TITLE: LIQUID DISTRIBUTION IN A 4 FOOT DIAMETER PACKED BED

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PRESENTED AT: AIChE Annual Meeting
Mass Transfer Using High Performance Packings

Los Angeles, NOVEMBER 1982

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by

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SUMMARY

This report describes an investigation into the effects of packing depth, packing size, liquid flow rate and vapor flow rate on liquid distribution in packed beds. A 7-spray liquid distributor was used with an air-water system. Three sizes of metal Pall rings were used in a 4 foot (1.2 m) diameter column. The packing sizes were 5/8, 1 and 2 inches (16, 25 and 51 mm). The effects of bed mixing were also examined.

To determine the liquid distribution at the base of the packed bed, local water flow rates were measured under the packing support at a minimum of 50 locations. The standard deviation of the local flowrates, s, showed no clear relationship with the gas rate, packing size or packing depth. However, s increased at the higher flow rates, indicating that the liquid streams descending

through the packing become less uniformly distributed across the bed cross-sectional area as the liquid rate was increased. This could result in a non-uniform L/V throughout the bed, with consequent effects on mass transfer efficiency. A greater variation in s for replicate runs was also observed at higher liquid flow rates.

As the packing depth was increased from two to four feet, the standard deviation did not show any strong trends. At the higher liquid rates, however, the liquid distribution leaving the packed bed was less evenly distributed than the distribution at the top of the bed, implying that the final distribution may be more a function of the packing than of the initial liquid distribution.

The experiments described in this paper are based on an air/water system at atmospheric pressure. The effects of changes in system properties on the liquid distribution are not known.

INTRODUCTION

To ensure that an appropriate distributor would be used in tests of packing efficiency, the effect of the reflux distributor on packed bed performance was investigated, starting with an examination of the effects of distributors on the hydraulics of packed beds with an air-water system. To apply the results to projected mass transfer work in a 4 foot (1.2 m) diameter column, a 4 foot (1.2 m) diameter simulator was used.

In the early investigations of Baker et al.[1] into liquid distribution in packed beds, bed diameters up to 2 feet (.6 m) were used. Recent work by Groenhof[2], Farid and Gunn[3], and Bemer and Zuiderweg[4], however, has been limited to packed bed diameters of less than .5 m.

This paper presents the results of an investigation into the effects of packing depth, packing size, bed repacking, total liquid flow rate, and vapor flow rate on the liquid distribution under a packed bed, using a 7-spray distributor, metal Pall rings, and an air-water system.

DESCRIPTION OF EQUIPMENT

Simulator

Experiments were conducted in a 4 foot (1.2 m) diameter test column fitted inside a 5.5 foot (1.7 m) diameter air-water simulator. A schematic drawing of the simulator is shown in Figure 1.

The Four Foot Test Column and Internals (Figure 2)

A 4 foot (1.2 m) diameter test column was made of 3/16 inch (4.8 mm) thick steel cylinder 13.3 feet (4.06 m) long. Ports were cut in the cylinder to provide access for visual observation and liquid sampling. The liquid sampler port was covered with a polyacetate window with a flexible neoprene inset to allow probe movement. To prevent air from by-passing the 4 foot (1.2 m) sleeve, a nylon shroud was installed.

The entering air was straightened with three perforated plates made of 11 gauge stainless steel, with 1/2 inch (13 mm) diameter holes on 1 inch (25 mm) triangular centers. The plates were installed with 6 inch (152 mm) spacings.

Seventeen inches (432 mm) above the top perforated plate, a bubble-cap tray was installed. Liquid ran off the tray into two liquid downpipes through openings in the walls of the 4 foot column at the tray level.

A tray ring with a 1 3/4 inch (44.5 mm) shelf was installed above the sampling port. A stainless steel grid with 2 1/2 inch (64 mm) square openings which served as a packing support was installed on the tray ring. For the 1 inch (25 mm) and 2 inch (51 mm) diameter packings, a wire grid with 1 inch (25 mm) square openings was installed above the packing support grid. For the 5/8 inch (16 mm) packing, a grid with 3/4 inch (19 mm) hexagonal openings was used.

<u>Liquid Distributor Support Manifold</u>

The distributor supporting assembly consists of the distributor support pipe, the distributor manifold, the spacing arms and the support collar.

The 7-Spray Distributor

The 7-spray distributor is shown in Figure 3. Built around a section of 6 inch (152 mm) schedule 80 pipe, the distributor has six arms, each bearing a spray nozzle. A seventh spray nozzle is located in the center. The spray nozzles, manufactured by Spraying Systems Co., have the model number 1HH8.

Packing

All the packings used were metal Pall rings. The sizes were 5/8, 1 and 2 inches (16, 25 and 51 mm). Figure 4 shows the packing dimensions.

Sampling Equipment

Local Liquid Volumetric Flow Rates. To minimize the interference with the airflow, only one liquid sampler was used. The sampler consisted of a funnel with a circular collection area 2.875 inches (73 mm) in diameter (Figure 5). The funnel was supported by a length of 1/2 inch (13 mm) OD aluminum tubing which was inscribed with a length scale. The tube was passed through a close-fitting metal sleeve in the sampling port. An angle scale was marked on a horizontal track across the simulator sampling window. The track restricted the vertical travel of the tube, and the angle scale allowed the measurement of the angle of entry of the tube into the column. With the length and angle readings, the position of the funnel could be calculated.

Air Velocity. To evaluate the velocity profile of the air entering the packing, air velocities were measured at specific points 1 inch (25 mm) below the packing support with an Alnor Model 8500 hot wire anemometer.

EXPERIMENTAL PROCEDURES

Air Velocity Profile Determination

Air velocity profiles were characterized by measuring point velocities at 24 points below the packing support. Measurements were made without packing in the column, and without water flow.

The blower was adjusted to obtain F_s values of 0.5, 1.0, and 1.5. These values were also used in the liquid distribution study. Figure 6 shows the air velocities measured along a column diameter for each of the three F_s values.

Packing Installation

Packing was poured into the column from boxes at the top of the simulator, and levelled with a board and level. No hold-down plate was used. Observations of bed heights during runs revealed no measurable changes.

It is well known that the efficiency of a packed bed can change dramatically after repacking. To examine the effects of reorienting the packing in the simulator, several runs were repeated after mixing the bed.

Liquid Distributor Positioning

The 7-spray distributor was always oriented so that three spray nozzles were located directly above the diameter of the 4 foot section extending through the center of the sampling window. The center nozzle of the distributor was always positioned above the center of the 4 foot section.

The 7-spray distributor was placed 13 inches (330 mm) above the top of the packed bed or, if there were no packing, 13 inches above the packing support plate. At this elevation, the coverage of adjacent individual sprays overlapped by

8 inches (203 mm), and the outside edge of the peripheral sprays contacted the column wall approximately 3 inches (76 mm) above the top of the packing. Figure 7 shows the nozzle orientation, the spray pattern, and the cross-section of the liquid distribution profiles at a liquid rate of 100 gpm (227 m^3/hr).

The relationship between the pressure drop across the spray nozzles and the flowrate from the 7-spray distributor was determined. A plot of flowrate vs. ΔP is shown in Figure 8.

Liquid Distribution below the Packing

The flow rate into the funnel was determined by collecting the liquid leaving the probe in a graduated cylinder for a measured period of time. The maximum flowrate through the liquid probe was first determined outside the column, where the funnel could be observed. The funnel had a maximum flow of approximately 250 ml/sec.

