

AN INVESTIGATION OF THE  
CONCENTRATION GRADIENT ACROSS  
A TRAY OF A BUBBLE-CAP COLUMN

Thesis for the Degree of M. S.

MICHIGAN STATE COLLEGE

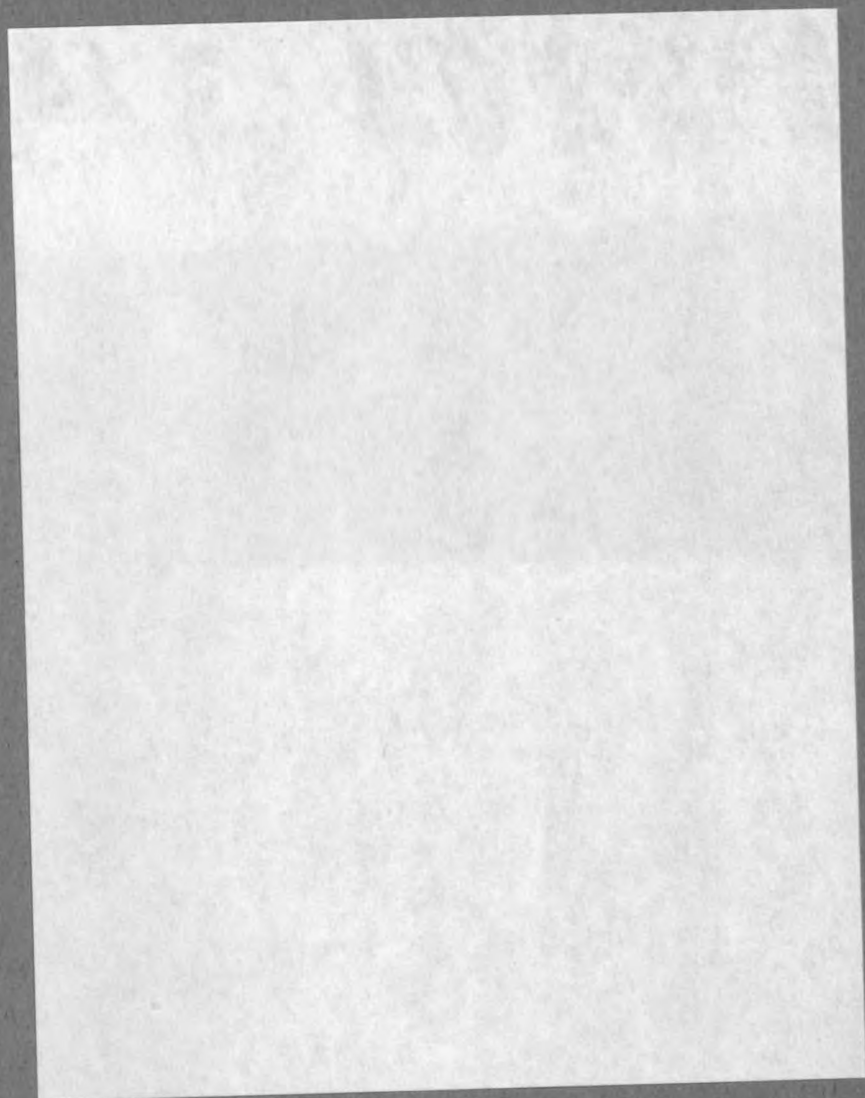
Webster Leroy Kaiser, Jr.

1949

THESIS







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AN INVESTIGATION OF THE CONCENTRATION GRADIENT  
ACROSS A TRAY OF A BUBBLE-CAP COLUMN

By

WEBSTER LEROY KAISER, JR.

A THESIS

Submitted to the School of Graduate Studies of Michigan  
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MASTER OF SCIENCE

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1949

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J. W. Donnell for his advice, counsel, and guidance.  
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and Mr. W. D. Clippinger for their suggestions and  
aid.

INTRO

HIST

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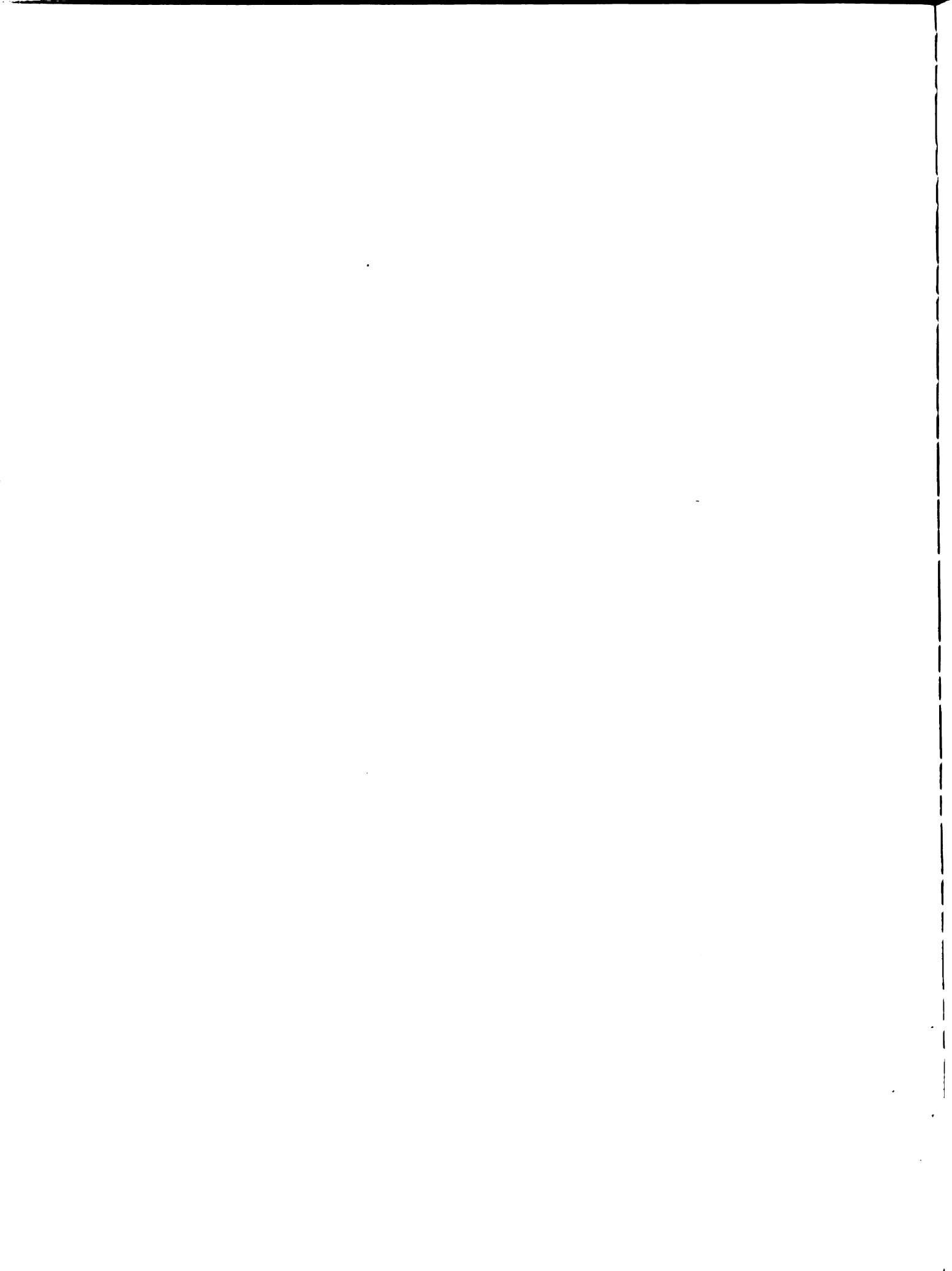
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## INTRODUCTION

The wide range of overall and plate efficiencies reported in the literature for bubble-cap columns is well known. Varying from the 7% calculated by Sherwood (12) from the data of Whitman and Davis (17) to 129% as stated by Brown (1). (A percentage over 100 apparently due to multi-vapor contacts on a single tray.)

Such a range of efficiencies indicates the need for more data on the operation characteristics of bubble-cap towers, particularly of commercial size.

The present work was concerned with the concentration distribution in the liquid on a bubble-cap tray. In order to study the concentration distribution independently of temperature variation, it was decided to use absorption rather than distillation. The bubble-cap tower constructed for this work was four feet in diameter. Four alternating liquid flow direction trays were spaced at twelve inches, with seventy slotted caps per tray. Sixty-two samples were taken simultaneously on the first tray during each run. Because of the low efficiency of the tower used by Whitman and Davis with carbon dioxide, it was decided to investigate the concentration distribution using carbon dioxide. Ethyl alcohol was used for comparison with reported data taken on smaller towers.

## HISTORY

Almost all of the data on concentration gradient reported in the literature is based on small laboratory columns.

Kirschbaum (3,4,5) reported on ethyl alcohol-water rectification using a single 52 mm. bubble-cap on a tray approximately 107 mm. (scaled from his drawing) inside diameter. He took four samples on this tray. Some of his results are reproduced in the discussion section.

Peavy and Baker (9) also used the ethyl alcohol-water system in their work. They reported on a 3 tray, 12 inch diameter inside, fractionating tower, with ten caps per tray arranged in three rows. Four samples were taken on this tray. The liquid was sampled entering, past the first row of caps, past the second row, and leaving the tray. Some of their data is also reproduced in the discussion section.

Murphree (8) developed two equations for distillation plate efficiency:

Diffusional resistance in vapor film governing,

$$E_{MV} = \frac{y_n - y_{n-1}}{y_n^* - y_{n-1}}$$

Liquid film resistance controlling,

$$E_{ML} = \frac{x_{n+1} - x_n}{x_{n+1} - x_n^*}$$

The values of  $x$  and  $y$  are the average mole fractions of the

liquid and

according to

entire pl

Let

on a al t

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assumpti

out mixi

insted,

and the

vapor,

factor

by our

trays

point

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liquid and vapor leaving a plate as defined by Murphee. Accordingly the efficiency refers to the performance of an entire plate.

Lewis (7) developed an equation for point efficiency on a plate for binary mixtures. He based this equation, for alternating liquid flow direction, on the following assumptions: That the liquid flowed across the plate without mixing, that vapor-film diffusional resistance predominated, that vapor rose through the column without mixing, and that the liquid was continually contacted with fresh vapor, as it flowed across the plate. His equation follows:

$$E_{TV} = \frac{e^{F_{MVP}\lambda} - 1}{\lambda}$$

A very thorough and comprehensive test covering many factors was made on a large commercial distillation column by Guinness (2). However, he did not take samples across trays, but used the method of Lewis to calculate the Murphee point efficiencies.

More data on concentration gradient, especially on large equipment with many sample determinations is, therefore, beneficial.





## EQUIPMENT

Drawings of the column, details of the sample location and arrangement, photographs of the tower and of the CO<sub>2</sub> analysis equipment follow this listing of other equipment and specifications.

Bubble-Cap Specifications:

Caps; 250 - 3 in. O.D. x 0.065 in. thick copper caps,  
70 per tray.

42 - 3/32 inch. wide x 13/16 inch high slots  
per cap.

Top of slot 7/8 in. above bottom edge of  
cap. Bottom of slot 0.0625 in. above  
plate. Slot area per cap = 3.12 sq. in.

Risers; 250 - 2 1/8 in. O.D. x 0.065 in. thick copper.  
Integral yoke style. 70 per tray.  
Overflow 1 7/16 in. above riser flange,  
1.35 in. above plate. Riser area equals  
3.14 sq. in.

General; Annular area equals 2.94 sq. in.

(Vulcan Copper and Supply Co., Cincinnati 2, Ohio.)

Fan (CM 1358): Type W, Design No. 3, Size 2 1/4, Serial No.  
100085.

(Clarage Fan Co., Kalamazoo, Michigan.)

Induction 'Red Band' Motor (CM 1434): Serial No. 808E 1

|           |                    |             |            |
|-----------|--------------------|-------------|------------|
| H.P. 40   | Frame 44           | R.P.M. 1760 | Type K     |
| Phase 3   | Cycles 60          | Rise 55     | Code F     |
| Volts 220 | Amps. 94.2         | Volts 440   | Amps. 47.1 |
| G.F. 8853 | (Connected 440 v.) |             |            |

140 - #701 1/4 in. Tube 1/8 in. Pipe Thread Connector  
Fittings.

(Charles A. Strelinger Co., Detroit 26, Michigan)

Beckman Model G pH Meter (CM 558): No. 2608

Chicago Scientific Co., Chicago, U.S.A.

(National Technical Laboratories, South Pasadena,  
California.)

External electrodes for pH meter.

1170 Calomel, Cenco 21144

1190 Glass, Cenc. 21106

(National Technical Laboratories, South Pasadena,  
California.)

Chainomatic Westphal Balance (CM 317): B-20766

(Christian Becker, Inc., New York.)

U.S.P. Alcohol: Proof 100, W.G. 54

P.G. 102.6

(U.S. Industrial Chemicals, Inc.)

CO<sub>2</sub> : 10-50 lb. cylinders 99.5%

(Pure Carbonic, Inc., New York, New York)

205 feet of 1/4" Copper Tubing:

| TOTAL SAMPLE TUBE LENGTH: |     |     |     |     |     |     |     |     |     |     |
|---------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|                           | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
| A                         | 44  | 43  | 43  | 52  | 46  | 40  | 38  | 30  |     |     |
| B                         | 47  | 43  | 50  | 50  | 48  | 46  | 43½ | 39½ | 36½ |     |
| C                         | 39½ | 34  | 33½ | 43  | 47  | 43  | 45  | 28  | 20  | 19½ |
| D                         | 33½ | 35½ | 35½ | 36½ | 33½ | 30½ | 27½ | 25½ |     |     |
| E                         | 30½ | 28½ | 25½ | 34  | 34  | 32½ | 30½ | 24½ | 19½ | 16½ |
| F                         | 21½ | 25½ | 27½ | 23½ | 23½ | 28½ | 23½ | 20½ | 17½ |     |
| G                         | 20  | 22½ | 24½ | 24½ | 24½ | 22½ | 20½ | 17½ |     |     |

TUBE LENGTH OF SAMPLE TUBES--INCHES

|          | BOTTOM | MIDDLE | TOP |
|----------|--------|--------|-----|
| Down in  | 5½     | 7½     | 9½  |
| out      | 1      | 3½     | 6½  |
| Down out | 4      | 2½     | 4½  |

Also manifold and bottle connection  
tubing—individually fitted.





DRILL 7 -  $\frac{19}{32}$  D HOLES FOR PLATE SUPPORTS  
6 ON 44 D CIRCLE 1 IN CENTER OF PLATE

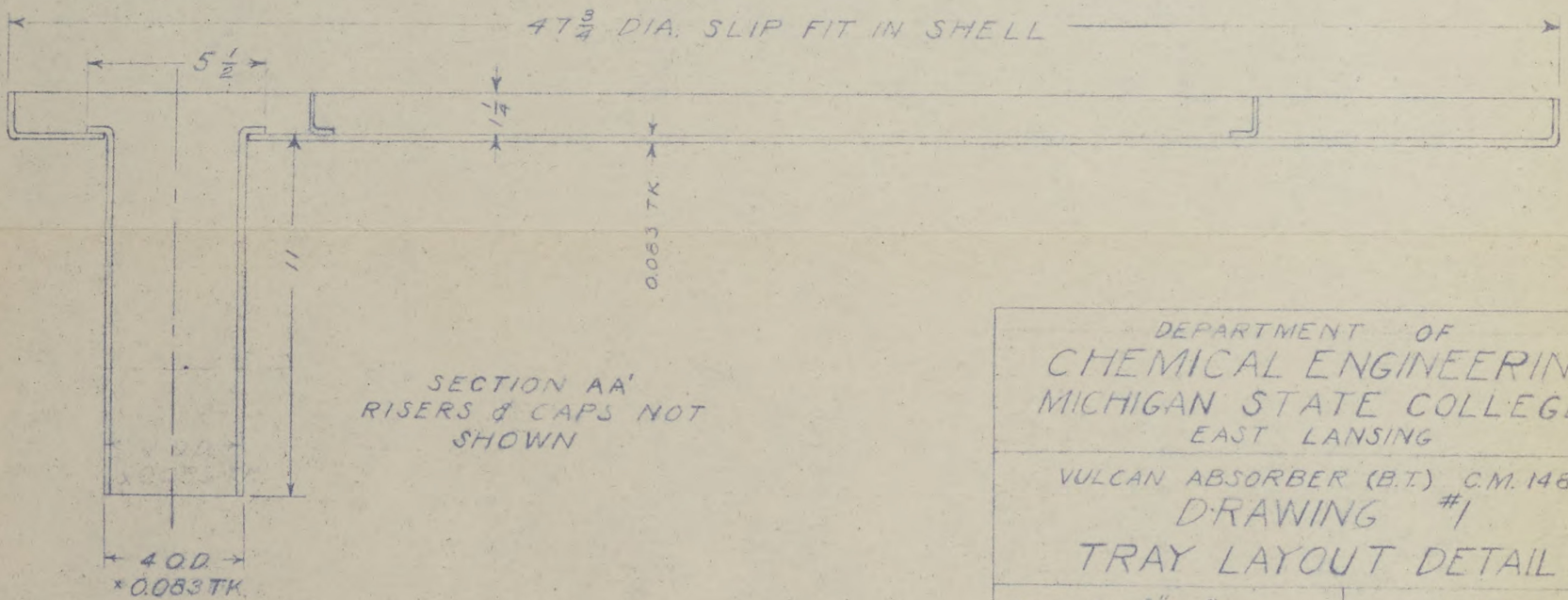
$\frac{1}{8} \times \frac{3}{4} \times \frac{1}{8}$  OVERFLOW WEIR  
DRILL 8 -  $\frac{9}{32}$  D HOLES FOR  
8 -  $\frac{1}{4}$  D  $\times \frac{3}{4}$  LG. BOLTS w 1  
HEX. NUT PEEN BOLT ENDS

$\frac{1}{2} \times \frac{3}{4} \times \frac{1}{8}$  DISTRIBUTING WEIR  
DRILL 8 -  $\frac{9}{32}$  D HOLES FOR  
8 -  $\frac{1}{4}$  D  $\times \frac{3}{4}$  LG. BOLTS w 1  
HEX. NUT PEEN BOLT ENDS

DRILL 2 -  $4 \frac{1}{8}$  HOLES  
FOR 4 O.D.  $\times$  0.083 TK.  
DOWNPIPES DRILL 4  
 $\frac{9}{32}$  D HOLES ON  $4 \frac{1}{8}$  D B.C.  
FOR 4 -  $\frac{1}{4}$  D  $\times \frac{3}{4}$  LG. BOLTS  
w 1 HEX. NUT PEEN  
BOLT ENDS

DRILL 70 -  $2 \frac{3}{16}$  D HOLES ON  $4 \frac{1}{4}$  TRIANGULAR  
CENTERS FOR 70 -  $2 \frac{1}{8}$  O.D. RISERS & 70 - 3  
O.D.  $\times$  0.065 TK. PRESSED CAPS - CROWN  
RADIUS TYPE

37 - APPROX. LENGTH OF WEIR



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EAST LANSING

VULCAN ABSORBER (B.T.) C.M. 1481  
DRAWING #1

TRAY LAYOUT DETAIL

SCALE:  $\frac{3}{16} = 1"$   
MATL: COPPER  
DATE: 11-29-49

DRAWN & TRACED: W.K.  
CHECKED: *[Signature]*  
PRINT: DEPT. ENG. DRAW.

MFGR. BY  
VULCAN COPPER & SUPPLY CO.





1/2 inch x 1/2 inch  
 5/8 inch x 1/2 inch  
 1/2 inch x 1/2 inch  
 1/2 inch x 1/2 inch

1/2 inch x 1/2 inch  
 5/8 inch x 1/2 inch  
 1/2 inch x 1/2 inch

1/2 inch x 1/2 inch  
 5/8 inch x 1/2 inch

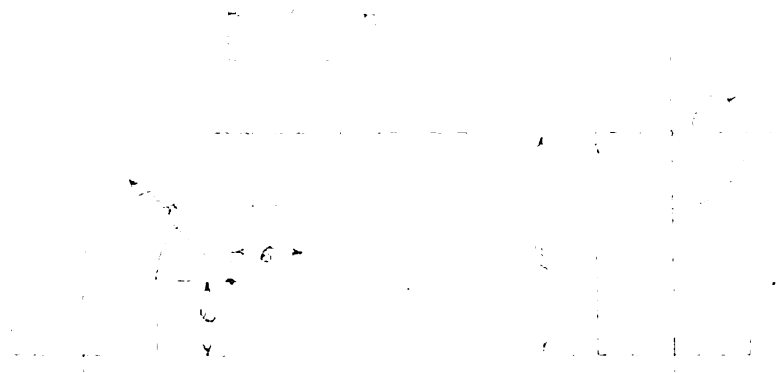
BOTTOM CORNER  
 1/2 inch x 1/2 inch

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 UNIVERSITY OF CALIFORNIA  
 BERKELEY  
 100 TOWNSEND HALL  
 BERKELEY, CALIF.

7-6-49

1/2 inch x 1/2 inch





1. 1/2" DIA. TO 1/4"

1. 1/2" DIA. TO 1/4"

1. 1/2" DIA. TO 1/4"

1. 1/2" DIA. TO 1/4"

1. 1/2" DIA. TO 1/4"

1. 1/2" DIA. TO 1/4"

1. The curve A is a straight line from the origin to the point (1, 1) and then continues as a horizontal line.

2. The curve B is a straight line from the origin to the point (1, 1) and then continues as a horizontal line.



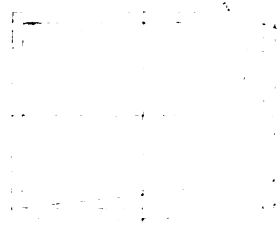
3. The curve C is a straight line from the origin to the point (1, 1) and then continues as a horizontal line.

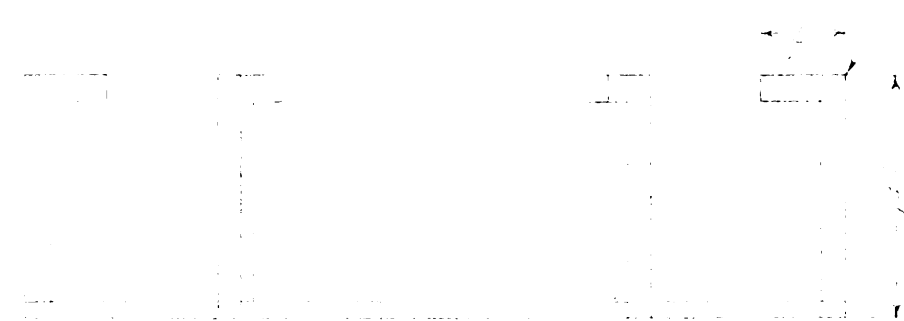
4. The curve D is a straight line from the origin to the point (1, 1) and then continues as a horizontal line.

