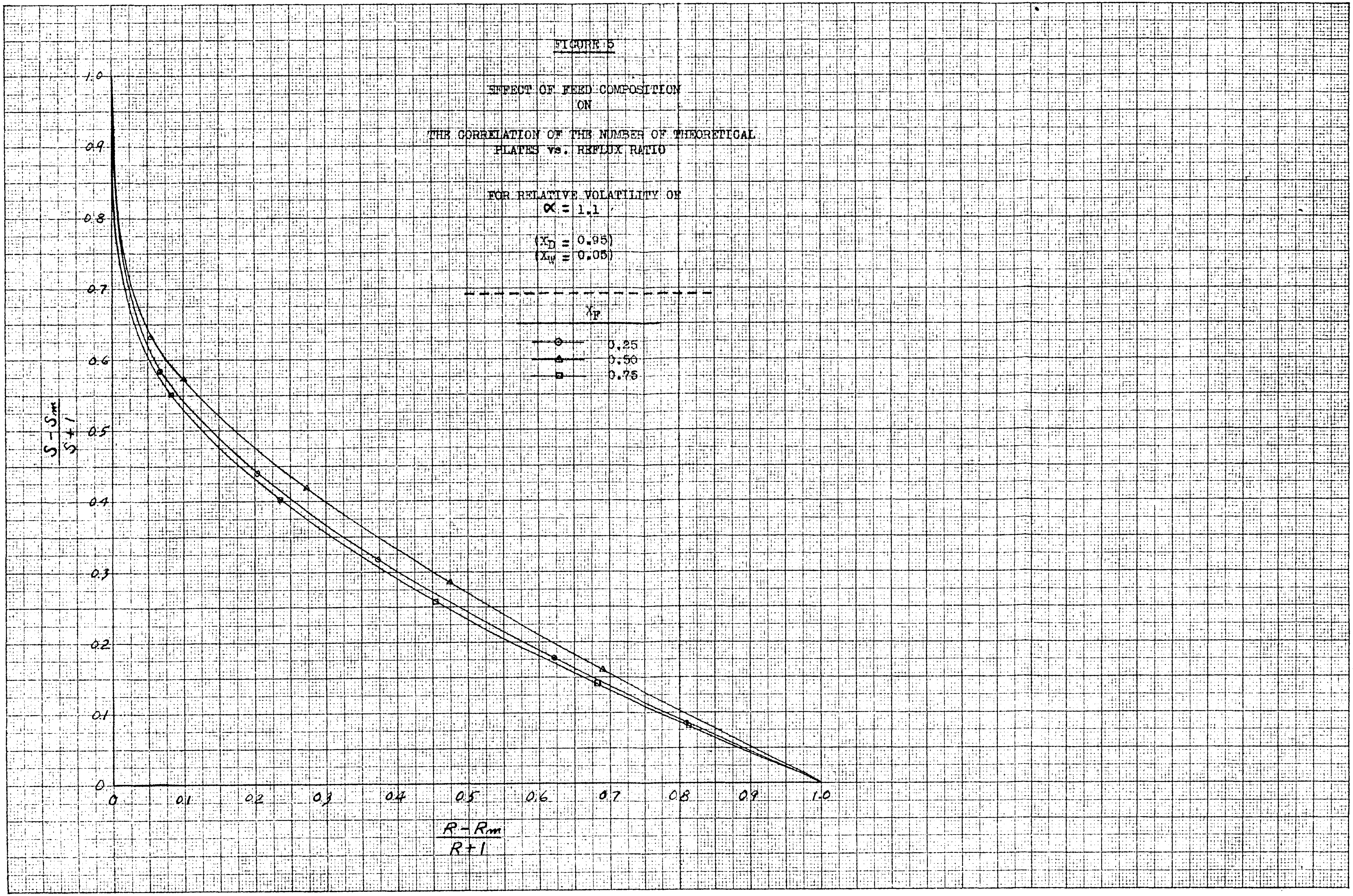


FIGURE 4
EFFECT OF FEED COMPOSITION
ON
THE CORRELATION OF THE NUMBER OF THEORETICAL
PLATES vs. REFLUX RATIO
EACH CURVE REPRESENTS AN AVERAGE OF
THE FOLLOWING RELATIVE VOLATILITIES
α = 1.1, 1.2, 1.5, & 2.0
(AVERAGE OF FIGURES 1, 2, & 3)
(X_D = 0.95)
(X_W = 0.05)
X_F = 0.25
X_F = 0.50
X_F = 0.75
(S − S_m)/(S + 1)
(R − R_m)/(R + 1)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0



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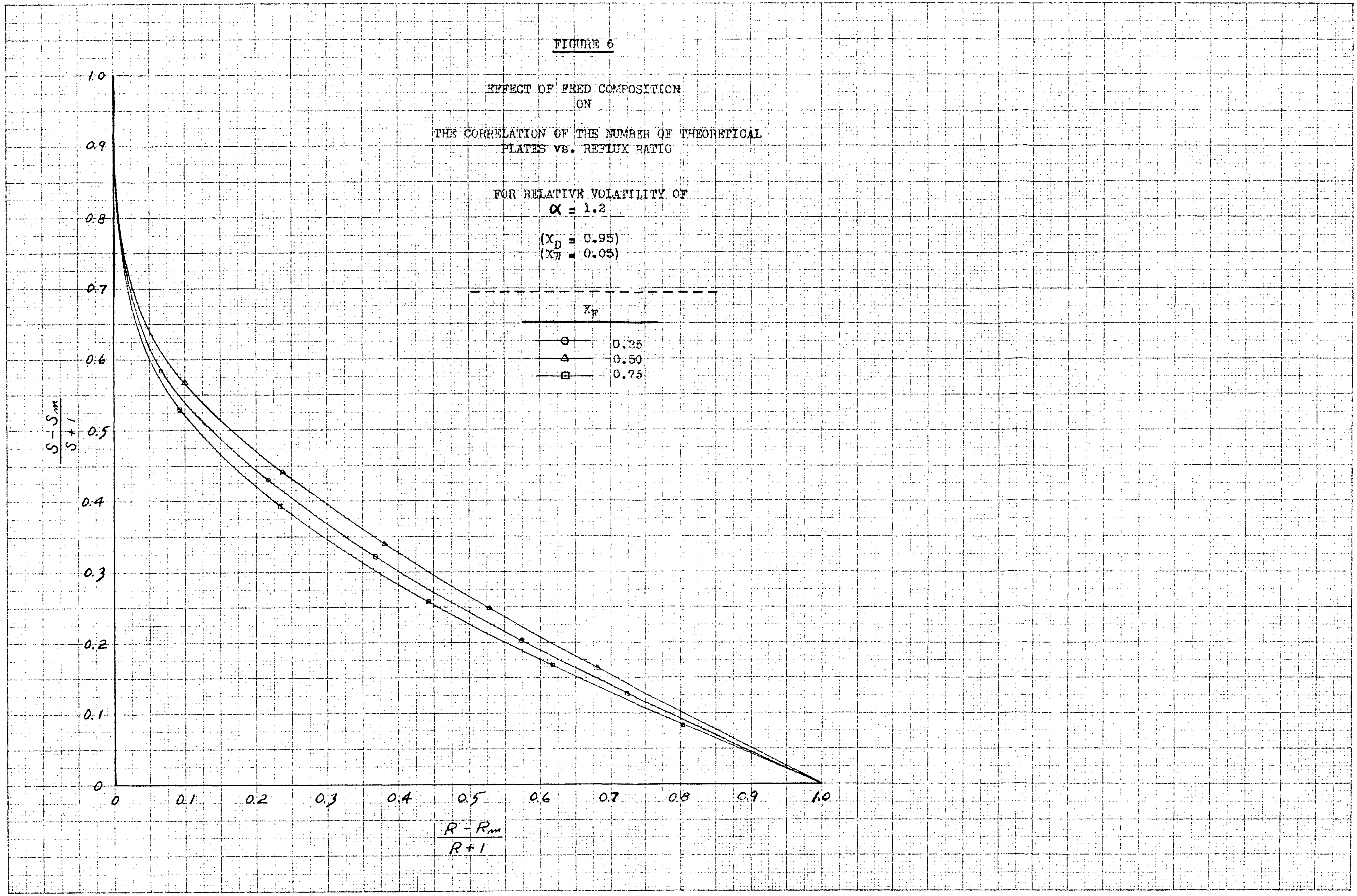
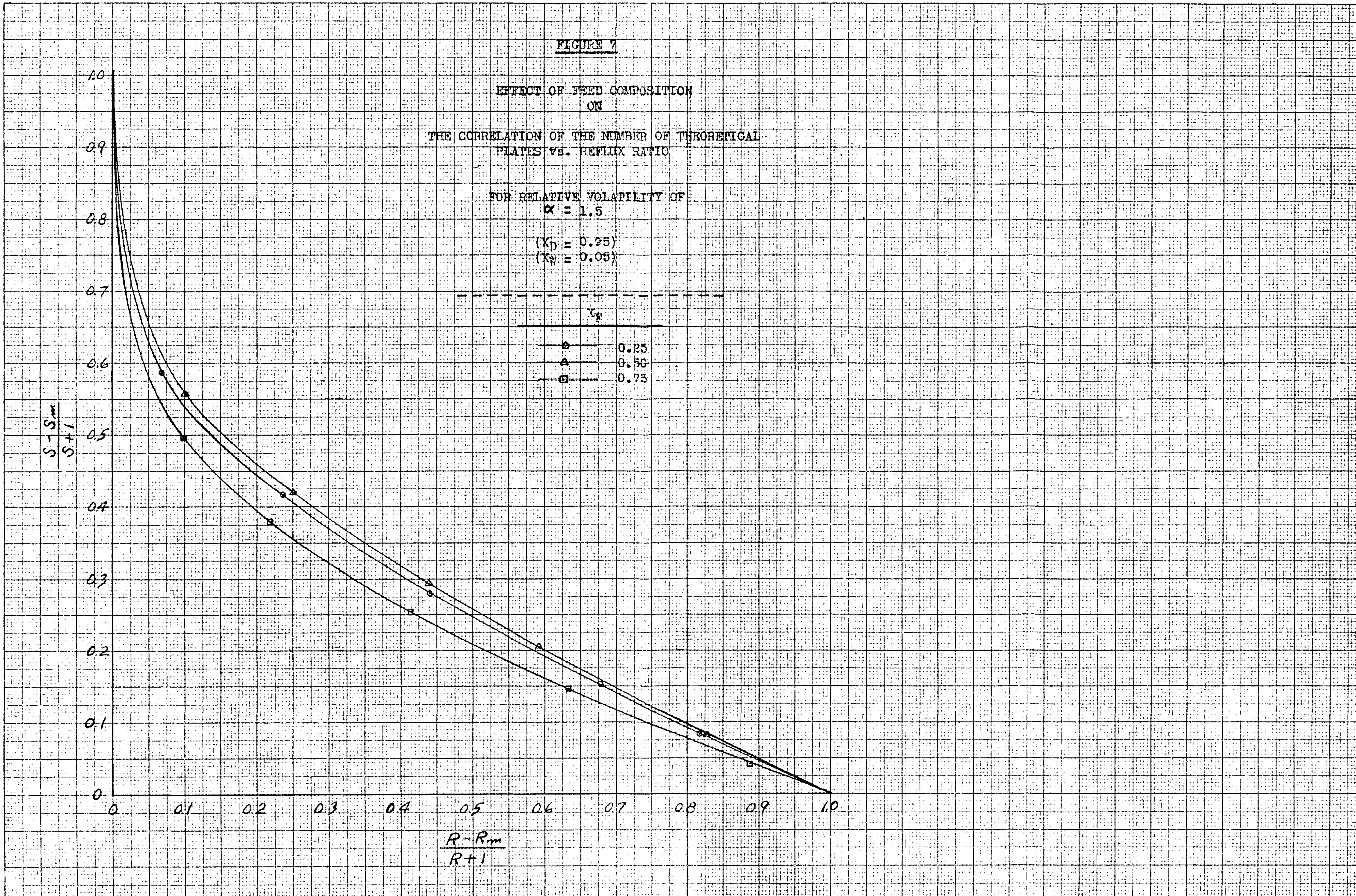


FIGURE 6
EFFECT OF FEED COMPOSITION
ON
THE CORRELATION OF THE NUMBER OF THEORETICAL
PLATES vs. REFLUX RATIO
FOR RELATIVE VOLATILITY OF
α = 1.2
(X_D = 0.95)
(X_W = 0.05)
X_F
0.25
0.50
0.75
(S − S_m)/(S + 1)
(R − R_m)/(R + 1)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0



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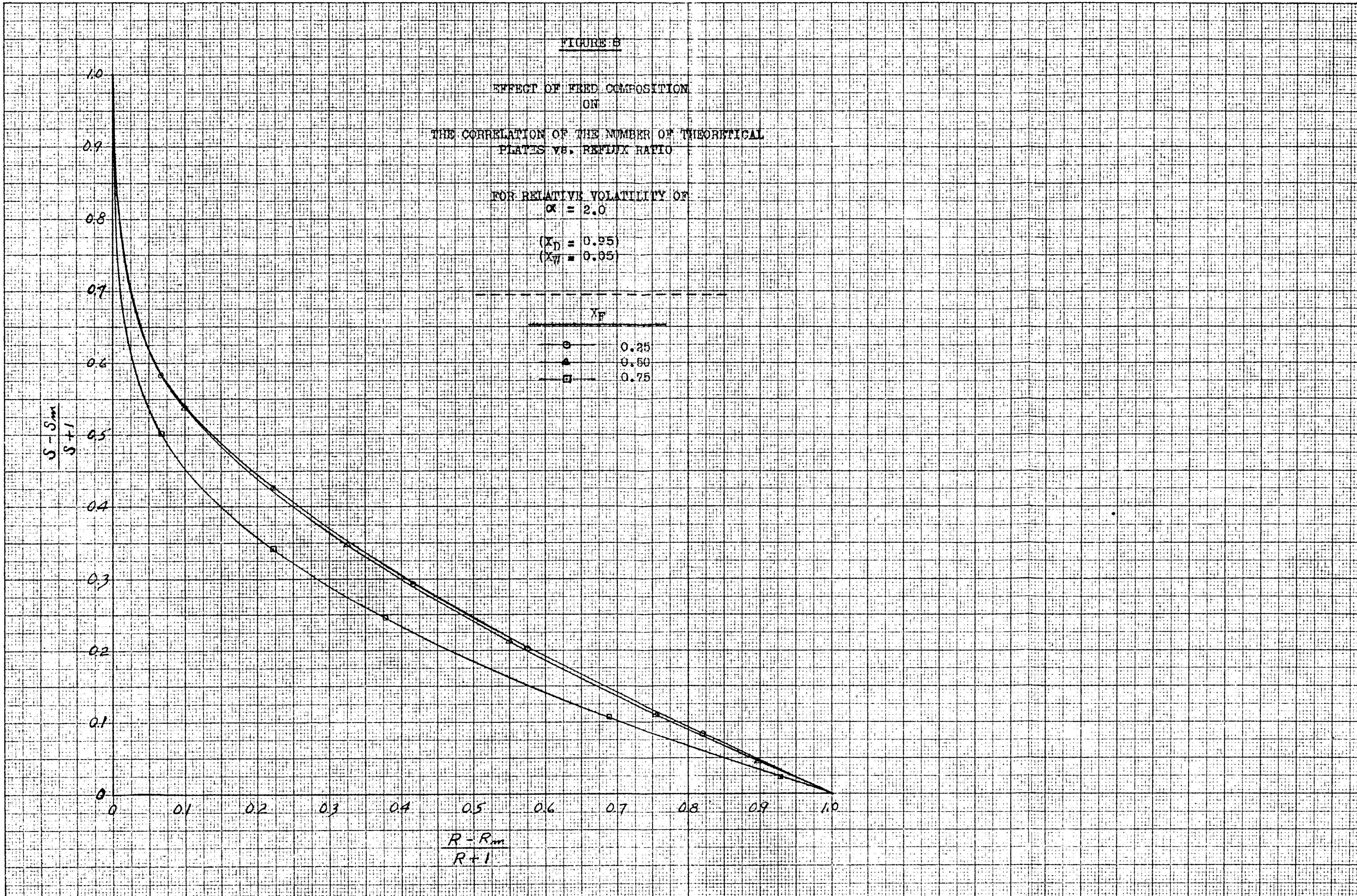