To sample all positions for a run in less than two hours, upper limits were set for the volume collected and the time for each sample. These were 500 ml and 45 seconds, respectively. After each sampling, the position, volume and time were recorded.

During the initial part of the experiment, flowrates were measured at approximately 100 positions beneath the packing support. Later, this was reduced to 53 evenly spaced points.

ANALYSIS OF DATA

The positions of local flowrate measurements were calculated for a Cartesian coordinate system centered at the column axis of symmetry. Local flowrates were calculated in ml/s.

In order to give equal weight to all flowrates measured in different areas under the packing, a subset of the measurements was chosen which was close to an evenly spaced grid. The standard deviation, s, of the local flowrates at these positions was used as a measure of the unevenness of the liquid distribution.

$$s = \frac{1}{(N-1)} \sum_{i=1}^{N} (f_i - \bar{f})^2$$

where $\bar{f} = \frac{1}{N} \sum_{i=1}^{N} f_i$

and N = the number of local flowrates

f_i = the i^{th} local flowrate

$\bar{f}$ = the average of the local flowrates

s = the sample standard deviation of the local flowrates

In order to evaluate the precision of the local flow measurements, replicate measurements of the flowrate were made at one point for several sets of conditions, and for several positions. From these measurements, the time variation of the flow rates could be determined.

Additionally, the reproducibility of the flowrate at one position after shutdown and restart of the liquid and gas flows was examined. Flowrates from replicate runs made with the same conditions of packing and fluid rates were compared.

For each run, a frequency plot was made of the local flowrates measured at evenly distributed positions. The range of flowrate values was divided into intervals, the number of measurements in each interval was counted, and the frequency was plotted vs. interval.

The reproducibilities of the maldistribution factors and the frequency plots were evaluated from replicate run data.

RESULTS

Local Flow Rates

Time Variation. Replicate measurements of the flowrate were made at one location to determine the reproducibility of the local flowrates. Measurements were made for several sets of conditions. Some representative data are plotted in Figure 9.

Point flowrates varied approximately 17% around the mean rate for each series. Although it would have increased the accuracy of the s value the sampling time was not increased due to the additional time required for the completion of a run.

Reproducibility of Local Flowrates After System Shutdown

Several runs were made with identical conditions. From these repeats, the reproducibility of the local flowrates could be evaluated after shutdown and subsequent startup of liquid flow. Table 1 compares local flowrates at several positions for runs repeated at the same conditions.

Figure 10 shows the variation in the patterns of high and low local flowrates for two runs with the same conditions. It is evident that the pattern of flow in the packed bed changes dramatically between runs with identical conditions, indicating that the flow paths of the descending liquid are not reproducible.

Reproducibility of s

Table 2 gives values of the standard deviation, s, for several runs made at identical conditions. Some of the sources of variability in s are the time variation in local flowrates, and errors in air rate and total liquid rate measurements and in time and volume measurements, and the number of local flowrates used in the calculation of the sample standard deviation.

From Table 2 it can be seen that there is variation in s for all conditions, and that the variation in s between replicate runs increases with increasing liquid rate.

Frequency Plots

A representative frequency plot is shown in Figure 11. As was characteristic for most runs, the distribution appears skewed towards the high flowrate side. When data for several replicate runs are combined, the asymmetry is made even clearer. Figure 12 illustrates this with a frequency plot of the combined data for runs 15345, 15347, and 15349.

Liquid Flow Near Wall

For all runs, the local liquid flows within 5 inches (127 mm) of the wall were averaged, and the ratio of that average with the average for all local flows for the same run was used to find if there were any tendency for liquid to migrate towards or away from the wall. This ratio showed no relationship with F_s or liquid flowrate. It was noted that when the rates were averaged for runs with conditions differing only in F_s, for 5/8" (16 mm) packing the wall flow approached the average flow more closely as packing depth increased. At 4 feet (1.2 m) of this packing, the average ratio was 1 ± .01 for most cases. This implies that for the 5/8" (16 mm) packing the liquid flow near the wall tends to approach the average if the two are initially different.

The 1 and 2 inch (25 and 51 mm) packings showed similar trends in wall flow with increasing depth, although the average ratios at 4 feet (1.2 m) were 1 ± .06.

Effects of Variations of Independent Variables on s

Tables 3, 4, and 5 show the standard deviations for runs with 5/8, 1, and 2 inch (16, 25, and 51 mm) metal Pall rings, respectively.

Effect of Vapor Rate. From Tables 3 through 5, no trends are apparent for differing air flowrates. To clarify the effects of other variables on s, values of s were averaged for runs which differed only in air flowrate, and are shown in Table 6.

Effect of Total Liquid Flowrate. From Table 6, it is clear that s increases as the total liquid flowrate is increased. Additionally, at higher liquid rates the s values for replicate runs vary more than at lower rates.

Effect of Packing Depth. From Table 6, as the packing depth increased from 2 to 4 feet (.6 to 1.2 m), there was no significant change in s. For the runs at 50 gpm (11.4 m^3/hr), the values of s under 2 and 4 feet of packing were about the same as the s values for the liquid distribution with no packing - i.e., at the top of the packed bed. At 150 gpm (34.0 m^3/hr), however, the s values with no packing were lower than those below 2 or 4 feet of packing, indicating that the first 2 feet of packing transformed the initial liquid distribution to a less even distribution. An additional 2 feet of packing made little or no further change in the evenness of the liquid distribution except for the 5/8 inch (16 mm) packing.

If packing controls liquid distribution after a sufficient depth and if there is a value of s characteristic of that distribution, the above results could have the following implications. First, the initial liquid distribution of the 7-spray distributor at 50 gpm (11.4 m^3/hr) could have had approximately the same s as the characteristic s of the packings investigated. Second, the depth of packing required for the packings to bring the liquid distribution to its final distribution appears to be less than 4 feet (1.2 m) for the 5/8" (16 mm) packing, but seems to increase for the larger packings to more than 4 feet. Also, it appears that for a given packing, the final s value increases with liquid flowrate.

Additional experiments with higher and lower initial values of s (i.e., other liquid distributor designs) would be necessary to clarify the effects of the packing on liquid distribution.

Effect of Packing Size. From Table 6, for both flowrates with 4 feet (1.2 m) of packing, average s values for runs with the same air flowrate increased slightly as the packing size increased. This effect, however, is small when compared to the variation $\bar{s}$ for replicate runs, and cannot be considered significant.

Effect of Bed Mixing. Values of s for several runs before and after bed mixing are shown in Table 7. There is no significant effect on s of bed mixing.

EXPERIMENTAL DATA

The data on which this report is based is available from Fractionation Research, Inc., 1517 Fair Oaks Avenue, South Pasadena, California 91030.

CONCLUSIONS

The standard deviation s of the local flowrates did not change with the air flowrate, and was not changed noticeably if the bed were mixed.

The unevenness of the liquid flow distribution below the packed bed as measured by s increased with increasing total liquid flowrate. Also, s values for replicate runs differed among themselves more at higher total liquid flow rates.

Changing the packing depth from 2 to 4 feet (.6 to 1.2 m) did not significantly affect the evenness of the liquid distribution below the bed. For runs at the higher liquid rate, the distribution leaving 2 or 4 feet (.6 to 1.2 m) of packing was less evenly distributed than the distribution at the top of the bed, implying that the first few feet redistributed the liquid to a less even distribution.

Finally, as the packing size increased, the unevenness of the liquid distribution at 4 feet (1.2 m) increased.

