

**CONTROLLED MALDISTRIBUTION STUDIES
ON RANDOM PACKING AT A COMMERCIAL SCALE**

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The experimental portion of a random packing research program which began over four years ago has recently been completed. After demonstrating the sensitivity of packing performance to the quality of liquid distribution, a program of controlled maldistribution studies was undertaken in a 1.2 m commercial scale column. Specific results are available which provide qualitative guidelines for the designers and fabricators of distributors as well as column operators. Progress has been made in modeling the results so that they can be extended to other column sizes and packings.

INTRODUCTION

Improper distribution with the resulting radial variation in L/V is frequently cited as the reason why a packed distillation column has failed to perform as designed (1,2,3), particularly at larger diameters. Consequently, researchers have been doing both experiments and theoretical modeling to quantify the effect of distribution on packed tower performance for over 50 years. In 1935 Baker and Chilton (3) ran water experiments which established 8 as the critical tower diameter to packing size ratio below which wall flow could be a significant problem. In 1957 Cihla and Schmidt (4) used a Gaussian distribution function to model flow through a bed of random packing and developed what is essentially a diffusion analogy in 1957. More recently Hoek (5) ran water studies which established the concept that a random packing always has a small scale "natural flow" maldistribution consisting of small scale natural channels which are an inherent property of the packing. If there is also a large scale maldistribution caused by poor initial distribution, downflowing liquid will tend toward "natural flow" as it is dispersed by the packing elements. He successfully modeled his results through a numerical integration of the diffusion analogy. Albright (6) used a random number numerical technique to come to essentially the same conclusion. Investigators such as Yuan and Spiegel (7) who have attempted to relate distribution to mass transfer efficiency have usually used a constant maldistribution. In a recently concluded experimental program, commercial scale packed distillation column performance was measured under controlled initial maldistribution conditions (8). A new zone - stage model proposed by Zuiderweg (9) has been applied to the data and appears to match the results quite well.

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LIQUID DISTRIBUTION

Early experimental work in the FRI 1.2 m diameter commercial scale columns (10) had used a notched trough distributor (Fig 1) almost exclusively. At the urging of Zuiderweg (11) a Tubed Drip Pan (TDP) similar to that described by Billet (12) was fabricated (Fig 2). However, Billet's 600 pour points/m² were reduced to approximately 100 corresponding to the natural channel density found by Hoek. The dramatic results may be seen in Fig. 3. The HETP's of "1 inch"* (25 mm) Pall rings measured in the 1.2 m column using cyclohexane/normal heptane at 165 kPa were now in the range of those reported by others using laboratory columns. These include Strigle and Porter's (13) 380-410 mm for iC₈/toluene at atmospheric pressure in a 380 mm column and Billet's (12) 330-500 mm for EB/styrene at 100 mm Hg abs in a 500 mm column. In addition, the efficiency was nearly constant over almost 80% of the usable capacity of the tower (Usable capacity is that boil up rate above which there is a marked decrease in efficiency even though the tower is still operational. A similar approach is recommended by Strigle (14)).

Although extreme care was devoted to the distributor design and installation, it was not perfect. The drip tubes must clear the inside of the pan wall, and the outside of the pan must clear the inside of the column. The equilateral triangular pitch of the holes results in an outermost hole pattern that is hexagonal with the corners cut off (Fig 2). The area enclosed by straight lines drawn through the outermost pour points is defined as the "geometric coverage" (9). Using the empirical method recently published by Moore and Rukovena (2) the TDP scores 93%. As a consequence, recognizing that it is impossible to fabricate and install a perfect distributor in a commercial size column, it was decided to undertake a program of controlled maldistribution studies to provide guidelines for the design, fabrication and installation of commercial distributors.

When planning was initiated, it was immediately recognized that it would be necessary to change distribution patterns with the column on stream. To shut down a 1.2 m packed column and change the distributor takes several days. Thus, obtaining a reasonable amount of data with shutdowns for distributor changes would be prohibitively time consuming and expensive. The design finally chosen was to supply liquid to each pour point by means of a slotted cylinder and piston. To vary the flow, the piston position was adjusted by means of a rod extending through a temporary flat head on the column. Rod adjustment was by means of a wing-nut against a fixed brace. Figure 4 is a drawing and figures 5 and 6 are photographs of the Adjustable Liquid Distributor (ALD). The device was tested with water on the ground to verify that the drip tube installation achieved proper flow uniformity and to determine the slot opening-flow rate relationship. The first run in the column verified that the new device reproduced the results obtained previously with the tubed drip pan.