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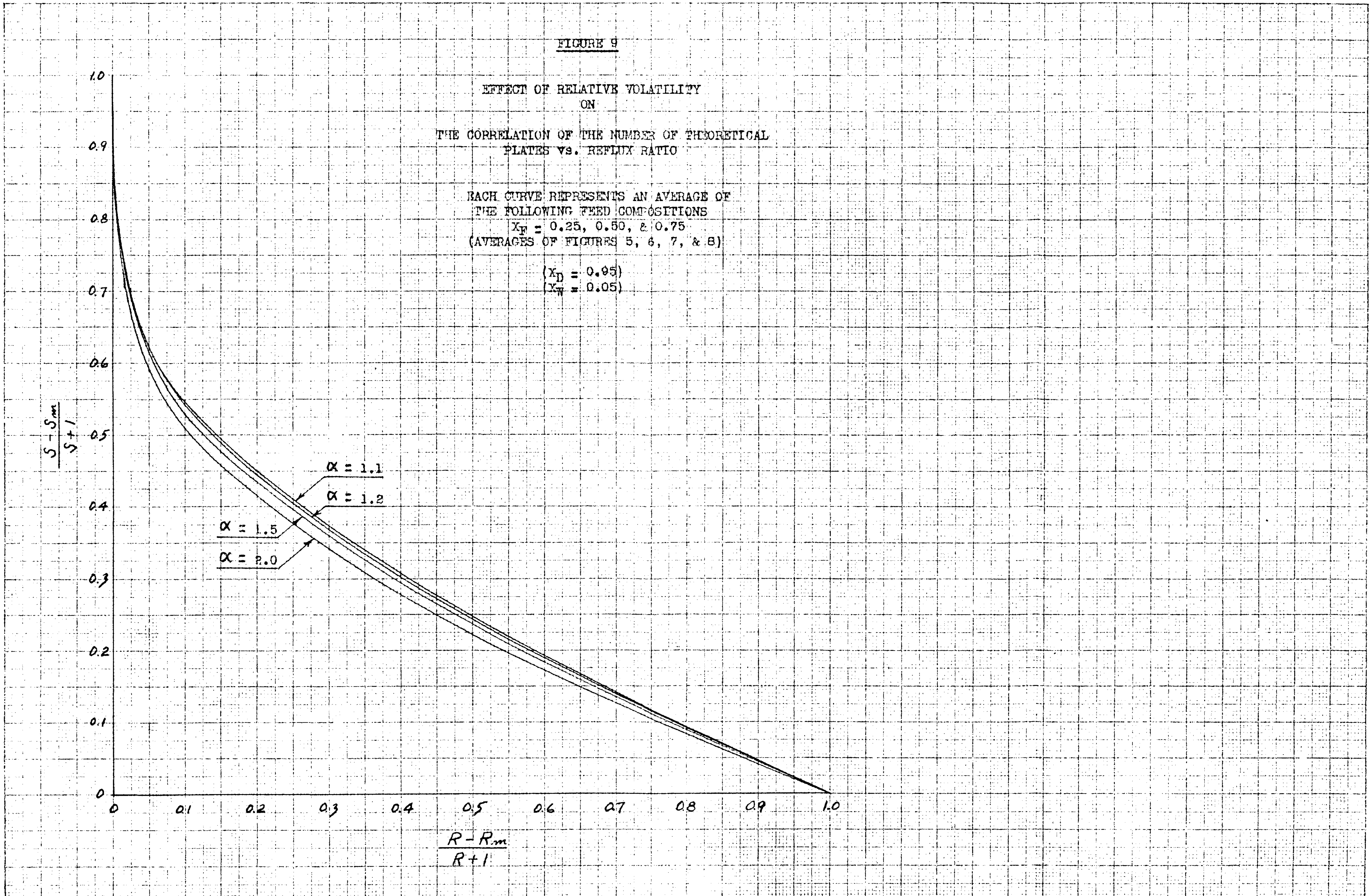


FIGURE 9
EFFECT OF RELATIVE VOLATILITY
ON
THE CORRELATION OF THE NUMBER OF THEORETICAL
PLATES vs. REFLUX RATIO
EACH CURVE REPRESENTS AN AVERAGE OF
THE FOLLOWING FEED COMPOSITIONS
X_F = 0.25, 0.50, & 0.75
(AVERAGES OF FIGURES 5, 6, 7, & 8)
(X_D = 0.95)
(X_W = 0.05)
α = 1.1
α = 1.2
α = 1.5
α = 2.0
$\frac{S - S_m}{S+1}$
$\frac{R - R_m}{R+1}$
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

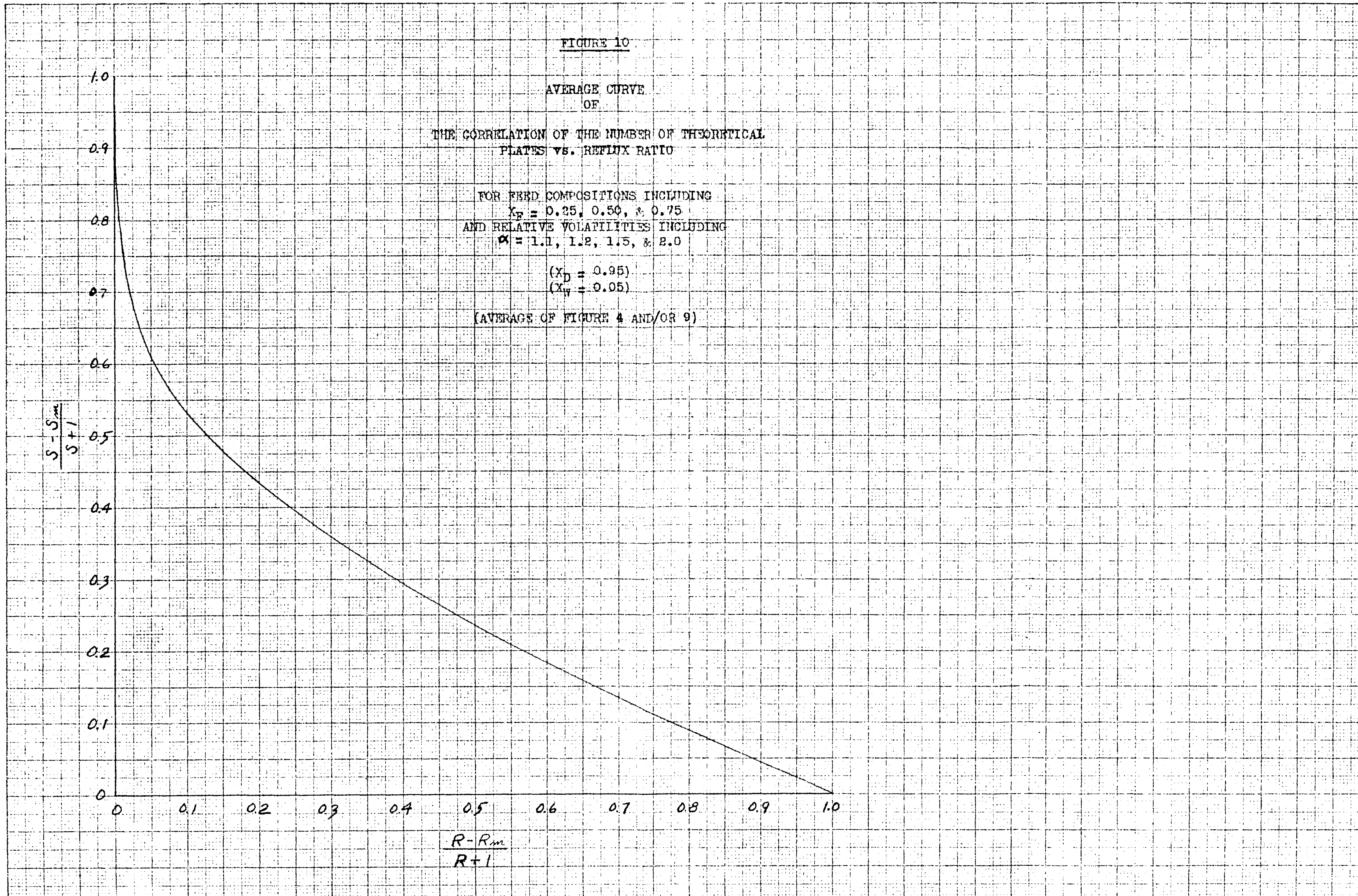


FIGURE 10

AVERAGE CURVE
OF
THE CORRELATION OF THE NUMBER OF THEORETICAL PLATES vs. REFLUX RATIO

FOR FEED COMPOSITIONS INCLUDING
X_F = 0.25, 0.50, & 0.75
AND RELATIVE VOLATILITIES INCLUDING
α = 1.1, 1.2, 1.5, & 2.0

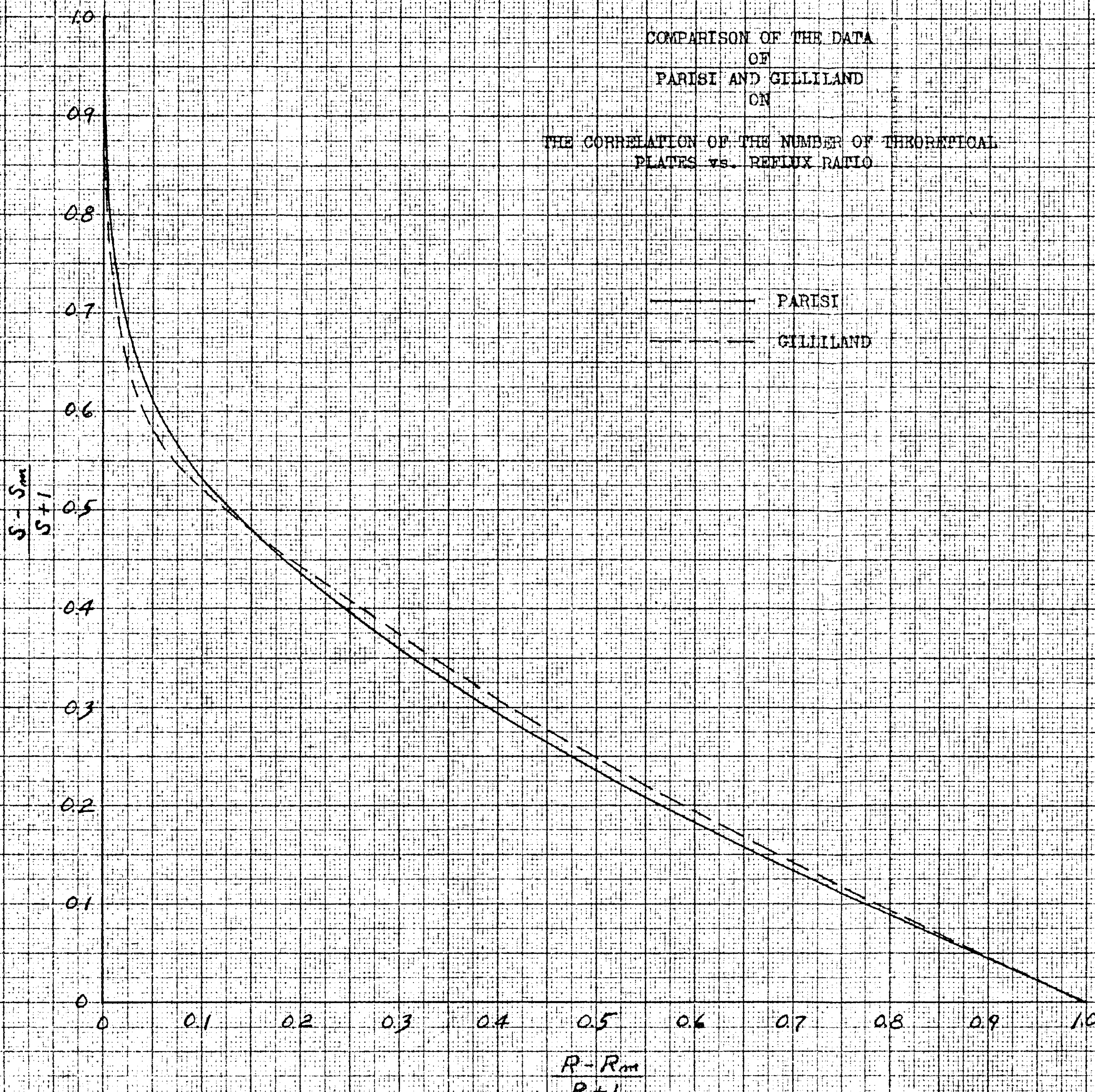
(X_D = 0.95)
(X_W = 0.05)

(AVERAGE OF FIGURE 4 AND/OR 9)