8. 10. 1974  
10. 10. 1974



10. 10. 1974  
10. 10. 1974





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VULCAN ABSORBER (BT) CM-1481

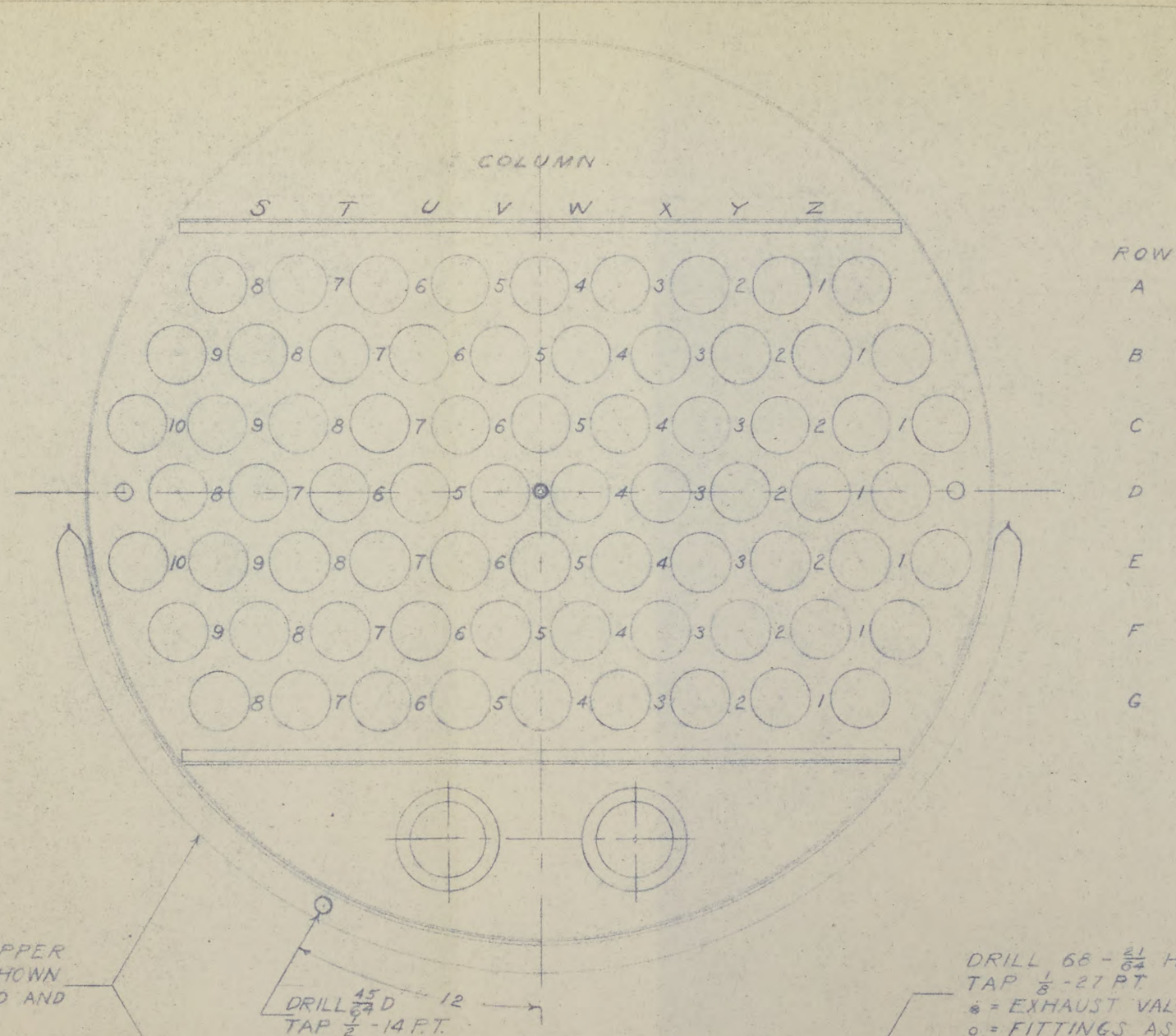
DRAWING No. 8

SAMPLE TUBE LOCATION

SCALE:  $1\frac{1}{2}" = 1'$   
MATL.: AS SHOWN  
DATE: 12-5-49

D.&T.: WLK  
CHECKED: *[Signature]*  
PRINT: D.E.D.

INVISIBLE LINES  
NOT SHOWN

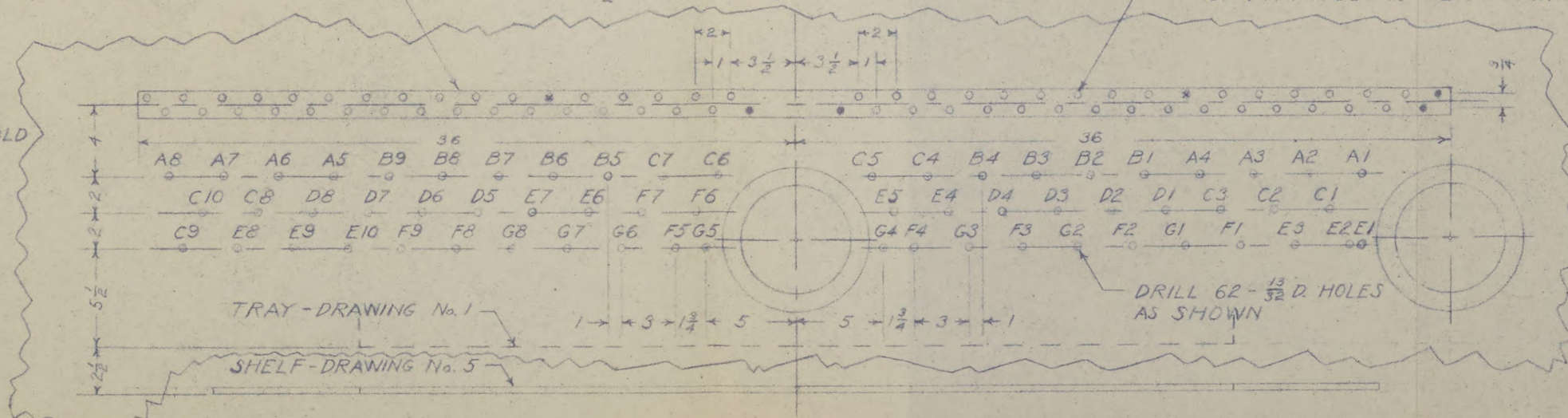


MANIFOLD -  $1\frac{1}{2} \times 12$  COPPER  
TUBE SHAPED AS SHOWN  
WITH ENDS PINCHED AND  
BRAZED

DRILL  $\frac{45}{64}$  D 12  
TAP  $\frac{1}{2}$  - 14 P.T.

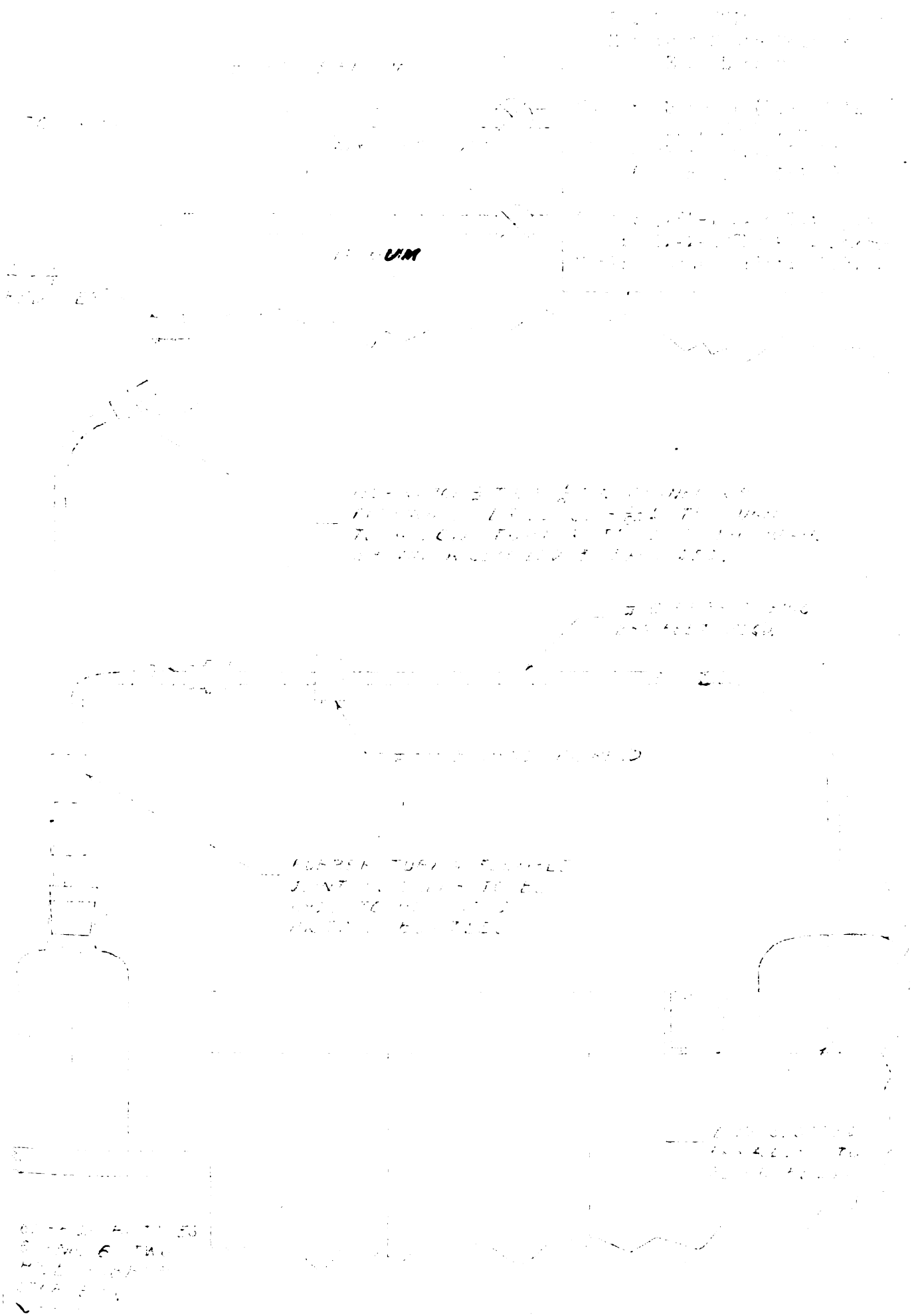
DRILL  $66 - \frac{21}{64}$  HOLES AS SHOWN  
TAP  $\frac{1}{8}$  - 27 P.T.  
\* = EXHAUST VALVES • = BLANKED OFF  
o = FITTINGS AS PER DRAWING No. 9

SHELL & MANIFOLD  
SHOWN FLAT



DRILL  $62 - \frac{13}{32}$  D. HOLES  
AS SHOWN









TO PITOT TUBE

1 INCH WATER PIPE  
SCHEMATIC

ATTACHES TO  
EXHAUST OF FAN

PRESS.  
VACUUM

WATER  
METER

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DRAWING No. 10

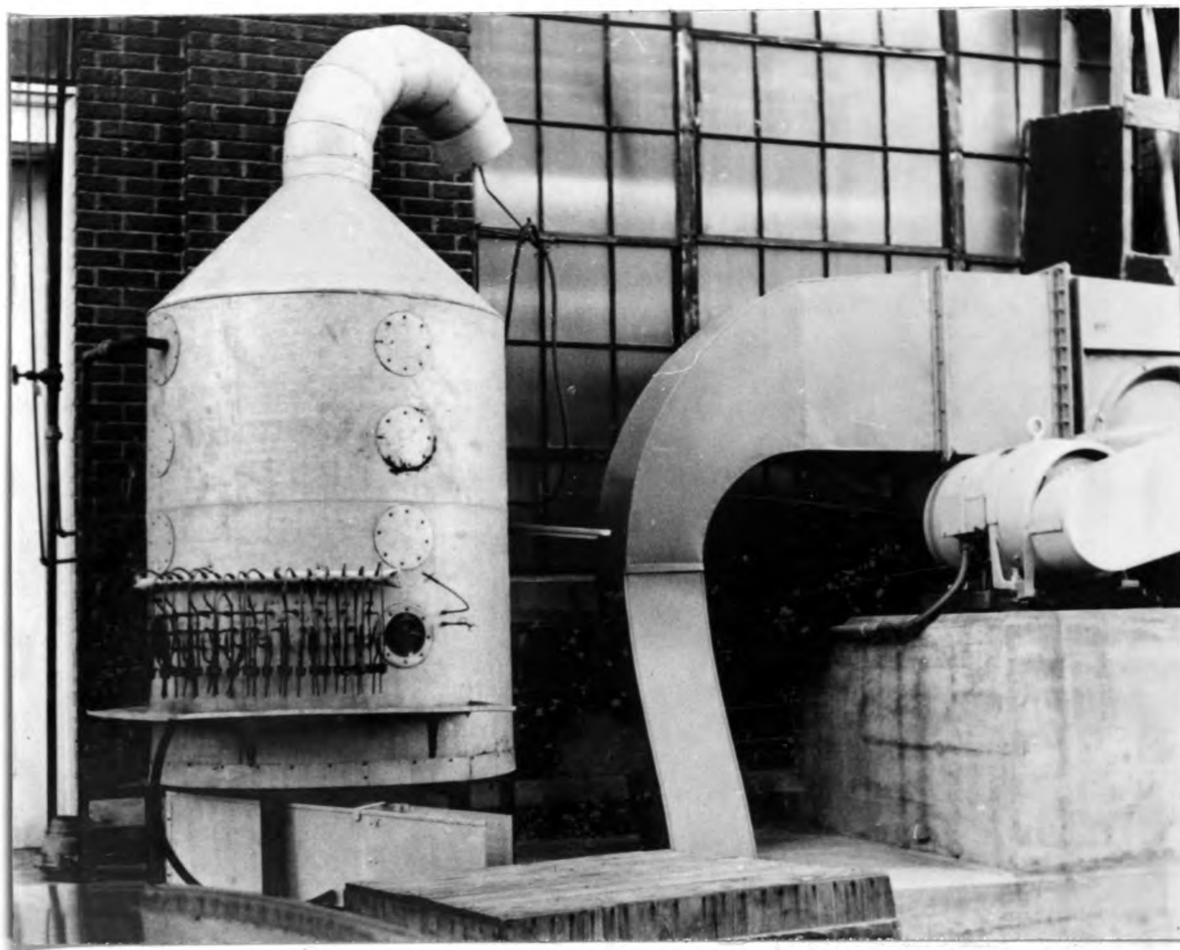
ASSEMBLY

Nos. REFER TO DETAILS

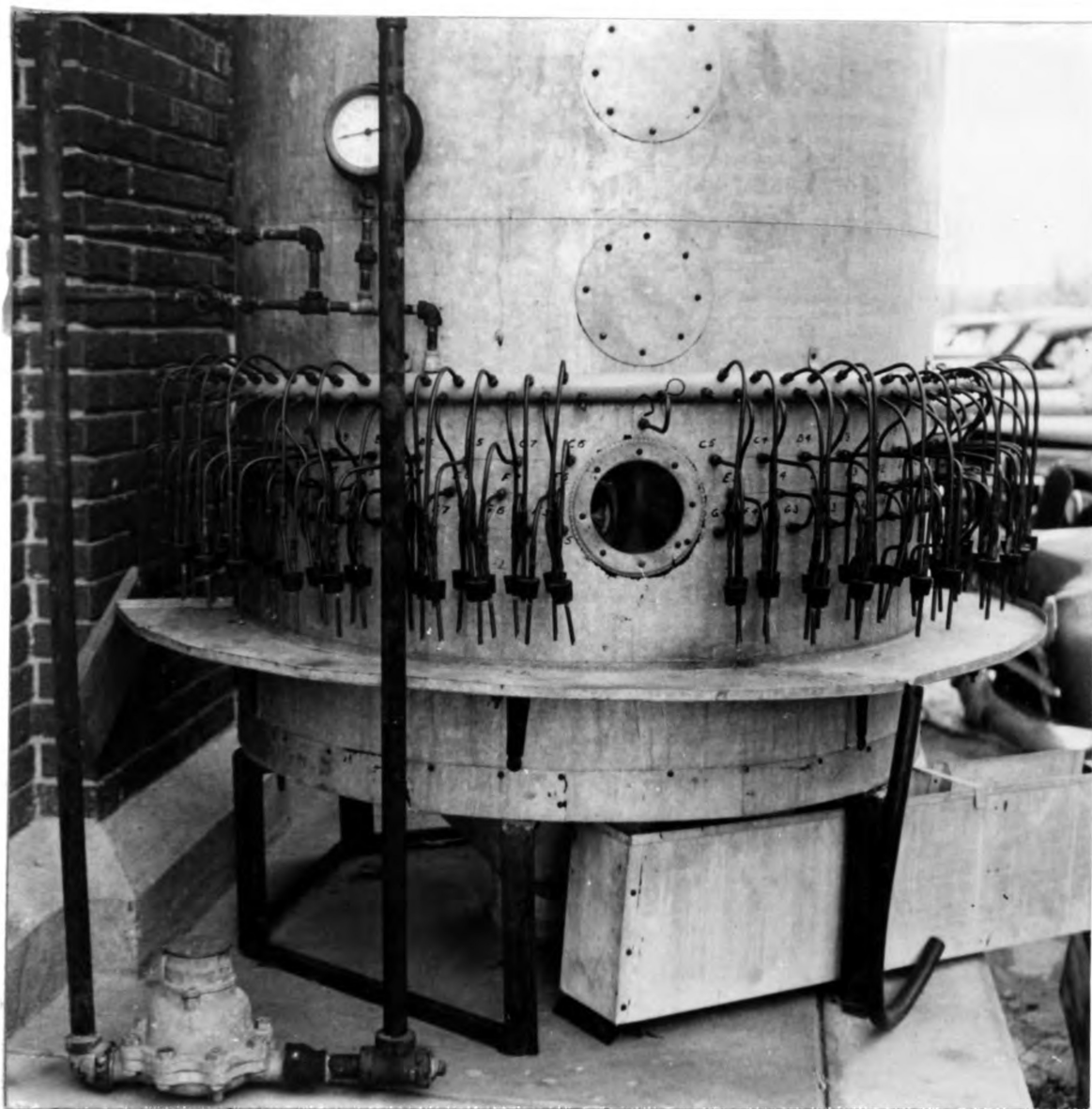
SCALE:  $\frac{3}{4}$ " = 1'  
MATL: SEE DETAILS  
DATE: 12-6-49

D. & T.: WLK  
CHECKED: J. J.  
PRINT: D. E. D





Photograph No. 1 - Tower constructed for this work.



Photograph No. 2 - Showing the manifold, piping, weir box, shelf, and sampling taps.



Photograph No. 3 - The analysis equipment for carbon dioxide sample determinations.

Photography by Smith & author.

## RUN PROGRAMME FOR CARBON DIOXIDE

A cylinder of fifty pounds of carbon dioxide was weighed. It was set up in an inclined rack with the discharge opening downward and directed to the intake duct of the fan. The cylinder was thus placed to make available all of the contents of the tank.

The sixty-two sample bottles were weighed before the first and second runs. Since there was no significant change in the weights of the bottles, this was not followed in the subsequent runs. A random weighing of ten bottles was made prior to these runs and no change was noted that was significant enough to justify weighing all the bottles. These weights always checked within 0.1 gram which was a relative error of  $\pm 0.00055$ .

To each of the bottles 100 ml. of the  $\text{Ba}(\text{OH})_2$  solution was added. The weight of 100 ml. of the  $\text{Ba}(\text{OH})_2$  having been determined by several weighings. Each bottle was stoppered immediately after filling to reduce to a minimum the absorption of carbon dioxide from the air. After all the bottles were thus prepared, they were attached to the sample taps on the tower. The water was then turned on to the column. When the water filled the weir box and started to overflow the weir, the fan was started to force air through the tower. The order of these last two operations was important. If the fan was started before the trays were full of water, the

water would be immediately forced into the sample bottles because of the low head. When the proper water and air rates had been attained, carbon dioxide was discharged from the cylinder into the intake duct of the fan. At the same time the water meter was read and a stop watch started. During the run the pitot tube manometer reading was recorded.

Since a cylinder of carbon dioxide was exhausted in about a minute and a half, no run was of longer duration. Naturally the question of having attained equilibrium arises with a run of such short duration. Since a complete change of water occurs in the column every seventy seconds and the gas changes even faster, seventy seconds after beginning the operation of the tower no variables would be affected. Upon this basis equilibrium was assumed to have been attained after seventy seconds. Because of the almost instantaneous method of drawing all of the samples, a concentration gradient would be detected, if present, whether equilibrium was attained or not.

Just prior to drawing the samples, the air pressure valve to the manifold was opened briefly to purge the sample lines. This step was not followed in runs where liquid from the tray was forced into any of the bottles to the height of the inlet tube prior to the general sample drawing. As this step would force  $\text{Ba}(\text{OH})_2$  onto the tray and put adjacent samples in error. The vacuum valve was then opened to draw the samples. After the vacuum valve was closed, the carbon dioxide was shutoff,

the water meter read, and the watch stopped. The fan and water were shut off. The sample bottles were then removed and immediately stoppered preparatory to analysis.

Sixty-two No. 6 rubber stoppers had each been ground to the weight of 28.6 grams. In this way no time was lost in attempting to fit a definite stopper to a definite bottle, as would have been necessary so that the individual sample weights could be determined. It was possible, by the method used, to stopper the bottles immediately after removal from the sample taps with a minimum exposure of the contents to the air.

After the analysis of the samples was completed, the carbon dioxide tank was reweighed to determine the quantity of  $\text{CO}_2$  used.

## RUN PROCEDURE FOR ETHYL ALCOHOL

A five gallon bottle containing ethyl alcohol was set up at the inlet duct to the fan. The bottle and its contents having been weighed. An aspirator was installed in the bottle and attached to the 100 psig air line. Several aspirators were constructed for this purpose.

The sample bottles were attached to the taps of the tower. The column was put into operation following the same order of starting as was described in the carbon dioxide run procedure. When the proper water and air rates were obtained, the air to the aspirator was turned on, care being taken that the air would not be oversaturated, i.e. no droplets of alcohol would reach the plate. The reading of the water meter was recorded, and the stop watch started. Since the supply of alcohol could be observed in the bottle, the tower was operated until approximately three-quarters of the amount had been charged to the column. The manometer of the pitot tube was checked repeatedly during this time.

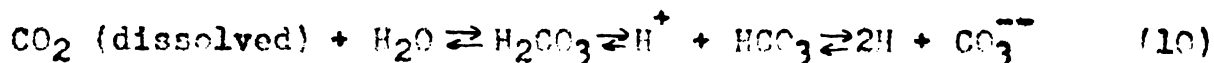
The sample procedure for drawing the samples and shutting down the column as was discussed for carbon dioxide was followed. The bottle and remaining ethyl alcohol being weighed to determine the quantity of alcohol used.



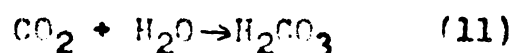


## ANALYSIS PROCEDURE FOR CARBON DIOXIDE

When carbon dioxide dissolves in water, the equilibrium may be written as follows:



If the pH of the liquid medium in which the hydration takes place is less than 8, the reaction is practically



The amount of free carbonic acid present in the dilute aqueous solution was determined by adding the sample to an excess of barium hydroxide and titrating the excess with HCl. Treadwell and Hall (13) specified that phenolphthalein be used as an indicator in this determination. The reason being that the carbonate does not begin to dissolve until the solution is more acid than corresponds to the end point of phenolphthalein. Thus, the mixture of soluble  $\text{Ba(OH)}_2$  and insoluble  $\text{BaCO}_3$  can be titrated with HCl and an end point obtained as soon as the  $\text{Ba(OH)}_2$  has been completely neutralized (14). Phenolphthalein was used in the first run, but it was most difficult to detect the end point. In subsequent runs a Beckman Model G pH meter was used. The titration being carried to a pH of 9. This value being within the pH range of phenolphthalein, namely 8.8 to 9.0 from base to acid (15).

The  $\text{Ba(OH)}_2$  solutions were mixed according to the method recommended by Treadwell and Hall, with slight modifi-

cation. According to Treadwell and Hall:

"The crystallized barium hydroxide of commerce always contains barium carbonate, so that the solution cannot be prepared by simply weighing out the necessary quantity and diluting to one liter. Dissolve about 20 grams of the commercial hydroxide in the necessary amount of distilled water within a large flask and shake until the crystals have completely disappeared and a light, insoluble powder of barium carbonate remains. Allow the solution to stand for two days, until the barium carbonate has completely settled; siphon it off into a bottle through which a current of air free from carbon dioxide has been passed for two hours previous. Connect this bottle with a soda-lime tube and with a buret....." (16).

Since 20 grams is recommended, while the theoretical is 15.78 grams, four-thirds of the theoretical were used in mixing the five gallon batches of the normalities used. The passing of air free from carbon dioxide into the bottle was dispensed with, as it was found unnecessary.