*The designations "5/8 inch", "1 inch", and "2 inch" are nominal sizes sold in the United States. Detail dimensions are close to but not identical to the 15 mm, 25 mm and 50 mm Pall rings sold in Europe.

EXPERIMENTAL PROGRAM

The experimental program used the cyclohexane/normal heptane system at atmospheric pressure in a 1.2 m column. All runs were made at total reflux. For each distribution pattern studied, runs were made at 30, 60 and 90 percent of maximum usable capacity to look for loading effects. Three sets of bed samples were obtained for most runs and at least two sets were obtained for all runs to verify that steady state had been achieved.

The program was intended not only to furnish insight into the effect of maldistribution type and severity, but also to provide guidelines for commercial distributors. Consequently, a wide variety of patterns was used, all with some type of distributor design or installation problem in mind. One hundred and four runs were made during the first phase of the program which employed a 3.7 m bed of "1 inch" (25 mm) Pall rings.

Subsequent phases of the program which utilized "2 inch" (50 mm) and "5/8 inch" (15 mm) Pall rings concentrated on those patterns which held the most promise of providing a basis to extend the results to still other packing sizes and bed geometries or which represent the most common design or installation tolerance problems. A final series of distribution runs was made as part of a general program on ceramic saddles to determine the relative sensitivity of different shapes.

INTERPRETATION OF RESULTS - OVERALL

The experimental results may be analyzed from two viewpoints: apparent overall efficiency and composition profiles through the bed. Apparent overall HETP is the only thing visible to the operator of a commercial column but it can be misleading due to its sensitivity to end effects (10). However in these tests where the same reboiler, condenser and bed length are employed, overall HETP can be used to draw qualitative conclusions from a large mass of data.

One anticipated result is that there is an effect of the type of maldistribution. Figures 7 through 10 compare results obtained in the first phase using "1 inch" Pall rings. Figure 7 compares the base (good initial distribution) to blanking 16% of the pour points in the center and to blanking 11% of the pour points in a chordal manner. Figure 8 presents the rather surprising tolerance to what might be called a "uniform" maldistribution, viz sag toward the center, sag toward the wall and tilt (1.25 is the ratio of highest to lowest flow rate with a linear variation from point to point). The impact of discontinuities in the distribution is much more severe. For example, as the liquid rate is reduced, a tilting distributor will ultimately lose flow completely from the high end. Figure 9 compares an 11% chordal blank in an otherwise level distributor to a 25 % tilt. Another type of discontinuity could be caused by an obstruction at a main branch point of a pipe grid distributor. Figure 10 compares a situation in which one half of the bed receives 25% more liquid than the other to the 25 and 50 per cent tilt. Thus analysis of the maldistribution effects from an overall efficiency viewpoint leads to the qualitative conclusion that although all types of maldistribution should be minimized, particular care is required to avoid flow discontinuities.

INTERPRETATION OF RESULTS - COMPOSITION PROFILE ANALYSIS

As is noted above, merely examining the apparent overall HETP can be very misleading. Consequently, FRI practice over the years has been to take bed samples (10). Analysis of the bed profiles is done as follows: At total reflux, making the usual assumptions, the Fenske equation is:

$$N_{\text{theo}} = \left[\frac{1}{\ln \alpha} \ln \left(\frac{x}{1-x} \right) t \left(\frac{1-x}{x} \right) b \right]$$

where $N_{\text{theo}} = \frac{\text{Bed Depth}}{\text{HETP}}$

If α and HETP are constant, a plot of $\ln(x/1-x)$ vs bed depth will yield a straight line with slope $(\ln \alpha)/\text{HETP}$. As it is generally accepted that for the system and conditions employed, both α and true HETP should be constant, a curving line implies that the "apparent" or "effective" HETP is changing. When this happens, the most obvious explanation in the case of an initial maldistribution, particularly if the slope becomes steeper and tends toward a straight line at deeper points in the bed, is that L/V is changing as the spreading tendency of the packing corrects the maldistribution until Hoek's "natural flow" is achieved. At this point, the bed should be operating at its "true" or "inherent" HETP. Thus it was hoped that a simple correlation between type and severity of maldistribution and bed length to achieve natural flow might be possible. This would permit a commercial column designer to simply add the appropriate amount of extra bed length to compensate for any anticipated maldistribution.