ACKNOWLEDGMENT

The authors with to thank C. F. Braun & Co. for the simulator used in this work.

DEFINITIONS AND ABBREVIATIONS

$\bar{f}$ average local flowrate for a run (ml/s)

f_i i^{th} local flowrate (ml/s)

F_s F-factor based on column cross-sectional area, $V_s \sqrt{\rho}$

GPM liquid rate, gallons per minute

N number of local flow measurements

$\dot{s}$ sample standard deviation of he local liquid flowrates, ml/sec

V_s vapor velocity based on column cross-sectional area, ft/sec

ρ density, lb/ft

REFERENCES

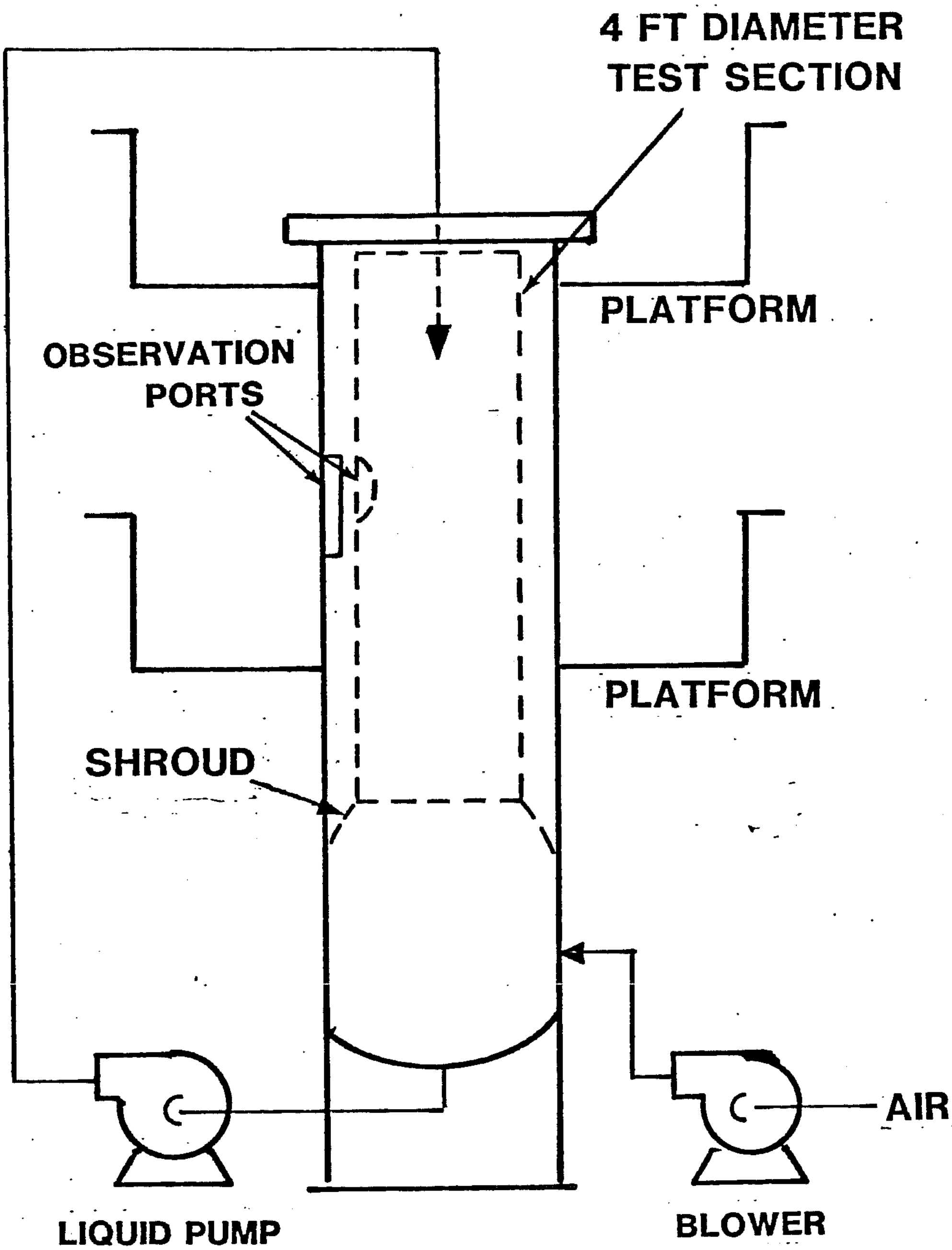
1. T. Baker, T. H. Chilton and H. C. Vernon, Trans. Am. Inst. Chem. Eng., 31, 296 (1935).