The  $\text{Ba}(\text{OH})_2$  solutions thus prepared were standardized against 0.1N HCl with an end point of pH 9. Solutions of HCl were prepared in the usual way and standardized against the  $\text{Ba}(\text{OH})_2$  solution used in each run. The end point also being pH 9.

Following a run, the sample bottles were weighed. Since the weight of the bottle, stopper, and  $\text{Ba}(\text{OH})_2$  solution added was known, the weight of each sample drawn was determined by difference. The excess barium hydroxide was then determined by titration with HCl of approximately the same normality as the  $\text{Ba}(\text{OH})_2$  used in the run. The titration being carried to an end point of pH 9.



Barium hydroxide of 0.0235 normality was originally used to determine the amount of  $\text{Ba}(\text{OH})_2$  necessary to raise one gram of the absorber water to pH 9. This correction was then applied to the concentration calculations as shown in the section on calculations.

## ALCOHOL ANALYSIS PROCEDURE

The density of the alcohol-water solutions was determined by a chainomatic Westphal balance. The densities then converted to per cent alcohol by weight using a graph (Fig. 1). This graph was plotted from Table IX. The 0%, 1%, 2%, and 3% concentration data at 10°C, 15°C, 25°C, 30°C, 35°C, and 40°C, and the more complete data available for 20°C are reproduced in Table IX from the handbooks of Perry and Lange (6). The intermediate values were interpolated on the basis of the more complete data available at 20°C.

# FIGURE 1

PARAMETER  $Wt. \% S_2 H_2 O$

0.9970

0.9960

0.9950

0.9940

0.9930

0.9920

0.9910

0.9900

0.9890

0.9880

DENSITY g/ml  $20^\circ C$

1%

2%

3%

TEMPERATURE  $^\circ C$

10

15

20

25

30

35

40



TABLE I

| SAMPLE | W <sub>1</sub> | W <sub>2</sub> | W <sub>3</sub> | W     | pH <sup>a</sup> | pH <sup>b</sup> |
|--------|----------------|----------------|----------------|-------|-----------------|-----------------|
| E1     | 181.9          | 299.7          | 384.7          | 85    | 9.48            | 9               |
| E2     | 183            | 300.8          | 417.9          | 117.1 | 9.42            | 9               |
| A1     | 182.3          | 300.1          | 394            | 93.9  | 9.4             | 9               |
| C1     | 182.3          | 300.1          | 385.6          | 65.5  | 9.4             | 9               |
| E3     | 181.9          | 299.7          | 391.5          | 91.8  | 9.4             | 9               |
| F1     | 182.7          | 300.5          | 399.2          | 99.7  | 9.98            | 9               |
| C2     | 182.3          | 300.1          | 393            | 95.9  | 9.43            | 9               |
| A2     | 182.8          | 300.6          | 433.3          | 152.7 | 9.45            | 9               |
| C3     | 182.9          | 300.7          | 445.1          | 145.4 | 9.4             | 9               |
| A3     | 182.2          | 300            | 393.3          | 93.3  | 9.81            | 9               |
| G1     | 181.8          | 299.6          | 447            | 147.4 | 9.42            | 9               |
| A4     | 182.0          | 299.8          | 407.2          | 137.4 | 9.4             | 9               |
| D1     | 182.8          | 300.6          | 404.9          | 134.3 | 9.42            | 9               |
| F2     | 182.0          | 299.8          | 416.6          | 113.8 | 9.4             | 9               |
| D2     | 183.1          | 300.9          | 374            | 73.1  | 10.15           | 9               |
| B1     | 183.1          | 300.9          | 408.1          | 107.2 | 9.4             | 9               |
| G2     | 183.1          | 300.9          | 409.1          | 108.2 | 9.4             | 9               |
| F3     | 183.1          | 300.9          | 430.3          | 129.7 | 9.43            | 9               |
| D3     | 183            | 300.8          | 359.1          | 58.3  | 10.28           | 9               |
| B2     | 182.8          | 300.6          | 415.5          | 114.9 | 9.39            | 9               |
| G3     | 182.1          | 299.9          | 413.8          | 113.9 | 9.39            | 9               |
| D4     | 182.4          | 300.2          | 441.3          | 141.1 | 9.42            | 9               |
| B3     | 183.2          | 301.0          | 420.9          | 119.9 | 9.4             | 9               |
| B4     | 182.3          | 300.6          | 442            | 141.4 | 9.43            | 9               |
| E4     | 182.8          | 300.6          | 449.9          | 149.3 | 9.42            | 9               |
| F4     | 182.1          | 299.9          | 437.1          | 137.2 | 9.42            | 9               |
| C4     | 182.1          | 299.9          | 433.2          | 133.1 | 9.43            | 9               |
| G4     | 182.4          | 300.2          | 459.7          | 159.5 | 9.45            | 9               |
| E5     | 181.5          | 299.3          | 373.9          | 79.6  | 10.09           | 8-96            |
| C5     | 183.1          | 300.9          | 367.7          | 36.3  | 10.56           | 9               |
| A6     | 182.2          | 300.0          | 385.5          | 85.5  | 9.32            | 9               |
| C9     | 182.0          | 299.8          | 403.4          | 103.6 | 9.32            | 9               |
| C10    | 182.0          | 299.8          | 401.7          | 101.9 | 9.4             | 9               |
| E9     | 182.4          | 300.2          | 413.3          | 113.1 | 9.17            | 9               |
| C8     | 182.1          | 299.9          | 403.3          | 103.7 | 9.4             | 9               |
| E6     | 182.7          | 300.5          | 426.1          | 126.6 | 9.33            | 9               |
| A7     | 183.2          | 301.0          | 395.9          | 94.9  | 9.55            | 9               |
| A6     | 183.4          | 301.2          | 411.1          | 99.9  | 9.43            | 9               |
| B9     | 183.1          | 300.9          | 421.3          | 121.0 | 9.4             | 9               |
| F9     | 183.2          | 300.9          | 420.1          | 120.1 | 9.7             | 9               |
| A5     | 183.1          | 300.9          | 420.9          | 120.9 | 9.37            | 9               |
| D7     | 183.6          | 300.4          | 366.8          | 86.4  | 10.02           | 9               |
| D3     | 183.4          | 301.2          | 424.2          | 123.0 | 9.4             | 9               |
| E10    | 182.9          | 300.7          | 417.6          | 116.9 | 9.41            | 9               |
| G7     | 182.2          | 300.0          | 439.5          | 139.5 | 9.47            | 9               |
| D5     | 182.0          | 299.8          | 442.7          | 142.9 | 9.37            | 9               |

RUN NO. 3 - CO<sub>2</sub>

| A     | N <sub>A</sub> A | EN <sub>B-N<sub>A</sub>A</sub> | $\frac{EN_{B-N_A A}}{N} \times 10^5$ | C x 10 <sup>4</sup> | C' x 10 <sup>5</sup> |
|-------|------------------|--------------------------------|--------------------------------------|---------------------|----------------------|
| 19.2  | 0.1409           | 0.714                          | 8.4                                  | 2.16                | 9.6                  |
| 18.3  | 0.181            | 0.674                          | 5.65                                 | 1.45                | 2.5                  |
| 14.6  | 0.1445           | 0.710                          | 7.57                                 | 1.95                | 7.5                  |
| 14.8  | 0.1465           | 0.708                          | 6.29                                 | 2.13                | 9.3                  |
| 14.7  | 0.1453           | 0.709                          | 7.73                                 | 1.99                | 7.9                  |
| 33.3  | 0.579            | 0.476                          | 6.10                                 | 2.03                | 8.6                  |
| 13.6  | 0.1342           | 0.691                          | 7.22                                 | 1.63                | 6.6                  |
| 20    | 0.198            | 0.657                          | 4.95                                 | 1.77                | 0.7                  |
| 31.4  | 0.311            | 0.544                          | 5.53                                 | 1.42                | 2.2                  |
| 13.35 | 0.162            | 0.693                          | 6.44                                 | 1.65                | 4.5                  |
| 17.7  | 0.1752           | 0.680                          | 6.51                                 | 1.67                | 4.7                  |
| 17.45 | 0.1739           | 0.681                          | 5.84                                 | 1.50                | 3.0                  |
| 42.8  | 0.422            | 0.433                          | 5.93                                 | 1.52                | 3.2                  |
| 16.7  | 0.1353           | 0.590                          | 6.42                                 | 1.65                | 4.5                  |
| 17.4  | 0.1722           | 0.603                          | 6.31                                 | 1.62                | 4.2                  |
| 19.7  | 0.195            | 0.630                          | 5.10                                 | 1.31                | 1.1                  |
| 37.05 | 0.367            | 0.488                          | 6.37                                 | 2.15                | 9.5                  |
| 17.3  | 0.171            | 0.684                          | 5.95                                 | 1.53                | 3.3                  |
| 13.9  | 0.1372           | 0.628                          | 6.05                                 | 1.55                | 3.5                  |
| 17.5  | 0.173            | 0.632                          | 5.69                                 | 1.43                | 2.6                  |
| 13.7  | 0.1535           | 0.699                          | 4.99                                 | 1.22                | 0.8                  |
| 17.3  | 0.171            | 0.684                          | 4.98                                 | 1.28                | 0.8                  |
| 19.3  | 0.194            | 0.631                          | 4.85                                 | 1.75                | 0.5                  |
| 16.9  | 0.167            | 0.698                          | 5.12                                 | 1.32                | 1.2                  |
| 22.4  | 0.222            | 0.633                          | 7.95                                 | 2.04                | 8.4                  |
| 48.55 | 0.481            | 0.374                          | 10.16                                | 2.31                | 14.1                 |
| 11    | 0.199            | 0.746                          | 8.72                                 | 2.14                | 10.4                 |
| 12.8  | 0.127            | 0.723                          | 7.03                                 | 1.87                | 6.7                  |
| 18.45 | 0.153            | 0.702                          | 6.89                                 | 1.77                | 5.7                  |
| 7.55  | 0.0747           | 0.7803                         | 6.72                                 | 1.73                | 5.3                  |
| 14.1  | 0.1393           | 0.7134                         | 6.78                                 | 1.74                | 5.4                  |
| 13.75 | 0.136            | 0.719                          | 5.73                                 | 1.47                | 2.7                  |
| 13.5  | 0.134            | 0.721                          | 7.60                                 | 1.95                | 7.5                  |
| 13.9  | 0.187            | 0.668                          | 6.88                                 | 1.77                | 5.7                  |
| 13.55 | 0.134            | 0.691                          | 5.71                                 | 1.47                | 2.7                  |
| 20.55 | 0.203            | 0.342                          | 5.34                                 | 1.57                | 1.7                  |
| 13.5  | 0.133            | 0.702                          | 5.85                                 | 1.50                | 3.0                  |
| 20.25 | 0.206            | 0.349                          | 7.52                                 | 1.93                | 7.3                  |
| 13.35 | 0.132            | 0.693                          | 5.63                                 | 1.45                | 2.5                  |
| 13.9  | 0.187            | 0.668                          | 5.42                                 | 1.39                | 1.9                  |
| 19.95 | 0.1975           | 0.3375                         | 4.71                                 | 1.61                | 0.1                  |
| 13.5  | 0.1525           | 0.7015                         | 4.32                                 | 1.73                | 0.6                  |

TABLE I (Cont'd)

| SAMPLE | $V_1$ | $V_2$ | $V_3$ | $V$   | pH <sup>a</sup> | pH <sup>b</sup> |
|--------|-------|-------|-------|-------|-----------------|-----------------|
| C3     | 182.9 | 300.7 | 441.4 | 140.7 | 9.33            | 9               |
| B8     | 182.5 | 300.3 | 435.9 | 135.3 | 9.38            | 9               |
| D8     | 182.3 | 300.1 | 435.4 | 135.3 | 9.32            | 9               |
| F3     | 182.2 | 300.0 | 445.6 | 145.6 | 9.43            | 9               |
| F5     | 182.9 | 300.7 | 438.2 | 137.5 | 9.51            | 9               |
| E3     | 182.2 | 300.0 | 354.3 | 52.3  | 10.4            | 8.98            |
| G3     | 181.8 | 299.6 | 437.2 | 137.6 | 9.4             | 9               |
| B3     | 182.6 | 300.4 | 456   | 137.6 | 9.42            | 9               |
| B7     | 183.0 | 300.8 | 427.8 | 137.0 | 9.43            | 9               |
| E7     | 182.6 | 300.4 | 437.8 | 137.4 | 9.43            | 9               |
| F6     | 187.9 | 300.7 | 366.2 | 87.5  | 10.0            | 8.92            |
| G5     | 182.9 | 300.7 | 440.4 | 139.7 | 9.4             | 9               |
| C6     | 182.3 | 300.1 | 359.9 | 39.8  | 10.53           | 8.98            |
| C7     | 181.8 | 299.6 | 349.1 | 49.5  | 10.42           |                 |
| B5     | 183.0 | 300.8 | 442.4 | 141.6 | 9.41            | 9               |
| F7     | 182.8 | 300.6 | 441.9 | 141.3 | 9.41            | 9               |

Solution Data: 0.00955 N  $\text{Ba}(\text{OH})_2$   
 0.0099 N HCl

Calculation Data: 100 mls. of  $\text{Ba}(\text{OH})_2$  plus  
 stopper weighed 117.8 gms.

| A     | N <sub>A</sub> A | EN <sub>B</sub> -N <sub>A</sub> A | $\frac{EN_B - N_A A}{W}$ | $\times 10^3$ | C $\times 10^4$ | C' $\times 10^5$ |
|-------|------------------|-----------------------------------|--------------------------|---------------|-----------------|------------------|
| 13.8  | 0.108            | 0.639                             | 4.93                     |               | 1.26            | 0.6              |
| 15.4  | 0.1524           | 0.7026                            | 5.13                     |               | 1.33            | 1.3              |
| 15.6  | 0.154            | 0.731                             | 5.13                     |               | 1.33            | 1.3              |
| 19.0  | 0.198            | 0.637                             | 4.65                     |               | 1.20            | 0.0              |
| 9.8   | 0.092            | 0.765                             | 5.55                     |               | 1.43            | 2.3              |
| 3.90  | 0.333            | 0.469                             | 3.97                     |               | 2.30            | 11.0             |
| 15.3  | 0.161            | 0.634                             | 5.04                     |               | 1.30            | 1.0              |
| 13.95 | 0.168            | 0.687                             | 5.00                     |               | 1.29            | 0.9              |
| 13.8  | 0.136            | 0.659                             | 4.81                     |               | 1.24            | 0.4              |
| 17.7  | 0.175            | 0.603                             | 4.94                     |               | 1.27            | 0.7              |
| 19.85 | 0.197            | 0.653                             | 7.52                     |               | 1.93            | 7.3              |
| 15.35 | 0.152            | 0.733                             | 5.03                     |               | 1.29            | 0.9              |
| 45.4  | 0.473            | 0.376                             | 9.44                     |               | 2.52            | 12.2             |
| 14.15 | 0.14             | 0.715                             | 5.06                     |               | 1.3             | 1.0              |
| 13.6  | 0.164            | 0.731                             | 4.93                     |               | 1.27            | 0.7              |

## Operation Data:

## Liquid Rate

| Check | a    | b    | c    | d    | e    | f    |
|-------|------|------|------|------|------|------|
| Gals. | 40   | 40   | 40   | 40   | 40   | 40   |
| Secs. | 79.7 | 77.2 | 73.7 | 73.4 | 80.2 | 80.2 |

## Gas Rate

## Manometer Readings

3.2" H<sub>2</sub>O3.3" H<sub>2</sub>O3.6" H<sub>2</sub>OLaboratory air used without the addition of CO<sub>2</sub>.

TABLE II

| SAMPLE | W <sub>1</sub> | W <sub>2</sub> | W <sub>3</sub> | W     | pH <sup>a</sup> | pE <sup>a</sup> |
|--------|----------------|----------------|----------------|-------|-----------------|-----------------|
| E1     | 181.9          | 300            | 487.4          | 137.4 | 9.43            | 9               |
| E2     | 183            | 301.1          | 486.4          | 134.3 | 9.8             | 9               |
| A1     | 182.3          | 300.4          | 415.4          | 115   | 9.59            | 9               |
| G1     | 182.3          | 300.4          | 404.2          | 103.8 | 9.3             | 8.35            |
| E3     | 181.9          | 300            | 489.7          | 138.7 | 9.3             | 9               |
| F1     | 182.7          | 300.6          | 453.1          | 132.3 | 9.32            | 9               |
| C2     | 182.3          | 300.4          | 428.1          | 127.7 | 9.71            | 9               |
| A2     | 182.3          | 300.9          | 416.3          | 116.9 | 9.7             | 9               |
| C3     | 182.3          | 301.0          | 367.3          | 69.9  | 10.7            | 9               |
| A3     | 182.2          | 300.3          | 435.4          | 135.1 | 9.7             | 9               |
| G1     | 181.8          | 299.9          | 445.8          | 145.9 | 9.34            | 9               |
| A4     | 182.0          | 300.1          | 413.2          | 113.1 | 9.62            | 9               |
| D1     | 182.6          | 300.9          | 427.5          | 126.6 | 9.68            | 9               |
| F2     | 182            | 300.1          | 455.2          | 135.1 | 9.61            | 8.35            |
| D2     | 183.1          | 301.2          | 373.3          | 72.1  | 10.68           | 8.35            |
| B1     | 183.1          | 301.2          | 421.5          | 120.3 | 9.62            | 9               |
| G2     | 183.1          | 301.2          | 413.5          | 128.3 | 9.62            | 9               |
| F3     | 183.1          | 301.2          | 399.7          | 98.5  | 10.41           | 9               |
| D3     | 183            | 301.1          | 353.6          | 55.5  | 10.75           | 9               |
| B2     | 182.3          | 300.9          | 433.6          | 132.7 | 9.64            | 8.35            |
| G3     | 182.1          | 300.2          | 426.3          | 123.4 | 9.53            | 9               |
| D4     | 182.4          | 300.5          | 367.1          | 63.6  | 10.7            | 8.35            |
| E3     | 183.2          | 301.3          | 424.2          | 132.9 | 9.65            | 9               |
| B4     | 182.8          | 300.9          | 382.9          | 82    | 10.6            | 9               |
| E4     | 182.8          | 300.9          | 382.6          | 81.7  | 10.57           | 9               |
| F4     | 182.1          | 300.2          | 369.3          | 89.4  | 10.52           | 9               |
| C4     | 182.1          | 300.2          | 447.6          | 147.6 | 9.7             | 9               |
| G4     | 182.4          | 300.5          | 437.3          | 136.8 | 9.61            | 9               |
| E5     | 181.5          | 299.3          | 435.6          | 126   | 9.62            | 9               |
| C5     | 183.1          | 301.2          | 344.3          | 43.6  | 10.53           | 9               |
| A6     | 182.2          | 300.3          | 391.7          | 91.4  | 9.47            | 9               |
| C9     | 182            | 300.1          | 413.9          | 113.3 | 9.5             | 9               |
| O10    | 182            | 300.1          | 433.6          | 123.5 | 9.6             | 9               |
| E9     | 182.4          | 300.5          | 413.3          | 115.8 | 9.3             | 9               |
| C3     | 182.1          | 300.2          | 429.4          | 129.2 | 9.41            | 9               |
| E3     | 182.7          | 300.3          | 437.9          | 137.1 | 9.61            | 9               |
| A7     | 183.2          | 301.3          | 400.9          | 93.6  | 9.55            | 9               |
| A3     | 183.4          | 301.5          | 415.4          | 113.9 | 9.42            | 9               |
| B9     | 183.1          | 301.2          | 435            | 123.8 | 9.42            | 9               |
| F9     | 182.2          | 300.3          | 437            | 133.7 | 9.47            | 9               |
| A5     | 183.1          | 301.2          | 421.3          | 120.1 | 9.35            | 9               |
| D7     | 183.6          | 300.7          | 393.9          | 93.2  | 10.39           | 9               |
| D8     | 183.4          | 301.5          | 443.9          | 143.4 | 9.25            | 9               |
| E10    | 182.9          | 301            | 443.3          | 147.6 | 9.22            | 9               |
| E7     | 182.2          | 300.3          | 440            | 120.7 | 9.32            | 9               |
| D5     | 182            | 300.1          | 381.6          | 81.5  | 10.51           | 9               |

RUN NO. 4 - CO<sub>2</sub>

| A     | N <sub>A</sub> A | EN <sub>E</sub> -N <sub>A</sub> A | $\frac{EN_E - N_A A}{N}$ x 10 <sup>2</sup> | C x 10 <sup>4</sup> | C' x 10 <sup>4</sup> |
|-------|------------------|-----------------------------------|--------------------------------------------|---------------------|----------------------|
| 4.4   | 0.0945           | 2.9555                            | 1.64                                       | 4.22                | 3.92                 |
| 12.1  | 0.26             | 2.09                              | 2.0                                        | 5.14                | 3.94                 |
| 5.35  | 0.115            | 2.485                             | 1.34                                       | 4.98                | 3.78                 |
| 5.4   | 0.118            | 2.284                             | 2.15                                       | 5.53                | 4.33                 |
| 6.5   | 0.183            | 2.187                             | 2.0                                        | 5.14                | 3.94                 |
| 6.7   | 0.144            | 2.506                             | 1.45                                       | 3.73                | 2.53                 |
| 6.55  | 0.141            | 2.200                             | 1.73                                       | 4.45                | 3.25                 |
| 6.3   | 0.155            | 2.215                             | 1.92                                       | 4.94                | 3.74                 |
| 44.6  | 0.985            | 1.505                             | 2.37                                       | 5.32                | 4.12                 |
| 6.7   | 0.144            | 2.206                             | 1.63                                       | 4.19                | 2.99                 |
| 3.35  | 0.072            | 2.276                             | 1.56                                       | 4.91                | 2.61                 |
| 5.75  | 0.124            | 2.233                             | 1.88                                       | 4.83                | 3.63                 |
| 6.3   | 0.155            | 2.215                             | 1.75                                       | 4.50                | 3.20                 |
| 5.9   | 0.127            | 2.213                             | 1.65                                       | 4.14                | 3.94                 |
| 29.65 | 0.857            | 1.493                             | 2.07                                       | 5.32                | 4.12                 |
| 5.5   | 0.118            | 2.232                             | 1.95                                       | 4.75                | 3.55                 |
| 5.75  | 0.124            | 2.233                             | 1.73                                       | 4.45                | 3.25                 |
| 23.45 | 0.533            | 1.781                             | 1.81                                       | 4.66                | 3.45                 |
| 46.7  | 1.005            | 1.345                             | 2.42                                       | 6.21                | 5.01                 |
| 6.3   | 0.135            | 2.215                             | 1.67                                       | 4.29                | 2.09                 |
| 4.9   | 0.105            | 2.245                             | 1.79                                       | 4.57                | 2.37                 |
| 42.1  | 0.935            | 1.245                             | 2.17                                       | 5.56                | 4.33                 |
| 5.9   | 0.127            | 2.213                             | 1.63                                       | 4.32                | 3.12                 |
| 36.3  | 0.73             | 1.57                              | 1.92                                       | 4.34                | 3.74                 |
| 34.3  | 0.737            | 1.513                             | 1.33                                       | 5.09                | 2.80                 |
| 23.4  | 0.718            | 1.632                             | 1.83                                       | 4.70                | 3.50                 |
| 7.5   | 0.161            | 2.189                             | 1.48                                       | 3.80                | 2.60                 |
| 5.95  | 0.123            | 2.202                             | 1.63                                       | 4.19                | 2.99                 |
| 9     | 0.133            | 2.157                             | 1.59                                       | 4.09                | 2.69                 |
| 47.4  | 1.02             | 1.23                              | 2.05                                       | 7.84                | 6.64                 |
| 3.4   | 0.073            | 2.277                             | 2.49                                       | 6.40                | 5.20                 |
| 4.1   | 0.088            | 2.262                             | 1.34                                       | 4.90                | 3.73                 |
| 6     | 0.129            | 2.231                             | 1.63                                       | 4.19                | 2.99                 |
| 2.8   | 0.08             | 2.29                              | 1.96                                       | 5.09                | 3.80                 |
| 5     | 0.108            | 2.242                             | 1.74                                       | 4.48                | 3.18                 |
| 6.35  | 0.137            | 2.213                             | 1.61                                       | 4.14                | 2.94                 |
| 4.35  | 0.0935           | 2.2865                            | 2.16                                       | 5.29                | 4.60                 |
| 4.1   | 0.088            | 2.262                             | 1.39                                       | 3.11                | 3.01                 |
| 5.8   | 0.125            | 2.225                             | 1.67                                       | 4.29                | 3.09                 |
| 4.95  | 0.103            | 2.244                             | 1.65                                       | 4.34                | 2.94                 |
| 4.5   | 0.097            | 2.253                             | 1.97                                       | 4.80                | 3.60                 |
| 23.1  | 0.605            | 1.745                             | 1.87                                       | 4.60                | 3.60                 |
| 5.75  | 0.124            | 2.233                             | 1.53                                       | 3.94                | 2.74                 |
| 4.55  | 0.096            | 2.252                             | 1.53                                       | 3.94                | 2.74                 |
| 5.75  | 0.124            | 2.233                             | 1.6                                        | 4.11                | 2.91                 |
| 26.7  | 0.73             | 1.57                              | 1.93                                       | 4.36                | 3.76                 |