Figure 11 tends to confirm the initial premise. The profile from the simulated sag curves, becoming steeper, until a straight line with the same slope as the good initial distribution case is achieved. However, Figure 12 presents a case in which there is apparent recovery, but to a shallower slope than the good distribution case (it should be noted that the "50% BLANKED" refers to 50% of the distributor pour points; the tower area blanked off is somewhat greater). Figure 13 presents a case where there is no sign of recovery. There were additional anomalies when the other sizes were tested. Thus, a more fundamental approach is required.

APPLICATION OF THE ZONE-STAGE MODEL

As was mentioned previously, maldistribution experiments using Sulzer BX packing (7) were simulated using a two zone model with no bulk transfer between the zones. Zuiderweg (9) has extended this approach by proposing a zone-stage model. Using the concept of a "basic" or "inherent" HETP which is a function of the packing and the system only, the column is subdivided axially into the appropriate number of theoretical stages. Radially, the column is divided into a convenient number of zones. He recommends that the size of the zones be two to three times the

size of a packing element. Using a numerical integration of Hoek's equations, liquid flow through the column is computed for a given initial distribution and then averaged for each zone-stage combination. Vapor flow is generally taken as being uniform across the column although this is not required by the model. Stage to stage computations are performed for each zone with iterations through the column until convergence to the appropriate end conditions is achieved (eg, simulating experiments performed at total reflux). Vapor and liquid flow through each zone-stage combination are taken as being constant with all interzone bulk liquid flow occurring between stages. The initial version of the model requires bulk liquid flow to be unidirectional (eg center to wall or wall to center). This is for ease of computation and is not basic to the model.

In order to use the model an additional concept is required: that of "effective" coverage of the bed by the entering liquid. Figures 14 and 15 show liquid falling through the open area above the bed and striking its surface. As may be seen the streams widen as they fall and splash as they strike the top surface. Hoek (15) found it necessary to employ the concept of a fictitious extra bed length to explain his data and it is implicit in the empirical formula referenced previously (2). Unfortunately splashing alone cannot explain the variation in the ratio of effective/geometric coverage among the various patterns studied. Zuiderweg (9) plots the relation between the two based on data from a variety of published sources and several systems. The results of this present work fall reasonably on his curve.

Use of the Zuiderweg model to simulate the present results appears to confirm that there is a basic HETP which is independent of the initial distribution, and which permits the effect of varying degrees of maldistribution to be computed. It also confirms that there is a relationship between the effective and geometric coverage which is independent of the packing. In the present experiments, the Adjustable Liquid Distributor was used to impose identical initial distribution patterns on both "1 inch" and "2 inch" Pall rings. As may be seen in Figures 16 through 20, use of the appropriate basic HETP for each ring size in the zone-stage model matches the composition profile through the bed generated by three different initial distribution patterns for the "1 inch" rings and two of the same patterns for the "2 inch" rings. "Good distribution" refers to a well leveled distributor with all pour points flowing at the same rate. The percent blanked is based on the total number of drip points working inward from the pan wall. The area blanked is greater.

Figure 17 presents the experimental data from blanking the outermost 25 percent of the drip points and compares it to computed profiles starting from 83 percent effective coverage with and without spreading. It thus illustrates the amount of "recovery" from initial maldistribution resulting from the natural spreading tendency of the packing. Figure 18 indicates that the data from the 50 percent blank used to illustrate "apparent recovery" in Figure 12 is simulated quite well by a 70 percent effective coverage with spreading.

The relationship between percent blanked and effective coverage shown in Figures 16 through 18 cannot be explained by splashing alone. The fact that this relationship is the same for the "1 inch" and "2 inch" rings when using the same initial distribution would seem to rule out initial spreading in the first few bed layers. Work is continuing to explain this phenomenon.

NOMENCLATURE

ALD	Adjustable Liquid Distributor
b	bottom of bed
HETP	Height of a theoretical plate
L	Molal Liquid Rate
N_{theo}	Number of Theoretical Stages
t	top of bed
TDP	Tubed Drip Pan Distributor
V	molal vapor rate
x	Liquid Concentration, Mol fraction
α	Relative Volatility

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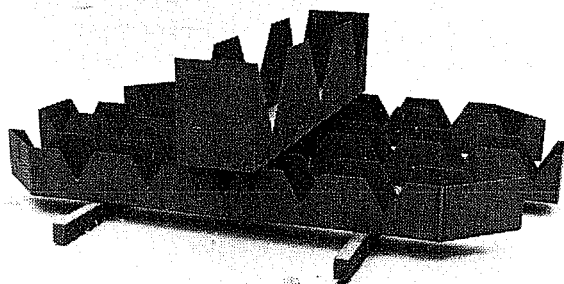