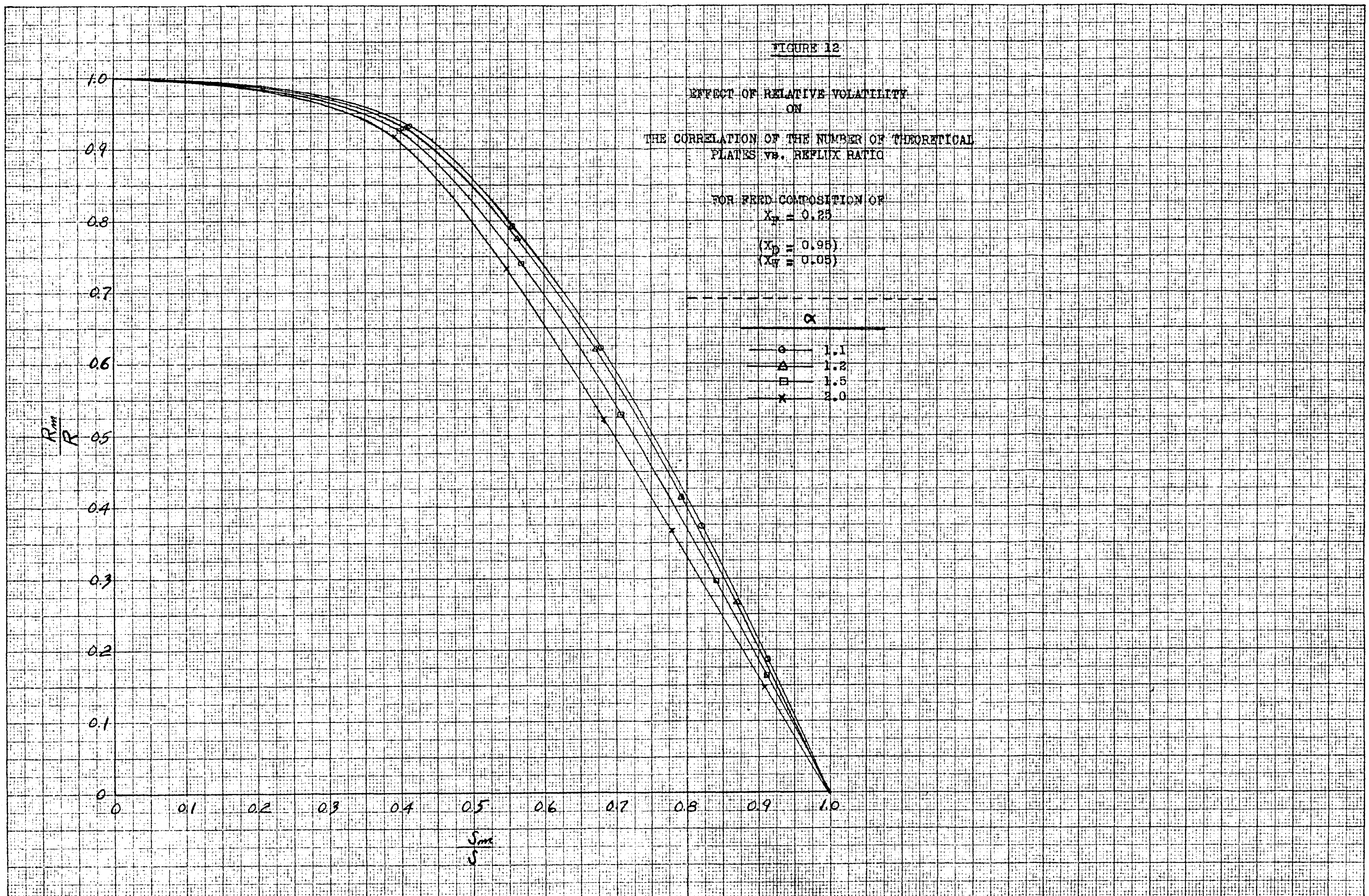
FIGURE 11

COMPARISON OF THE DATA
OF
PARISI AND GILLILAND
ON

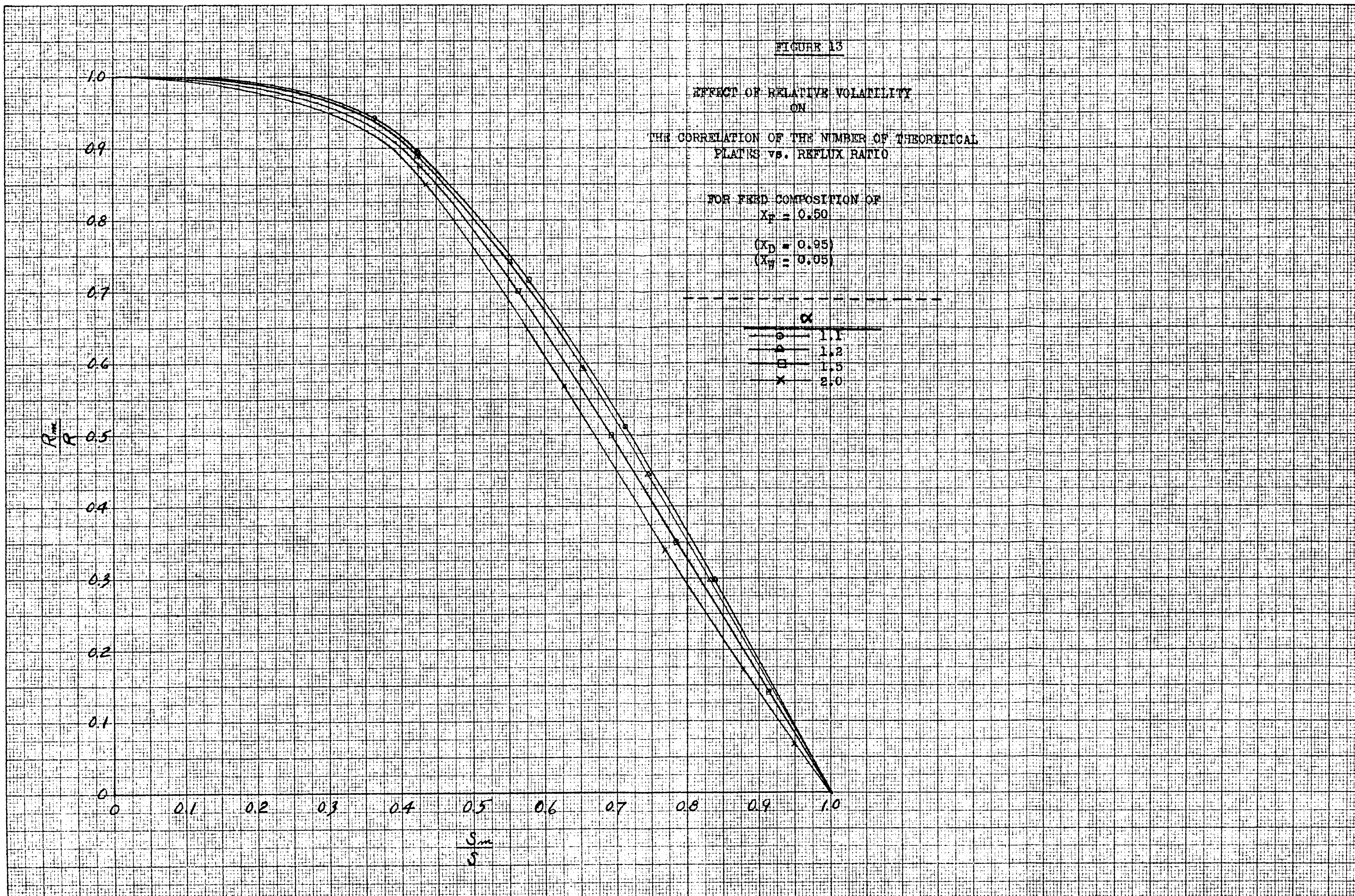
THE CORRELATION OF THE NUMBER OF THEORETICAL
PLATES vs. REFLUX RATIO



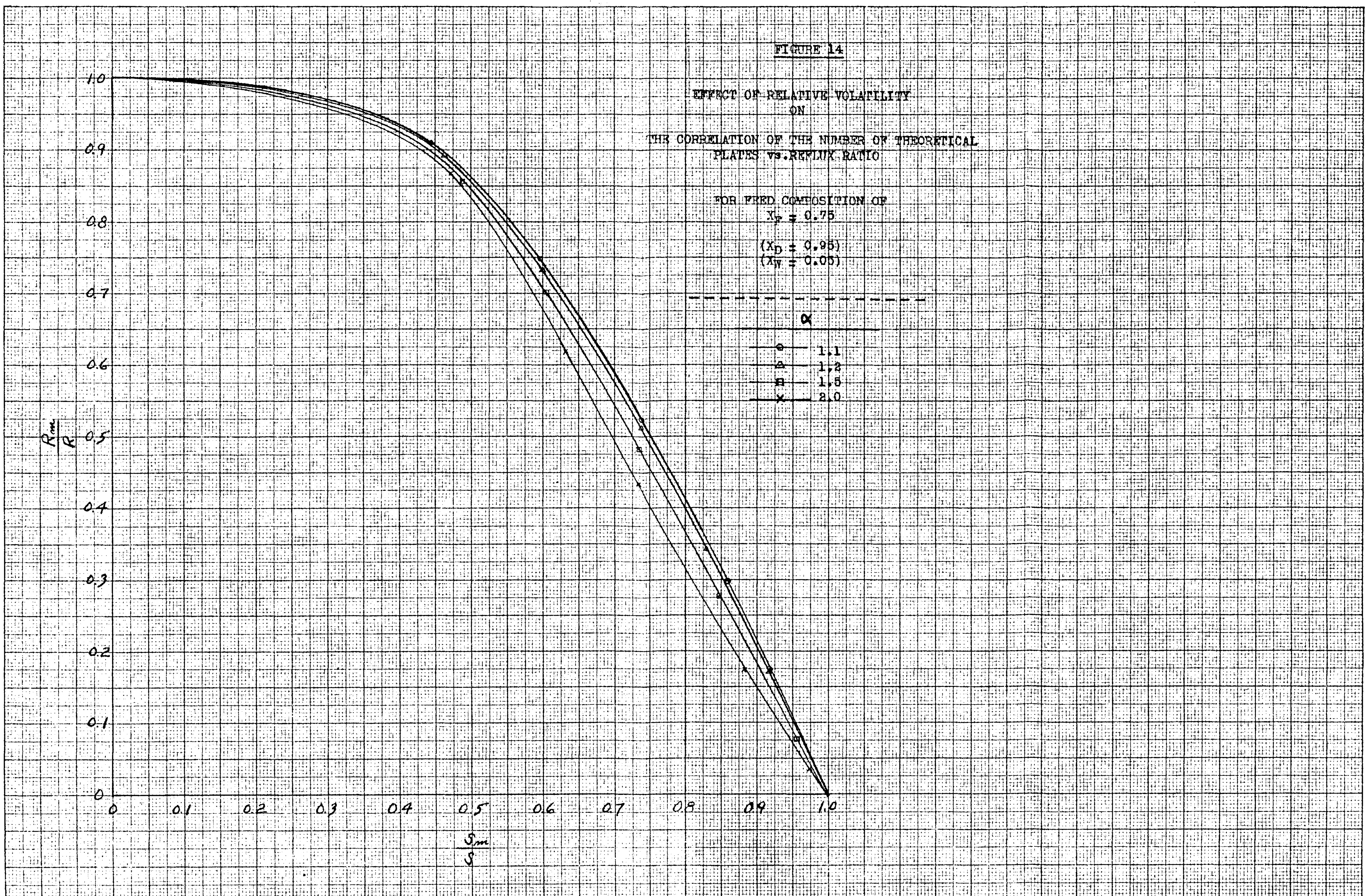
359-14L KEUFFEL & ESSER CO.
Millimeters, 5 mm. lines accented, cm. lines heavy.
MADE IN U.S.A.



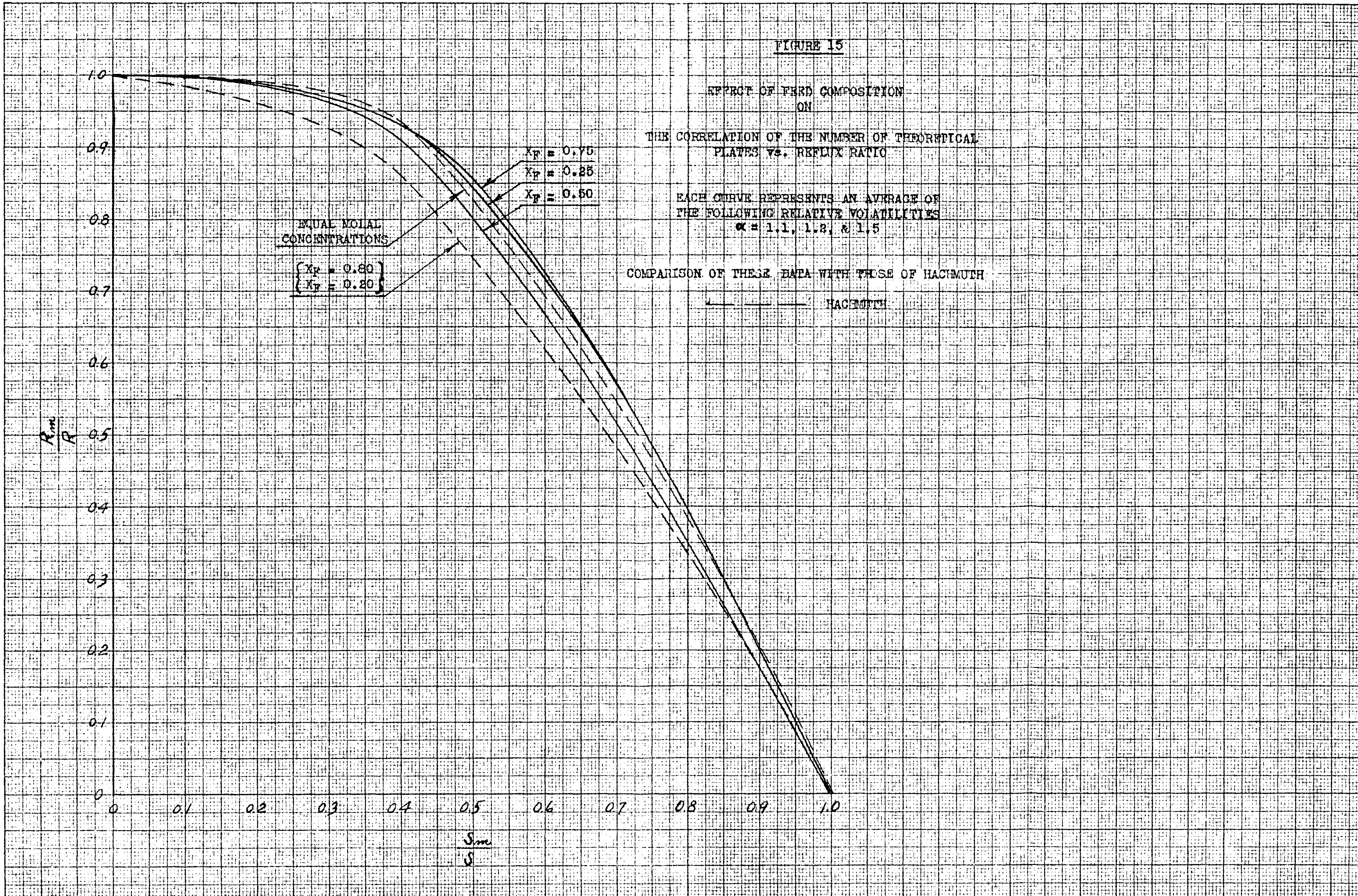
359-14L KEUFFEL & ESSER CO. Millimeters, 5 mm. lines accented, cm. lines heavy. MADE IN U.S.A.



359-14L KEUFFEL & ESSER CO.
Millimeters, 5 mm. lines accented, cm. lines heavy.
MADE IN U.S.A.



359-14L KEUFFEL & ESSER CO.
Millimeters, 5 mm. lines accented, cm. lines heavy.
MADE IN U.S.A.



359-14L KEUFFEL & ESSER CO.
Millimeters, 5 mm. lines accented, cm. lines heavy.
MADE IN U.S.A.

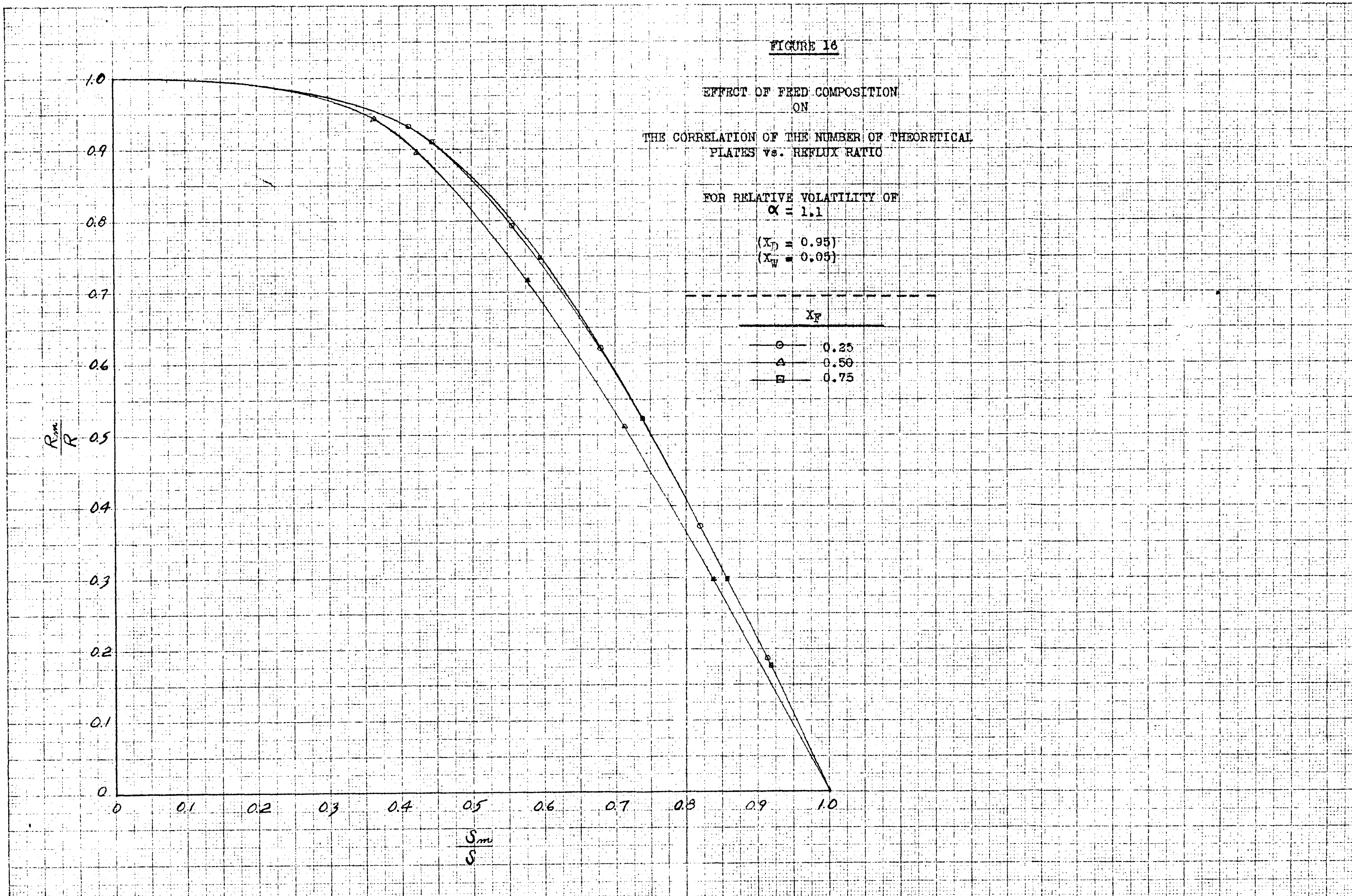


FIGURE 16
EFFECT OF FEED COMPOSITION
ON
THE CORRELATION OF THE NUMBER OF THEORETICAL
PLATES vs. REFLUX RATIO
FOR RELATIVE VOLATILITY OF
α = 1.1
(X_D = 0.95)
(X_W = 0.05)
X_F
0.25
0.50
0.75
Rm/R
Sm/S
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