TABLE II (Cont'd)

| SAMPLE | V <sub>1</sub> | V <sub>2</sub> | V <sub>3</sub> | V     | pH <sup>a</sup> | pH <sup>b</sup> |
|--------|----------------|----------------|----------------|-------|-----------------|-----------------|
| G2     | 188.9          | 301            | 441.9          | 140.9 | 8.75            |                 |
| B6     | 188.5          | 300.3          | 437.5          | 136.9 | 9.32            | 9               |
| D6     | 188.2          | 300.4          | 391.7          | 91.3  | 10.33           | 9               |
| F3     | 188.2          | 300.3          | 420.5          | 129.2 | 9.7             | 9               |
| F5     | 188.9          | 301            | 383.1          | 91.1  | 10.41           | 9               |
| L6     | 188.7          | 300.5          | 373.9          | 78.6  | 10.51           | 9               |
| G3     | 181.8          | 300.9          | 450.6          | 159.7 | 9.33            | 9               |
| B6     | 182.6          | 300.7          | 385.7          | 85    | 10.5            | 8.95            |
| B7     | 183            | 301.1          | 437.9          | 136.8 | 9.36            | 9               |
| E7     | 182.6          | 300.7          | 383            | 52.3  | 10.73           | 9               |
| F6     | 188.9          | 301            | 397.4          | 96.4  | 10.36           | 8.7             |
| G5     | 182.9          | 301            | 440.1          | 133.1 | 9.29            | 9               |
| C6     | 182.3          | 300.4          | 347            | 43.6  | 10.72           | 9               |
| C7     | 181.8          | 300.9          | 334.3          | 64.9  | 10.5            | 9               |
| E5     | 183            | 301.1          | 442.5          | 141.4 | 9.5             | 9               |
| F7     | 182.3          | 300.9          | 416            | 115.1 | 10.11           | 9               |

Solution Data: 0.0135 N Ba(OH)<sub>2</sub>  
0.0115 N HCl

Calculation Data: 100 ml. of Ba(OH)<sub>2</sub>  
plus stopper weighed 115.1 gms.



| A     | $H_A A$ | $BM_B - H_A A$ | $\frac{BM_B - H_A A}{W} \times 10^3$ | $C \times 10^4$ | $C' \times 10^4$ |
|-------|---------|----------------|--------------------------------------|-----------------|------------------|
| 5.75  | 0.124   | 2.253          | 1.85                                 | 4.13            | 2.33             |
| 26.9  | 0.533   | 1.822          | 2.0                                  | 5.14            | 2.34             |
| 10.15 | 0.221   | 2.123          | 1.85                                 | 4.25            | 2.05             |
| 20.95 | 0.644   | 1.706          | 1.85                                 | 4.75            | 2.55             |
| 35.5  | 0.76    | 1.59           | 2.02                                 | 5.20            | 4.00             |
| 6     | 0.129   | 2.241          | 1.43                                 | 3.60            | 2.60             |
| 35.5  | 0.73    | 1.59           | 1.87                                 | 4.80            | 2.00             |
| 51.2  | 1.12    | 1.33           | 2.55                                 | 6.04            | 4.64             |
| 27    | 0.59    | 1.77           | 1.84                                 | 4.73            | 2.52             |
| 3.85  | 0.085   | 2.237          | 1.03                                 | 4.13            | 2.33             |
| 47.5  | 1.32    | 1.33           | 2.86                                 | 7.35            | 6.15             |
| 35.2  | 0.756   | 1.534          | 1.86                                 | 4.84            | 3.64             |
| 7.46  | 0.13    | 2.19           | 1.55                                 | 3.98            | 2.78             |
| 17.3  | 0.372   | 1.979          | 1.72                                 | 4.42            | 3.22             |

## Operation Data:

## Liquid Rate

| Check | a    | b    | c    |
|-------|------|------|------|
| Gals. | 40   | 40   | 40   |
| Secs. | 67.5 | 63.5 | 63.5 |

## Gas Rate

Manometer Reading 1.33" H<sub>2</sub>O

|                  |        | Run   |       | Difference |
|------------------|--------|-------|-------|------------|
|                  |        | Prior | After |            |
| CO <sub>2</sub>  | -lbs.  | 152.5 | 124   | 19.5       |
| H <sub>2</sub> O | -gals. | 5510  | 5541  | 31         |

Time of Run 51.3 seconds.

TABLE III

| SAMPLE | $\bar{W}_1$ | $\bar{W}_2$ | $\bar{W}_3$ | $\bar{W}$ | pH <sup>a</sup> | pH <sup>b</sup> |
|--------|-------------|-------------|-------------|-----------|-----------------|-----------------|
| B1     | 181.9       | 300.7       | 432.1       | 81.4      | 11.32           | 9               |
| B2     | 182         | 301.3       | 433.3       | 104.5     | 11.3            | 9               |
| A1     | 182.3       | 301.1       | 333         | 81.9      | 11.25           | 9               |
| C1     | 182.3       | 301.1       | 331.2       | 80.1      | 11.28           | 9               |
| B3     | 181.9       | 300.7       | 432.5       | 101.3     | 11.27           | 9               |
| F1     | 182.7       | 301.5       | 433.3       | 154.8     | 11.24           | 9               |
| C2     | 182.3       | 301.1       | 335.1       | 94.3      | 11.29           | 9               |
| A2     | 182.8       | 301.3       | 331.5       | 30        | 11.23           | 9               |
| C3     | 182.9       | 301.7       | 407.2       | 136.5     | 11.23           | 9               |
| A3     | 182.2       | 301.0       | 330         | 89        | 11.2            | 9               |
| G1     | 181.8       | 300.6       | 407.4       | 136.2     | 11.12           | 9               |
| A4     | 182         | 300.8       | 333.3       | 35.1      | 11.2            | 9               |
| D1     | 182.8       | 301.3       | 433.1       | 134.5     | 11.22           | 9               |
| F2     | 182         | 300.9       | 444.1       | 143.3     | 11.21           | 9               |
| D2     | 183.1       | 301.3       | 435.5       | 153.3     | 11.32           | 9               |
| B1     | 183.1       | 301.3       | 432.5       | 130.3     | 11.34           | 9               |
| G2     | 183.1       | 301.3       | 437.5       | 135.3     | 11.3            | 9               |
| F3     | 183.1       | 301.9       | 443.2       | 141.3     | 11.32           | 9               |
| D3     | 183         | 301.8       | 330         | 88.2      | 11.5            | 8.55            |
| B2     | 182.8       | 301.6       | 437         | 125.4     | 11.34           | 9               |
| G3     | 182.1       | 300.9       | 413.4       | 112.5     | 11.3            | 9               |
| D4     | 183.4       | 301.2       | 413.3       | 112.3     | 11.4            | 9               |
| B3     | 183.2       | 302.0       | 433.7       | 134.7     | 11.21           | 9               |
| B4     | 182.6       | 301.6       | 429.2       | 127.6     | 11.26           | 6.8             |
| F4     | 182.3       | 301.6       | 431         | 129.4     | 11.29           | 9               |
| F4     | 182.1       | 300.3       | 439         | 126.1     | 11.28           | 9               |
| C4     | 182.1       | 300.9       | 434.4       | 125.5     | 11.28           | 9               |
| G4     | 182.4       | 301.2       | 423         | 121.3     | 11.29           | 9               |
| E5     | 181.5       | 300.3       | 407.5       | 137.2     | 11.25           | 9               |
| C5     | 183.1       | 301.9       | 336.2       | 33.4      | 11.49           | 9               |
| A8     | 182.2       | 301         | 379.5       | 78.5      | 11.4            | 9               |
| C9     | 182         | 300.8       | 337.1       | 86.3      | 11.2            | 9               |
| C10    | 182         | 300.8       | 333         | 95.2      | 11.22           | 9               |
| E9     | 182.4       | 301.2       | 433         | 137.8     | 11.12           | 9               |
| C8     | 182.1       | 300.9       | 444.3       | 143.9     | 11.35           | 9               |
| E3     | 182.7       | 301.5       | 433.8       | 135.5     | 11.37           | 9               |
| A7     | 183.2       | 302.0       | 389.4       | 87.4      | 11.32           | 9               |
| A6     | 183.4       | 302.2       | 433.4       | 134.2     | 11.32           | 9               |
| B9     | 183.1       | 301.9       | 435.9       | 127       | 11.32           | 9               |
| F9     | 182.2       | 301.3       | 432         | 121       | 11.28           | 9               |
| A5     | 183.1       | 301.9       | 417.1       | 115.2     | 11.32           | 9               |
| D7     | 182.6       | 301.4       | 428.8       | 127.4     | 11.3            | 9               |
| D6     | 183.4       | 302.2       | 443.3       | 143.6     | 11.3            | 9               |
| E10    | 182.9       | 301.7       | 416         | 113.3     | 11.29           | 9               |
| G7     | 182.2       | 301.0       | 445.1       | 144.1     | 11.3            | 9               |
| E5     | 182         | 300.8       | 441.1       | 149.3     | 11.32           | 9               |

RUN NO. 6 - CO<sub>2</sub>

| A    | N <sub>AA</sub> | ML - N <sub>AA</sub> | $\frac{ML - N_{AA}}{N}$ $\times 10^2$ | C $\times 10^3$ | C <sub>tr</sub> $10^3$ |
|------|-----------------|----------------------|---------------------------------------|-----------------|------------------------|
| 46   | 4.86            | 6.14                 | 7.34                                  | 1.335           | 1.915                  |
| 51.6 | 5.84            | 5.16                 | 4.33                                  | 1.27            | 1.15                   |
| 47.7 | 5.39            | 6.61                 | 3.33                                  | 1.70            | 1.67                   |
| 47.2 | 5.34            | 5.63                 | 7.37                                  | 1.32            | 1.70                   |
| 50.5 | 6.25            | 4.75                 | 3.31                                  | 1.35            | 0.91                   |
| 51.8 | 6.98            | 4.92                 | 2.61                                  | 0.743           | 0.513                  |
| 50.2 | 5.57            | 5.73                 | 5.67                                  | 1.23            | 1.34                   |
| 50.7 | 5.73            | 5.27                 | 5.36                                  | 1.61            | 1.39                   |
| 52.7 | 5.95            | 5.05                 | 4.79                                  | 1.23            | 1.11                   |
| 49.1 | 5.55            | 6.45                 | 3.13                                  | 1.30            | 1.43                   |
| 49   | 4.32            | 6.48                 | 6.98                                  | 1.53            | 1.44                   |
| 51.2 | 5.73            | 5.22                 | 5.32                                  | 1.37            | 1.25                   |
| 51.6 | 6.33            | 4.64                 | 3.99                                  | 0.77            | 0.65                   |
| 60.9 | 7.1             | 3.9                  | 2.72                                  | 0.70            | 0.52                   |
| 51.8 | 5.84            | 5.16                 | 4.33                                  | 1.33            | 1.13                   |
| 51.8 | 5.33            | 5.14                 | 5.11                                  | 1.31            | 1.19                   |
| 47   | 5.31            | 5.69                 | 5.39                                  | 1.33            | 1.36                   |
| 51.2 | 6.92            | 4.08                 | 2.33                                  | 0.743           | 0.623                  |
| 73.1 | 8.26            | 2.74                 | 3.11                                  | 0.39            | 0.62                   |
| 53.7 | 6.34            | 4.66                 | 3.43                                  | 0.895           | 0.775                  |
| 50.8 | 5.74            | 5.26                 | 4.63                                  | 1.20            | 1.06                   |
| 68.8 | 7.77            | 3.23                 | 2.97                                  | 0.787           | 0.617                  |
| 52.2 | 6.53            | 4.42                 | 3.39                                  | 0.645           | 0.775                  |
| 59.6 | 6.74            | 4.26                 | 3.24                                  | 0.858           | 0.753                  |
| 59   | 6.63            | 4.34                 | 3.35                                  | 0.86            | 0.74                   |
| 53.9 | 6.45            | 4.57                 | 3.66                                  | 0.915           | 0.795                  |
| 61   | 6.39            | 4.11                 | 3.03                                  | 0.731           | 0.671                  |
| 53.1 | 6.34            | 4.63                 | 3.83                                  | 0.924           | 0.864                  |
| 70.2 | 7.94            | 3.06                 | 2.65                                  | 0.732           | 0.612                  |
| 71.5 | 8.65            | 2.35                 | 2.54                                  | 0.91            | 0.79                   |
| 46   | 4.86            | 6.14                 | 7.12                                  | 1.63            | 1.71                   |
| 50.1 | 5.63            | 5.34                 | 5.61                                  | 1.44            | 1.32                   |
| 62.9 | 7.1             | 3.9                  | 2.71                                  | 0.696           | 0.576                  |
| 51.9 | 5.63            | 5.14                 | 5.02                                  | 1.29            | 1.17                   |
| 45.8 | 5.39            | 5.71                 | 3.64                                  | 1.63            | 1.66                   |
| 52.3 | 5.95            | 5.25                 | 4.64                                  | 1.74            | 1.12                   |
| 59   | 6.63            | 4.34                 | 3.42                                  | 0.879           | 0.759                  |
| 51.2 | 5.73            | 5.22                 | 3.93                                  | 1.02            | 0.90                   |
| 55.2 | 6.34            | 4.76                 | 4.13                                  | 1.36            | 0.94                   |
| 56.1 | 6.4             | 4.6                  | 3.61                                  | 0.933           | 0.898                  |
| 59.9 | 6.73            | 4.25                 | 2.9                                   | 0.745           | 0.635                  |
| 48.2 | 5.45            | 5.55                 | 4.77                                  | 1.23            | 1.11                   |
| 55.3 | 6.59            | 4.41                 | 3.06                                  | 0.786           | 0.663                  |
| 62.1 | 7.32            | 3.98                 | 2.84                                  | 0.73            | 0.61                   |

TABLE III (Cont'd)

| SAMPLE | $\bar{W}_1$ | $\bar{W}_2$ | $\bar{W}_3$ | $\bar{W}$ | $\text{pH}^a$ | $\text{pH}^b$ |
|--------|-------------|-------------|-------------|-----------|---------------|---------------|
| C8     | 137.9       | 351.7       | 440.3       | 138.6     | 11.73         | 9             |
| D9     | 137.5       | 351.3       | 434.3       | 138.6     | 11.32         | 9             |
| D8     | 138.3       | 351.1       | 433.4       | 138.3     | 11.32         | 9             |
| F8     | 132.2       | 351.0       | 437.1       | 143.1     | 11.32         | 9             |
| F5     | 132.5       | 351.7       | 440.5       | 140.9     | 11.31         | 9             |
| E3     | 132.2       | 351.0       | 395.3       | 31.3      | 11.5          | 9             |
| C6     | 131.3       | 350.6       | 439.3       | 139       | 11.3          | 9             |
| B3     | 137.3       | 351.4       | 439.1       | 137.7     | 11.31         | 9             |
| E7     | 135         | 352.3       | 436.2       | 136.4     | 11.32         | 9             |
| E7     | 132.6       | 351.4       | 440.9       | 140.5     | 11.32         | 9             |
| F3     | 132.9       | 351.7       | 440         | 138.3     | 11.3          | 9             |
| G5     | 132.9       | 351.7       | 451.3       | 150.2     | 11.3          | 9             |
| C3     | 131.5       | 351.1       | 440.5       | 130.4     | 11.32         | 9             |
| G7     | 131.3       | 350.6       | 443.7       | 143.1     | 11.3          | 9             |
| B5     | 133         | 351.3       | 440.3       | 141       | 11.33         | 9             |
| F7     | 132.3       | 351.3       | 444.9       | 143.3     | 11.3          | 9             |

SOLUTION DATA: 0.11 N  $\text{Ba}(\text{OH})_2$

0.113 N HCl

CALCULATION DATA: 100 ml. of  $\text{Ba}(\text{OH})_2$  plus

stopper weighed 113.8 gms.

| A    | $N_{AA}$ | $M_E - N_{AA}$ | $\frac{M_E - N_{AA}}{N}$ $\times 10^2$ | $C \times 10^3$ | $C' \times 10^3$ |
|------|----------|----------------|----------------------------------------|-----------------|------------------|
| 40.0 | 5.53     | 3.43           | 3.93                                   | 1.92            | 0.99             |
| 50.5 | 6.84     | 4.16           | 3.12                                   | 0.902           | 0.632            |
| 59.1 | 8.8      | 4.2            | 3.1                                    | 0.796           | 0.676            |
| 66.2 | 7.15     | 3.55           | 2.33                                   | 0.675           | 0.555            |
| 62.2 | 7.04     | 3.96           | 2.32                                   | 0.725           | 0.605            |
| 75.7 | 8.53     | 2.37           | 3.37                                   | 0.84            | 0.70             |
| 54.3 | 6.13     | 4.51           | 3.43                                   | 0.859           | 0.739            |
| 61.1 | 6.9      | 4.1            | 2.33                                   | 0.735           | 0.645            |
| 61.6 | 6.93     | 4.04           | 2.33                                   | 0.731           | 0.641            |
| 62   | 7.01     | 3.99           | 2.33                                   | 0.735           | 0.615            |
| 61.6 | 6.93     | 4.04           | 2.32                                   | 0.75            | 0.63             |
| 62   | 7.01     | 3.99           | 2.33                                   | 0.834           | 0.534            |
| 61.2 | 6.91     | 4.03           | 2.34                                   | 0.755           | 0.655            |
| 59.4 | 7.05     | 3.35           | 2.33                                   | 0.739           | 0.539            |
| 61.3 | 7.53     | 3.47           | 2.33                                   | 0.732           | 0.512            |
| 55.3 | 7.15     | 3.25           | 2.75                                   | 0.737           | 0.537            |

## Operation Data:

## Liquid Rate

| Check | a     | b     | c    | d    | e    | f    | g    | h     |
|-------|-------|-------|------|------|------|------|------|-------|
| Gals. | 40    | 40    | 40   | 40   | 40   | 40   | 40   | 40    |
| Secs. | 70.75 | 71.65 | 72.7 | 73.9 | 72.9 | 71.5 | 71.1 | 70.55 |

## Gas Rate

Manometer Reading 0.62"  $H_2O$ 

|                | Run      |         |            |
|----------------|----------|---------|------------|
|                | Prior    | After   | Difference |
| $CO_2$ - lbs.  | 126 5/16 | 129 1/2 | 26 13/16   |
| $H_2O$ - gals. | 6733     | 6730    | 33         |

Time of Run 53.2 Seconds.

TABLE IV  
Run #8 Alcohol

| SAMPLE | DENSITY | TEMP. °C | Wt. % |
|--------|---------|----------|-------|
| E1     | 0.9958  | 20.5     | 1.25  |
| E2     | 0.9950  | 20       | 1.84  |
| A1     | 0.9960  | 21       | 1.175 |
| C1     | 0.9955+ | 21       | 1.35  |
| E3     | 0.9973  | 23       | 0.13* |
| F1*    |         |          |       |
| C2     | 0.996   | 21       | 1.175 |
| A2     | 0.9958  | 20.5     | 1.25  |
| C3     | 0.9948  | 22       | 1.60  |
| A3     | 0.9941  | 21       | 2.10  |
| G1     | 0.9948  | 22       | 1.60  |
| A4     | 0.9953  | 22.5     | 1.27  |
| D1     | 0.9950  | 23       | 1.37  |
| F2     | 0.9942  | 23       | 1.80  |
| D2     | 0.9949  | 24       | 1.30  |
| E1     | 0.9954  | 23       | 1.16  |
| G2     | 0.9936  | 23.5     | 2.75  |
| F3     | 0.9932  | 23.5     | 2.29  |
| D3     | 0.9939  | 24.5     | 1.88  |
| E2     | 0.9951+ | 23.5     | 1.26  |
| G3     | 0.9932  | 23       | 2.36  |
| D4     | 0.9936  | 23       | 2.13  |
| E3     | 0.9948  | 23       | 1.475 |
| E4     | 0.9946  | 23       | 1.58  |
| E4     | 0.9937  | 23.5     | 2.02  |
| F4*    |         |          |       |
| C4     | 0.9943  | 22       | 1.88  |
| G4     | 0.9940  | 20       | 2.29  |
| E5     | 0.9932  | 22.5     | 2.42  |
| C5     | 0.9942  | 22.5     | 1.88  |
| A8     | 0.9952  | 24       | 1.14  |
| C9     | 0.9952  | 24       | 1.14  |
| C10    | 0.9953  | 23.5     | 1.14  |
| E9     | 0.9943  | 23       | 1.76  |
| C8     | 0.9945  | 23       | 1.64  |
| E8     | 0.9938  | 22.5     | 2.09  |
| A7     | 0.9954  | 22.5     | 1.22  |
| A6     | 0.9952  | 23       | 1.26  |
| B9     | 0.9954  | 22.5     | 1.22  |
| F9*    |         |          |       |
| A5     | 0.9952+ | 22       | 1.39  |
| D7     | 0.9943  | 22       | 1.88  |
| D8*    |         |          |       |
| E10    | 0.9947  | 22.5     | 1.59  |
| B7     | 0.9937  | 23       | 2.08  |
| D5     | 0.9936  | 22       | 2.27  |

TABLE IV (Cont'd)

## Run #3 Alcohol

| SAMPLE | DENSITY | TEMP. °C | WT. % |
|--------|---------|----------|-------|
| G8     | 0.9942  | 22       | 1.94  |
| B3     | 0.9952  | 22       | 1.38  |
| D6     | 0.9939  | 23       | 1.98  |
| F8     | 0.99375 | 22.5     | 2.11  |
| F5     | 0.9931  | 23       | 2.41  |
| E6*    |         |          |       |
| O6     | 0.9930  | 22.5     | 2.54  |
| B6     | 0.9948  | 22.5     | 1.54  |
| B7     | 0.9947  | 22.5     | 1.59  |
| E7     | 0.9933  | 23       | 2.30  |
| F6     | 0.9928  | 23       | 2.58  |
| O5     | 0.9930  | 23       | 2.475 |
| C6     | 0.99405 | 23       | 1.89  |
| C7     | 0.9942  | 23       | 1.80  |
| B5     | 0.9956  | 23       | 1.05  |
| F7     | 0.9932  | 23       | 2.36  |

Water Rate: (a) 20/81.7 (c) 20/118 (e) 20/124.6  
 Gals./secs. (b) 20/96.9 (d) 20/116 (f)

## Gas Rate

Manometer Reading 6.0" H<sub>2</sub>O  
 6.2" H<sub>2</sub>O

## Run

|                          | Prior    | After   | Difference |
|--------------------------|----------|---------|------------|
| Alcohol-lbs.             | 27 12/16 | 8 12/16 | 19         |
| H <sub>2</sub> O - gals. | 19940    | 19993   | 53         |

Time of Run 331.1 Seconds

\*This sample bottle filled prior to drawing of samples.