Figure 1. Notched Trough Distributor

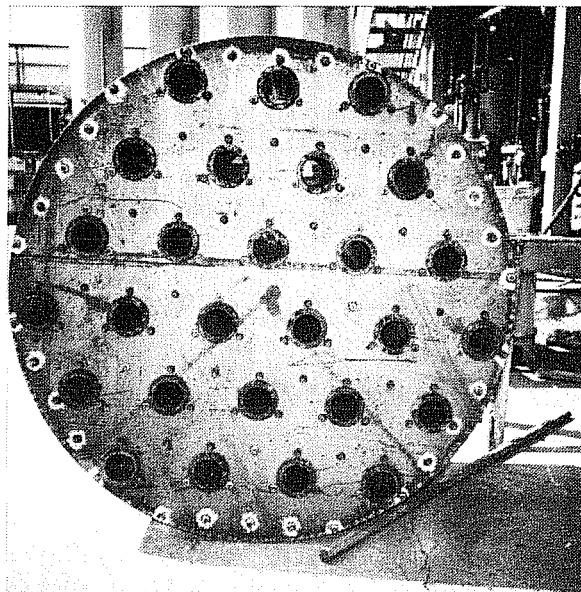


Figure 2. Tubed Drip Pan (TDP)

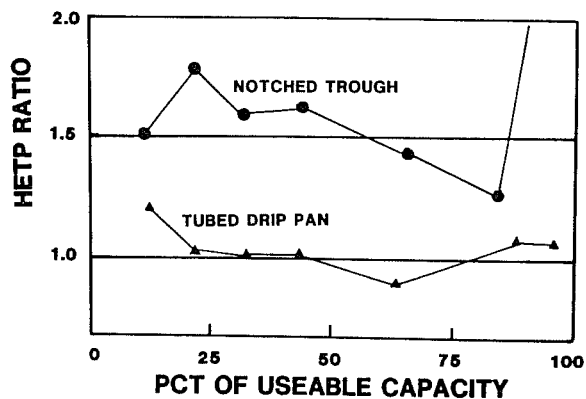


Figure 3. Comparison of apparent efficiency of "1 inch" Pall rings using the Notched Trough and Tubed Drip Distributors, hexane/heptane, 3.5 kPa, total reflux.

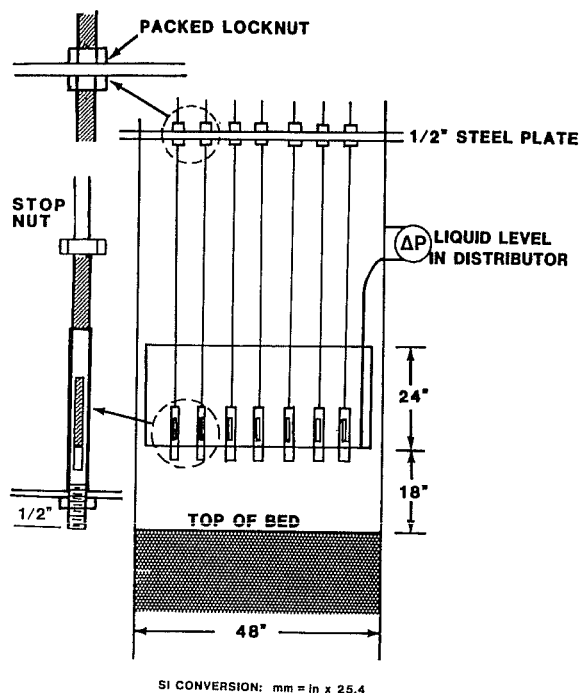


Figure 4. Adjustable Liquid Distributor.