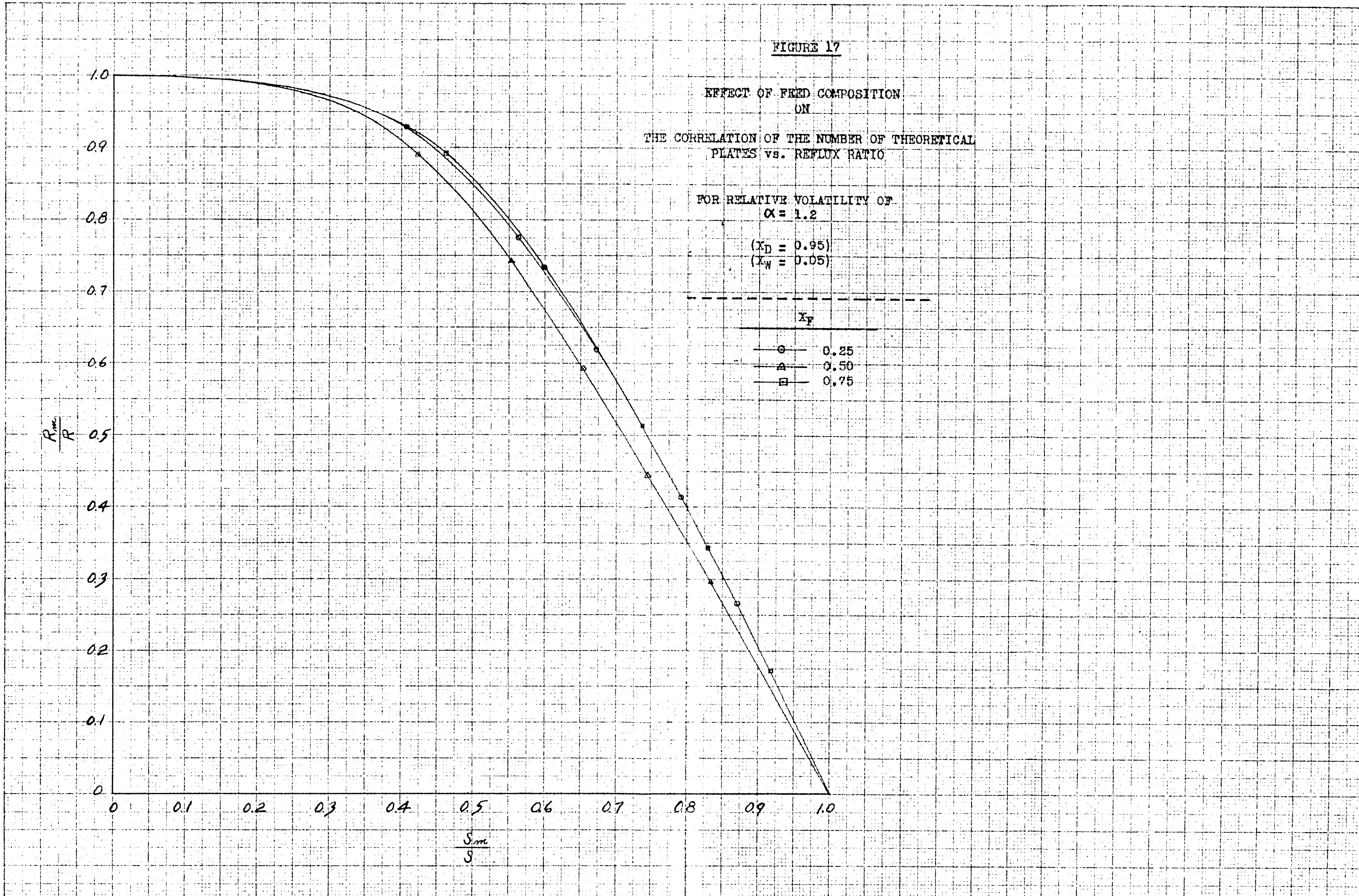


FIGURE 17
EFFECT OF FEED COMPOSITION
ON
THE CORRELATION OF THE NUMBER OF THEORETICAL
PLATES vs. REFLUX RATIO
FOR RELATIVE VOLATILITY OF
α = 1.2
(X_D = 0.95)
(X_W = 0.05)
X_F
0.25
0.50
0.75
R_m / R
S_m / S
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

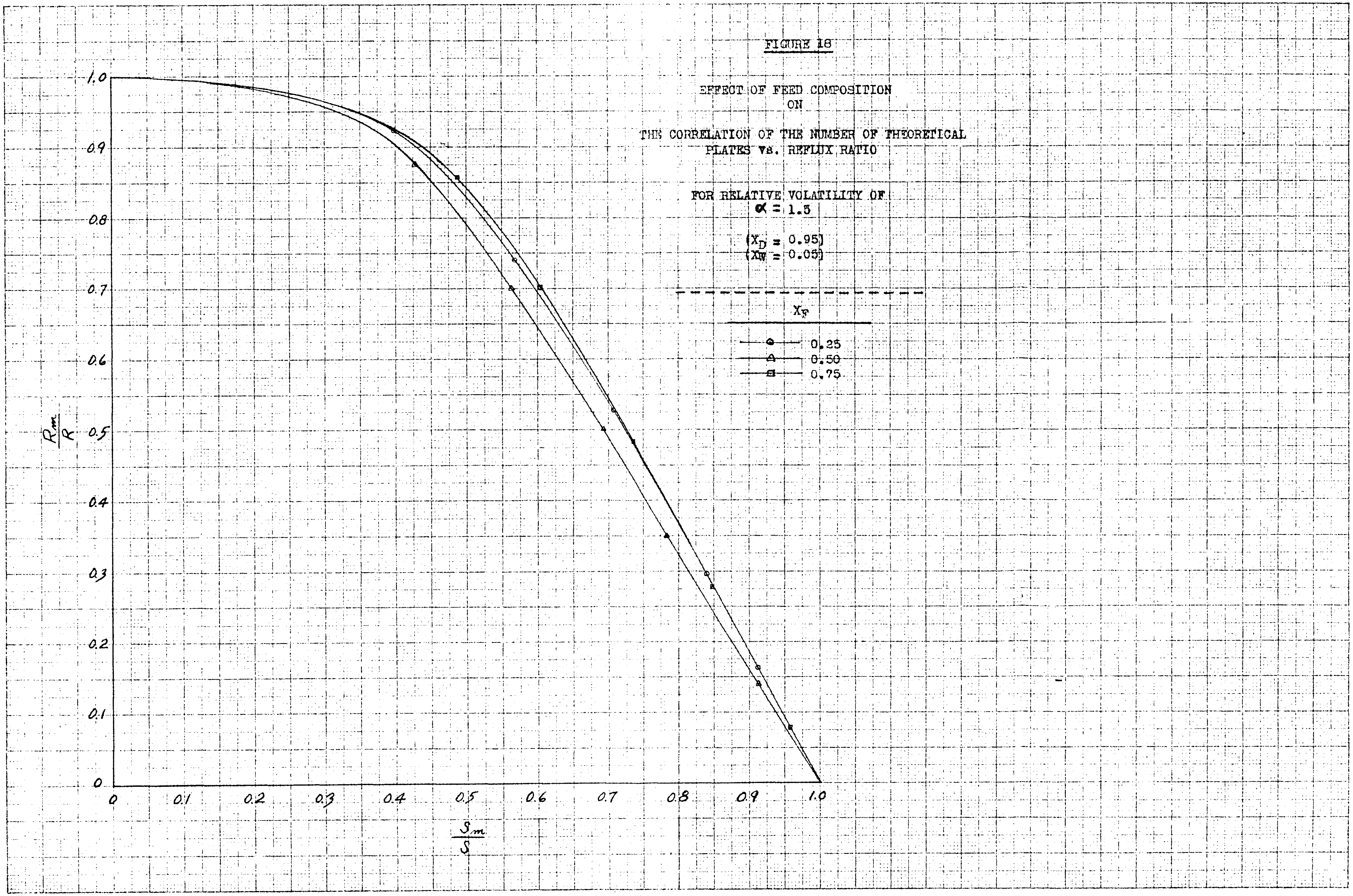


FIGURE 18
EFFECT OF FEED COMPOSITION
ON
THE CORRELATION OF THE NUMBER OF THEORETICAL
PLATES vs. REFLUX RATIO
FOR RELATIVE VOLATILITY OF
α = 1.5
(X_D = 0.95)
(X_W = 0.05)
X_F
0.25
0.50
0.75
$\frac{R_m}{R}$
$\frac{S_m}{S}$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

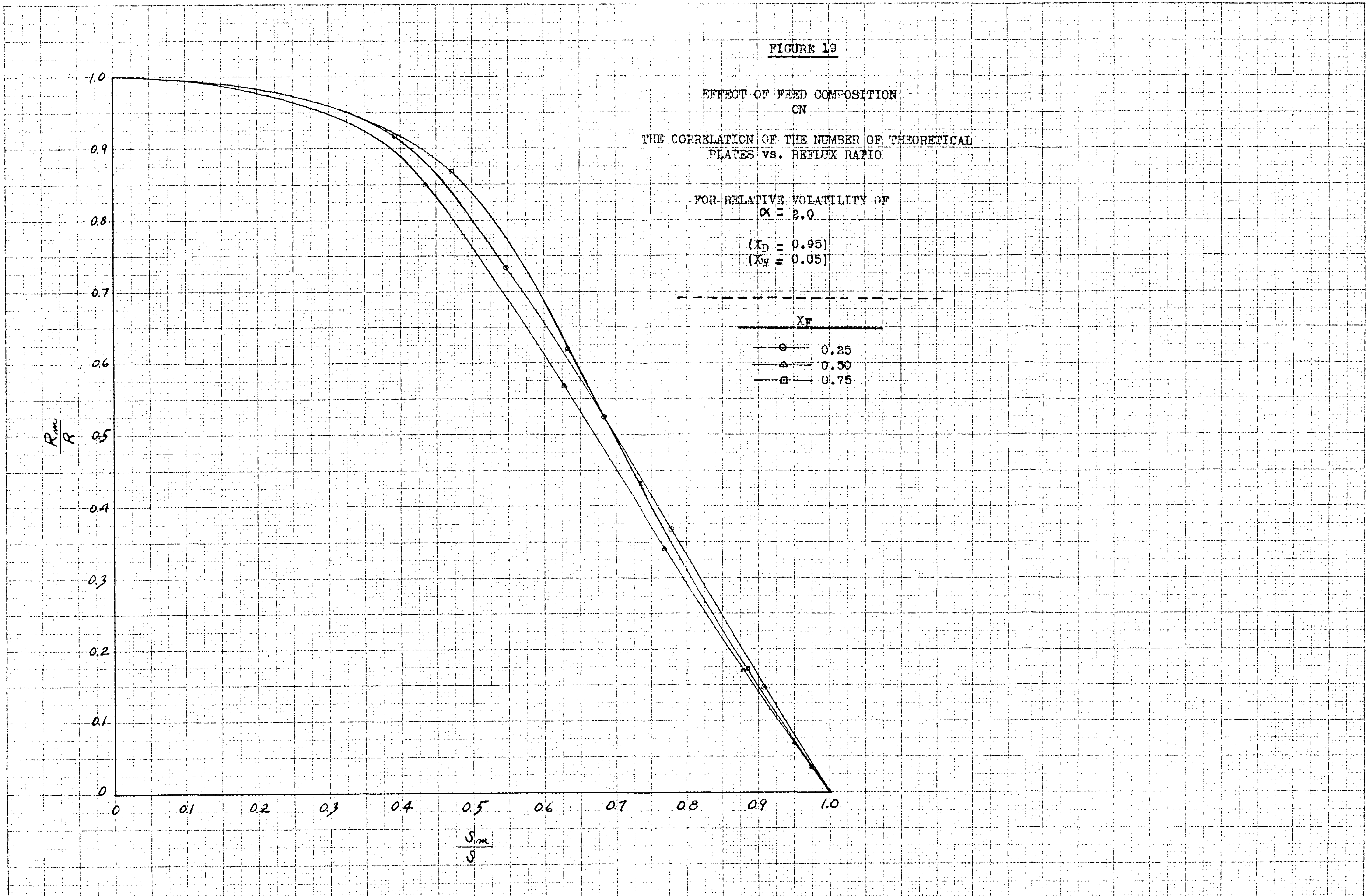


FIGURE 19
EFFECT OF FEED COMPOSITION
ON
THE CORRELATION OF THE NUMBER OF THEORETICAL
PLATES vs. REFLUX RATIO
FOR RELATIVE VOLATILITY OF
α = 2.0
(X_D = 0.95)
(X_W = 0.05)
X_F
0.25
0.50
0.75
Rm/R
Sm/S
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

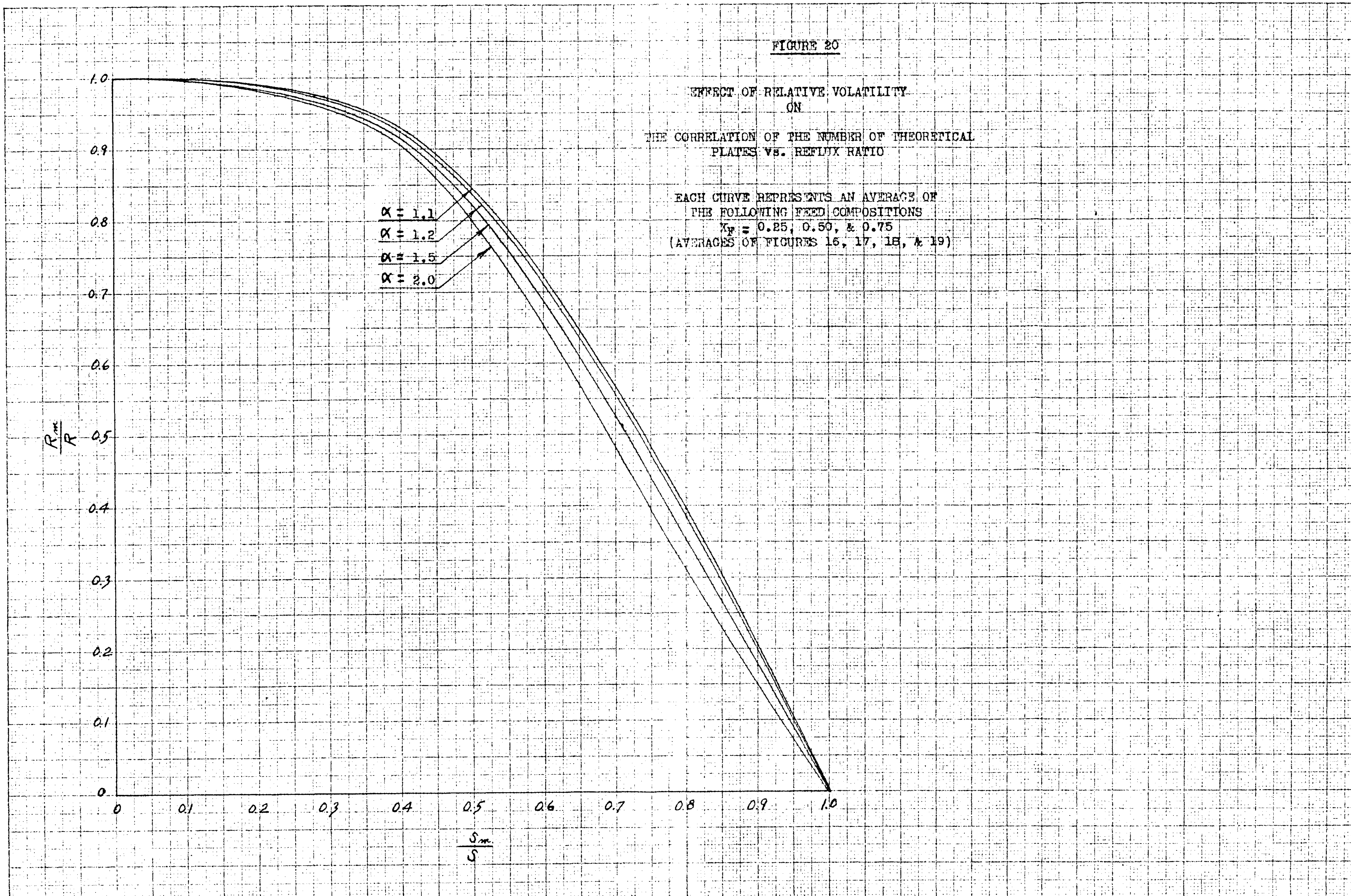


FIGURE 20
EFFECT OF RELATIVE VOLATILITY
ON
THE CORRELATION OF THE NUMBER OF THEORETICAL
PLATES Vs. REFLUX RATIO
EACH CURVE REPRESENTS AN AVERAGE OF
THE FOLLOWING FEED COMPOSITIONS
X_F = 0.25, 0.50, & 0.75
(AVERAGES OF FIGURES 16, 17, 18, & 19)
α = 1.1
α = 1.2
α = 1.5
α = 2.0
$\frac{R_m}{R}$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
$\frac{S_m}{S}$