2. H. C. Groenhof, Chem. Eng. J., 14, 181 (1977).

3. M. M. Farid and D. J. Gunn, Chem. Eng. Sci., 33, 1221 (1978).

4. G. G. Bemer and F. J. Zuiderweg, Chem. Eng. Sci., 33, 1637 (1978).

FIGURE 1
FLOW DIAGRAM
FOR
LIQUID DISTRIBUTION STUDY



m = feet x .3048

FIGURE 2
FOUR FOOT TEST SECTION

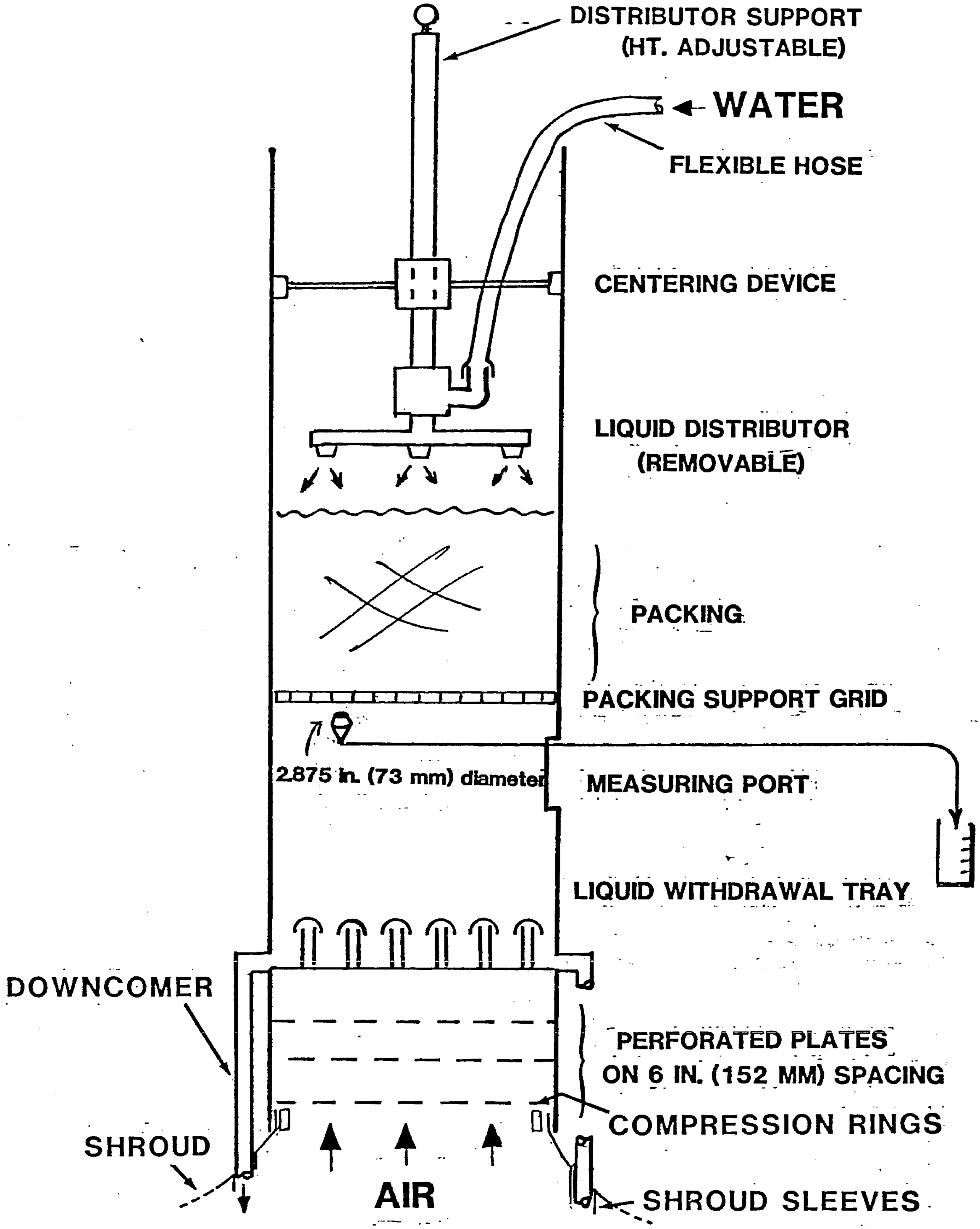


FIGURE 3

7 SPRAY DISTRIBUTOR

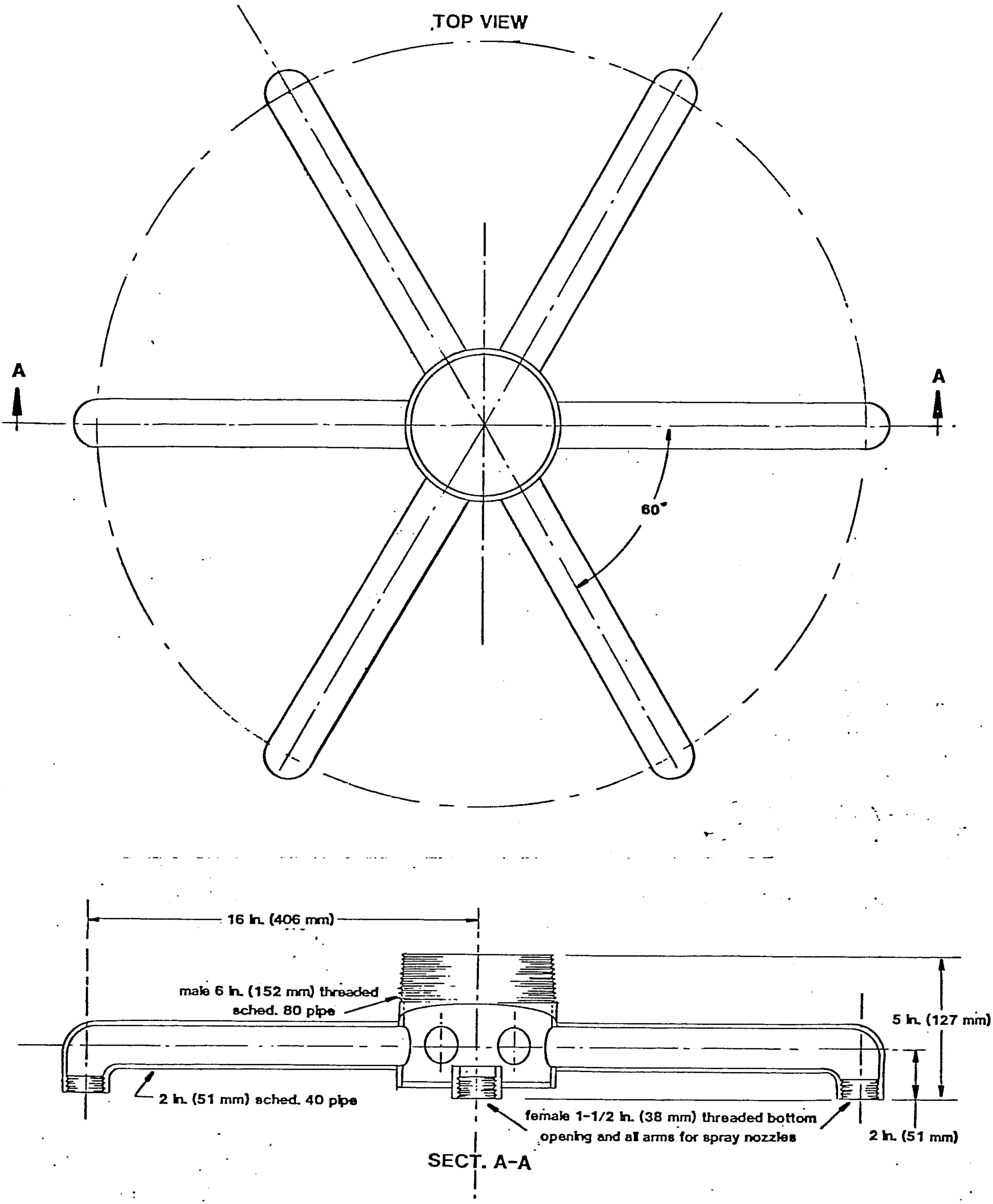
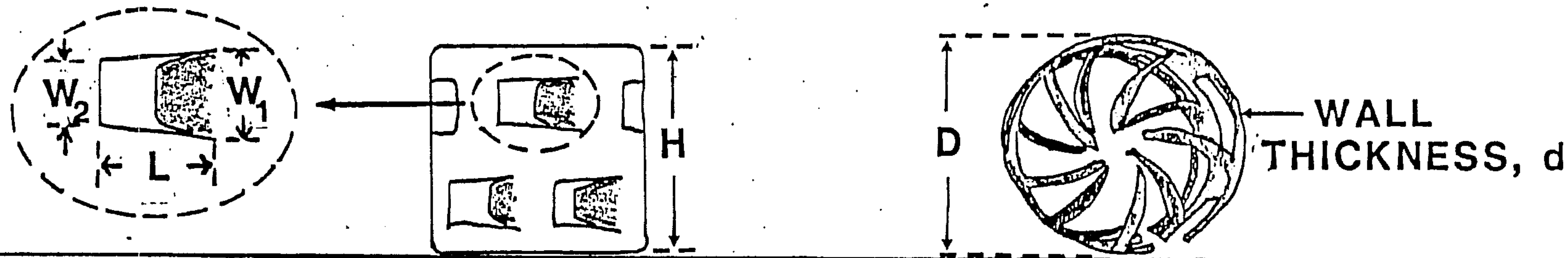