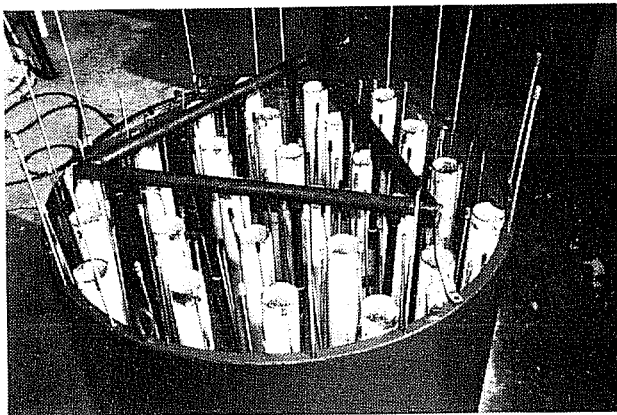


Figure 5. Adjustable Liquid Distributor

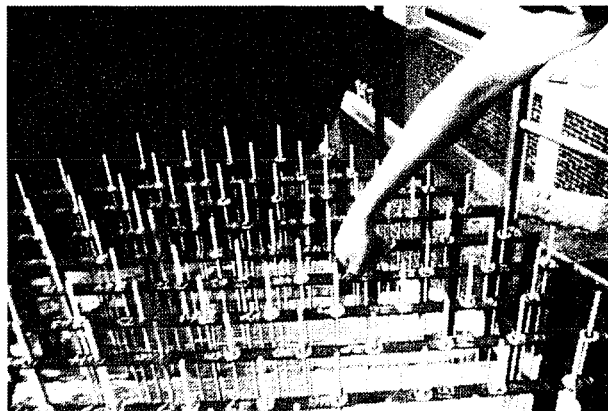


Figure 6. Setting Pistons at Top of Column During Operation.

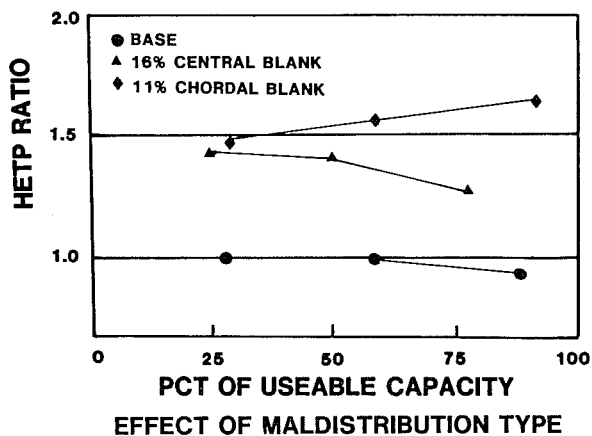


Figure 7. Comparison of the effects of different types of maldistribution on the performance of "1 inch" Pall rings.

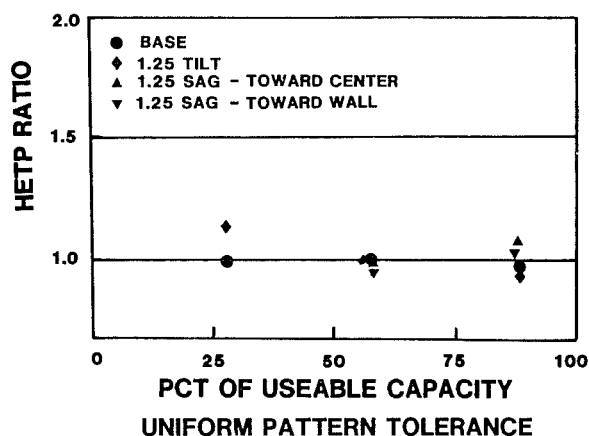


Figure 8. Illustration of the tolerance of "1 inch" Pall rings to a uniform, gradual change in distribution.

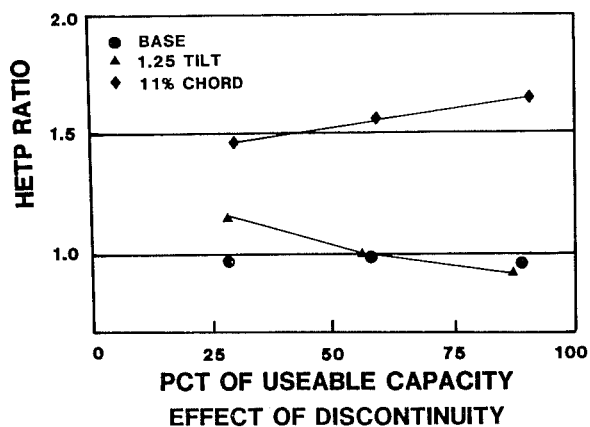


Figure 9. Comparison of the effect of a discontinuity represented by a chordal blank to a uniform variation in distribution.