TABLE V

Run No. 3, CO<sub>2</sub> Divide by 1000 for Wt. %

(Refer to Drawing #8)

| COLUMN | A     | B     | C     | RCW<br>D | E     | F     | G     |
|--------|-------|-------|-------|----------|-------|-------|-------|
| Z"     |       |       | 0.093 |          | 0.096 |       |       |
| Z'     |       | 0.045 |       | 0.047    |       | 0.088 |       |
| Z      | 0.075 |       | 0.066 |          | 0.025 |       | —     |
| Y'     |       | 0.033 | —     | 0.032    |       | 0.03  |       |
| Y      | 0.007 |       | —     |          | 0.079 |       | 0.042 |
| X'     |       | 0.026 |       | 0.095    |       | 0.011 |       |
| X      | 0.022 |       | 0.005 |          | 0.008 |       | 0.035 |
| W'     |       | —     |       | —        |       | 0.002 |       |
| W      | 0.045 |       | 0.14  |          | 0.084 |       | 0.012 |
| V'     |       | 0.01  |       |          |       | 0.023 |       |
| V      | 0.03  |       | 0.122 |          | 0.11  |       | 0.009 |
| U'     |       | 0.009 |       | 0.006    |       | 0.073 |       |
| U      | 0.057 |       | —     |          | 0.007 |       | 0.01  |
| T'     |       | 0.004 |       | 0.013    |       | 0.007 |       |
| T      | 0.075 |       | 0.054 |          | 0.027 |       | 0.001 |
| S'     |       | 0.013 |       | 0.073    |       | 0.000 |       |
| S      | 0.104 |       | 0.067 |          | 0.053 |       | 0.006 |
| R'     |       | 0.027 |       | 0.025    |       | 0.017 |       |
| R      |       |       | 0.057 |          | 0.019 |       |       |
| Ave.   | 0.052 | 0.018 | 0.067 | 0.036    | 0.051 | 0.029 | 0.014 |

Liquid Rate: 29.9 G.P.M.

Gas Rate: 1470 C.F.M.

Gas Conc.: Laboratory air



TABLE VI

Run No. 4, CO<sub>2</sub>. Divide by 1000 for Wt. %

(Refer to Drawing #3)

| COLUMN | A     | B     | C     | RCN<br>D | E     | F     | G     |
|--------|-------|-------|-------|----------|-------|-------|-------|
| Z"     |       |       | 0.423 |          | 0.302 |       |       |
| Z'     |       | 0.355 |       | 0.330    |       | 0.253 |       |
| Z      | 0.373 |       | 0.325 |          | 0.394 |       | 0.281 |
| Y'     |       | 0.309 |       | 0.412    |       | 0.304 |       |
| Y      | 0.374 |       | 0.412 |          | 0.394 |       | 0.325 |
| X'     |       | 0.312 |       | 0.501    |       | 0.345 |       |
| X      | 0.299 |       | 0.260 |          | 0.389 |       | 0.337 |
| W'     |       | 0.374 |       | 0.436    |       | 0.350 |       |
| W      | 0.363 |       | 0.664 |          | 0.289 |       | 0.299 |
| V'     |       | 0.278 |       |          |       | 0.355 |       |
| V      | 0.360 |       | 0.615 |          | 0.400 |       | 0.299 |
| U'     |       | 0.360 |       | 0.376    |       | 0.353 |       |
| U      | 0.391 |       | 0.364 |          | 0.484 |       | 0.26  |
| T'     |       | —     |       | 0.394    |       | 0.322 |       |
| T      | 0.460 |       | 0.328 |          | 0.294 |       | 0.291 |
| S'     |       | 0.299 |       | 0.560    |       | 0.305 |       |
| S      | 0.520 |       | 0.379 |          | 0.389 |       | —     |
| R'     |       | 0.309 |       | 0.274    |       | 0.304 |       |
| R      |       |       | 0.299 |          | 0.274 |       |       |
| Ave.   | 0.393 | 0.325 | 0.408 | 0.385    | 0.361 | 0.321 | 0.299 |

Liquid Rate: 36.3 G.P.M.

Gas Rate: 933. C.F.M.

Gas Conc.: 17.5% by vol.

TABLE VII

Run No. 6,  $\text{CO}_2$ . Divide by 1000 for wt. %

(Refer to Drawing #3)

| COLUMN         | ROW  |       |       |       |       |       |       |
|----------------|------|-------|-------|-------|-------|-------|-------|
|                | A    | B     | C     | D     | E     | F     | G     |
| Z <sup>W</sup> |      |       | 1.70  |       | 1.815 |       |       |
| Z <sup>I</sup> |      | 1.19  |       | 0.65  |       | 0.548 |       |
| Z              | 1.67 |       | 1.34  |       | 1.15  |       | 1.44  |
| Y <sup>I</sup> |      | 0.775 |       | 1.16  |       | 0.58  |       |
| Y              | 1.39 |       | 1.11  |       | 0.91  |       | 1.26  |
| X <sup>I</sup> |      | 0.775 |       | 0.68  |       | 0.623 |       |
| X              | 1.46 |       | 0.671 |       | 0.74  |       | 1.08  |
| W <sup>I</sup> |      | 0.738 |       | 0.617 |       | 0.795 |       |
| W              | 1.25 |       | 0.79  |       | 0.612 |       | 0.864 |
| V <sup>I</sup> |      | 0.512 |       |       |       | 0.605 |       |
| V              | 0.94 |       | 0.635 |       | 0.72  |       | 0.564 |
| U <sup>I</sup> |      | 0.645 |       | 0.61  |       | 0.63  |       |
| U              | 1.12 |       | 0.589 |       | 0.615 |       | 0.769 |
| T <sup>I</sup> |      | 0.641 |       | 0.676 |       | 0.587 |       |
| T              | 1.56 |       | 0.576 |       | 1.17  |       | 0.666 |
| S <sup>I</sup> |      | 0.682 |       | 0.608 |       | 0.555 |       |
| S              | —    |       | 1.71  |       | —     |       | 0.90  |
| R <sup>I</sup> |      | 0.759 |       | 0.625 |       | 0.90  |       |
| R              |      |       | 1.32  |       | 1.11  |       |       |
| Ave.           | 1.34 | 0.741 | 1.044 | 0.728 | 0.932 | 0.647 | 0.943 |

Liquid Rate: 33.9 G.P.M.

Gas Rate: 628 C.F.M.

Gas Conc.: 37.6% by Vol.

TABLE VIII

Run No. 8, Alcohol

Concentration (Wt.%)

(Refer to Drawing #8)

| COLUMN                | A     | B     | C     | RCW<br>D | E    | F    | G     |
|-----------------------|-------|-------|-------|----------|------|------|-------|
| Z <sup>u</sup>        |       |       | 1.35  |          | 1.25 |      |       |
| Z <sup>i</sup>        |       | 1.16  |       | 1.37     |      | —    |       |
| Z                     | 1.175 |       | 1.175 |          | 1.84 |      | 1.60  |
| Y <sup>i</sup>        |       | 1.26  |       | 1.30     |      | 1.80 |       |
| Y                     | 1.25  |       | 1.60  |          | —    |      | 2.75  |
| X <sup>i</sup>        |       | 1.475 |       | 1.88     |      | 2.29 |       |
| X                     | 2.10* |       | 1.88  |          | 2.02 |      | 2.36  |
| W <sup>i</sup>        |       | 1.53  |       | 2.13     |      | —    |       |
| W                     | 1.27  |       | 1.88  |          | 2.42 |      | 2.29  |
| V <sup>i</sup>        |       | 1.05* |       |          |      | 2.41 |       |
| V                     | 1.39  |       | 1.89  |          | —    |      | 2.475 |
| U <sup>i</sup>        |       | 1.54  |       | 2.27     |      | 2.58 |       |
| U                     | 1.26  |       | 1.80  |          | 2.30 |      | 2.54  |
| T <sup>i</sup>        |       | 1.59  |       | 1.98     |      | 2.36 |       |
| T                     | 1.22  |       | 1.64  |          | 2.09 |      | 2.08  |
| S <sup>i</sup>        |       | 1.33  |       | 1.83     |      | 2.11 |       |
| S                     | 1.14  |       | 1.14  |          | 1.76 |      | 1.94  |
| R <sup>i</sup>        |       | 1.22  |       | —        |      | —    |       |
| R                     |       |       | 1.14  |          | 1.59 |      |       |
| * Not Used in Average |       |       |       |          |      |      |       |
| Ave.                  | 1.24  | 1.40  | 1.55  | 1.83     | 1.91 | 2.26 | 2.25  |

Liquid Rate: 9.6 G.P.M.

Gas Rate: 1930 C.F.M.

Gas Conc.: 7.9% by Vol.



1. The first step is to identify the problem or question that needs to be addressed. This involves understanding the context and the specific requirements of the task.

4.









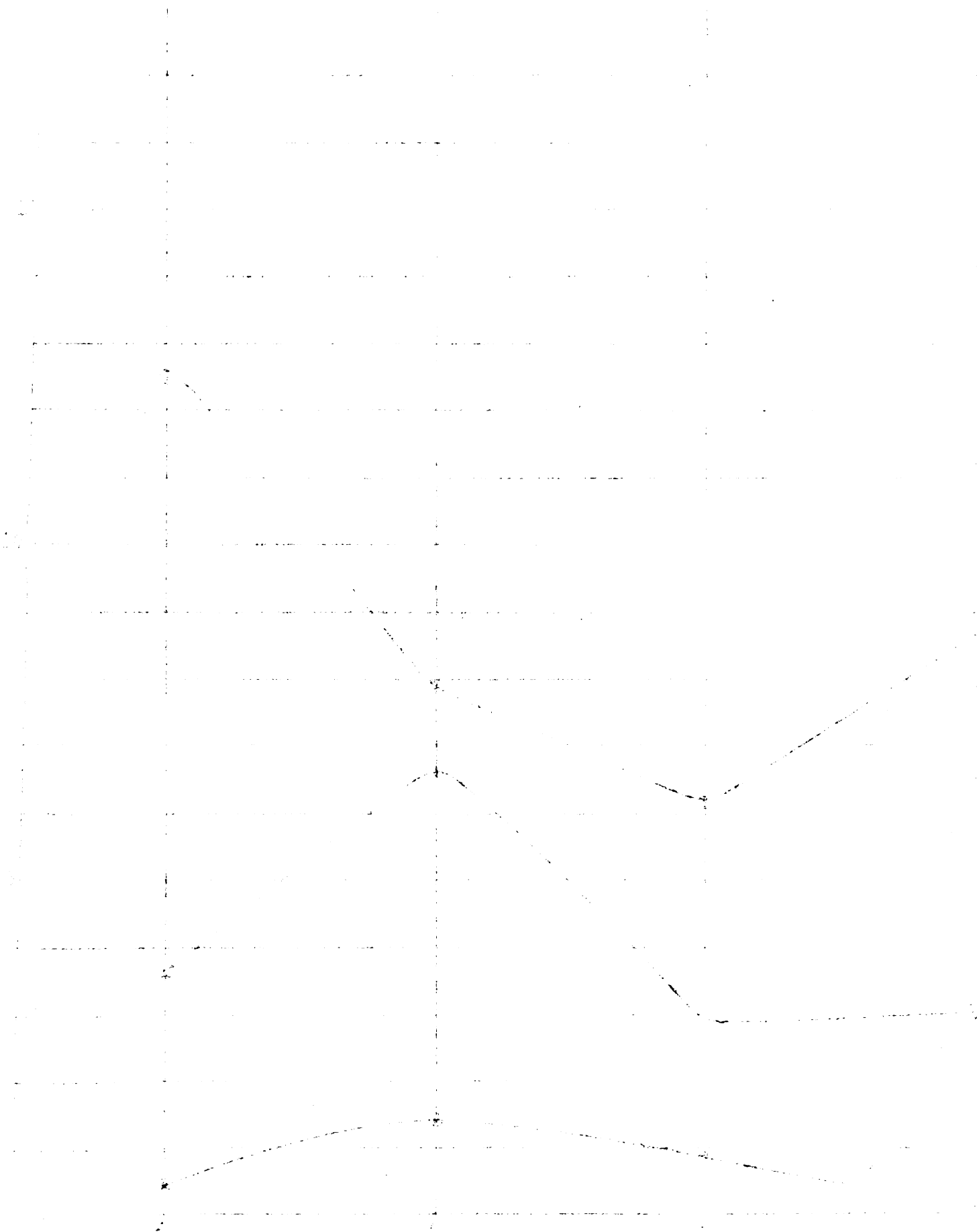


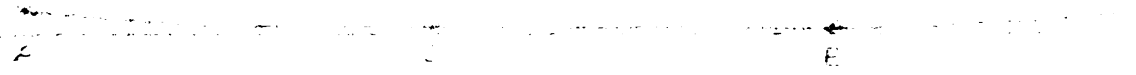
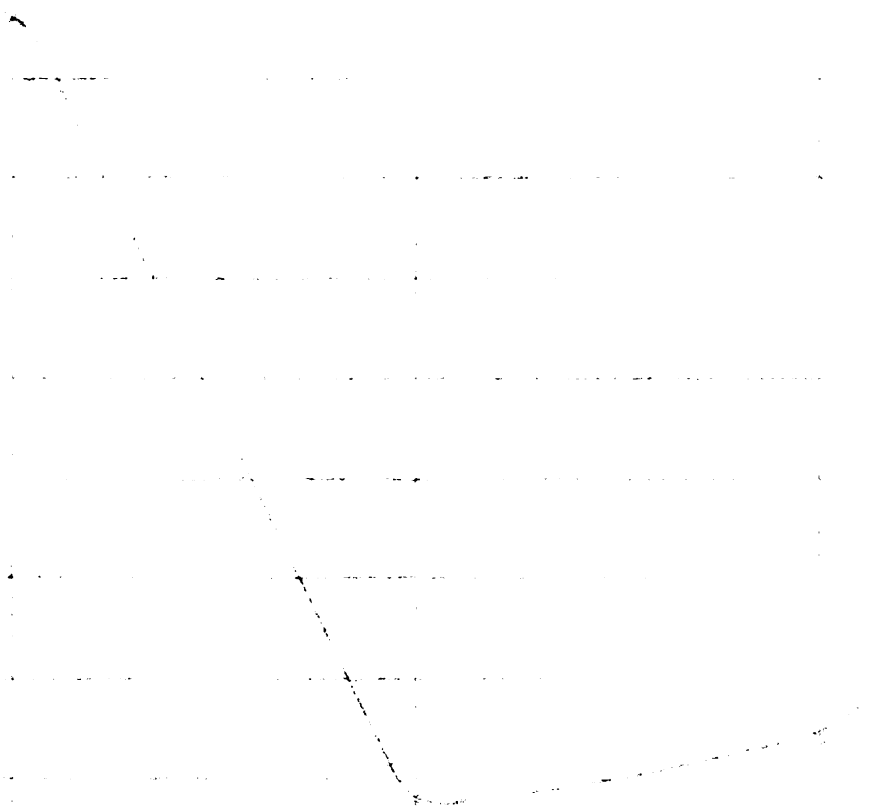