FIGURE 4

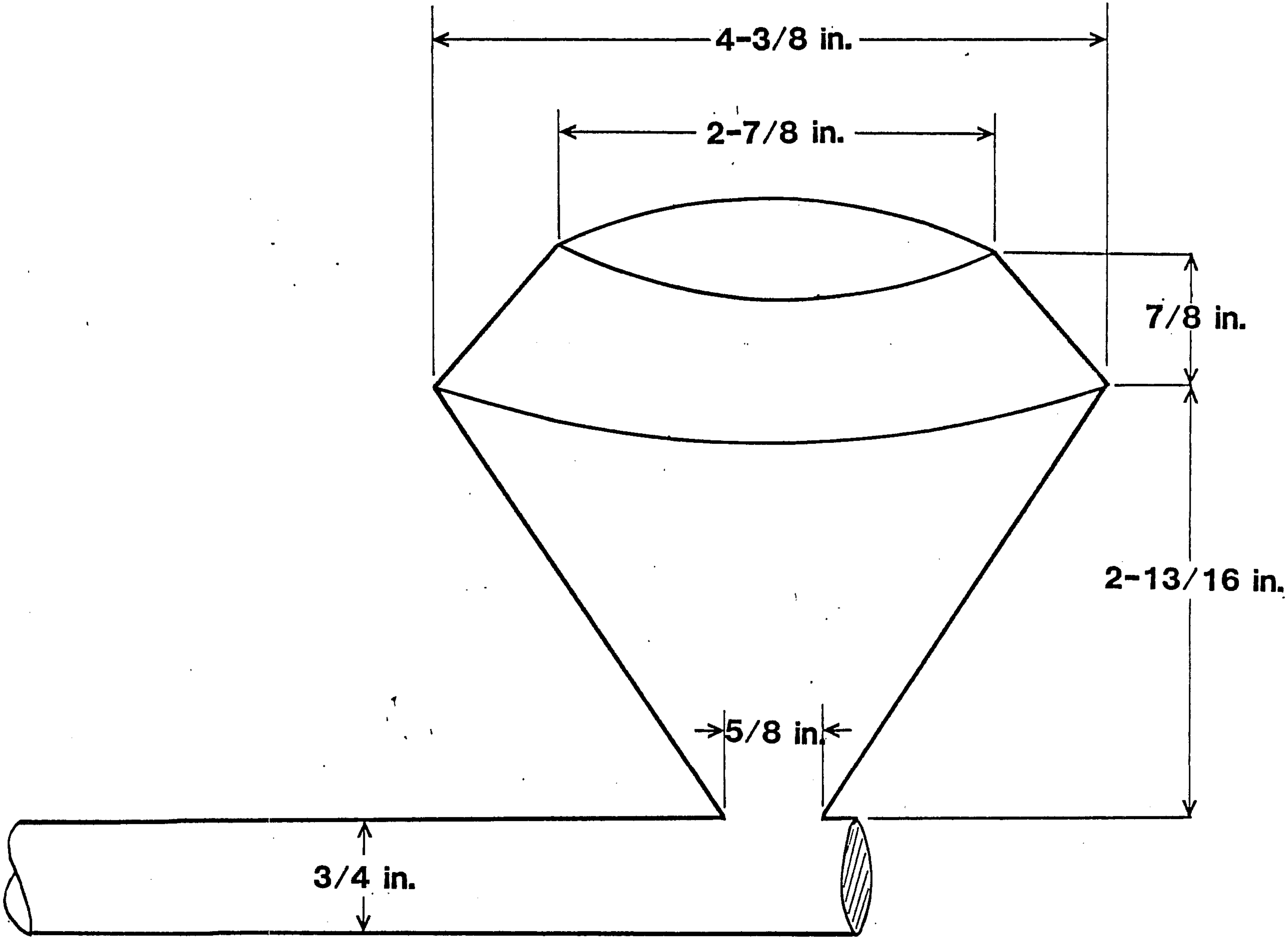
PALL RING PACKING DIMENSIONS



PACKING SIZE (IN)	H_{avg} (mm)	D (mm)	L (mm)	W_1 (mm)	W_2 (mm)	d (mm)	% SLOT AREA
5/8	16.0	16.2	7.2	3.8	3.3	.40	31
1	25.5	26.1	11.2	6.2	5.5	.63	31
2	50.9	52.6	25.1	12.7	12.0	.57	37

mm = inches x 25.4

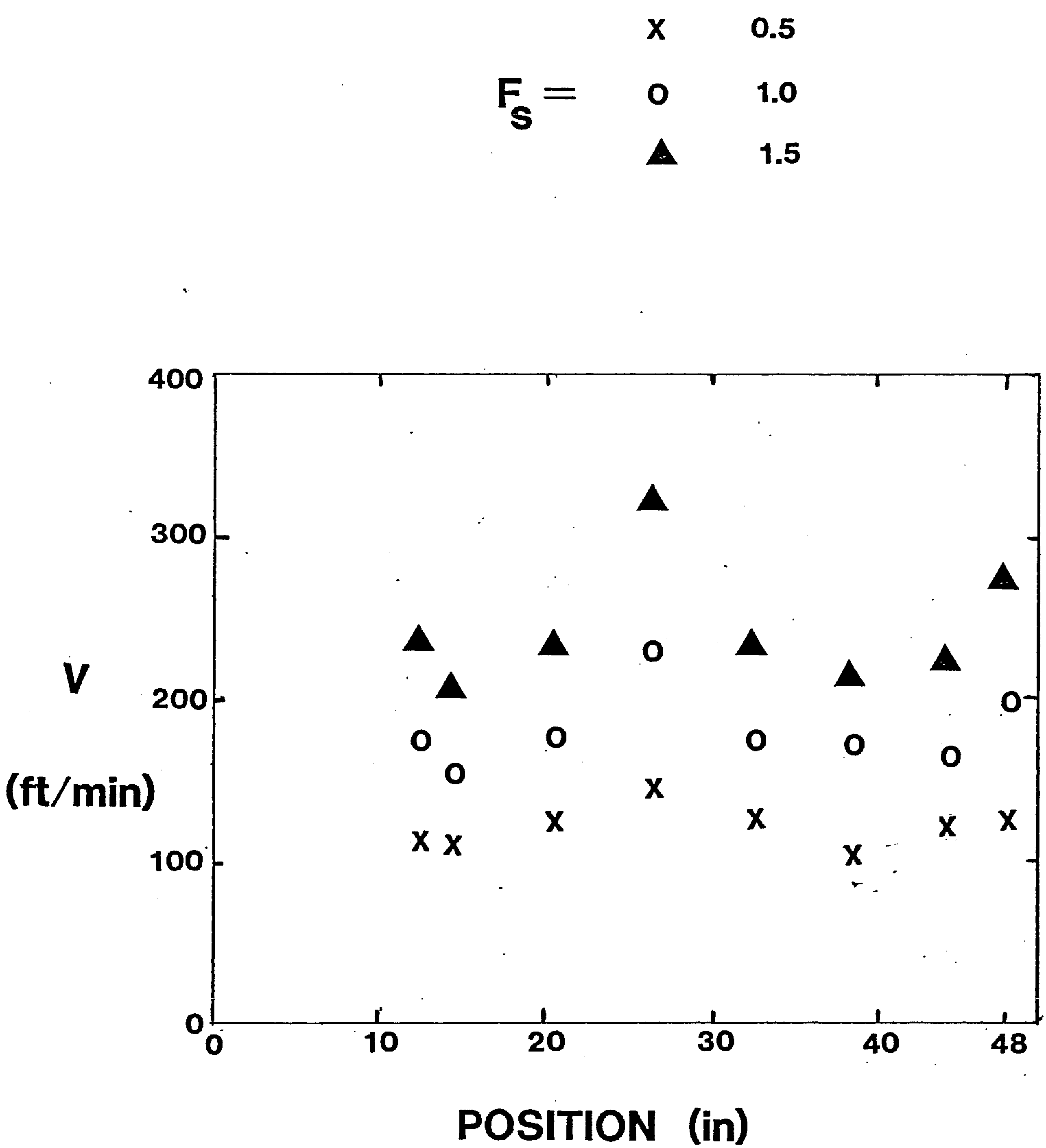
LIQUID COLLECTOR PROBE



mm = inches x 25.4

FIGURE 6

VERTICAL AIR VELOCITY ACROSS COLUMN



SI CONVERSION:

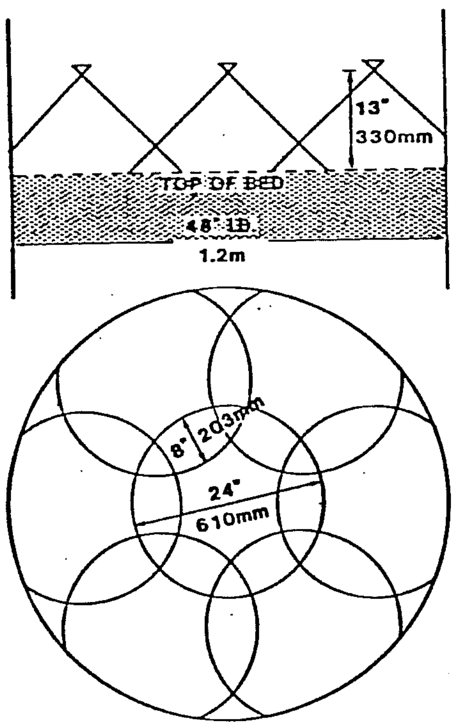
m/s = ft/min x .00508

mm = inches x 25.4

FIGURE 7

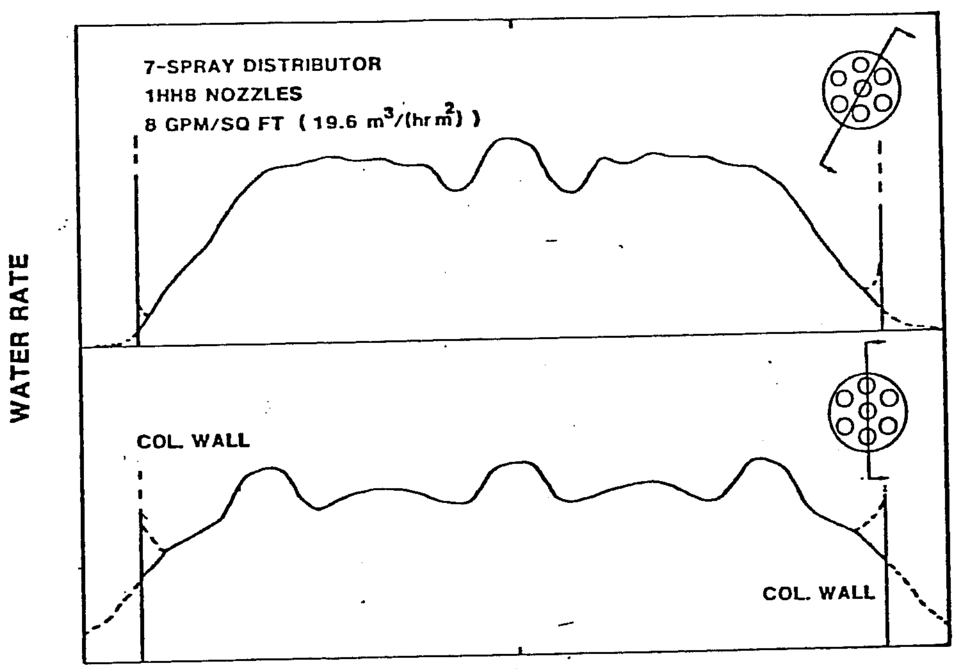
SPRAY ARRANGEMENT AND LIQUID DISTRIBUTION

7-SPRAY DISTRIBUTOR



SPRAY PATTERN IN DIST'N COLUMN

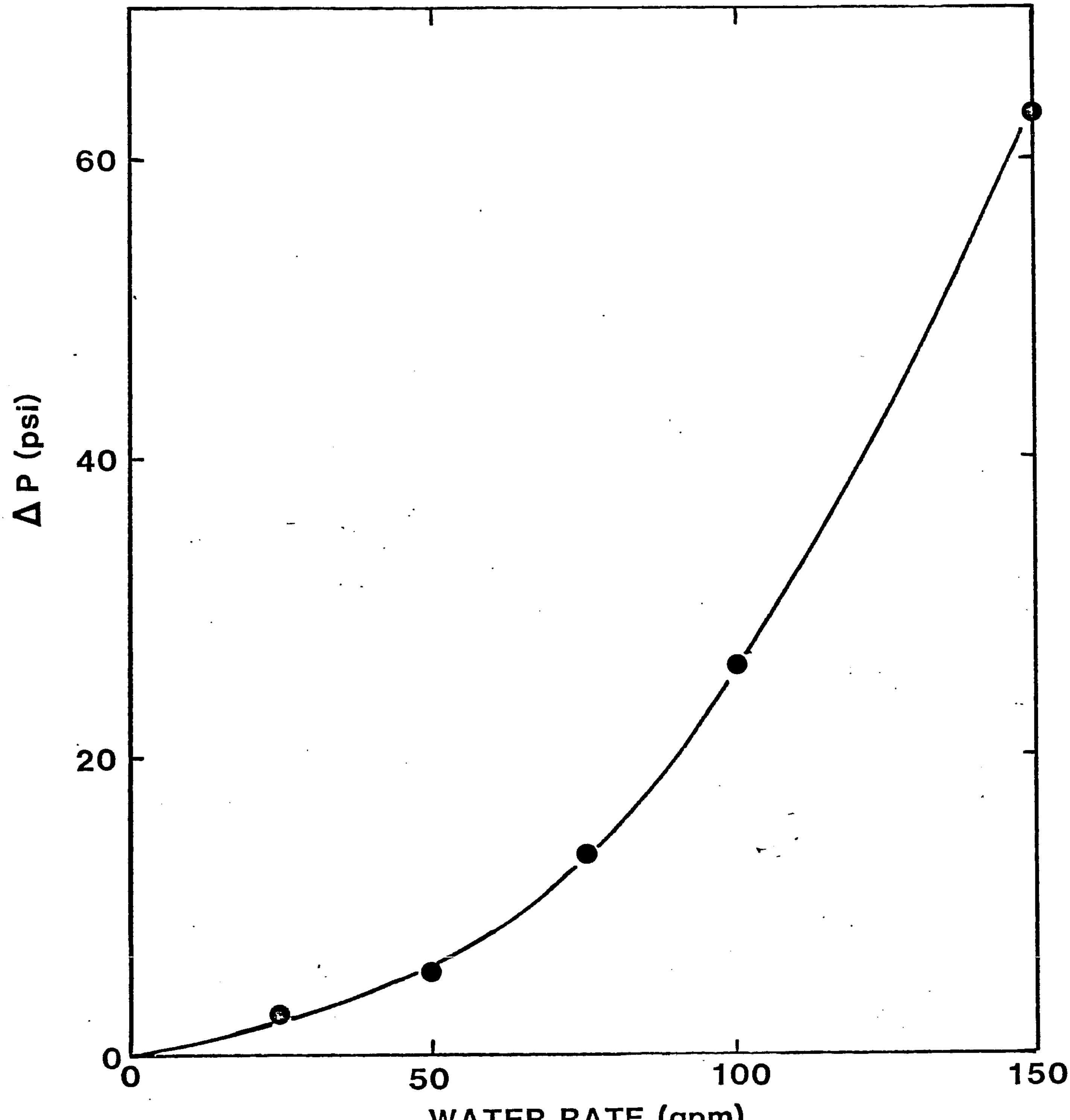
DISTRIBUTION PROFILE