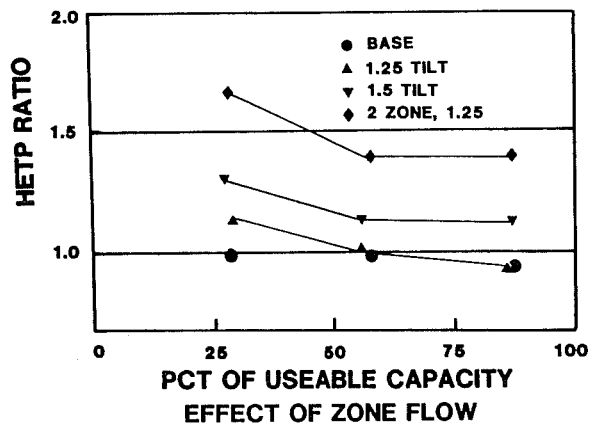


Figure 10. Comparison of the effect of uniform variations in flow to a step change in flow between two zones.

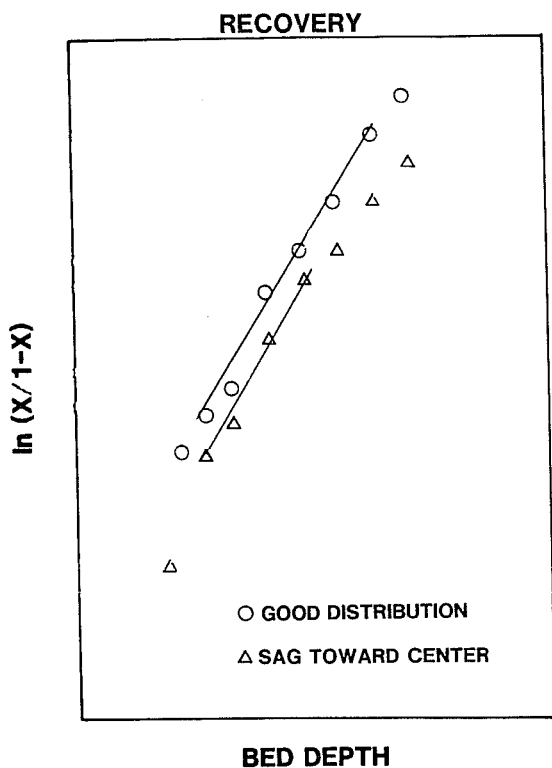


Figure 11. Bed composition profiles. Recovery from moderate maldistribution.

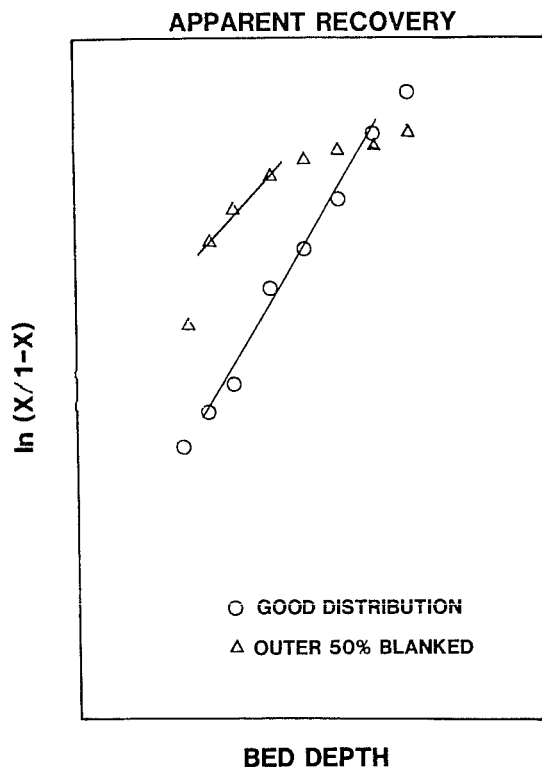


Figure 12. Bed composition profiles. Apparent recovery to shallower slope than good initial distribution.

NO RECOVERY

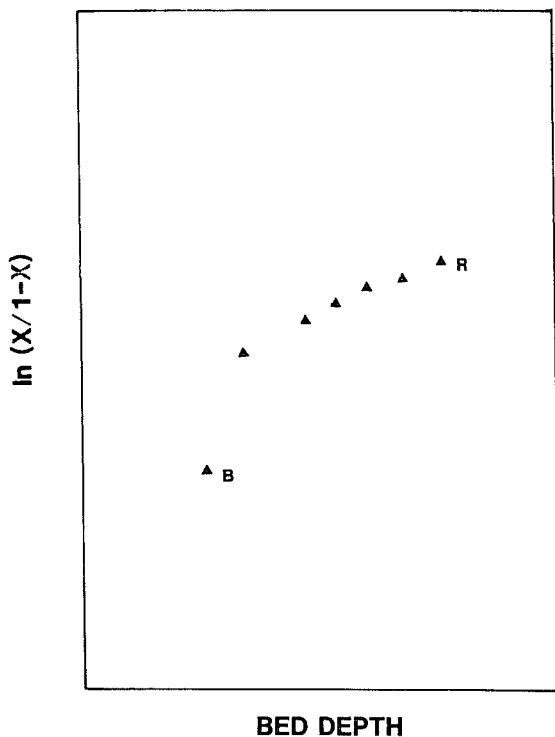


Figure 14. Reflux exiting pan. Cyclohexane/normal heptane, atmospheric pressure.