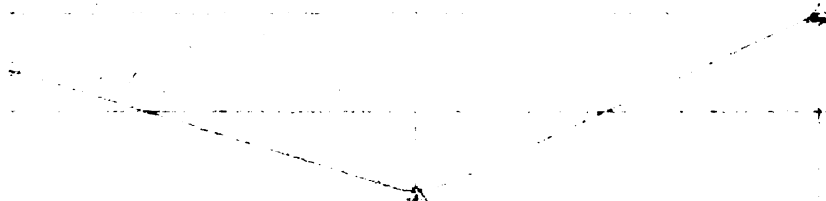




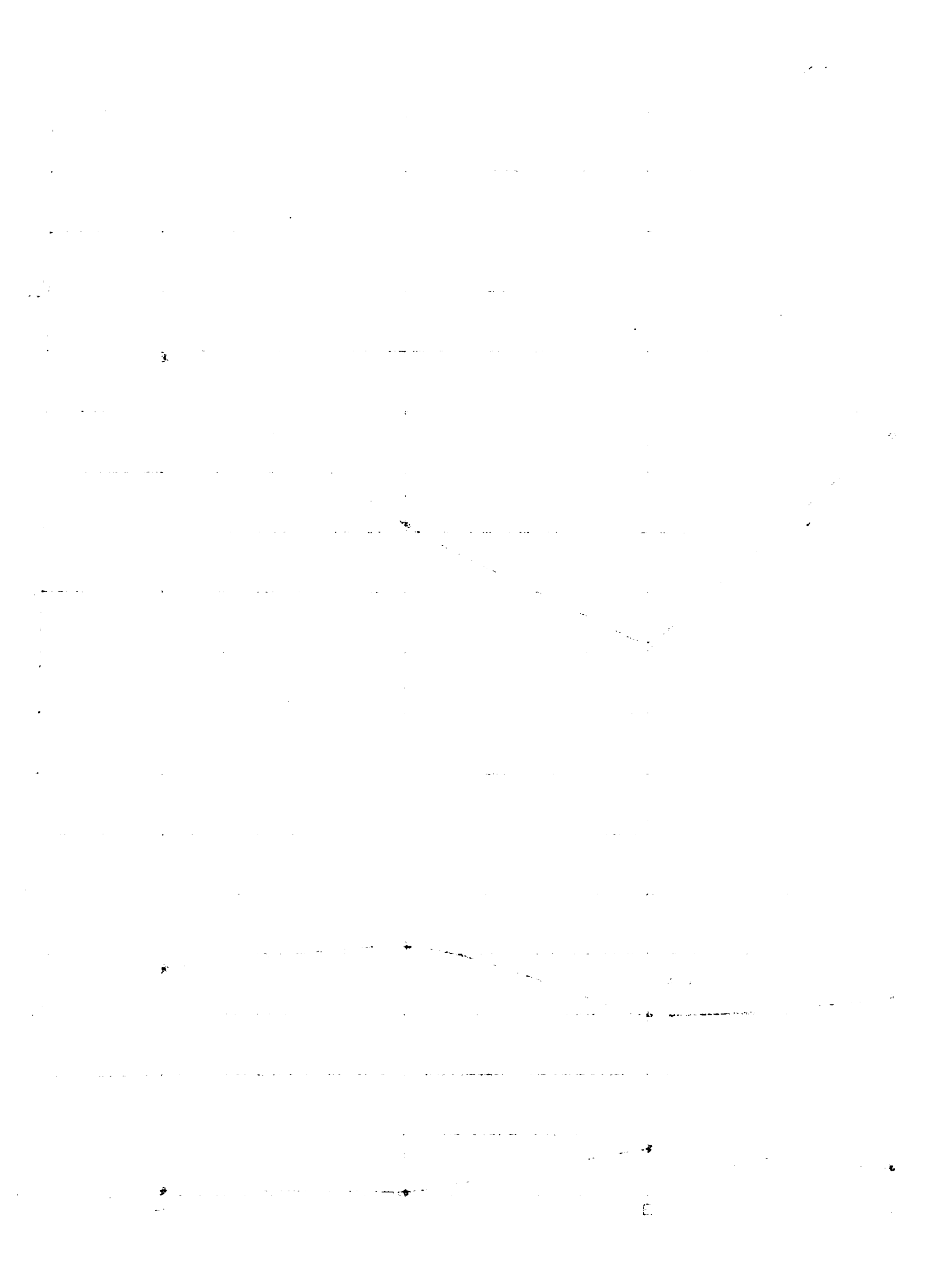








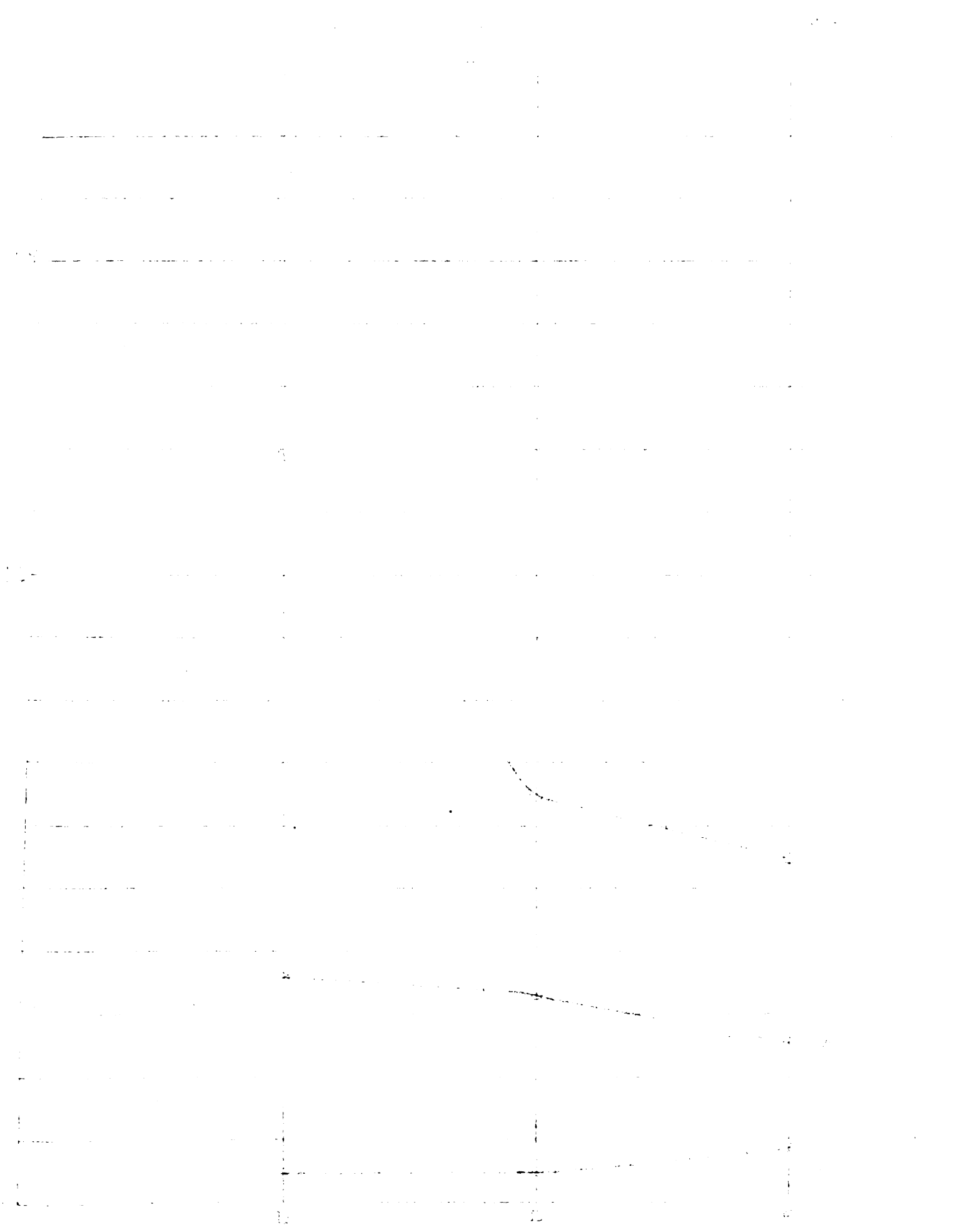














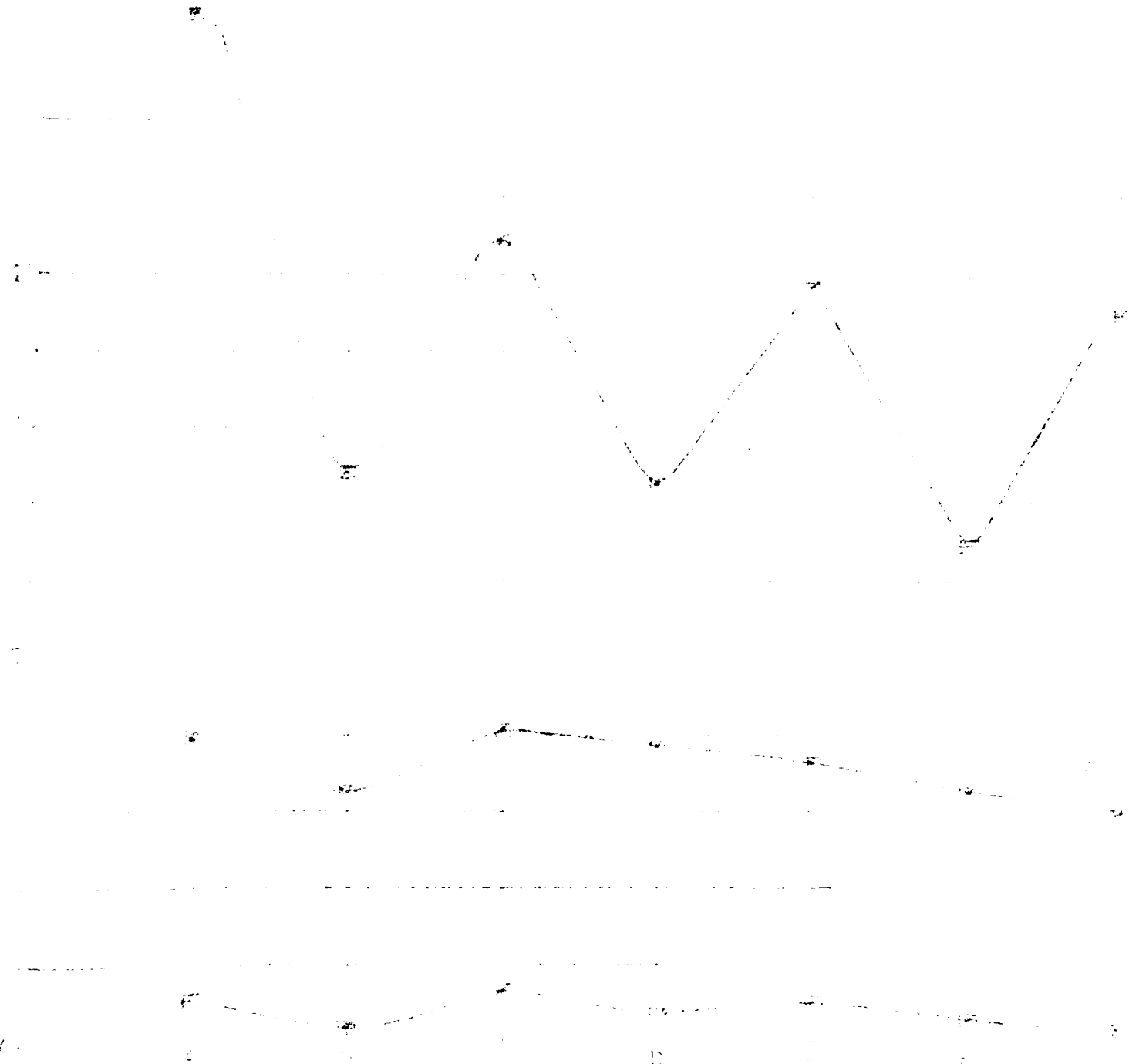
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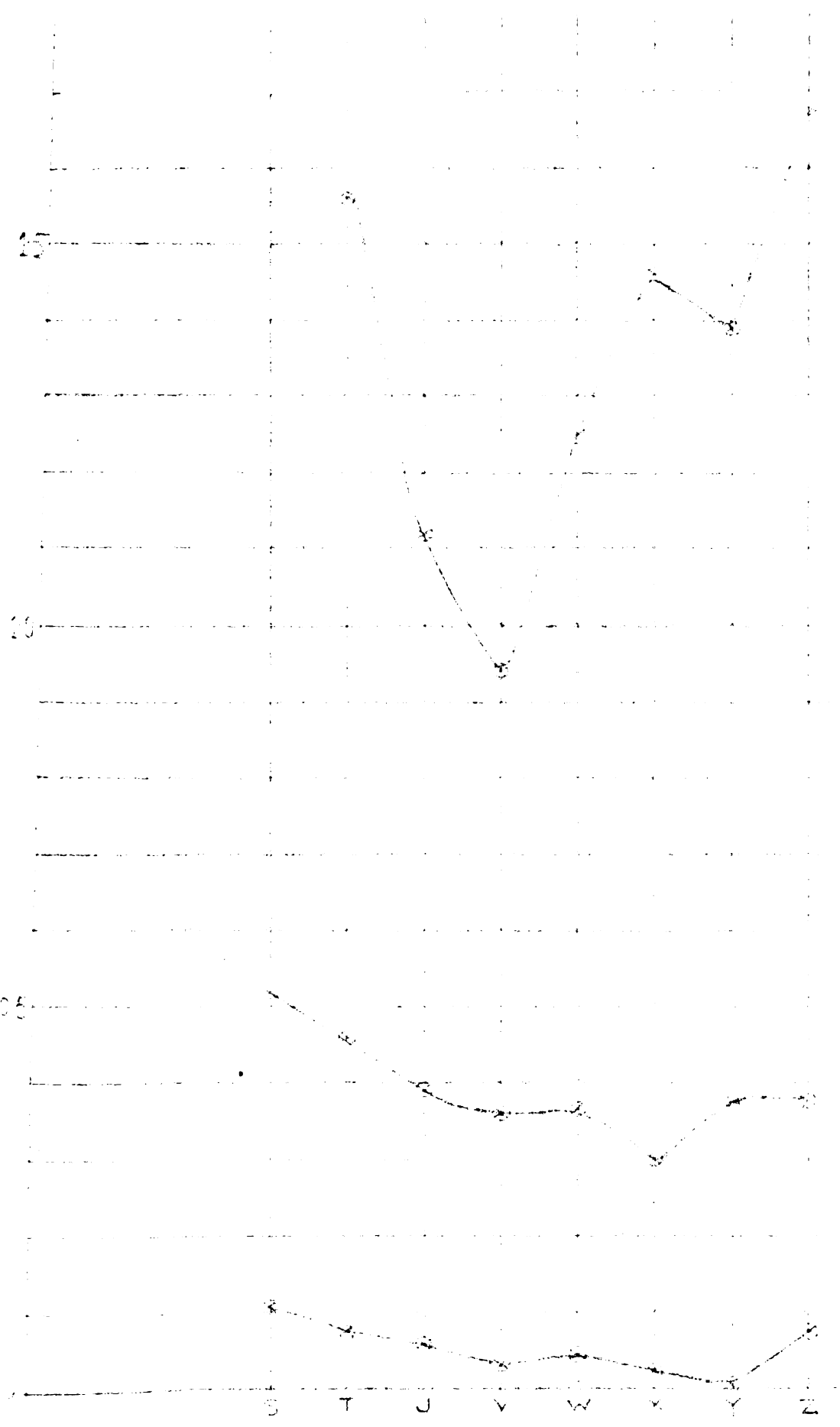
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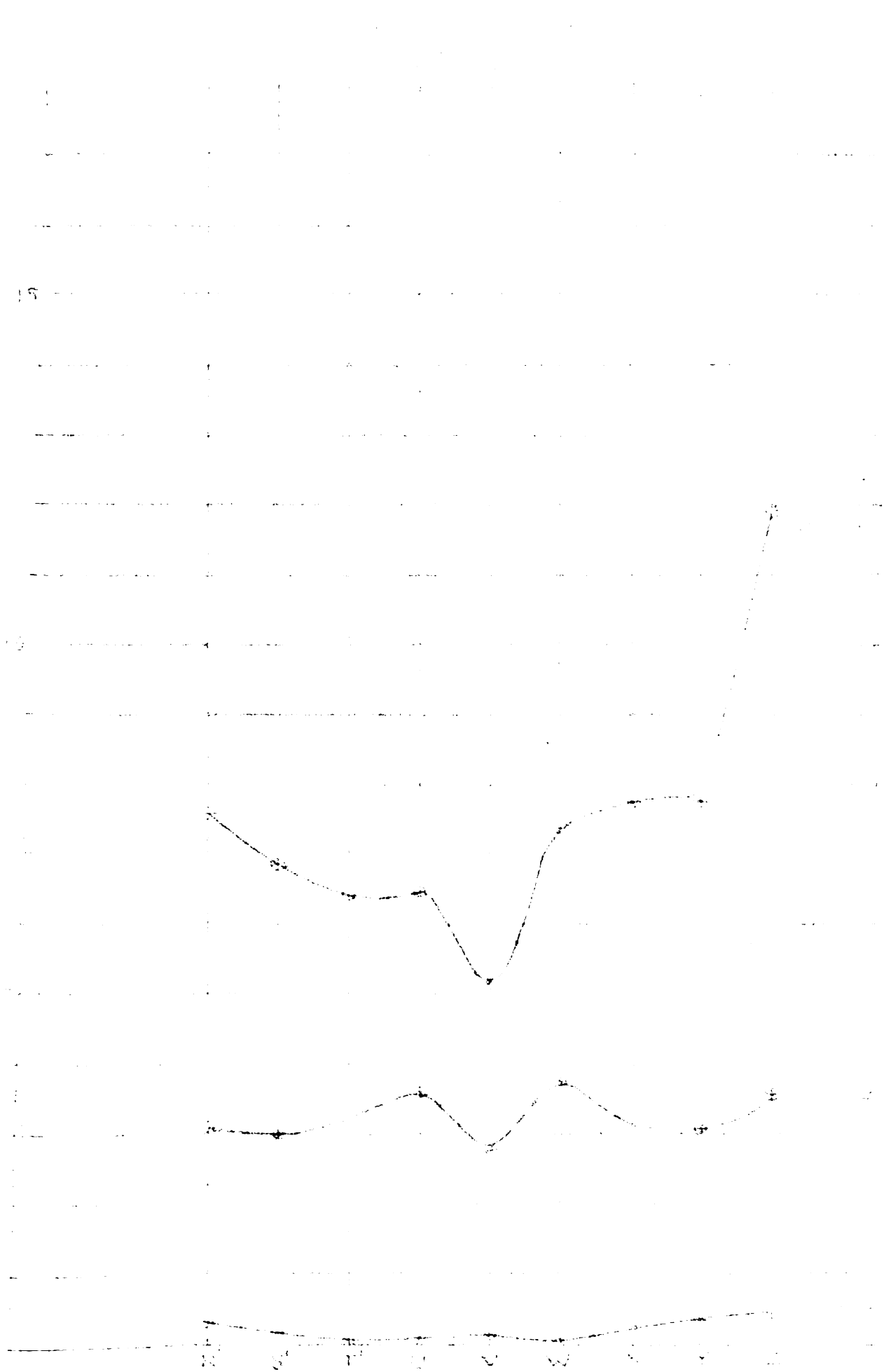
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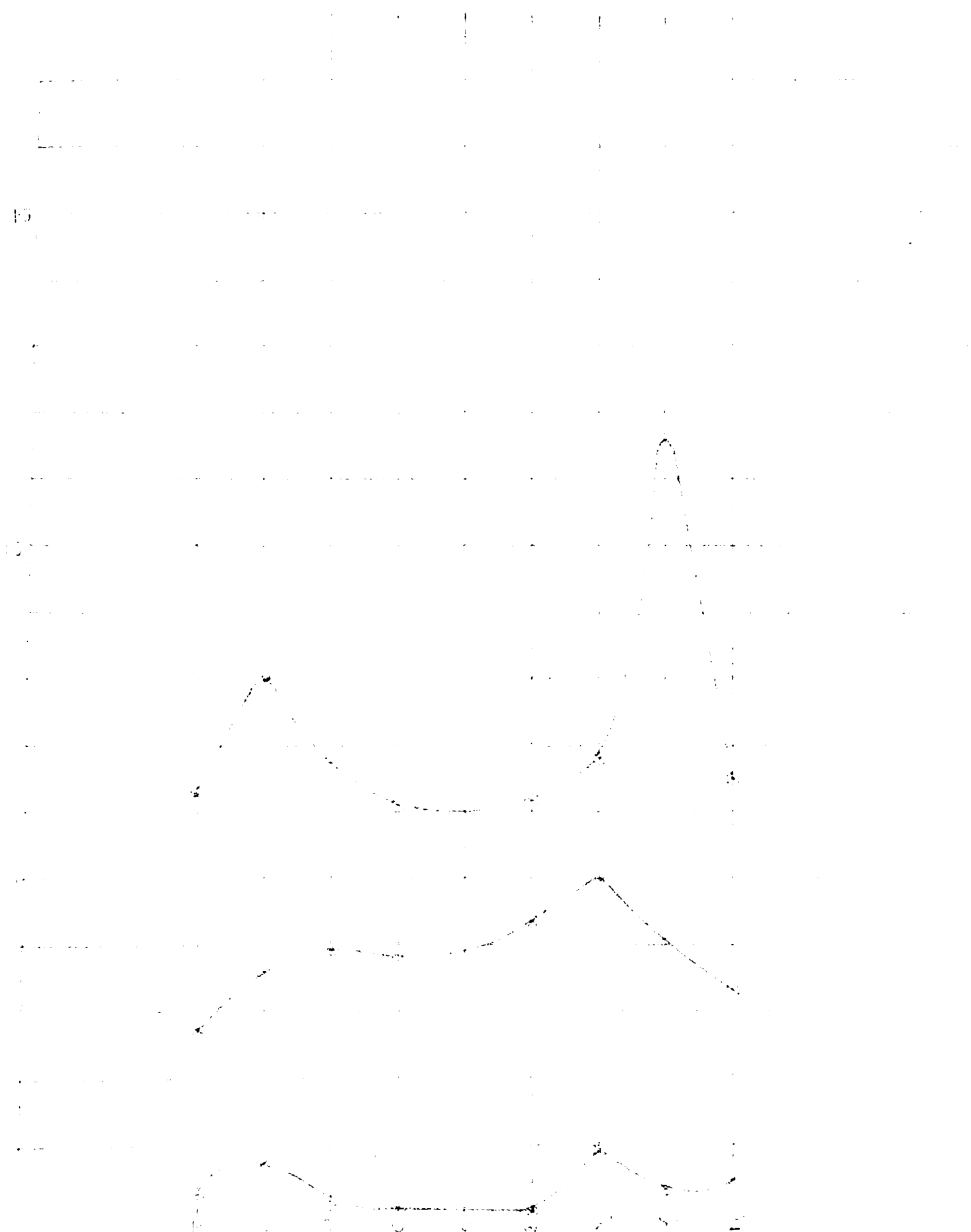