RADIAL POSITION

FIGURE 8: 7 - SPRAY DISTRIBUTOR

NOZZLE PRESSURE DROP vs. WATER RATE



SI CONVERSION: Pa = gpm x .227

m^3 /hr = psi x 6895

TIME VARIATION OF LOCAL FLOWRATE UNDER 4 FT. OF 5/8 IN. PACKING

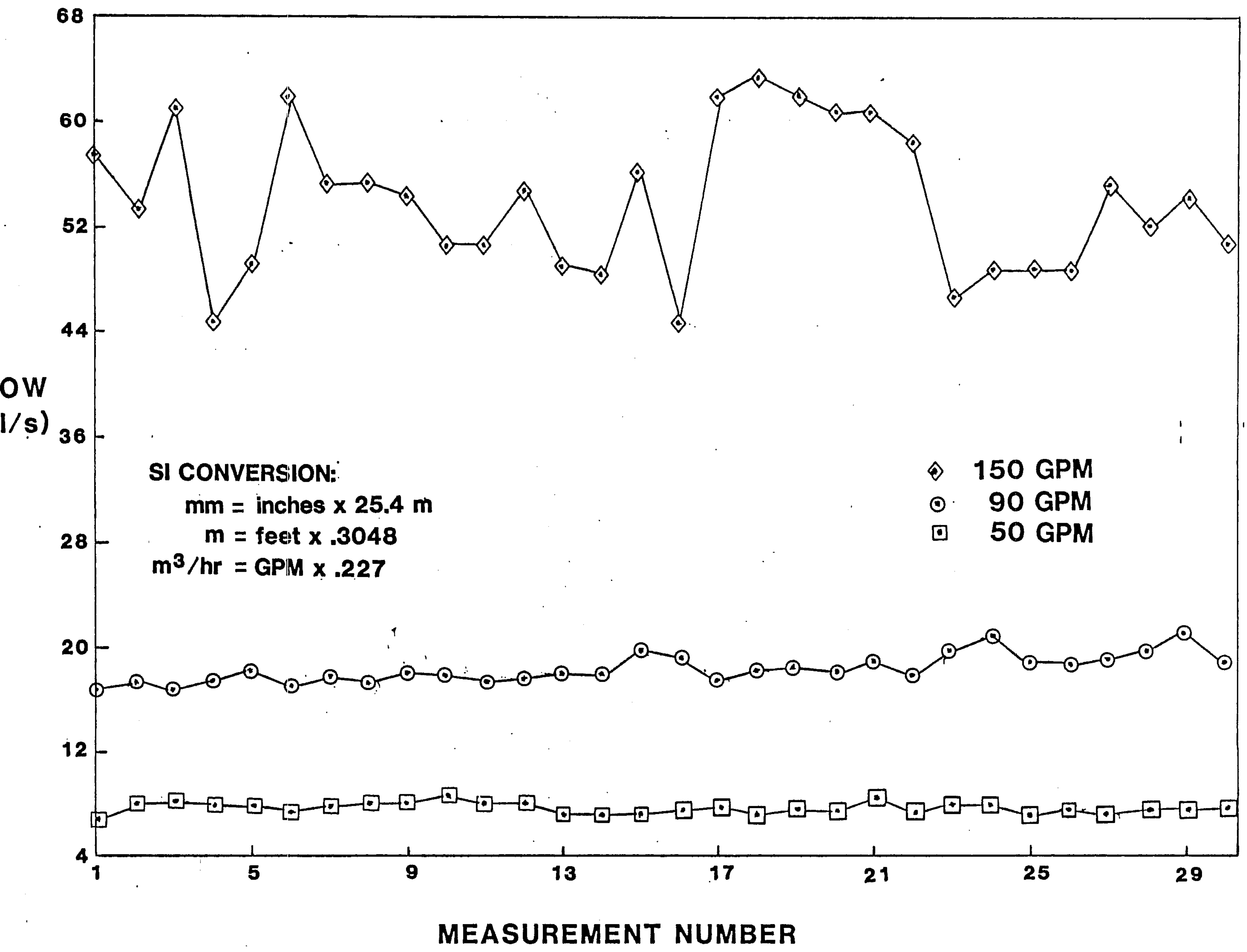
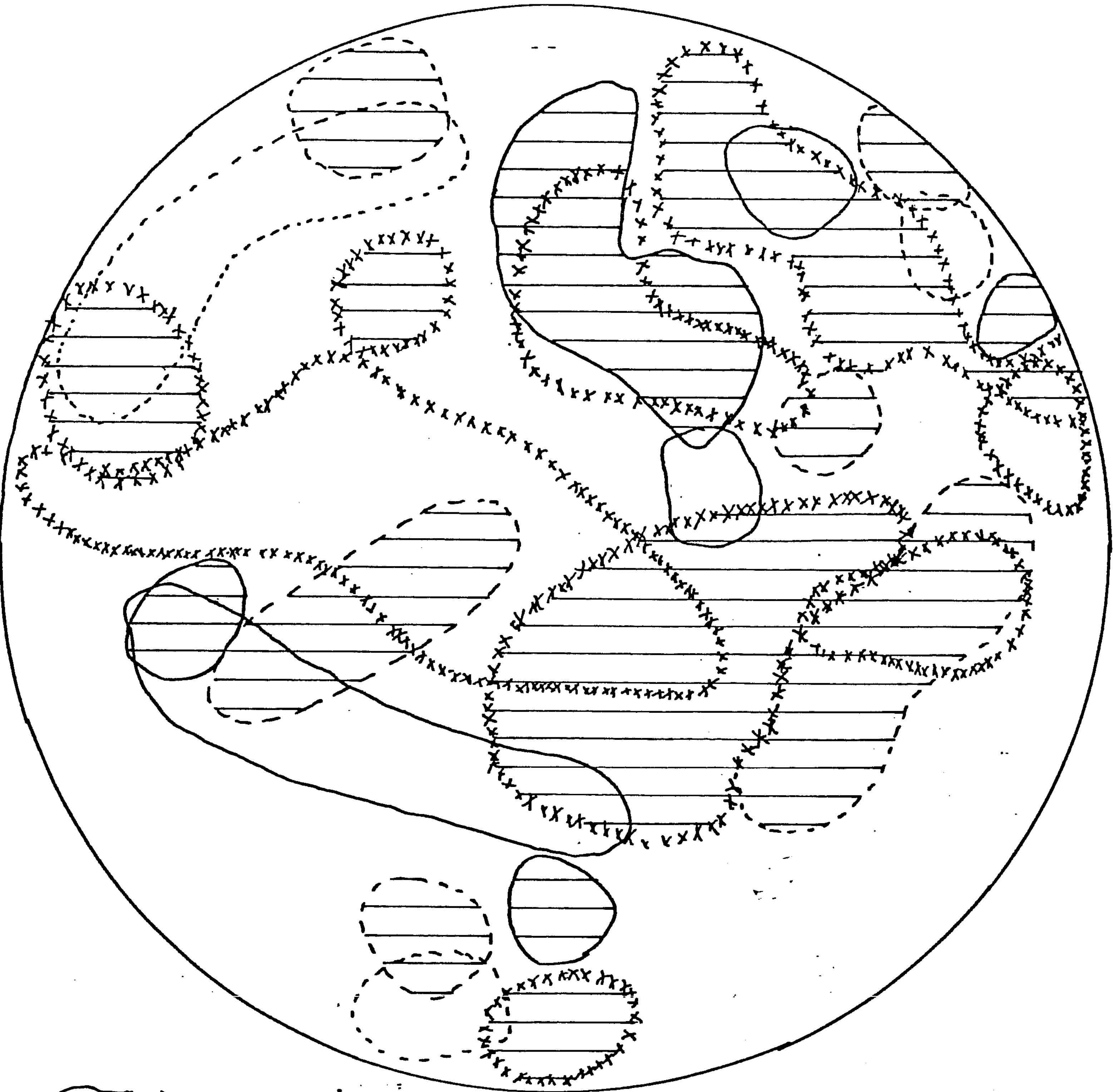