Figure 13. Bed composition profiles, no indication of recovery from maldistribution.

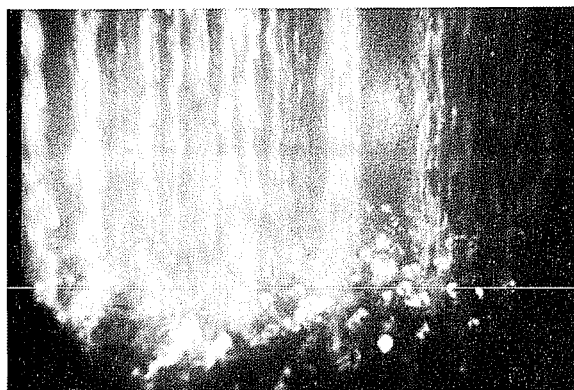


Figure 15. Reflux striking top of bed.

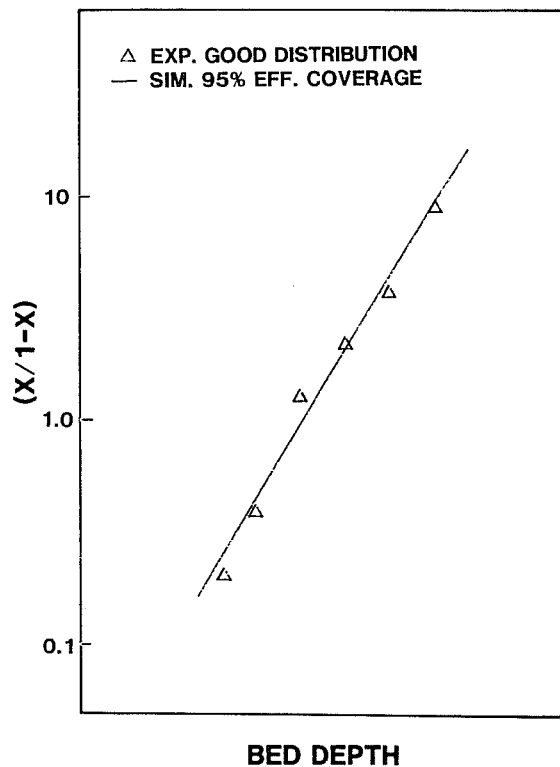
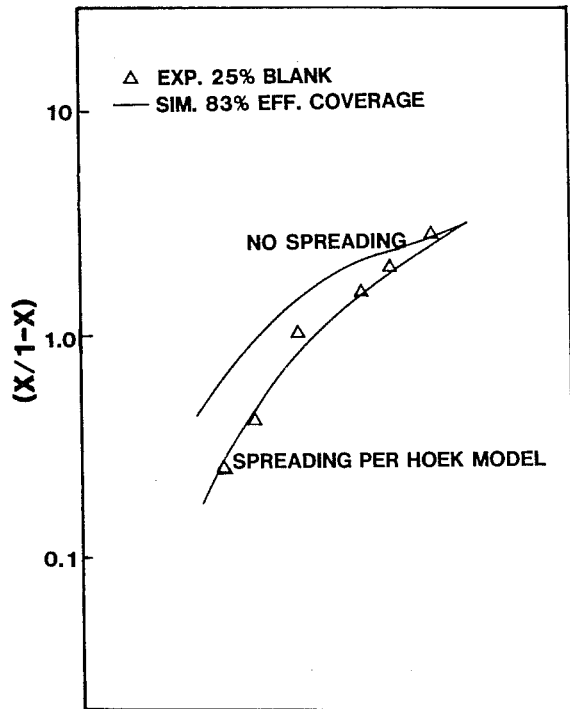
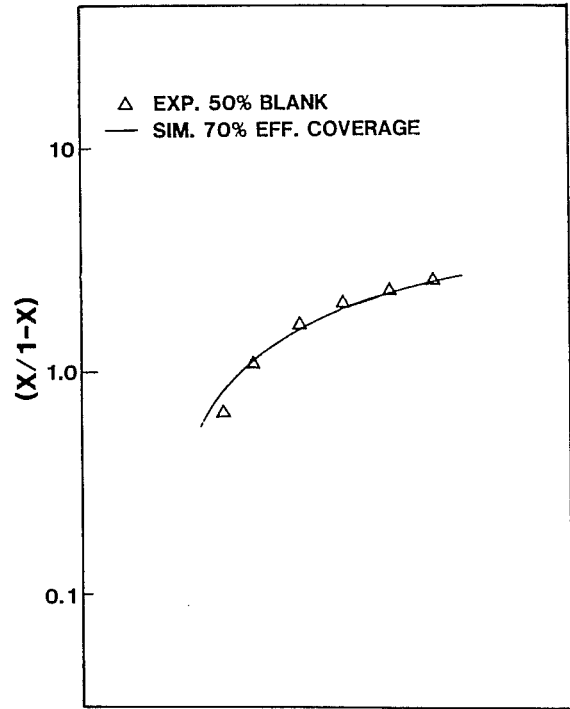