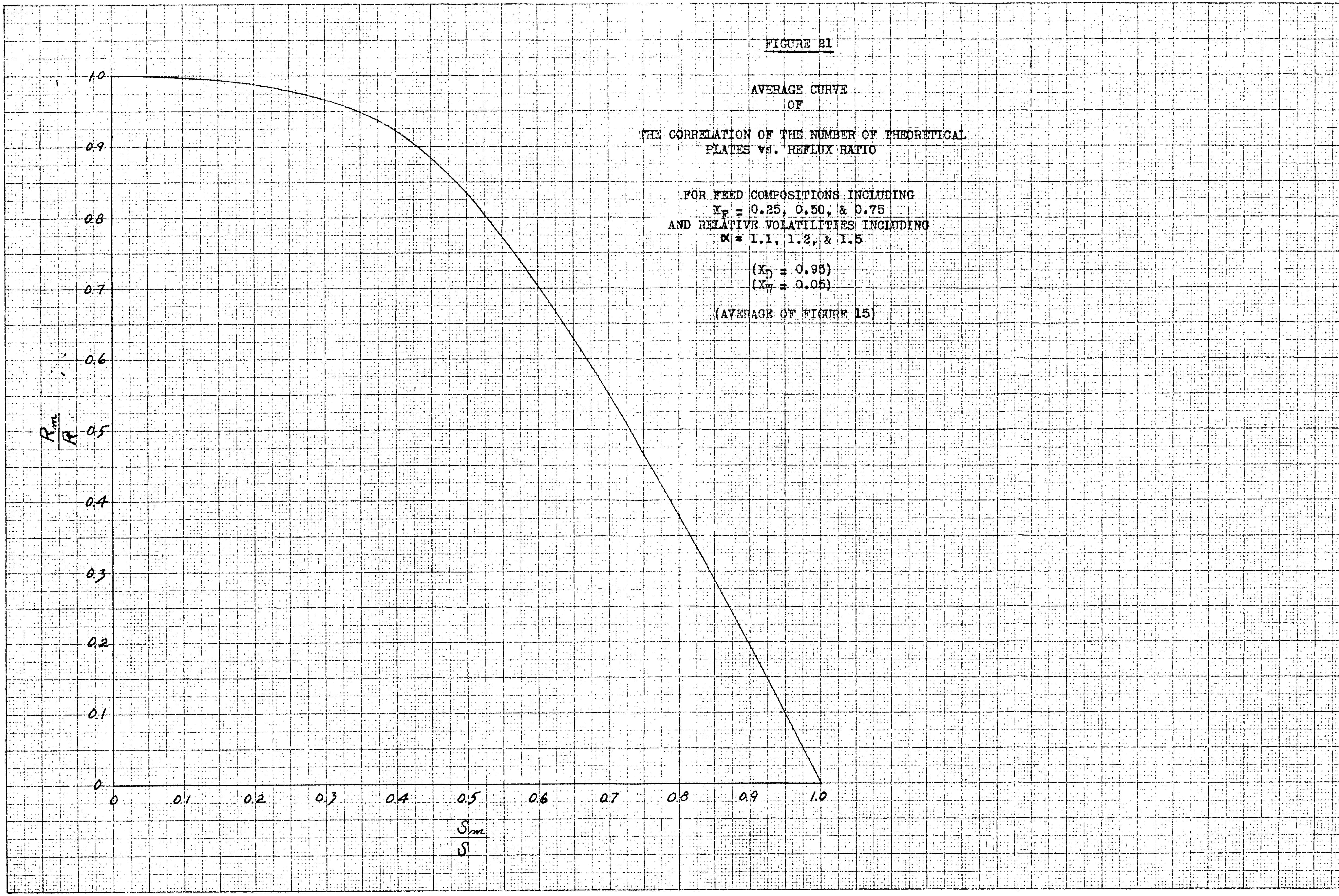


FIGURE 21

AVERAGE CURVE
OF

THE CORRELATION OF THE NUMBER OF THEORETICAL PLATES vs. REFLUX RATIO

FOR FEED COMPOSITIONS INCLUDING
X_F = 0.25, 0.50, & 0.75
AND RELATIVE VOLATILITIES INCLUDING
α = 1.1, 1.2, & 1.5

(X_D = 0.95)
(X_W = 0.05)

(AVERAGE OF FIGURE 15)

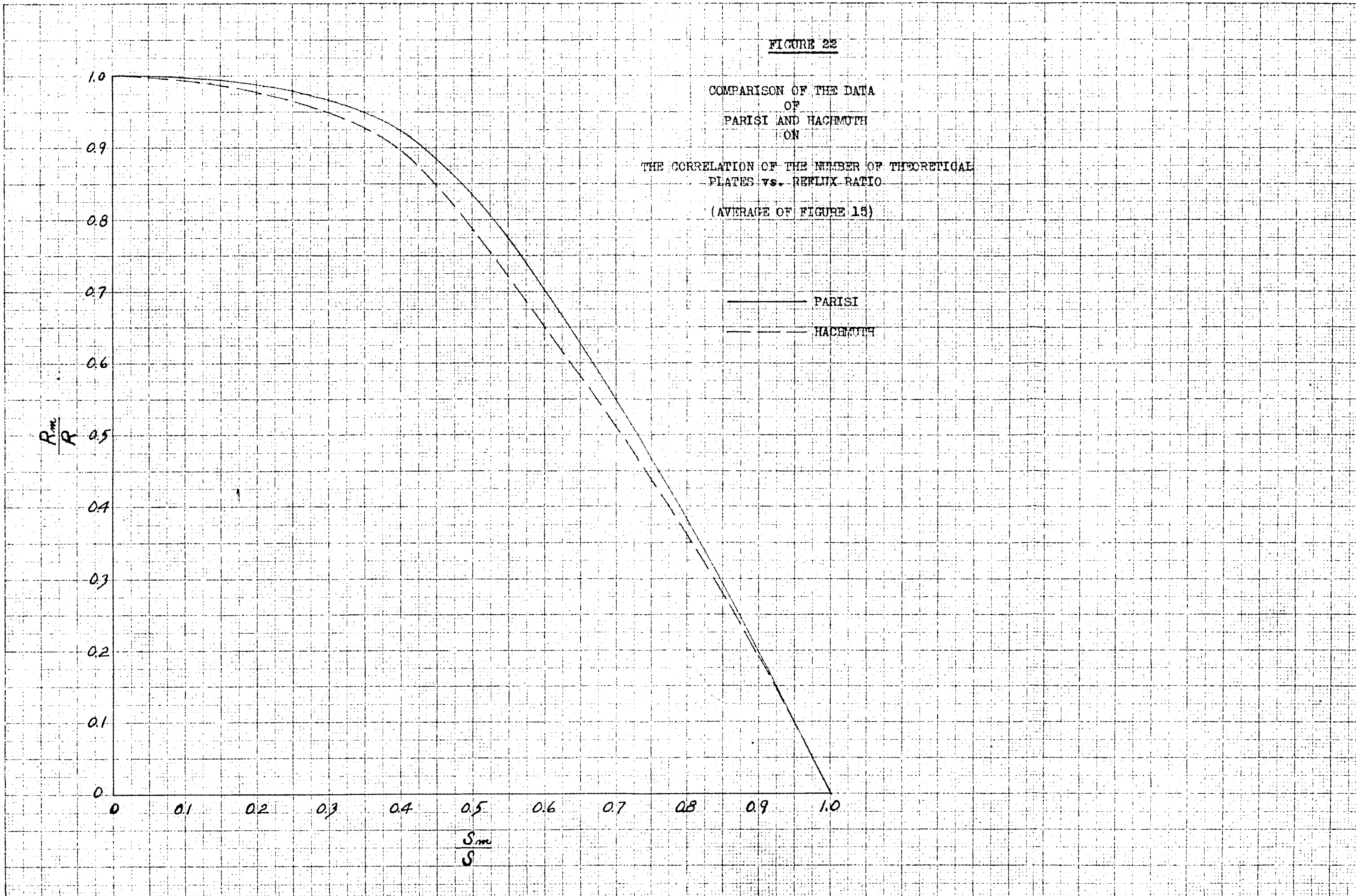


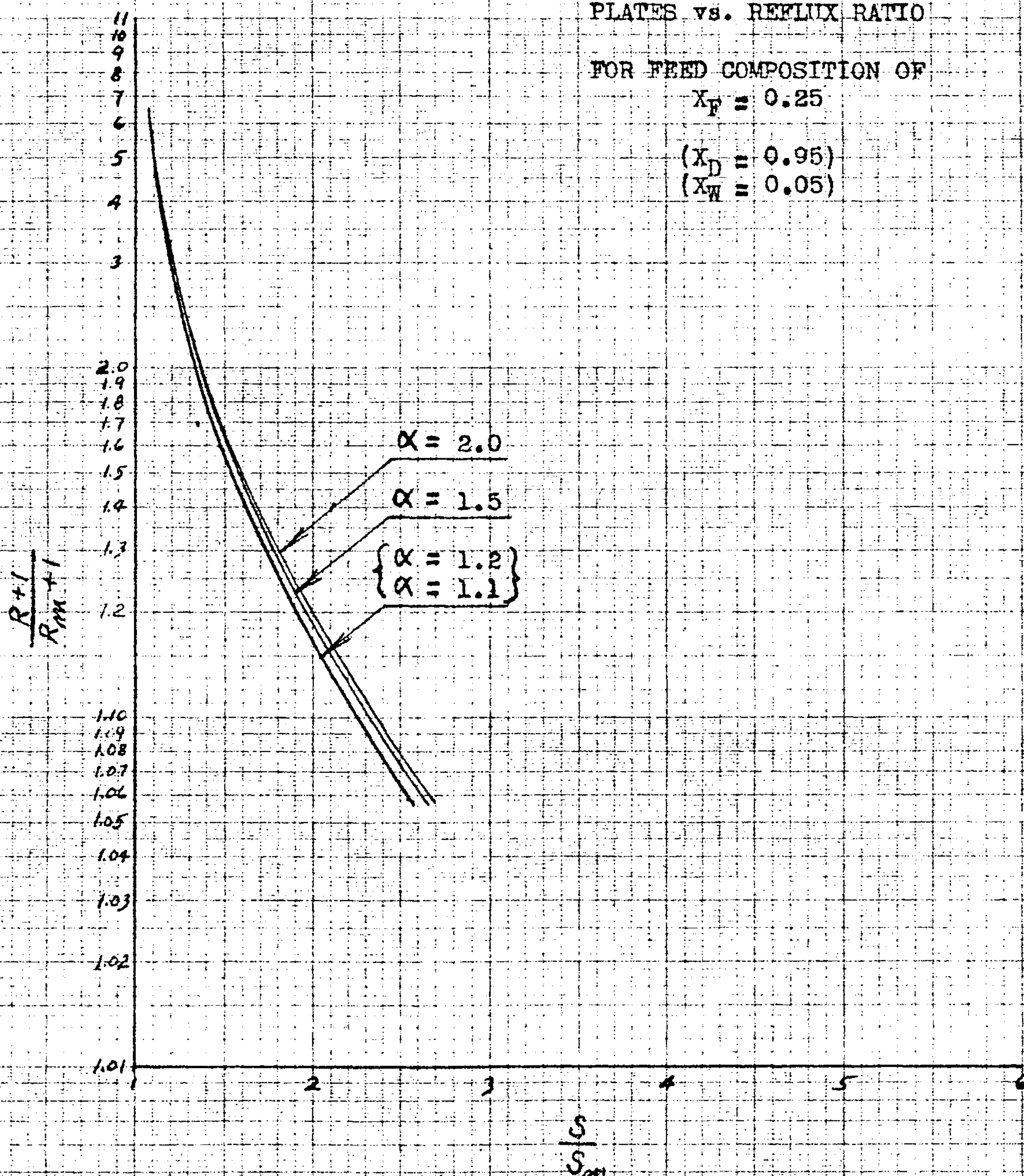
FIGURE 22
COMPARISON OF THE DATA
OF
PARISI AND HACHMUTH
ON
THE CORRELATION OF THE NUMBER OF THEORETICAL PLATES vs. REFLUX RATIO
(AVERAGE OF FIGURE 15)
PARISI
HACHMUTH
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
$\frac{R_m}{R}$
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
$\frac{S_m}{S}$

FIGURE 23

EFFECT OF RELATIVE VOLATILITY
ON
THE CORRELATION OF THE NUMBER OF THEORETICAL PLATES vs. REFLUX RATIO

FOR FEED COMPOSITION OF
$X_F = 0.25$

($X_D = 0.95$)
($X_W = 0.05$)



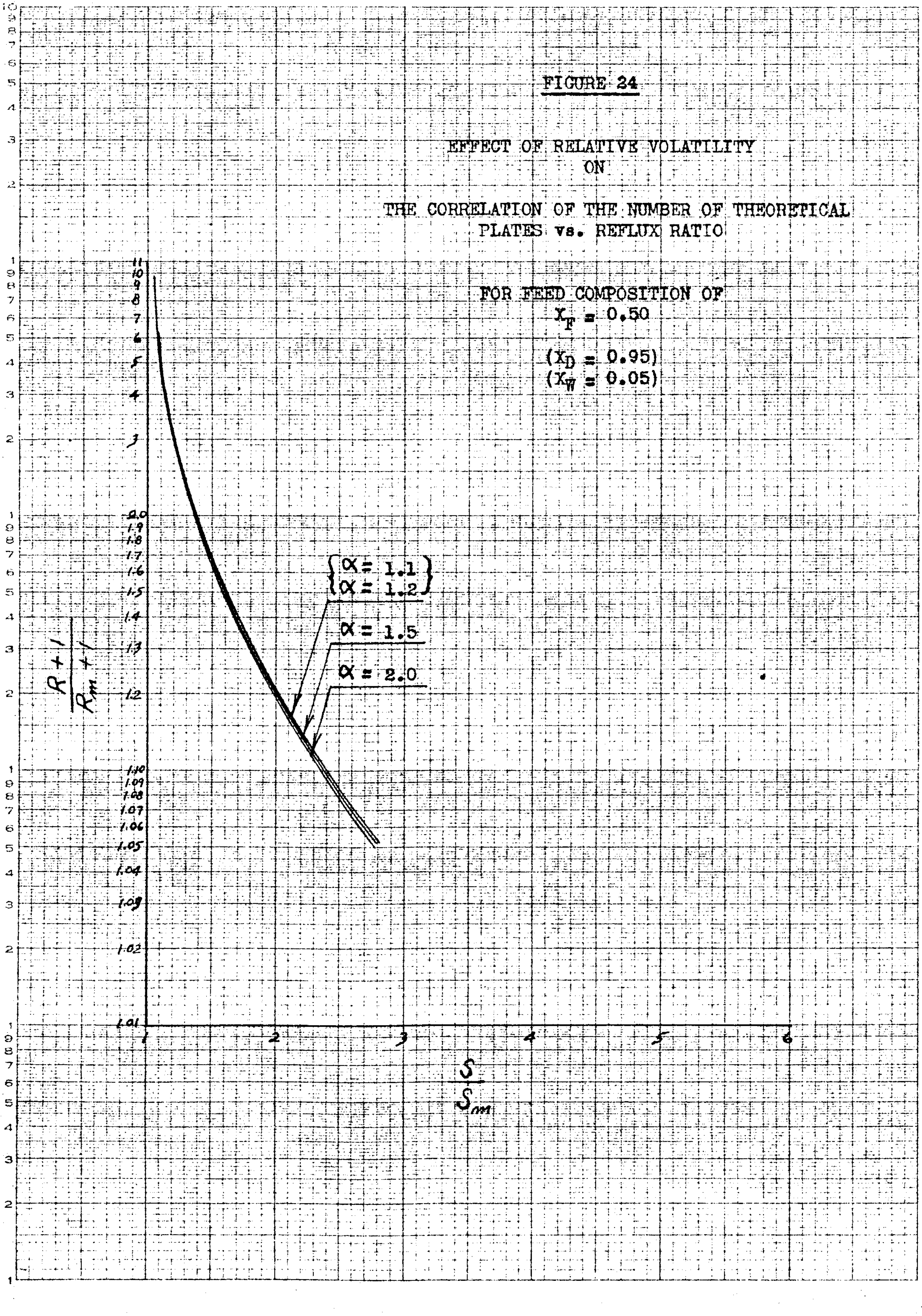


FIGURE 24
EFFECT OF RELATIVE VOLATILITY
ON
THE CORRELATION OF THE NUMBER OF THEORETICAL
PLATES vs. REFLUX RATIO
FOR FEED COMPOSITION OF
X_F = 0.50
(X_D = 0.95)
(X_W = 0.05)
α = 1.1
α = 1.2
α = 1.5
α = 2.0
(R + 1)/(R_m + 1)
S/S_m
11
10
9
8
7
6
5
4
3
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.10
1.09
1.08
1.07
1.06
1.05
1.04
1.03
1.02
1.01
1
2
3
4
5
6