FIGURE 10

ZONES OF HIGH AND LOW LIQUID FLOW



$>$ MEAN $+ \sigma$

MEAN TO MEAN $+ \sigma$

$<$ MEAN $- \sigma$

SHADED: REPLICATE 1

OPEN: REPLICATE 2

GPM: 50

Fs : .5

DEPTH: 1 ft.

1 in. PALL RINGS

FIGURE 11
FREQUENCY PLOT OF RUN 15345

FLOWRATE (ml/s)

```
           -------------------------------
  .0-  4.0    0
 4.0-  8.0    2   **
 8.0- 12.0    2   **
12.0- 16.0    0
16.0- 20.0    2   **
20.0- 24.0    3   ***
24.0- 28.0    3   ***
28.0- 32.0    5   *****
32.0- 36.0    6   ******
36.0- 40.0    4   ****
40.0- 44.0    4   ****
44.0- 48.0    2   **
48.0- 52.0    4   ****
52.0- 56.0    1   *
56.0- 60.0    2   **
60.0- 64.0    2   **
64.0- 68.0    2   **
68.0- 72.0    1   *
72.0- 76.0    1   *
76.0- 80.0    0
80.0- 84.0    0
84.0- 88.0    0
88.0- 92.0    0
92.0- 96.0    1   *
96.0-100.0    4   ****
           -------------------------------
```

OCCURRENCES

FIGURE 12
FREQUENCY PLOT OF
COMBINED RUNS 15345, 15347, AND 15349.

FLOWRATE (ml/s)

```
            ---------------------------------------
   .0-   4.0     2    **
  4.0-   8.0     5    *****
  8.0-  12.0     3    ***
 12.0-  16.0     2    **
 16.0-  20.0     4    ****
 20.0-  24.0     9    *********
 24.0-  28.0    13    *************
 28.0-  32.0    12    ************
 32.0-  36.0    18    ******************
 36.0-  40.0     7    *******
 40.0-  44.0    14    **************
 44.0-  48.0     8    ********
 48.0-  52.0    10    **********
 52.0-  56.0     8    ********
 56.0-  60.0     7    *******
 60.0-  64.0     5    *****
 64.0-  68.0     6    ******
 68.0-  72.0     3    ***
 72.0-  76.0     1    *
 76.0-  80.0     1    *
 80.0-  84.0     3    ***
 84.0-  88.0     1    *
 88.0-  92.0     1    *
 92.0-  96.0     1    *
 96.0-100.0      1    *
100.0-104.0      0
104.0-108.0      3    ***
108.0-112.0      2    **
112.0-116.0      1    *
116.0-120.0      0
120.0-124.0      1    *
            ---------------------------------------
```

OCCURRENCES

TABLE 1

VARIATION OF LOCAL FLOWRATES BETWEEN RUNS.

POSITION	RUN 1 ml/s	RUN 2 ml/s	RATIO MAX/MIN
a	9.1	15.5	1.7
b	7.2	4.8	1.5
c	5.9	8.0	1.4
d	3.6	8.9	2.5
e	12.5	4.7	2.7
f	4.6	1.6	2.9

SOME EXAMPLES OF LARGE DIFFERENCES BETWEEN POINT FLOW MEASUREMENTS WHEN A RUN IS REPEATED AFTER A SHUTDOWN - 24 HOURS BETWEEN RUNS

STANDARD DEVIATION FOR 5/8 INCH METAL PALL RINGS. 7 SPRAY DISTRIBUTOR

	50 GPM			150 GPM		
D \ F_s	0	.5	1.5	0	.5	1.5
0	3.9	4.3	4.2	10.9	20.2	14.1
2	6.7 5.1	5.5	7.6 6.2	30.7	23.3 27.5	26.7
4	4.4 4.8	3.8 5.0 4.8	6.5 6.7 4.7 6.2	16.2 11.7 31.2	15.2	17.1 19.2 17.1

D = DEPTH OF PACKING (FT)

SI CONVERSION:

mm = inches x 25.4
m^3/hr = GPM x .227
m = feet x .3048
F_s (SI) = F_s (ENG) x 1.22

STANDARD DEVIATIONS FOR 1 INCH METAL PALL RINGS. 7 SPRAY DISTRIBUTOR

	50 GPM			150 GPM		
F_S / D	0	.5	1.5	0	.5	1.5
0	3.90	4.34	4.20	10.86	20.18	14.14
2	6.44	4.83	5.10	20.50	20.44	19.10
4	5.56	4.69	5.02	21.54	15.35	17.95

D = PACKING DEPTH (FT)

SI CONVERSION:

mm = inches x 25.4

m^3/hr = GPM x .227

m = feet x .3048

F_s (SI) = F_s (ENG) x 1.22

TABLE 5

STANDARD DEVIATIONS FOR
2 INCH METAL PALL RINGS.
7 SPRAY DISTRIBUTOR

	50 GPM			150 GPM		
D \ F_S	0	.5	1.5	0	.5	1.5
0	3.90	4.34	4.20	10.86	20.18	14.14
2	4.47	4.70 4.84	4.42	10.20	27.00	26.44
4	9.00	4.02	5.99	21.38	18.47	19.38

D = PACKING DEPTH (FT)
SI CONVERSION:
mm = inches x 25.4
m^3/hr = GPM x .227
m = feet x .3048
F_S (SI) = F_S (ENG) x 1.22

TABLE 6

STANDARD DEVIATIONS AVERAGED OVER AIR FLOW RATE.

GPM	PACKING SIZE (in) / PACKING DEPTH (ft)	5/8	1	2
50	0	4.1	4.1	4.1
	2	6.2	5.5	4.6
	4	5.0	5.1	6.3
150	0	15.1	15.1	15.1
	2	27.0	20.0	21.2
	4	18.2	18.3	19.7

SI CONVERSION:

mm = inches x 25.4
m = feet x .3048
m^3/hr = GPM x .227

TABLE 7

EFFECT OF BED MIXING ON STANDARD DEVIATIONS (S)
5/8 INCH METAL PALL RINGS
7 SPRAY DISTRIBUTOR

BED DEPTH (FT)	2	2	2	4	4	4
F_s	0	1.5	.5	0	.5	1.5
GPM	50	50	150	50	150	50
S UNMIXED	6.7	7.6	23.3	5.6	11.1	6.7
S MIXED	5.1	6.2	27.5	4.8	15.2	6.5

SI CONVERSION:
mm = inches x 25.4
m^3/hr = GPM x .227
F_s (SI) = F_s (ENG) x 1.22
m = feet x .3048