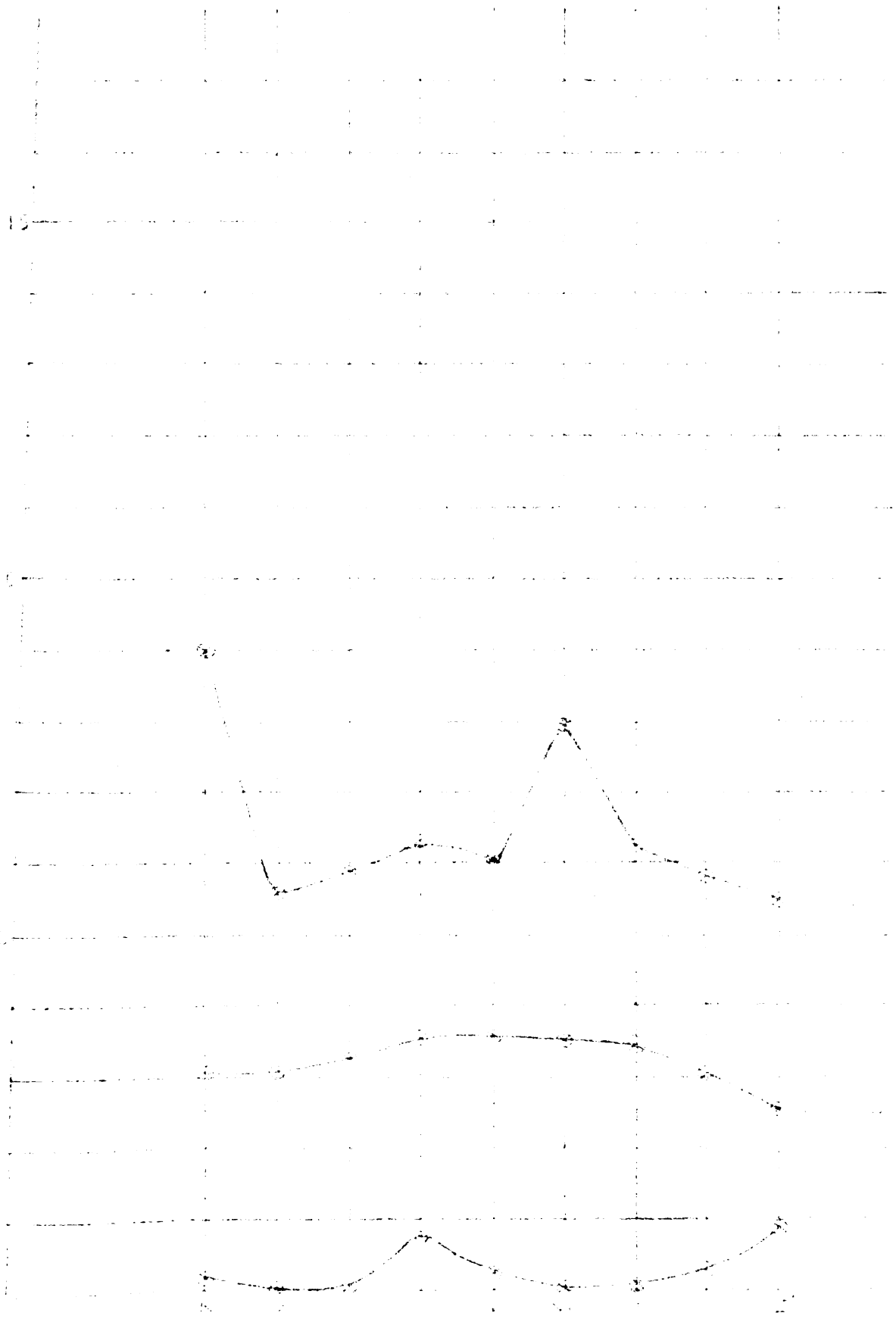


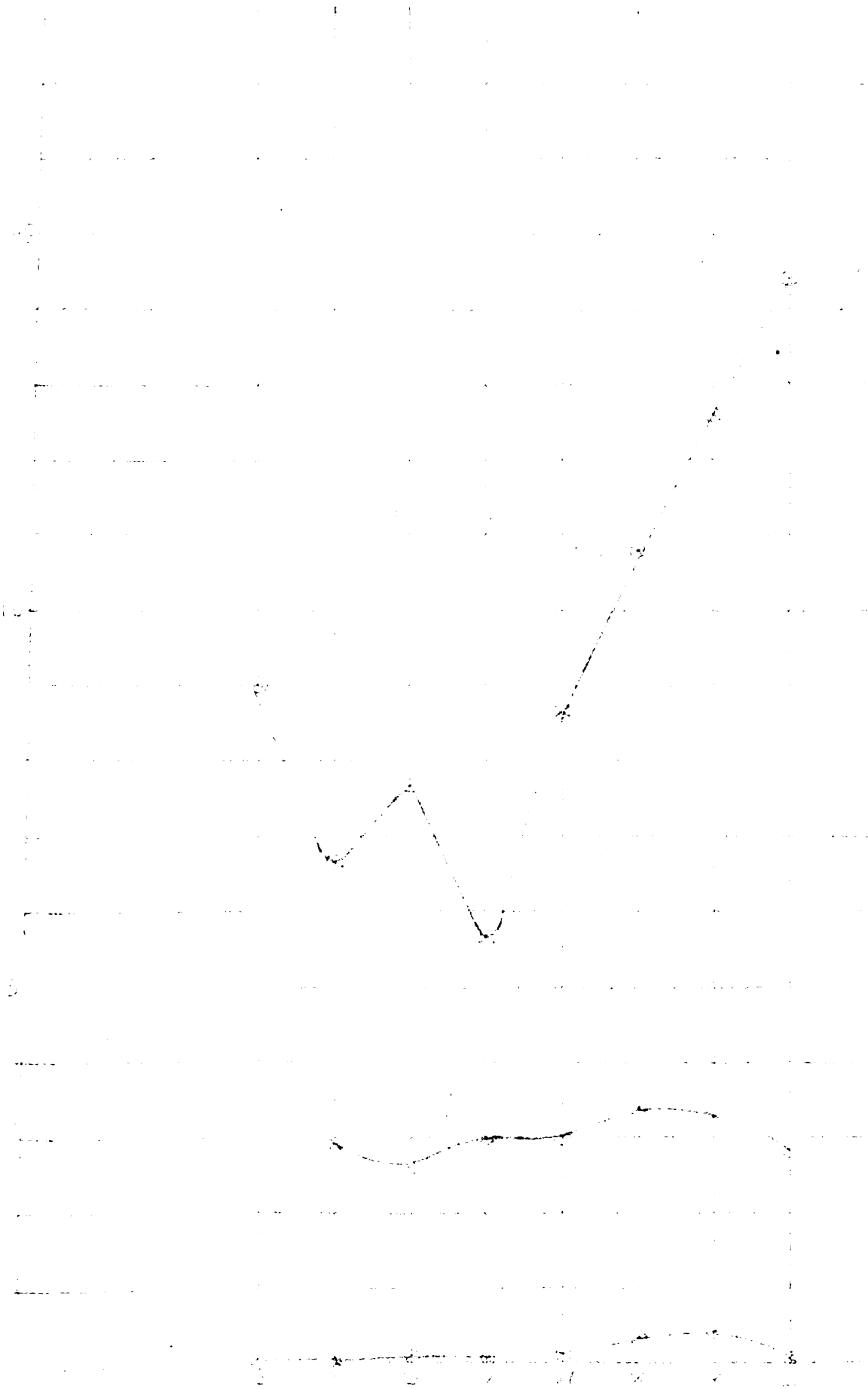


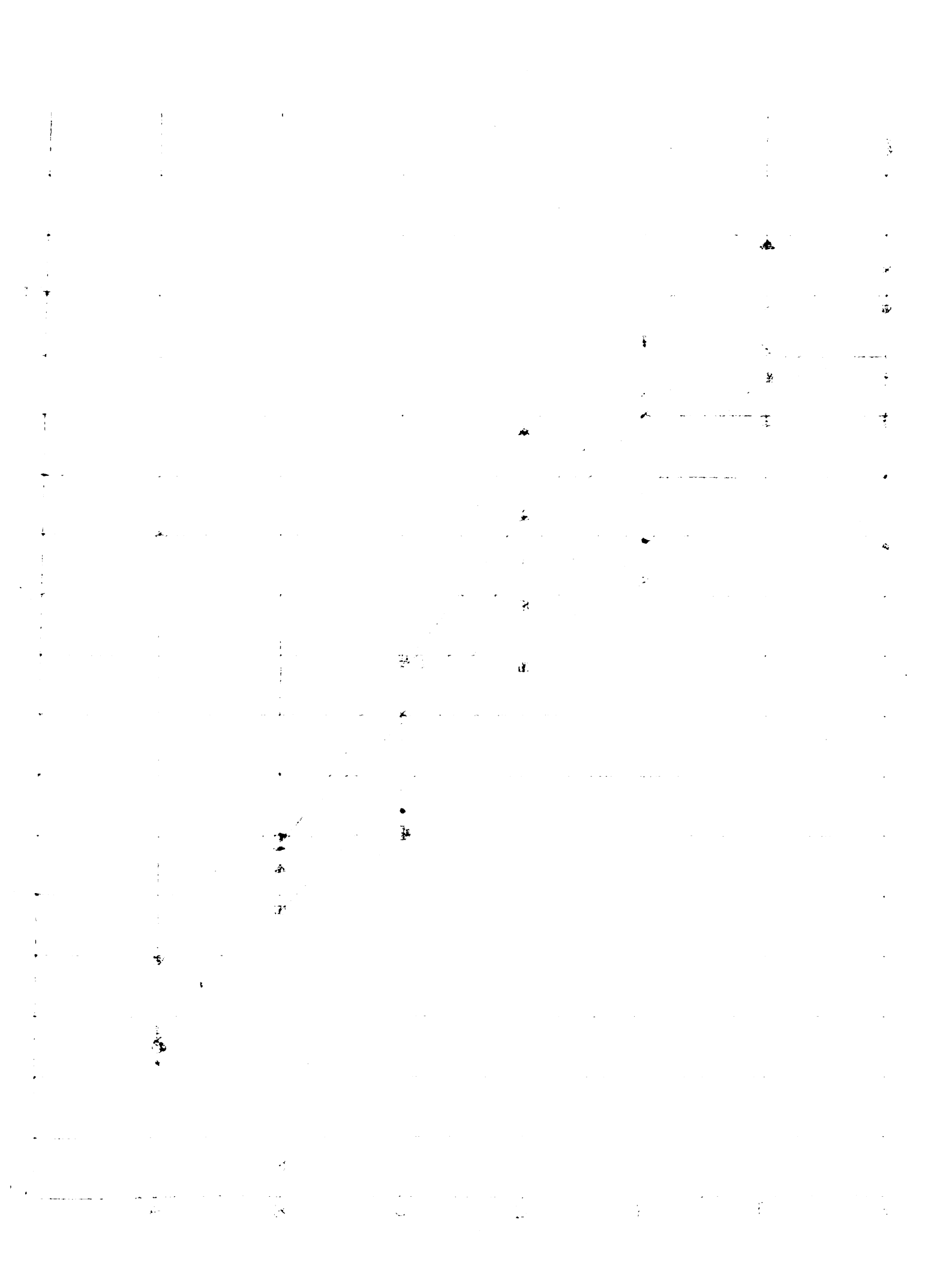


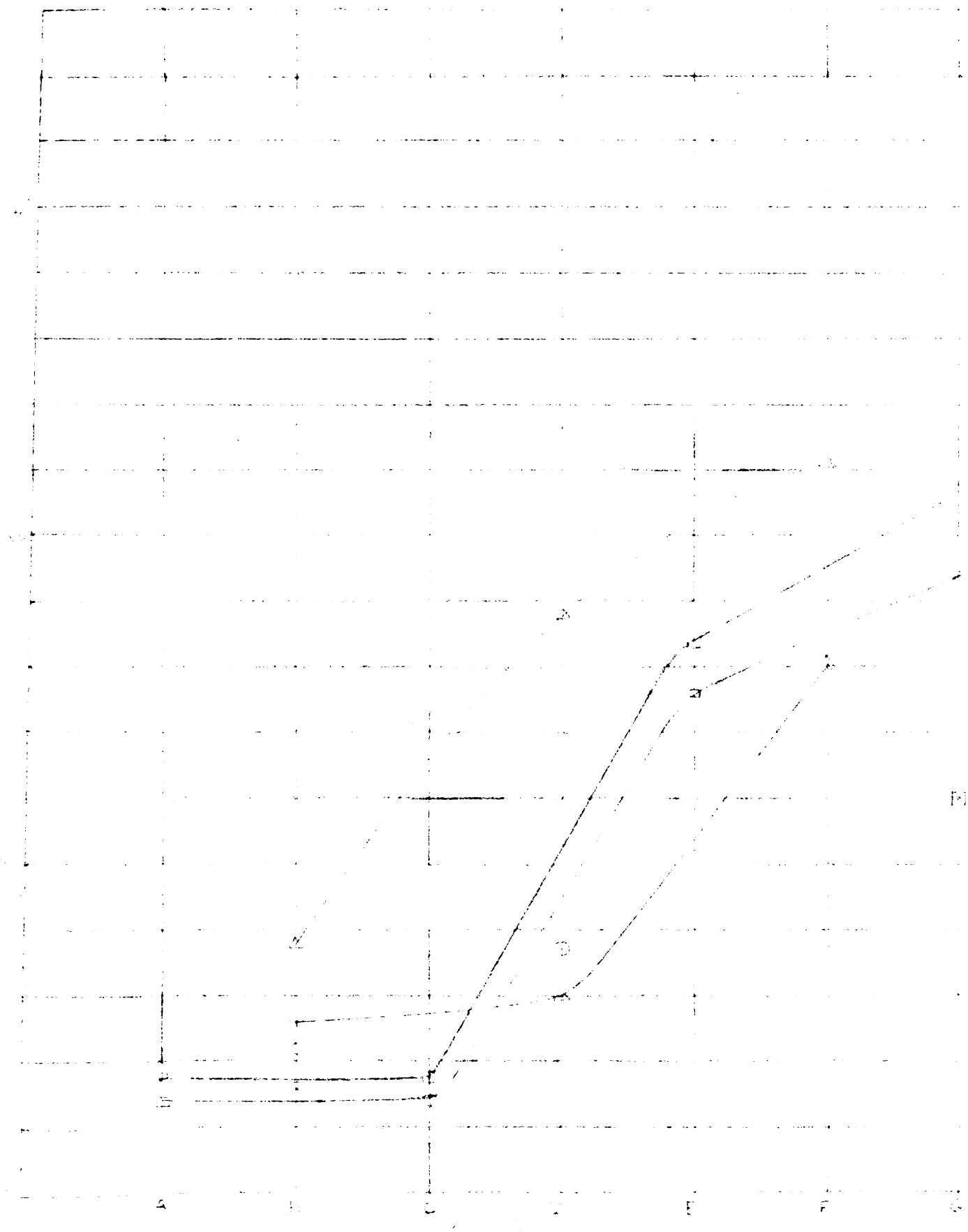




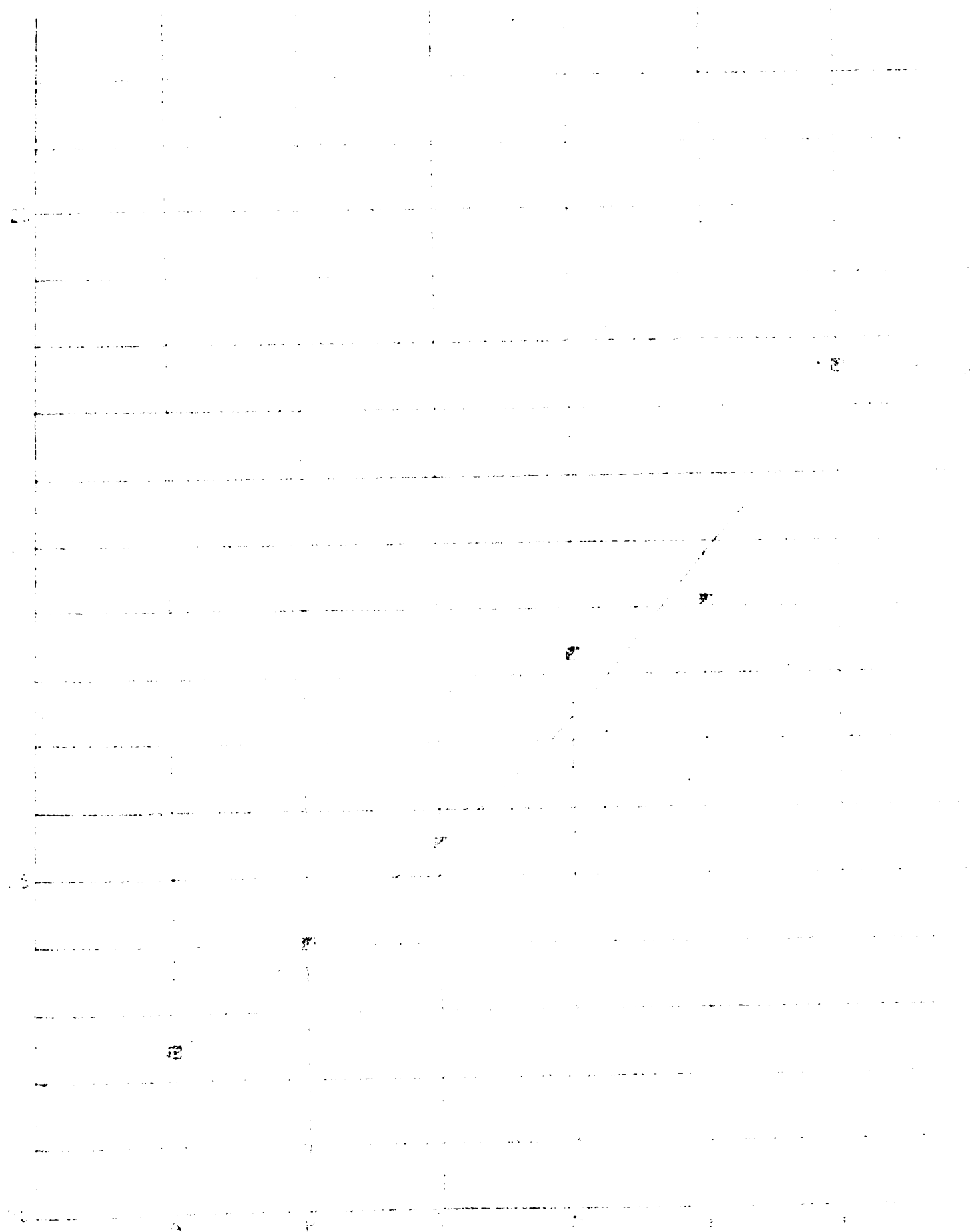


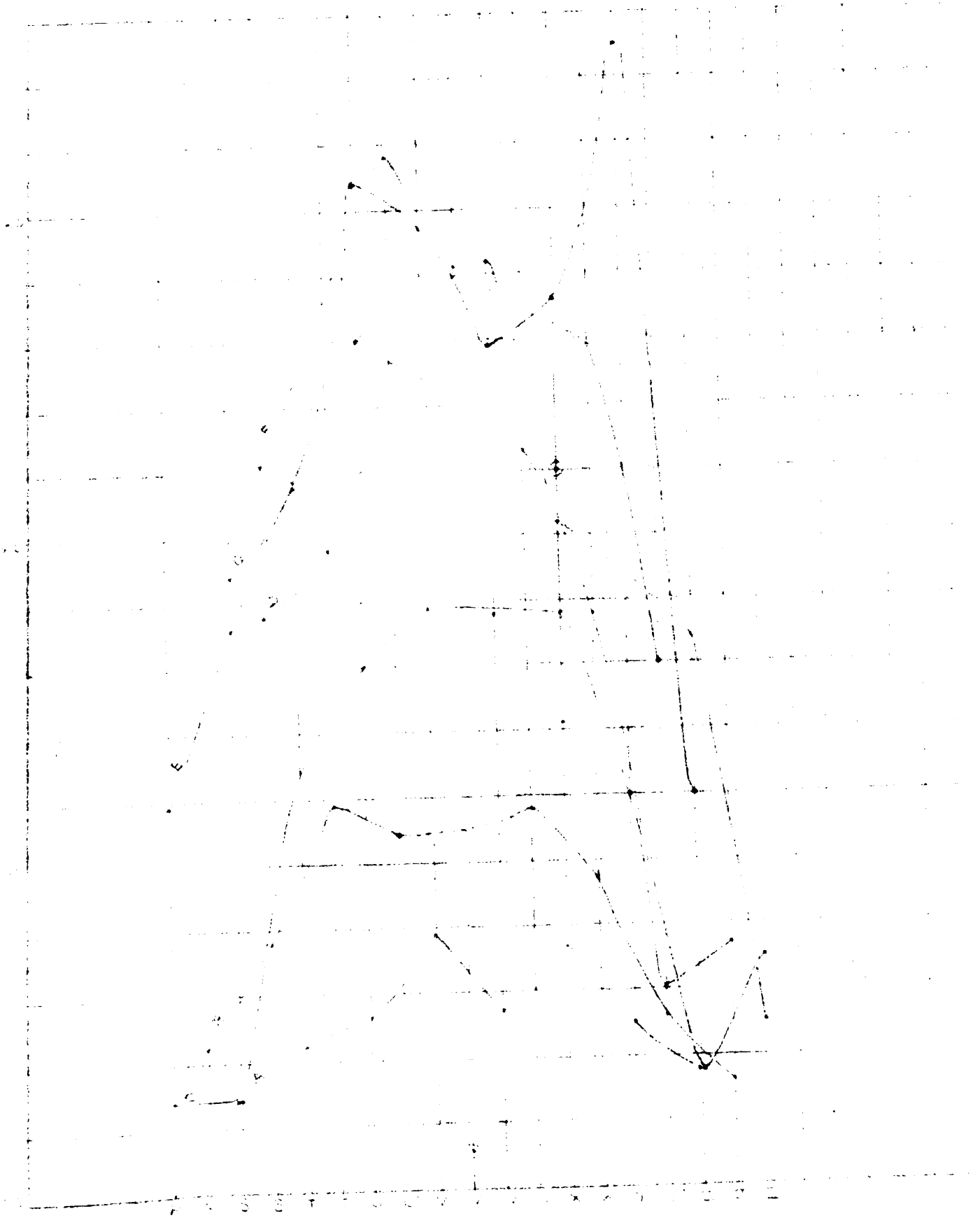












## CALCULATIONS

Following is the derivation of the equation used in calculating the concentration of the CO<sub>2</sub> samples.

The reaction for the titration of the excess Ba(OH)<sub>2</sub> was



Letting B' represent the ml. of excess Ba(OH)<sub>2</sub>, N<sub>B</sub> the normality of the HCl, A the ml. of this HCl used in equation 1, then

$$N_B B' = N_A A \quad \text{or} \quad B' = \frac{N_A A}{N_B} \quad 2.$$

If B then represents the total ml. of Ba(OH)<sub>2</sub> to which the sample was added and B'' the ml. of Ba(OH)<sub>2</sub> used to raise the pH of the H<sub>2</sub>O in the sample to 9, then B-(B' + B'') would represent the ml of Ba(OH)<sub>2</sub> used in the neutralization of the carbonic acid in the sample.

Therefore, from equation 2

$$M = B - B'' - B' = B - B'' - \frac{N_A A}{N_B} = \frac{(B - B'')N_B - N_A A}{N_B} \quad 3.$$

If F represents the ml. of Ba(OH)<sub>2</sub> necessary to raise one gram of H<sub>2</sub>O to pH 9, then in dilute solutions B'' = WF, where W is the weight of the sample in grams. Substituting WF for B'' in the right side of equation 3,

$$M = \frac{(B - WF)N_B - N_A A}{N_B} \quad 4.$$

The grams of Ba(OH)<sub>2</sub> used in the neutralization of the carbonic acid would then be,

$$G = M \times \frac{N_B}{1000} = \frac{(B - WF)N_B - N_A A}{1000} \quad 5.$$

and the mols,

$$m = \frac{G}{171.4} = \frac{(B-WF) N_B - N_A A}{171,400} \quad 6.$$

which equals the mols of  $\text{CO}_2$ . The weight of  $\text{CO}_2$  in the sample would then be

$$W = m \times 44 = 0.000257 (N_B B - N_A A - W F N_B) \quad 7.$$

The weight per cent of  $\text{CO}_2$  being,

$$C' = \frac{W}{W} \times 100 = 0.0257 \frac{(N_B B - N_A A)}{W} - 0.0257 F N_B \quad 8.$$

For ease of calculation, equation 8 was applied as follows:

$$C = 0.025 \frac{(N_B B - N_A A)}{W}$$

$$C' = C - 0.0257 F N_B$$

The velocity was calculated from the manometer reading of the pitot tube with the following formula

$$V' = 0.81 (2 g_c \triangle P \sin \arctan 0.1)^{\frac{1}{2}}$$

This pitot tube was calibrated against the laboratory standard orifice and against a velometer.

The volume of CO was calculated from the weight of the liquid CO using the Ideal Gas Law.

TABLE IX

| Concentration | Density g/ml $\frac{t^{\circ}\text{C}}{1^{\circ}\text{C}}$ |         |         |         |
|---------------|------------------------------------------------------------|---------|---------|---------|
|               | 15°C                                                       | 20°C    | 25°C    | 30°C    |
| 0.0           | 0.99913                                                    | 0.99823 | 0.99708 | 0.99568 |
| 0.1           | 0.99894                                                    | 0.99804 | 0.99689 | 0.99549 |
| 0.2           | 0.99875                                                    | 0.99785 | 0.99670 | 0.99530 |
| 0.3           | 0.99856                                                    | 0.99766 | 0.99651 | 0.99511 |
| 0.4           | 0.99838                                                    | 0.99748 | 0.99633 | 0.99492 |
| 0.5           | 0.99819                                                    | 0.99729 | 0.99614 | 0.99473 |
| 0.6           | 0.99800                                                    | 0.99710 | 0.99595 | 0.99454 |
| 0.7           | 0.99782                                                    | 0.99692 | 0.99577 | 0.99436 |
| 0.8           | 0.99763                                                    | 0.99673 | 0.99558 | 0.99417 |
| 0.9           | 0.99744                                                    | 0.99655 | 0.99539 | 0.99398 |
| 1.0           | 0.99725                                                    | 0.99636 | 0.99520 | 0.99379 |
| 1.1           | 0.99707                                                    | 0.99618 | 0.99502 | 0.99361 |
| 1.2           | 0.99689                                                    | 0.99599 | 0.99484 | 0.99342 |
| 1.3           | 0.99671                                                    | 0.99581 | 0.99466 | 0.99324 |
| 1.4           | 0.99652                                                    | 0.99562 | 0.99447 | 0.99305 |
| 1.5           | 0.99633                                                    | 0.99544 | 0.99428 | 0.99287 |
| 1.6           | 0.99614                                                    | 0.99525 | 0.99409 | 0.99268 |
| 1.7           | 0.99596                                                    | 0.99507 | 0.99391 | 0.99250 |
| 1.8           | 0.99578                                                    | 0.99489 | 0.99373 | 0.99231 |
| 1.9           | 0.99560                                                    | 0.99471 | 0.99355 | 0.99213 |
| 2.0           | 0.99542                                                    | 0.99453 | 0.99336 | 0.99194 |
| 2.1           | 0.99524                                                    | 0.99435 | 0.99318 | 0.99176 |
| 2.2           | 0.99507                                                    | 0.99417 | 0.99300 | 0.99158 |
| 2.3           | 0.99489                                                    | 0.99399 | 0.99282 | 0.99140 |
| 2.4           | 0.99471                                                    | 0.99381 | 0.99264 | 0.99122 |
| 2.5           | 0.99453                                                    | 0.99363 | 0.99246 | 0.99104 |
| 2.6           | 0.99435                                                    | 0.99345 | 0.99228 | 0.99086 |
| 2.7           | 0.99417                                                    | 0.99327 | 0.99210 | 0.99068 |
| 2.8           | 0.99400                                                    | 0.99310 | 0.99193 | 0.99050 |
| 2.9           | 0.99382                                                    | 0.99292 | 0.99175 | 0.99032 |
| 3.0           | 0.99365                                                    | 0.99275 | 0.99157 | 0.99014 |

The equation of Lewis (7) cited on page 3 was redeveloped for use with absorption. The same final result was obtained. The steps in this development follow:

$$(y_{n+1} - y_n) dV = 0 dx_n$$

$$\text{letting } d\bar{W} = \frac{dV}{V}$$

$$(y_{n+1} - y_n) = \frac{Q}{V} \frac{dx_n}{d\bar{W}} = R \frac{dx_n}{d\bar{W}}$$

$$y^* = Kx$$

$$dy^* = K dx$$

$$dx = \frac{dy^*}{K}$$

$$(y_{n+1} - y_n) = \frac{R}{K} \frac{dy_n^*}{d\bar{W}}$$

$$\text{let } \frac{K}{R} = \lambda$$

$$(y_{n+1} - y_n) \lambda = \frac{dy_n^*}{d\bar{W}}$$

$$E_{LVP} = \frac{y_{n+1} - y_n}{y_{n+1} - y_n^*}$$

$$-E_{LVP} y_n^* = y_{n+1} - y_n - E_{LVP} y_{n+1}$$

$$y_n^* = \frac{y_n}{E_{LVP}} + \frac{E_{LVP} - 1}{E_{LVP}} y_{n+1}$$

$$(y_{n+1} - y_n) \lambda = \frac{1}{E_{LVP}} \frac{dy_n}{d\bar{W}} + \frac{E_{LVP} - 1}{E_{LVP}} \frac{dy_{n+1}}{d\bar{W}}$$

Integrating over the plate from  $\bar{W} = 0$  to  $\bar{W} = \bar{W}_1$

$$\int_{\bar{W}=0}^{\bar{W}=\bar{W}_1} E_{LVP} \lambda d\bar{W} = \int_{\bar{W}=0}^{\bar{W}=\bar{W}_1} \frac{dy_n}{y_{n+1} - y_n} + (E_{LVP} - 1) \int_{\bar{W}=0}^{\bar{W}=\bar{W}_1} \frac{dy_{n+1}}{y_{n+1} - y_n}$$

$$E_{MVP} \lambda \, dW = \ln \frac{y_{n+1} - y_n}{y_{n+1} - (y_n)_o}$$

$$e^{E_{MVP} \lambda \, dW} = \frac{y_{n+1} - y_n}{y_{n+1} - (y_n)_o}$$

$$y_n = y_{n+1} - e^{E_{MVP} \lambda \, dW} [y_{n+1} - (y_n)_o]$$

$$(y_n)_{av.} = \int_0^1 y_n \, dW = \int_0^1 \left\{ y_{n+1} - e^{E_{MVP} \lambda \, W} [y_{n+1} - (y_n)_o] \right\} dW$$

$$(y_n)_{av.} = y_{n+1} + \frac{(1 - e^{E_{MVP} \lambda}) [y_{n+1} - (y_n)_o]}{E_{MVP} \lambda}$$

$$E_{MV} = \frac{(y_{n+1})_{av.} - (y_n)_{av.}}{(y_{n+1})_{av.} - (y_n^*)_o} \quad \text{by definition of Murphree}$$

$$E_{MV} = \frac{y_{n+1} - y_{n+1} - \left\{ \frac{(1 - e^{E_{MVP} \lambda}) [y_{n+1} - (y_n)_o]}{E_{MVP} \lambda} \right\}}{y_{n+1} - (y_n^*)_o}$$

$$E_{MV} = \frac{(e^{E_{MVP} \lambda} - 1) [y_{n+1} - (y_n)_o]}{E \lambda} \times \frac{1}{y_{n+1} - (y_n^*)_o}$$

$$\text{but } E_{MVP} = \frac{y_{n+1} - (y_n)_o}{y_{n+1} - (y_n^*)_o}$$

$$E_{MV} = \frac{e^{E_{MVP} \lambda} - 1}{E_{MVP} \lambda} \times E_{MVP}$$

$$E_{MV} = \frac{e^{E_{MVP} \lambda} - 1}{\lambda}$$

## DISCUSSION

It should be emphasized that previous work on liquid concentration gradient has been done on only small diameter columns, with samples taken in the direction of liquid flow only. This work was also all based on the system ethyl alcohol-water, in which the mechanism of transfer is definitely gaseous phase controlling.

The presentation of results of  $\text{CO}_2$  runs depicted in Figs. 2 through 13 was first attempted on a single graph, but the distribution was so random that it was impossible to detect if there was a trend in the results. The results, of this  $\text{CO}_2$  runs reported on, were then plotted column by column as shown in Figs. 2 through 13. While in Figs. 2 and 4 it appeared there might be a trend, as the plots for the three runs were of a corresponding shape, this was not supported by any of the other plots. In most cases the curve for Run No. 6 went down, while that for Run No. 4 went up, or vice versa. (No curves were drawn in Fig. 9 as the center tray support prevented the taking of a sample at DY<sup>1</sup>.) The plot of the averages of the rows, Fig. 13, in the direction of the liquid flow also indicated the complete randomness of the concentration distribution in that direction, i.e., along the columns.

Figures 20 through 26 depict the distribution of the concentration at right angles to the direction of flow, i.e., the distribution along the rows. There seemed to be more of an agreement between the runs on the distribution of concentration, in this direction, than in the other. It would still have to be termed a random distribution, however.

The contrast between the  $\text{CO}_2$  data and that of the alcohol data was apparent, when the definite trend of the alcohol data was observed, Fig. 27.