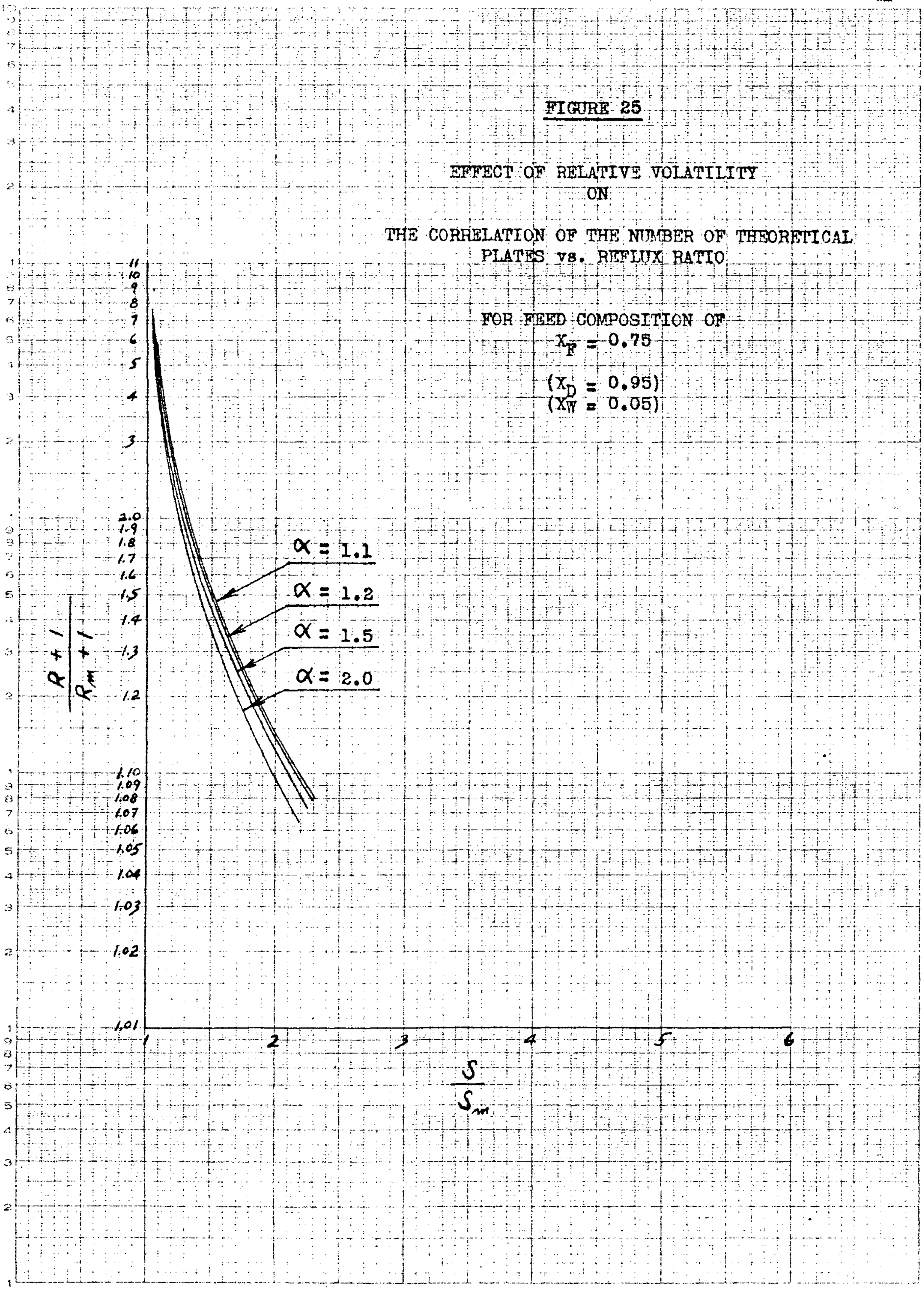
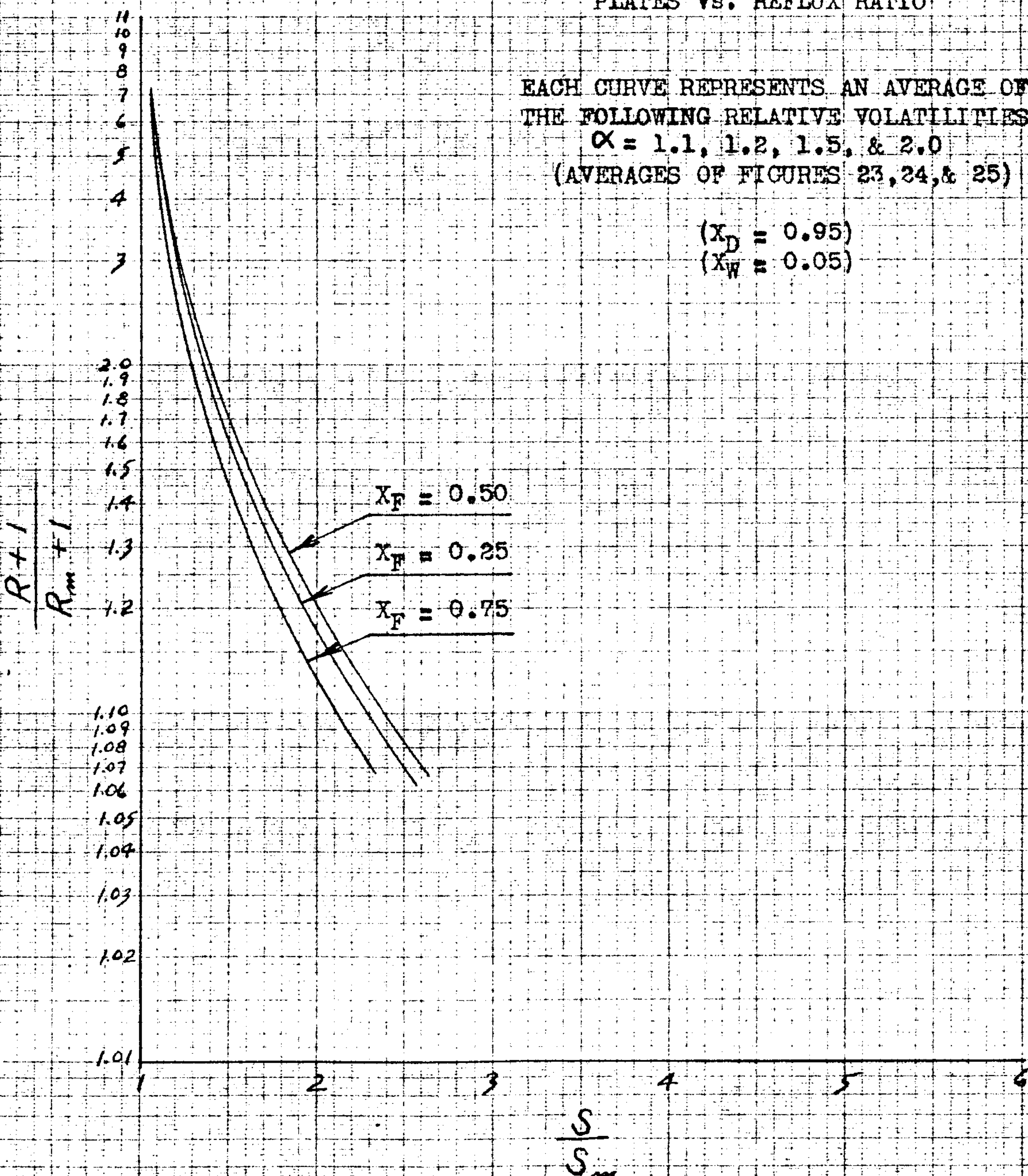


FIGURE 25
EFFECT OF RELATIVE VOLATILITY
ON
THE CORRELATION OF THE NUMBER OF THEORETICAL
PLATES vs. REFLUX RATIO
FOR FEED COMPOSITION OF
X_F = 0.75
(X_D = 0.95)
(X_W = 0.05)
α = 1.1
α = 1.2
α = 1.5
α = 2.0
$\frac{R+1}{R_m+1}$
$\frac{S}{S_m}$

FIGURE 26

EFFECT OF FEED COMPOSITION
ON
THE CORRELATION OF THE NUMBER OF THEORETICAL PLATES vs. REFLUX RATIO



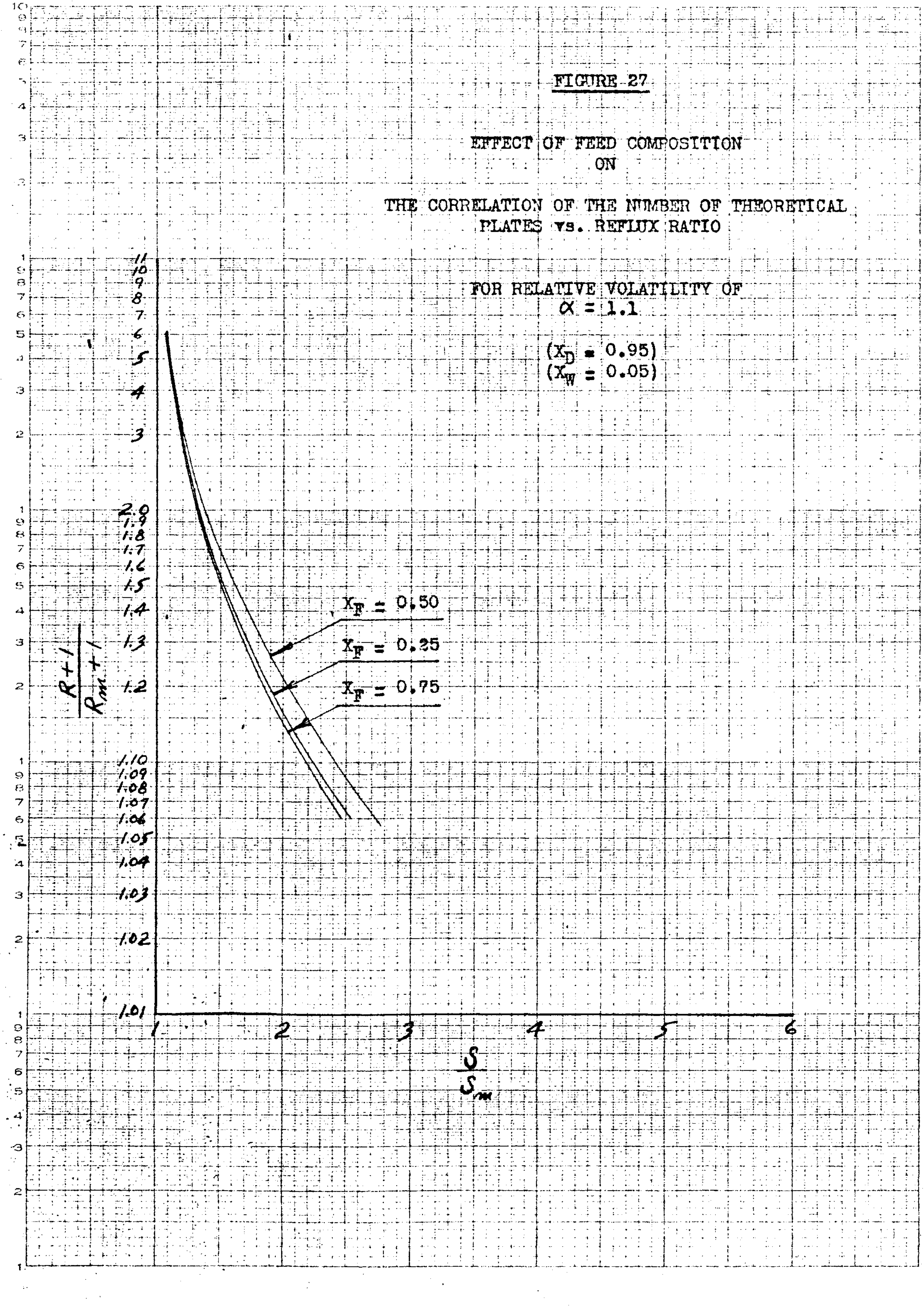


FIGURE 27
EFFECT OF FEED COMPOSITION
ON
THE CORRELATION OF THE NUMBER OF THEORETICAL PLATES vs. REFLUX RATIO
FOR RELATIVE VOLATILITY OF
α = 1.1
(X_D = 0.95)
(X_W = 0.05)
X_F = 0.50
X_F = 0.25
X_F = 0.75
(R+1)/(R_m+1)
S/S_m
11
10
9
8
7
6
5
4
3
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.10
1.09
1.08
1.07
1.06
1.05
1.04
1.03
1.02
1.01
1
2
3
4
5
6