Figure 16



BED DEPTH

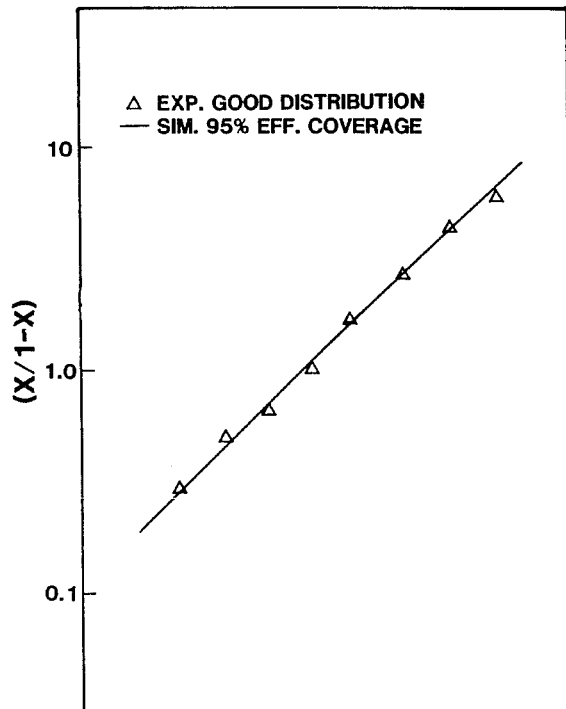
Figure 17



BED DEPTH

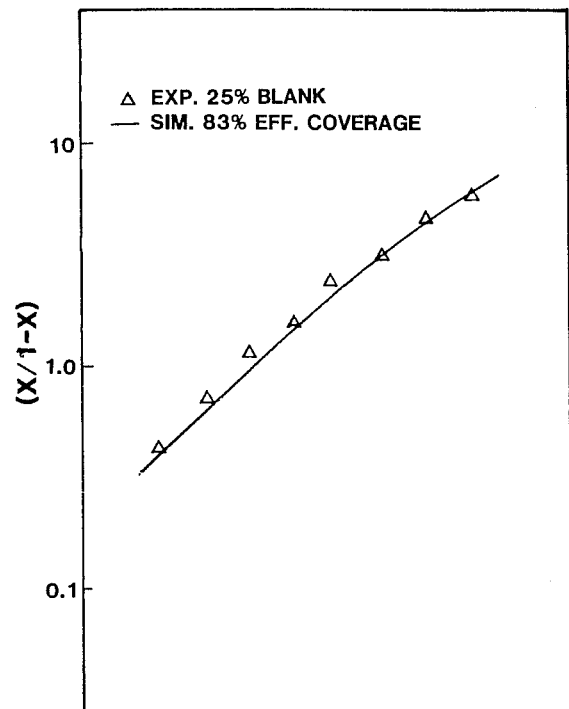
Figure 18

Figures 16, 17, 18. Comparison of zone-stage model simulation with experimental results. Cyclohexane/normal heptane, atmospheric pressure, "1 inch" Pall rings, total reflux.



BED DEPTH

Figure 19



BED DEPTH

Figure 20

Figures 19, 20. Comparison of zone-stage model simulation with experimental results. Cyclohexane/normal heptane, atmospheric pressure, "2 inch" Pall rings, total reflux.