FIGURE 28

EFFECT OF FEED COMPOSITION
ON
THE CORRELATION OF THE NUMBER OF THEORETICAL
PLATES vs. REFLUX RATIO

FOR RELATIVE VOLATILITY OF
$\alpha = 1.2$

$(X_D = 0.95)$
$(X_W = 0.05)$

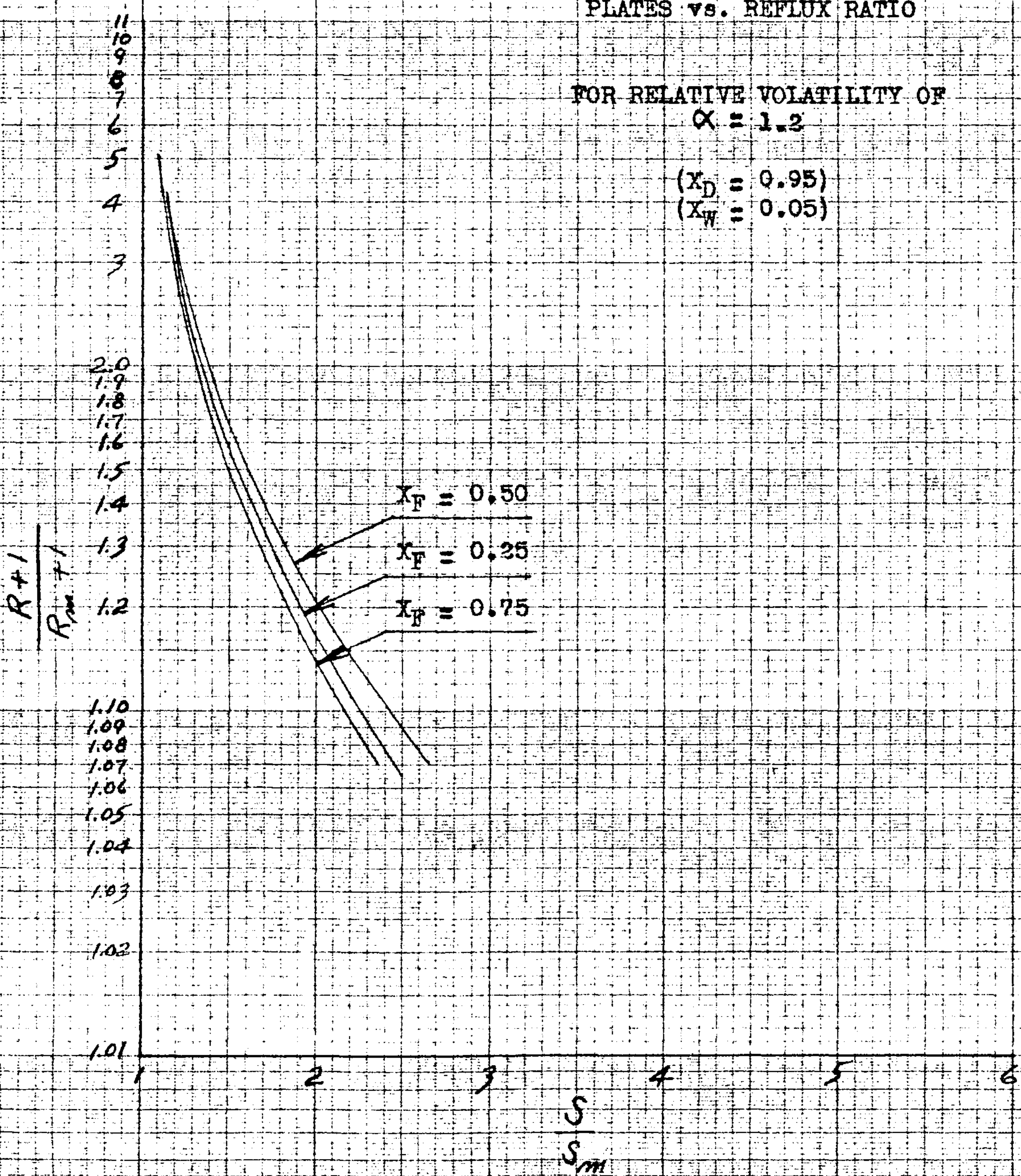


FIGURE 29

EFFECT OF FEED COMPOSITION
ON

THE CORRELATION OF THE NUMBER OF THEORETICAL
PLATES vs. REFLUX RATIO

FOR RELATIVE VOLATILITY OF
$\alpha = 1.5$

$(X_D = 0.95)$
$(X_W = 0.05)$

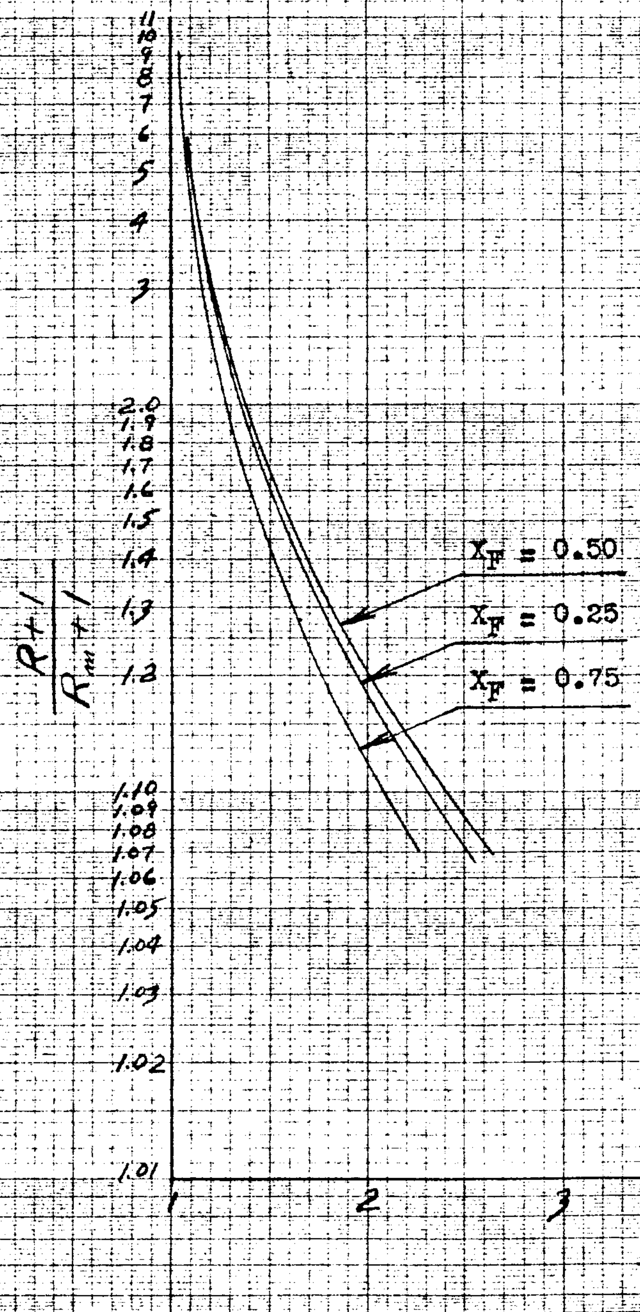
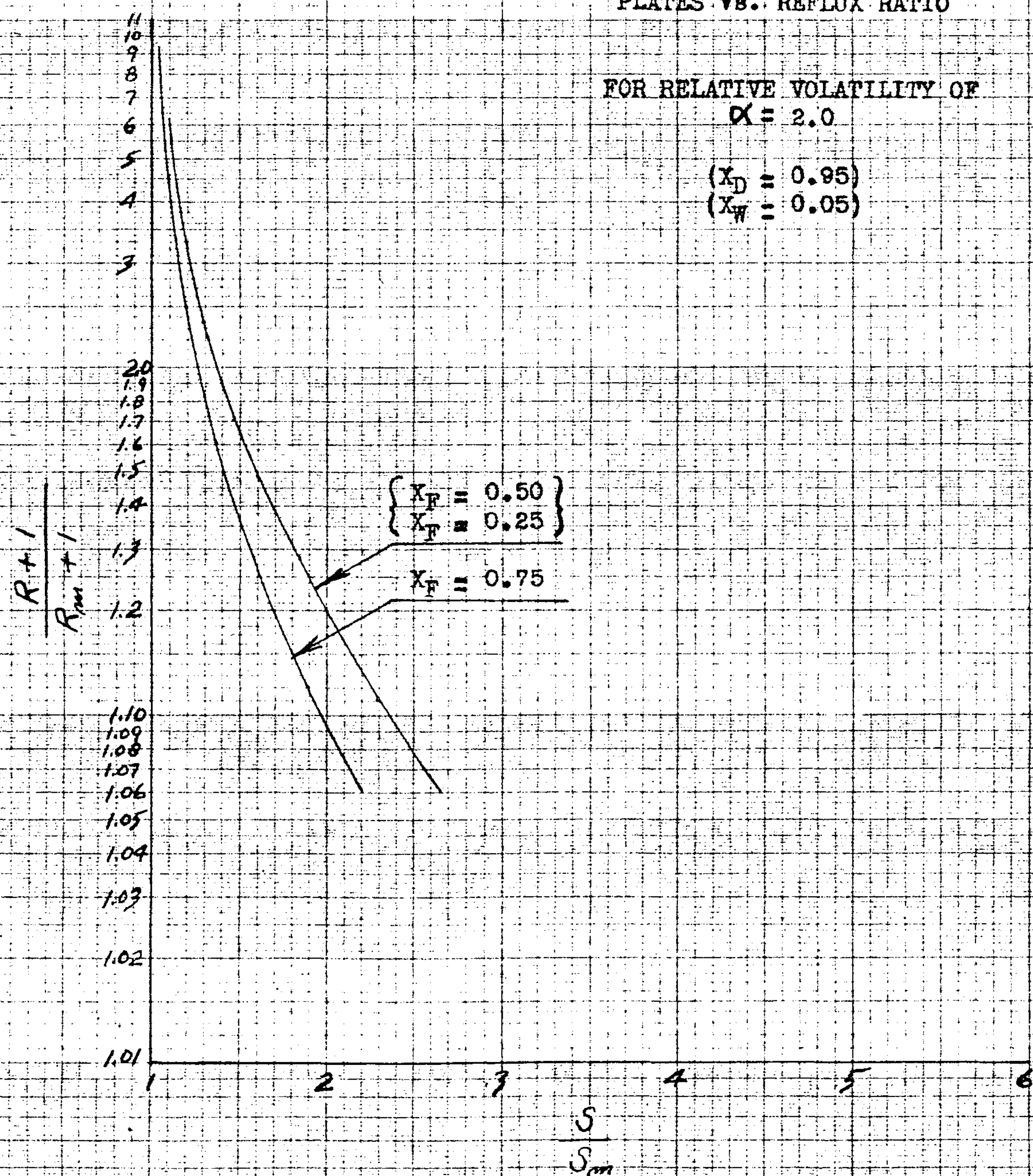


FIGURE 30

EFFECT OF FEED COMPOSITION
ON
THE CORRELATION OF THE NUMBER OF THEORETICAL
PLATES vs. REFLUX RATIO

FOR RELATIVE VOLATILITY OF
$\alpha = 2.0$

$(X_D = 0.95)$
$(X_W = 0.05)$



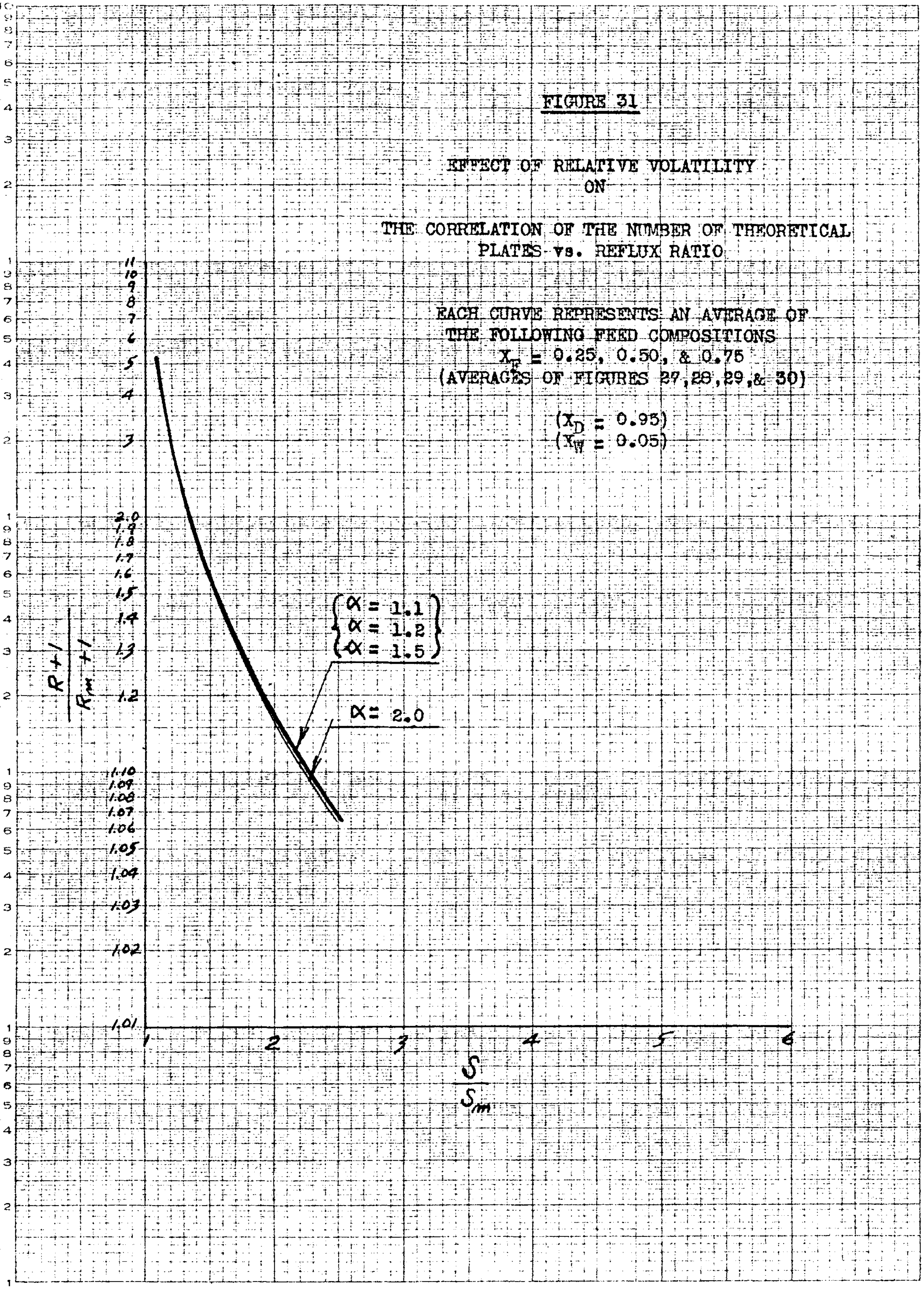


FIGURE 31

EFFECT OF RELATIVE VOLATILITY
ON
THE CORRELATION OF THE NUMBER OF THEORETICAL
PLATES vs. REFLUX RATIO

EACH CURVE REPRESENTS AN AVERAGE OF
THE FOLLOWING FEED COMPOSITIONS
X_F = 0.25, 0.50, & 0.75
(AVERAGES OF FIGURES 27, 28, 29, & 30)

(X_D = 0.95)
(X_W = 0.05)

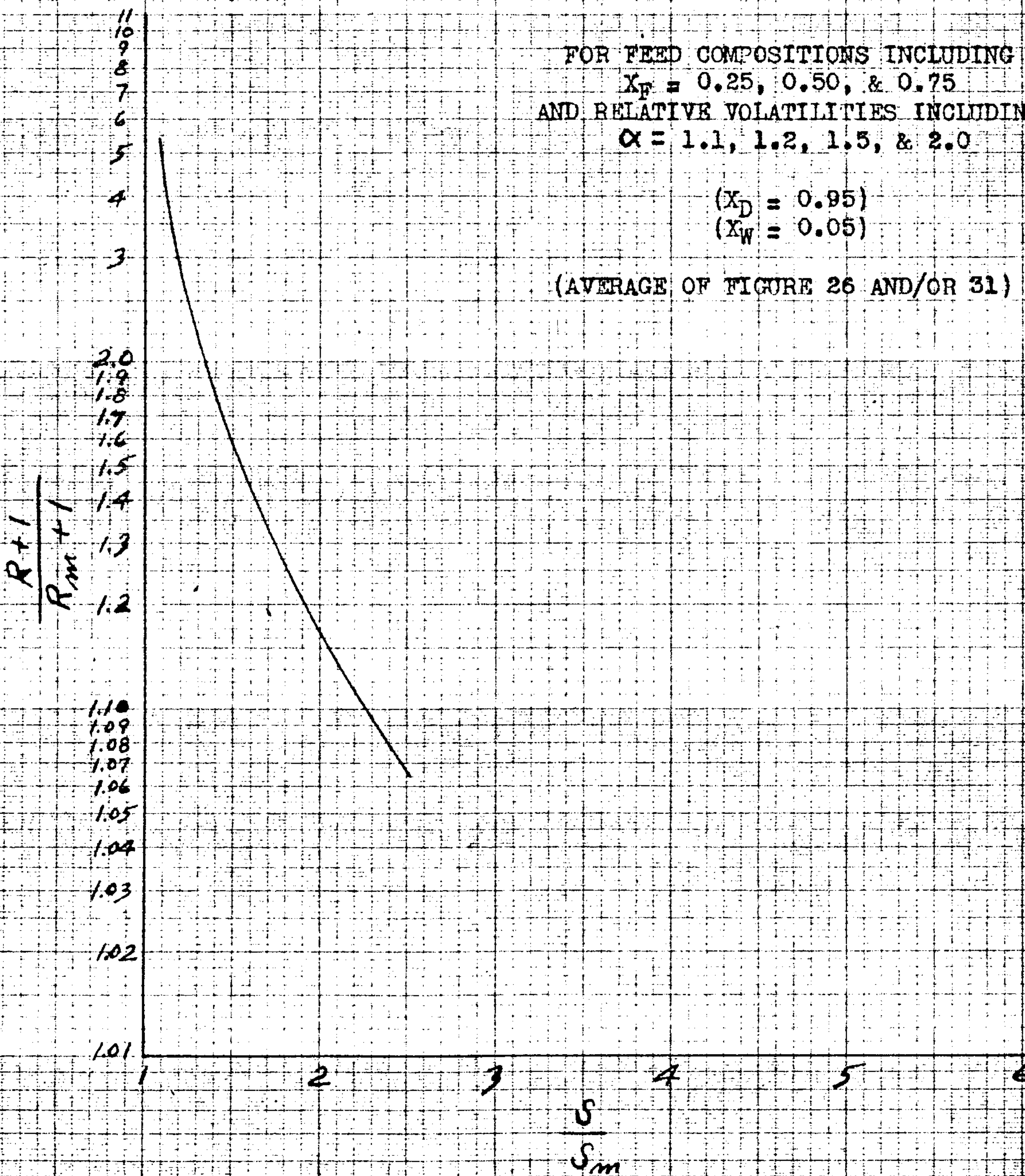


FIGURE 32

AVERAGE CURVE
OF

THE CORRELATION OF THE NUMBER OF THEORETICAL PLATES vs. REFLUX RATIO

FOR FEED COMPOSITIONS INCLUDING
X_F = 0.25, 0.50, & 0.75
AND RELATIVE VOLATILITIES INCLUDING
α = 1.1, 1.2, 1.5, & 2.0

(X_D = 0.95)
(X_W = 0.05)

(AVERAGE OF FIGURE 26 AND/OR 31)

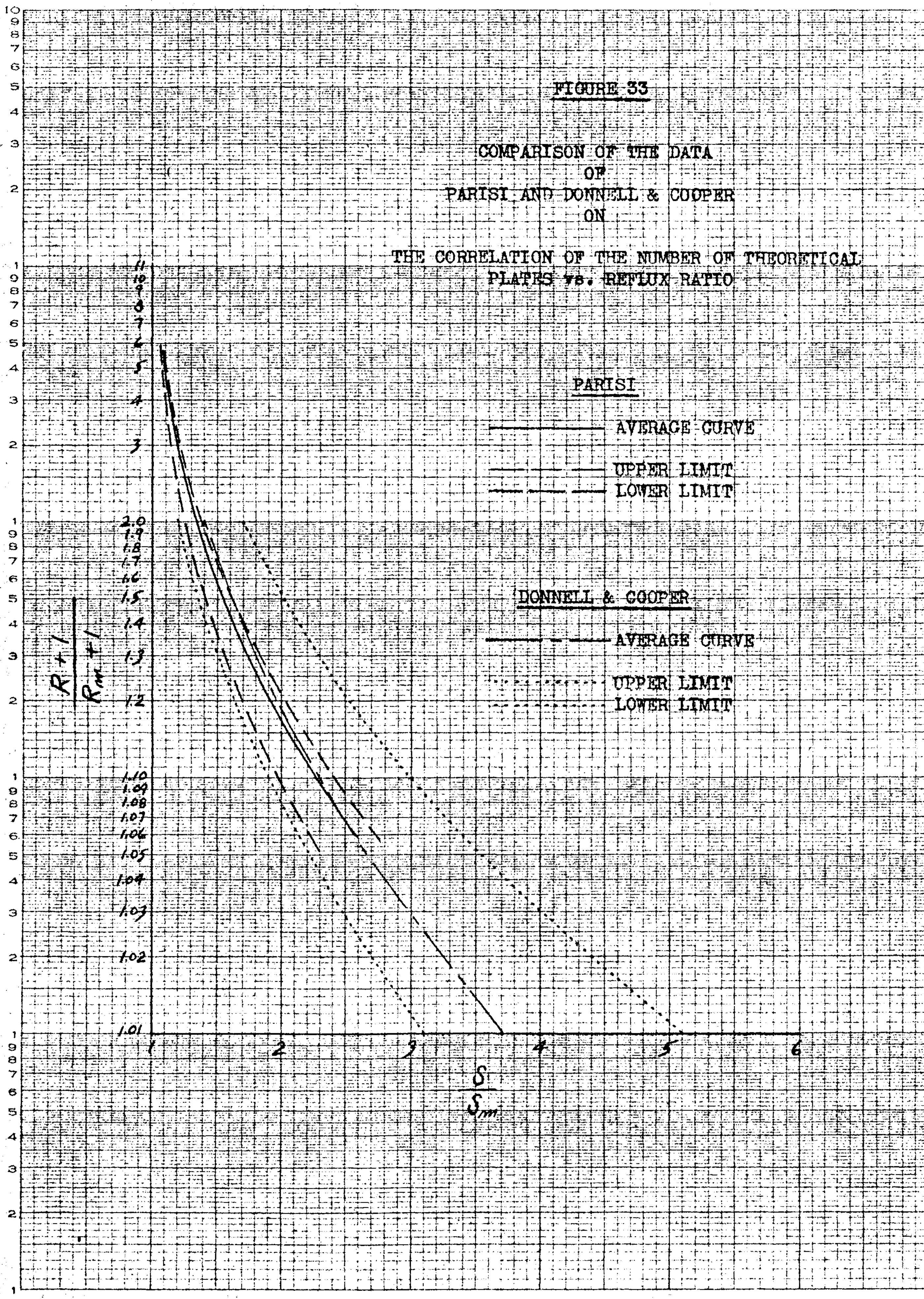


FIGURE 33

COMPARISON OF THE DATA
OF
PARISI AND DONNELL & COOPER
ON
THE CORRELATION OF THE NUMBER OF THEORETICAL PLATES vs. REFLUX RATIO

SAMPLE CALCULATION

Given parameters:

$$X_F = 0.50$$
$$X_D = 0.95$$
$$X_W = 0.05$$
$$\alpha = 1.5$$

Minimum reflux ratio:

$$R_m = \frac{1}{\alpha - 1}\left[\frac{X_D}{X_F} - \alpha \frac{1 - X_D}{1 - X_F}\right]$$

$$= \frac{1}{1.5 - 1}\left[\frac{0.95}{0.50} - 1.5\frac{1 - 0.95}{1 - 0.50}\right] = 3.50$$

Choose R = 4.0

In the rectifying section:

$$M = \frac{R}{R+1} = \frac{4}{4+1} = 0.800000$$

$$b = \frac{X_D}{R+1} = \frac{0.95}{4+1} = 0.190000$$

$$M(\alpha - 1)k^2 + [M + b(\alpha - 1) - \alpha]k + b = 0$$

$$0.800000(1.5-1)k^2 + [0.800000 + 0.190000(1.5-1) - 1.5]k + 0.190000 = 0$$

solving for k (the root of the quadratic equation between 0 and 1.)

$$k = 0.444940$$

Therefore:

$$x_0 = X_D - k$$
$$= 0.95 - 0.444940 = 0.505060$$
$$x_n = X_F - k$$
$$= 0.50 - 0.444940 = 0.055060$$
$$C = 1 + (\alpha - 1) k$$
$$= 1 + (1.5-1)\, 0.444940 = 1.222470$$

Then:

$$n = \frac{\log \dfrac{x_0\left(1 - \dfrac{MC(\alpha-1)}{\alpha - MC^2} x_n\right)}{x_n\left(1 - \dfrac{MC(\alpha-1)}{\alpha - MC^2} x_0\right)}}{\log \dfrac{\alpha}{MC^2}}$$

$$n = \frac{\log \dfrac{0.505060\left(1 - \dfrac{0.800000 \times 1.222470(1.5-1)}{1.5 - 0.800000(1.222470)^2}\, 0.055060\right)}{0.055060\left(1 - \dfrac{0.800000 \times 1.222470(1.5-1)}{1.5 - 0.800000(1.222470)^2}\, 0.505060\right)}}{\log \dfrac{1.5}{0.800000(1.222470)^2}}$$

$$n = 16.71$$

In the stripping section:

$$M = \frac{RX_F + X_D - (R+1) X_W}{(R+1)(X_F - X_W)}$$
$$= \frac{4 \times 0.50 + 0.95 - (4+1)\, 0.05}{(4+1)(0.50 - 0.05)}$$
$$= 1.200000$$

$$b = \frac{(X_F - X_D)\,X_W}{(R+1)(X_F - X_W)}$$

$$= \frac{(0.50 - 0.95)\,0.05}{(4+1)(0.50 - 0.05)} = -0.010000$$

$$M(\alpha - 1)k^2 + [M + b(\alpha - 1) - \alpha]k + b = 0$$

$$1.200000(1.5-1)k^2 + [1.200000 - 0.010000(1.5-1) - 1.5]k - 0.010000 = 0$$

solving for k (the root between 0 and 1)

$$k = 0.539242$$

Therefore:

$$x_o = X_F - k$$

$$= 0.50 - 0.539242 = -0.039242$$

$$x_n = X_W - k$$

$$= 0.05 - 0.539242 = -0.489242$$

$$C = 1 + (\alpha - 1)k$$

$$= 1 + (1.5-1)\,0.539242 = 1.269621$$

Then:

$$n' = \frac{\log \dfrac{x_o\left(1 - \dfrac{MC(\alpha-1)}{\alpha - MC^2}\,x_n\right)}{x_n\left(1 - \dfrac{MC(\alpha-1)}{\alpha - MC^2}\,x_o\right)}}{\log \dfrac{\alpha}{MC^2}}$$

$$n' = \frac{\log \dfrac{-0.039242\left[1 - \dfrac{1.200000 \times 1.269621\,(1.5-1)}{1.5 - 1.200000\,(1.269621)^2}(-0.489242)\right]}{-0.489242\left[1 - \dfrac{1.200000 \times 1.269621\,(1.5-1)}{1.5 - 1.200000\,(1.269621)^2}(-0.039242)\right]}}{\log \dfrac{1.5}{1.200000\,(1.269621)^2}}$$

$$n' = 17.32$$

Total plates:

$$S = n + n'$$

$$= 16.71 + 17.32 = 34.03$$

Minimum number of plates:

$$S_m = \frac{\log \left(\dfrac{X_D}{1-X_D}\right)\left(\dfrac{1-X_W}{X_W}\right)}{\log \alpha}$$

$$= \frac{\log \left(\dfrac{0.95}{1-0.95}\right)\left(\dfrac{1-0.05}{0.05}\right)}{\log 1.5}$$

$$= 14.52$$

The coordinate groups:

$$\frac{S - S_m}{S+1} \doteq \frac{34.03 - 14.52}{34.03 + 1} = 0.556951$$

$$\frac{R - R_m}{R + 1} = \frac{4.0 - 3.50}{4.0 + 1} = 0.100000$$

$$\frac{R_m}{R} = \frac{3.50}{4.0} = 0.875000$$

$$\frac{S_m}{S} = \frac{14.52}{34.03} = 0.426682$$

$$\frac{S}{S_m} = \frac{34.03}{14.52} = 2.343665$$

$$\frac{R + 1}{R_m + 1} = \frac{4.0 + 1}{3.50 + 1} = 1.111111$$

CALCULATED DATA

X_F	X_D	X_W	α	Rm	Sm	R	n	n'	S	$\frac{S-Sm}{S+1}$	$\frac{R-Rm}{R+1}$	$\frac{Rm}{R}$	$\frac{Sm}{S}$	$\frac{S}{Sm}$	$\frac{R+1}{Rm+1}$
0.50	0.95	0.05	1.1	17.90	61.79	19.00	84.67	84.98	169.65	0.632054	0.055000	0.942105	0.364220	2.745593	1.058201
0.50	0.95	0.05	1.1	17.90	61.79	20.00	72.78	73.37	146.15	0.573293	0.100000	0.895000	0.422785	2.365268	1.111111
0.50	0.95	0.05	1.1	17.90	61.79	25.00	53.22	53.94	107.16	0.419471	0.273077	0.716000	0.576614	1.734262	1.375661
0.50	0.95	0.05	1.1	17.90	61.79	35.00	43.09	43.67	86.76	0.284526	0.475000	0.511429	0.712195	1.404109	1.904762
0.50	0.95	0.05	1.1	17.90	61.79	60.00	36.71	37.04	73.75	0.160000	0.690164	0.298333	0.837831	1.193558	3.227513
0.50	0.95	0.05	1.2	8.90	32.30	10.00	37.85	38.43	76.28	0.569099	0.100000	0.890000	0.423440	2.361609	1.111111
0.50	0.95	0.05	1.2	8.90	32.30	12.00	28.96	29.69	58.65	0.441744	0.238462	0.741666	0.550725	1.815788	1.313131
0.50	0.95	0.05	1.2	8.90	32.30	15.00	24.40	25.05	49.45	0.339941	0.381250	0.593333	0.653185	1.530959	1.616161
0.50	0.95	0.05	1.2	8.90	32.30	20.00	21.41	21.91	43.32	0.248646	0.528571	0.445000	0.745614	1.341176	2.121212
0.50	0.95	0.05	1.2	8.90	32.30	30.00	19.22	19.56	38.78	0.162896	0.680645	0.296667	0.832904	1.200618	3.131313
0.50	0.95	0.05	1.5	3.50	14.52	4.00	16.71	17.32	34.03	0.556951	0.100000	0.875000	0.426682	2.343665	1.111111
0.50	0.95	0.05	1.5	3.50	14.52	5.00	12.52	13.25	25.77	0.420247	0.250000	0.700000	0.563446	1.774792	1.333333
0.50	0.95	0.05	1.5	3.50	14.52	7.00	10.19	10.78	20.97	0.293582	0.437500	0.500000	0.692418	1.444214	1.777778
0.50	0.95	0.05	1.5	3.50	14.52	10.00	9.04	9.47	18.51	0.204510	0.590909	0.350000	0.784441	1.274793	2.444444
0.50	0.95	0.05	1.5	3.50	14.52	25.00	7.87	8.05	15.92	0.082742	0.826923	0.140000	0.912060	1.096419	5.777778
0.50	0.95	0.05	2.0	1.70	8.50	2.00	9.44	10.10	19.54	0.537488	0.100000	0.850000	0.435005	2.298824	1.111111
0.50	0.95	0.05	2.0	1.70	8.50	3.00	6.43	7.12	13.55	0.347079	0.325000	0.566667	0.627306	1.594118	1.481481
0.50	0.95	0.05	2.0	1.70	8.50	5.00	5.30	5.77	11.07	0.212925	0.550000	0.340000	0.767841	1.302352	2.222222
0.50	0.95	0.05	2.0	1.70	8.50	10.00	4.72	4.96	9.68	0.110487	0.754545	0.170000	0.878099	1.138823	4.074074
0.50	0.95	0.05	2.0	1.70	8.50	25.00	4.42	4.53	8.95	0.045226	0.896154	0.068000	0.949721	1.052940	9.629629

CALCULATED DATA

X_F	X_D	X_W	α	Rm	Sm	R	n	n'	S	$\frac{S-Sm}{S+1}$	$\frac{R-Rm}{R+1}$	$\frac{Rm}{R}$	$\frac{Sm}{S}$	$\frac{S}{Sm}$	$\frac{R+1}{Rm+1}$
0.25	0.95	0.05	1.1	37.27	61.79	40.00	83.73	66.35	150.08	0.584392	0.066585	0.931750	0.411714	2.428870	1.071335
0.25	0.95	0.05	1.1	37.27	61.79	47.00	67.15	43.39	111.04	0.439575	0.202708	0.792979	0.556466	1.797054	1.254246
0.25	0.95	0.05	1.1	37.27	61.79	60.00	57.77	33.26	91.03	0.317722	0.372623	0.621167	0.678737	1.473216	1.593938
0.25	0.95	0.05	1.1	37.27	61.79	100.00	49.80	25.53	75.33	0.177383	0.621089	0.372700	0.820258	1.219128	2.639142
0.25	0.95	0.05	1.1	37.27	61.79	200.00	45.68	21.98	67.66	0.085494	0.809602	0.186350	0.913243	1.094998	5.252155
0.25	0.95	0.05	1.2	18.60	32.30	20.00	43.86	35.41	79.27	0.585150	0.066667	0.930000	0.407468	2.454180	1.071429
0.25	0.95	0.05	1.2	18.60	32.30	24.00	34.61	22.82	57.43	0.430027	0.216000	0.775000	0.562424	1.778018	1.275510
0.25	0.95	0.05	1.2	18.60	32.30	30.00	30.29	17.84	48.13	0.322206	0.367742	0.620000	0.671099	1.490093	1.581633
0.25	0.95	0.05	1.2	18.60	32.30	45.00	26.66	14.13	40.79	0.203159	0.573913	0.413333	0.791861	1.262847	2.346939
0.25	0.95	0.05	1.2	18.60	32.30	70.00	24.77	12.37	37.14	0.126901	0.723944	0.265714	0.869682	1.149845	3.622449
0.25	0.95	0.05	1.5	7.40	14.52	8.00	19.81	16.65	36.46	0.585691	0.066667	0.925000	0.398245	2.511017	1.071429
0.25	0.95	0.05	1.5	7.40	14.52	10.00	15.22	10.36	25.58	0.416102	0.236364	0.740000	0.567631	1.761707	1.309523
0.25	0.95	0.05	1.5	7.40	14.52	14.00	12.92	7.64	20.56	0.280148	0.440000	0.528571	0.706226	1.415977	1.785714
0.25	0.95	0.05	1.5	7.40	14.52	25.00	11.35	5.94	17.29	0.151449	0.676923	0.296000	0.839792	1.190771	3.095238
0.25	0.95	0.05	1.5	7.40	14.52	45.00	10.68	5.25	15.93	0.083284	0.817391	0.164444	0.911488	1.097107	5.476190
0.25	0.95	0.05	2.0	3.67	8.50	4.00	11.62	10.14	21.76	0.582601	0.066000	0.917500	0.390625	2.560000	1.070664
0.25	0.95	0.05	2.0	3.67	8.50	5.00	8.99	6.55	15.54	0.425635	0.221667	0.734000	0.546976	1.828233	1.284797
0.25	0.95	0.05	2.0	3.67	8.50	7.00	7.62	4.82	12.44	0.293155	0.416250	0.524286	0.683280	1.463528	1.713062
0.25	0.95	0.05	2.0	3.67	8.50	10.00	6.94	3.99	10.93	0.203638	0.575455	0.367000	0.777676	1.285882	2.355460
0.25	0.95	0.05	2.0	3.67	8.50	25.00	6.23	3.13	9.36	0.083012	0.820335	0.146800	0.908120	1.101176	5.567452

CALCULATED DATA

X_F	X_D	X_W	α	Rm	Sm	R	n	n'	S	$\frac{S-Sm}{S+1}$	$\frac{R-Rm}{R+1}$	$\frac{Rm}{R}$	$\frac{Sm}{S}$	$\frac{S}{Sm}$	$\frac{R+1}{Rm+1}$
0.75	0.95	0.05	1.1	10.47	61.79	11.50	58.55	80.29	138.84	0.550987	0.082400	0.910435	0.445045	2.246963	1.089799
0.75	0.95	0.05	1.1	10.47	61.79	14.00	39.06	64.78	103.84	0.401087	0.235333	0.747857	0.595050	1.680531	1.307759
0.75	0.95	0.05	1.1	10.47	61.79	20.00	38.97	54.75	83.72	0.258853	0.453810	0.523500	0.738055	1.354912	1.830363
0.75	0.95	0.05	1.1	10.47	61.79	35.00	23.67	48.42	72.09	0.140922	0.641339	0.299143	0.857123	1.166693	3.138622
0.75	0.95	0.05	1.1	10.47	61.79	60.00	21.62	45.68	67.30	0.080673	0.811967	0.174500	0.918128	1.089172	5.318221
0.75	0.95	0.05	1.2	5.13	32.30	5.75	28.75	41.08	69.83	0.529860	0.091852	0.892174	0.462552	2.161919	1.101142
0.75	0.95	0.05	1.2	5.13	32.30	7.00	19.98	33.92	53.90	0.393443	0.233750	0.732857	0.599258	1.668730	1.305057
0.75	0.95	0.05	1.2	5.13	32.30	10.00	15.03	28.83	43.86	0.257691	0.442727	0.513000	0.736434	1.357894	1.794453
0.75	0.95	0.05	1.2	5.13	32.30	15.00	12.84	26.14	38.98	0.167084	0.616875	0.342000	0.828630	1.206811	2.610114
0.75	0.95	0.05	1.2	5.13	32.30	30.00	11.29	23.98	35.27	0.081886	0.802258	0.171000	0.915792	1.091951	5.057096
0.75	0.95	0.05	1.5	1.93	14.52	2.25	11.66	18.15	29.81	0.496267	0.098461	0.857778	0.487085	2.053029	1.109215
0.75	0.95	0.05	1.5	1.93	14.52	2.75	8.60	15.44	24.04	0.380192	0.218667	0.701818	0.603993	1.655648	1.279863
0.75	0.95	0.05	1.5	1.93	14.52	4.00	6.60	13.20	19.80	0.253846	0.414000	0.482500	0.733333	1.363636	1.706485
0.75	0.95	0.05	1.5	1.93	14.52	7.00	5.51	11.66	17.17	0.145845	0.623750	0.275714	0.845661	1.182506	2.730375
0.75	0.95	0.05	1.5	1.93	14.52	25.00	4.78	10.42	15.20	0.0419753	0.887308	0.077200	0.955263	1.046832	8.873720
0.75	0.95	0.05	2.0	0.867	8.50	1.00	6.83	11.23	18.06	0.501574	0.066500	0.866667	0.470653	2.124707	1.071237
0.75	0.95	0.05	2.0	0.867	8.50	1.40	4.49	8.95	13.44	0.342105	0.222083	0.619286	0.632440	1.581777	1.285485
0.75	0.95	0.05	2.0	0.867	8.50	2.00	3.70	7.89	11.59	0.245433	0.377667	0.433500	0.733391	1.363529	1.606856
0.75	0.95	0.05	2.0	0.867	8.50	5.00	3.00	6.64	9.64	0.107143	0.688833	0.173400	0.881743	1.134117	3.213712
0.75	0.95	0.05	2.0	0.867	8.50	25.00	2.73	6.00	8.73	0.023638	0.928192	0.034680	0.973654	1.027058	13.926084

NOTATION

X - Mole fraction of lower boiling component in liquid phase.

Y - Mole fraction of lower boiling component in vapor phase.

α - Relative volatility of the two components.

R - Reflux ratio, or moles reflux per unit time divided by moles product per unit time.

S - Total number of theoretical plates.

n - Number of theoretical plates in rectifying section.

n' - Number of theoretical plates in stripping section.

Subscripts:

F - In feed to column.

D - In distillate or overhead product.

W - In bottoms or waste product.

m - minimum.

Arbitrary constants defined by intermediate equations:

x_o	k
x_n	b
M	c

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