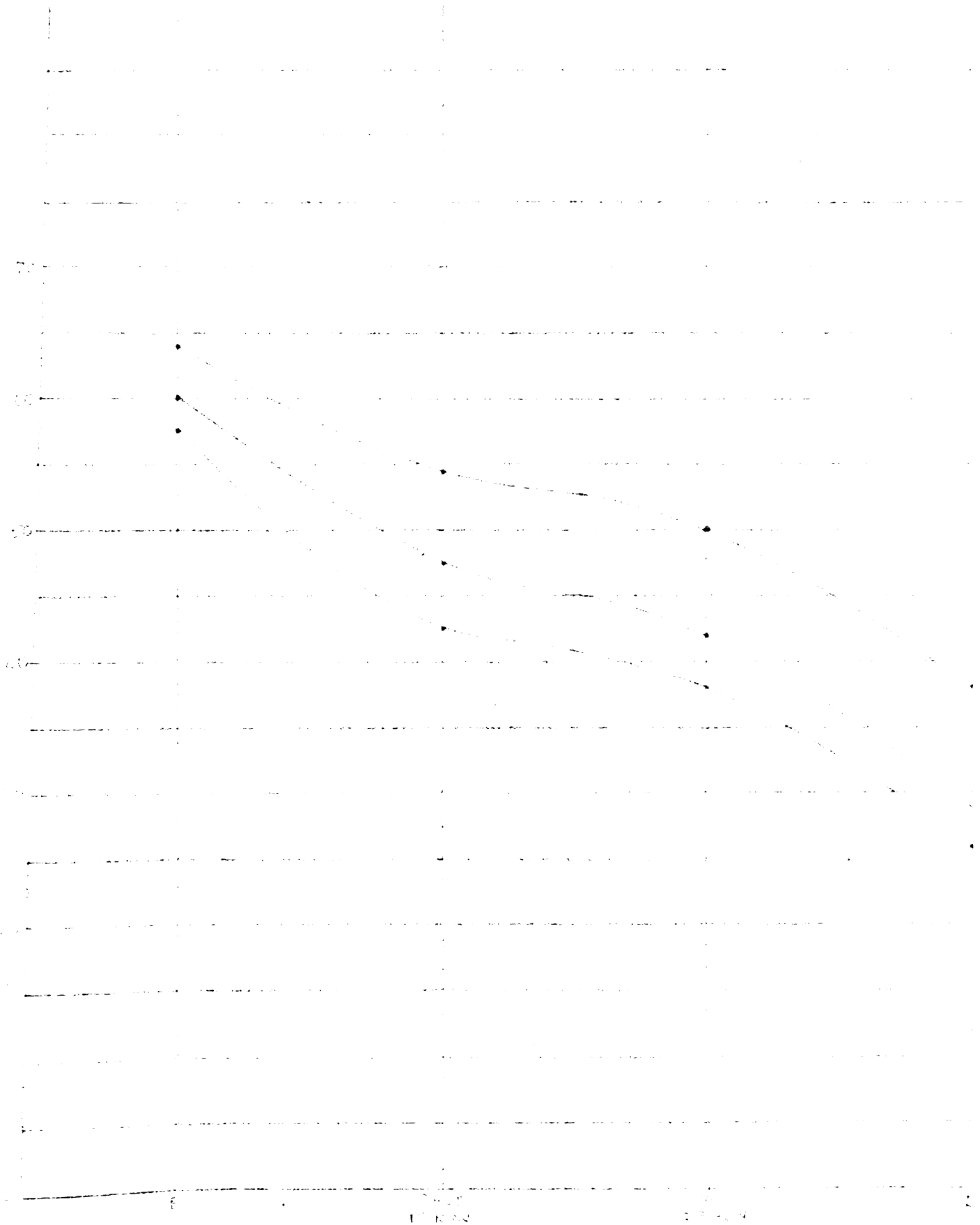


This figure shows the distribution of the concentration in the direction of liquid flow, for the center columns, T' to X'. These columns were separated from the edge columns, because of the similarity of the shape of the latter column's data for that of the columns symmetrically opposite from them. The edge column data was plotted in Fig. 28.

The average of the rows, for alcohol, is shown in Fig. 29. This gradient corresponds favorably with that found by Peavy and Baker (3), also for ethyl alcohol-water, shown in Fig. 31. (It must be realized, in this comparison, that their data was for rectification on a 18 inch column, as compared to a 48 inch column used in this absorption). It also is fairly comparable, on the same basis to the data reported by Kirschbaum and Andrews (4), Fig. 32, who reported on the rectification of ethyl alcohol-water in a small column.

The plot of concentration distribution at a right angle to the direction of liquid flow is shown in Fig. 30, it definitely shows a greater exchange between the gas and liquid in the center of the tray. This edge effect would be expected in a large column due to the different flow conditions of both the liquid and gas near the wall of the tower. This effect may have been magnified by the use of the bottom tray for sampling. Consequently, the quantity of incoming gas might not have been equally distributed on rising through the tray, even though it had to pass through the screen baffle first.

Lewis' equation (7) applied to absorption, shown in calculations section, was used to calculate the concentration distribution for Run No. 6-CO<sub>2</sub>. The average analysis, C, for the first row of caps was used for this purpose, with the assumption that the concentration in the water entering







the tray was zero.

The comparison of the calculation with the analysis follows:

| ROW | Calculated<br>Wt.% $\times 10^2$ | Analysis<br>C $\times 10^2$ |
|-----|----------------------------------|-----------------------------|
| A   | 0*                               | 0.146                       |
| B   | 0.946                            | 0.033                       |
| C   | 1.01                             | 0.116                       |
| D   | 2.69                             | 0.035                       |
| E   | 3.51                             | 0.110                       |
| F   | 4.43                             | 0.077                       |
| G   | 5.31                             | 0.106                       |
|     | 6.13                             |                             |

This equation was based on gaseous phase controlling. This is too often assumed in calculations for towers. Since  $\text{CO}_2$  is only slightly soluble in water, the liquid film is governing. This indicates that most of the absorption would take place in the spray above the tray. The extreme dispersion of the droplets would account for the random concentration distribution in the case of  $\text{CO}_2$ . Ethyl alcohol, on the other hand, dissolves readily in water and is thus gaseous phase controlling; therefore accounting for the concentration gradient with alcohol.

## CONCLUSIONS

1. In view of the findings in this work it appears necessary to determine the controlling phase, i.e., whether the absorption takes place predominately in the liquid on the tray or predominately in the droplets above the tray, for any work with liquid concentration distribution.
2. Inasmuch as the large quantity of droplets above the tray are dispersed at random, no liquid concentration gradient would be expected in the case where the exchange between solute and solvent occurs in these droplets.
3. The absence of a liquid concentration gradient in the absorption of carbon dioxide with water is attributed to liquid phase controlling.
4. The presence of a liquid concentration gradient in the absorption of ethyl alcohol from air, with water, is attributed to gaseous phase controlling.

## NOMENCLATURE

A = ml. of HCl used to neutralize excess  $\text{Ba}(\text{OH})_2$ .

B = total ml. of  $\text{Ba}(\text{OH})_2$  to which  $\text{CO}_2$  was added.

B' = excess  $\text{Ba}(\text{OH})_2$ , ml.

B'' = ml. of  $\text{Ba}(\text{OH})_2$  used to raise pH. of  $\text{H}_2\text{O}$  to 9.

$E_{AV}$  = plate efficiency which equals,  $\frac{(y_{n+1})_{av.} - (y_n)_{av.}}{(y_{n+1})_{av.} - (y_n^*)_0}$

$E_{LVP}$  = local point efficiency which equals,  $\frac{y_{n+1} - y_n}{y_{n+1} - y_n^*}$

C = uncorrected concentration of  $\text{CO}_2$  sample.

C' = corrected concentration of  $\text{CO}_2$  sample.

e = base of natural logs.

F = ml. of  $\text{Ba}(\text{OH})_2$  necessary to raise one gram of  $\text{H}_2\text{O}$  to pH 9.

G = grams of  $\text{Ba}(\text{OH})_2$  used to neutralize  $\text{CO}_2$  sample.

$E_C$  = conversion factor of 32.17 ft./sec.<sup>2</sup>

K =  $dy^*/dx$ , slope of equilibrium curve.

M = ml. of  $\text{Ba}(\text{OH})_2$  used to neutralize  $\text{CO}_2$  sample,  $M = B - (B'' + B')$ .

m = moles of  $\text{Ba}(\text{OH})_2$  used to neutralize  $\text{CO}_2$  sample, also moles of  $\text{CO}_2$  in sample.

$N_A$  = normality of HCl.

$N_B$  = normality of  $\text{Ba}(\text{OH})_2$ .

n = subscript, denotes tray under consideration.

n+1 = subscript, denotes tray below n tray.

O = rate of liquid flow down column, moles per unit time.

$P = R' \left( \frac{62.4}{12} \right)$ , #/ft.<sup>2</sup>

$\rho$  = density, #/ft.<sup>3</sup>

R = C/V.

$R'$  = manometer reading, inches of  $H_2O$ .

$V$  = rate of vapor flow up column, moles per unit time.

$V'$  = velocity of flow, ft/sec.

$W$  = weight of  $CO_2$  sample, grams.

$W_1$  = weight of sample bottle, grams.

$W_2$  = weight of sample bottle plus weight of stopper and weight of  $Ba(OH)_2$ , added, grams.

$W_3 = W_1 + W_2$ .

$\underline{W} = d\underline{W} = \frac{dV}{V}$ .

$\underline{W}$  = weight of  $CO_2$  in sample, grams.

$(x_n)\underline{W}$  = mole fraction of absorbent in liquid on tray  $n$ , at a point on the tray corresponding to some specific value of  $\underline{W}$ .

$(y_n)\underline{W}$  = mole fraction of absorbent in vapor leaving tray  $n$ , at a point on the tray corresponding to some specific value of  $\underline{W}$ .

$(y_n^*)\underline{W}$  = mole fraction of absorbent in the vapor which would be in equilibrium with  $(x_n)\underline{W}$

$\lambda = K/R$



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## CONCENTRATION GRADIENT ACROSS COMMERCIAL SIZE BUBBLE TRAYS

The wide range of overall and plate efficiency reported in the literature for bubble-cap columns is well known. These reported efficiencies vary from 7 per cent calculated by Sherwood (12) from the data of Whitman and Davis (17) to 120 per cent as stated by Brown (1). (A percentage of 100 apparently is due to multiple vapor contacts on a single tray.)

Such a range of efficiency indicate need for more data on the operation characteristics of bubble-cap towers, particularly of commercial size.

The present work was concerned with the concentration distribution in the liquid on a bubble-cap tray. In order to ascertain the concentration distribution independently of temperature variation, and avoid the expense and operation and sampling difficulties of distillation operation it was decided to use absorption rather than distillation. The bubble-cap tower used for this work was a four foot in diameter consisting of four alternating liquid flow direction trays spaced to 12 inches with 70 slotted caps per tray. Sixty-two samples were taken simultaneously for the first tray during each run. Absorption in this work was confined to the absorption of carbon dioxide from air with water and the absorption of ethyl alcohol vapor in air with water.

### EQUIPMENT

Photograph number 1 shows a picture of the apparatus used. The fan with its driving motor may be seen at the extreme right of the photograph with the discharging duct going beneath the foundation and up and under the column to the left. The sampling arrangement together with the tray for holding the sample bottles is shown attached to the tower. Drawing number 10 shows a cross-sectional drawing of the apparatus while drawing number 1 shows bubble-cap layout together with sampling arrangement. The numbers on the tray layout in drawing number 1 have reference to the position of the sampling tubes, while figure 9 page 14, shows a detail of the sample arrangement for one sample. The remaining 61 being quite



comparable except for lengths of the copper tubing.

Bubble-Cap Specifications:

Caps: 280 - 3 in. O. D. x 0.065 in. thick copper caps, 70 per tray

42 - 3/32 inch. wide x 13/16 inch high slots per cap.

Top of slot 7/8 in. above bottom edge of cap. Bottom of slot

0.0625 in. above plate. Slot area per cap = 3.12 sq. in.

Risers: 280 - 2 1/8 in. O.D. x 0.065 in. copper. Integral yoke style.

70 per tray. Overflow 1 7/16 in. above riser flange, 1.35 in.

above plate. Riser area equals 3.14 sq. in.

General: Annular area equals 2.94 sq. in.

(Vulcan Copper and Supply Co., Cincinnati 2, Ohio)

Fan: Clarage fan size 2 1/4 (20000 cuft per min @ 6") electric pulled by a 40 hp motor.

The six liquid samples were drawn simultaneously by applying a vacuum to the semi circular manifold shown in fig. \_\_\_\_\_. This manifold was connected to each sample bottle and in turn each bottle was connected to its individual sampling tube.

Two clean plastic windows 6" diameter were provided between each tray for visual observation.

A water meter (calibrated) was provided for measuring the water to the top tray while a pilot (calibrated) tube placed in the tower exit was used to measure the air velocity. The air velocity was varied by a damper arrangement on the suction side of the fan.

Test Procedures

In case of the carbon dioxide runs liquid a weakened amount of  $\text{CO}_2$  was introduced into the suction side of the fan. The sample latter having been partly filled with a known amount of .0235 normal barium hydroxide previous to the run. After sufficient time had elapsed after starting the air- $\text{CO}_2$  and water flow to allow a complete change in both liquid and vapor thru the tower the equal samples were taken. The samples were then removed and each titrated with HCl to ascertain the



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42 -  $3/32$  inch. wide x  $13/16$  inch high slots per cap.

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70 per tray. Overflow  $1\ 7/16$  in. above riser flange, 1.35 in.

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General: Annular area equals 2.94 sq. in.

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Test Procedures

In case of the carbon dioxide runs liquid a weakened amount of  $\text{CO}_2$  was introduced into the suction side of the fan. The sample latter having been partly filled with a known amount of .0235 normal barium hydroxide previous to the run. After sufficient time had elapsed after starting the air- $\text{CO}_2$  and water flow to allow a complete change in both liquid and vapor thru the tower the equal samples were taken. The samples were then removed and each titrated with HCl to ascertain the



CO<sub>2</sub> absorption. Beckman ph meter was used in tetrating these solutions to a ph of 9.0. The amount of barium hydioxide required to raise the fresh water to the tower to a ph of 9.0 was determined for each run and the proper correction applied to the tetration calculation. The resulting data together with the operating conditions of water rate, vapor rate, temperature, etc., are given under the section for data and correlation.

The ethyl alcohol-air absorption runs were made by asperating alcohol into the suction of the fan taking care that the asperation rate was constant and that the alcohol saturation point of the air was never exceeded. The 62 samples of alcohol water solution were analized for alcohol by the density method using a chainomatic Westphal balance. Due account was taken of the temperature and the density of the alcohol free water charged to the tower. The data for the alcohol-air runs are also included in the following section for data and correlation.

#### Data and Correlation

Although numerous runs were made the following three runs are typical of the results obtained.



TABLE VIII

Run No. 8, Alcohol

Concentration (Wt.%)

(Refer to Drawing #8)

| COLUMN               | ROW   |       |       |       |       |       |       |
|----------------------|-------|-------|-------|-------|-------|-------|-------|
|                      | A     | B     | C     | D     | E     | F     | G     |
| Z <sup>n</sup>       |       |       | 1.35  |       | 1.25  |       |       |
| Z <sup>i</sup>       |       | 1.16  |       | 1.37  |       | ----- |       |
| Z                    | 1.175 |       | 1.175 |       | 1.84  |       | 1.60  |
| Y <sup>i</sup>       |       | 1.26  |       | 1.30  |       | 1.80  |       |
| Y                    | 1.25  |       | 1.60  |       | ----- |       | 2.75  |
| X <sup>i</sup>       |       | 1.475 |       | 1.88  |       | 2.29  |       |
| X                    | 2.10* |       | 1.88  |       | 2.02  |       | 2.36  |
| W <sup>i</sup>       |       | 1.58  |       | 2.13  |       | ----- |       |
| W                    | 1.27  |       | 1.88  |       | 2.22  |       | 2.29  |
| V <sup>i</sup>       |       | 1.05* |       |       |       | 2.41  |       |
| V                    | 1.39  |       | 1.89  |       | ----- |       | 2.475 |
| U <sup>i</sup>       |       | 1.54  |       | 2.27  |       | 2.58  |       |
| U                    | 1.26  |       | 1.80  |       | 2.30  |       | 2.54  |
| T <sup>i</sup>       |       | 1.59  |       | 1.98  |       | 2.36  |       |
| T                    | 1.22  |       | 1.64  |       | 2.09  |       | 2.08  |
| S <sup>i</sup>       |       | 1.38  |       | 1.88  |       | 2.11  |       |
| S                    | 1.14  |       | 1.14  |       | 1.76  |       | 1.94  |
| R <sup>i</sup>       |       | 1.22  |       | ----- |       | ----- |       |
| R                    |       |       | 1.14  |       | 1.59  |       |       |
| *Not used in average |       |       |       |       |       |       |       |
| Ave.                 | 1.24  | 1.40  | 1.55  | 1.83  | 1.91  | 2.26  | 2.25  |

Liquid Rate: 9.6 G.P.M.

Gas Rate: 1980 C.F.M.

Gas Conc.: 7.9% by Vol.



## CONCENTRATION GRADIENT ACROSS COMMERCIAL SIZE BUBBLE TRAYS

The wide range of overall and plate efficiency reported in the literature for bubble-cap columns is well known. These reported efficiencies vary from 7 per cent calculated by Sherwood (12) from the data of Whitman and Davis (17) to 120 per cent as stated by Brown (1). (A percentage of 100 apparently is due to multiple vapor contacts on a single tray.)

Such a range of efficiency indicate need for more data on the operation characteristics of bubble-cap towers, particularly of commercial size.

The present work was concerned with the concentration distribution in the liquid on a bubble-cap tray. In order to ascertain the concentration distribution independently of temperature variation, and avoid the expense and operation and sampling difficulties of distillation operation it was decided to use absorption rather than distillation. The bubble-cap tower used for this work was a four foot in diameter consisting of four alternating liquid flow direction trays spaced to 12 inches with 70 slotted caps per tray. Sixty-two samples were taken simultaneously for the first tray during each run. Absorption in this work was confined to the absorption of carbon dioxide from air with water and the absorption of ethyl alcohol vapor in air with water.

### EQUIPMENT

Photograph number 1 shows a picture of the apparatus used. The fan with its driving motor may be seen at the extreme right of the photograph with the discharging duct going beneath the foundation and up and under the column to the left. The sampling arrangement together with the tray for holding the sample bottles is shown attached to the tower. Drawing number 10 shows a cross-sectional drawing of the apparatus while drawing number 1 shows bubble-cap layout together with sampling arrangement. The numbers on the tray layout in drawing number 1 have reference to the position of the sampling tubes, while figure 9 page 14, shows a detail of the sample arrangement for one sample. The remaining 61 being quite



TABLE V

Run No. 3,  $CO_2$  Divide by 1000 for Wt. %

(Refer to Drawing #8)

| COLUMN         | ROW   |       |       |       |       |       |       |
|----------------|-------|-------|-------|-------|-------|-------|-------|
|                | A     | B     | C     | D     | E     | F     | G     |
| Z <sup>W</sup> |       |       | 0.093 |       | 0.096 |       |       |
| Z <sup>I</sup> |       | 0.045 |       | 0.047 |       | 0.088 |       |
| Z Z            | 0.075 |       | 0.066 |       | 0.025 |       | ----- |
| Y <sup>I</sup> |       | 0.033 |       | 0.032 |       | 0.03  |       |
| Y              | 0.007 |       | ----- |       | 0.079 |       | 0.042 |
| X <sup>I</sup> |       | 0.026 |       | 0.095 |       | 0.011 |       |
| X              | 0.022 |       | 0.005 |       | 0.008 |       | 0.035 |
| W <sup>I</sup> |       | ----- |       | ----- |       | 0.002 |       |
| W W            | 0.045 |       | 0.14  |       | 0.084 |       | 0.012 |
| V <sup>I</sup> |       | 0.01  |       |       | 0.023 |       |       |
| V              | 0.03  |       | 0.122 |       | 0.11  |       | 0.009 |
| U <sup>I</sup> |       | 0.009 |       | 0.006 |       | 0.073 |       |
| U              | 0.057 |       | ----- |       | 0.007 |       | 0.01  |
| T <sup>I</sup> |       | 0.004 |       | 0.013 |       | 0.007 |       |
| T              | 0.075 |       | 0.054 |       | 0.027 |       | 0.001 |
| S <sup>I</sup> |       | 0.013 |       | 0.073 |       | 0.000 |       |
| S              | 0.104 |       | 0.067 |       | 0.053 |       | 0.006 |
| R <sup>I</sup> |       | 0.027 |       | 0.025 |       | 0.017 |       |
| R              |       |       | 0.057 |       | 0.019 |       |       |
| Ave.           | 0.052 | 0.018 | 0.067 | 0.036 | 0.051 | 0.029 | 0.014 |

Liquid Rate: 29.9 G.P.M.

Gas

Gas Rate: 1470 C.F.M.

Gas Conc.: Laboratory Air



TABLE VI

Run No. 4, CO<sub>2</sub>. Divide by 1000 for Wt. %

(Refer to Drawing #8)

| COLUMN | A     | B     | C     | D     | E     | F     | G     |
|--------|-------|-------|-------|-------|-------|-------|-------|
| Z"     |       |       | 0.423 |       | 0.302 |       |       |
| Z'     |       | 0.355 |       | 0.330 |       | 0.253 |       |
| Z      | 0.378 |       | 0.325 |       | 0.394 |       | 0.281 |
| Y'     |       | 0.309 |       | 0.412 |       | 0.304 |       |
| Y      | 0.374 |       | 0.412 |       | 0.394 |       | 0.325 |
| X'     |       | 0.312 |       | 0.501 |       | 0.345 |       |
| X      | 0.299 |       | 0.260 |       | 0.389 |       | 0.337 |
| W'     |       | 0.374 |       | 0.436 |       | 0.350 |       |
| W      | 0.363 |       | 0.664 |       | 0.289 |       | 0.299 |
| V'     |       | 0.278 |       |       |       | 0.355 |       |
| V      | 0.360 |       | 0.615 |       | 0.400 |       | 0.299 |
| U'     |       | 0.360 |       | 0.376 |       | 0.353 |       |
| U      | 0.391 |       | 0.364 |       | 0.484 |       | 0.26  |
| T'     |       | ----- |       | 0.394 |       | 0.322 |       |
| T      | 0.460 |       | 0.328 |       | 0.294 |       | 0.291 |
| S'     |       | 0.299 |       | 0.360 |       | 0.305 |       |
| S      | 0.520 |       | 0.379 |       | 0.389 |       | ----- |
| R'     |       | 0.309 |       | 0.274 |       | 0.304 |       |
| R      |       |       | 0.299 |       | 0.274 |       |       |
| Ave.   | 0.393 | 0.325 | 0.408 | 0.385 | 0.361 | 0.321 | 0.299 |

Liquid Rate: 36.3 G.P.M.

Gas Rate: 933. C.F.M.

Gas Conc.: 17.5% by vol.



TABLE VII

Run No. 6, CO<sub>2</sub>. Divide by 1000 for Wt. %

(Refer to Drawing #8)

| COLUMN | A     | B     | C     | ROW<br>D | E     | F     | G     |
|--------|-------|-------|-------|----------|-------|-------|-------|
| Z"     |       |       | 1.70  |          | 1.815 |       |       |
| Z'     |       | 1.19  |       | 0.65     |       | 0.548 |       |
| Z      | 1.67  |       | 1.34  |          | 1.15  |       | 1.44  |
| Y'     |       | 0.775 |       | 1.16     |       | 0.58  |       |
| Y      | 1.39  |       | 1.11  |          | 0.91  |       | 1.26  |
| X'     |       | 0.775 |       | 0.68     |       | 0.623 |       |
| X      | 1.46  |       | 0.671 |          | 0.74  |       | 1.08  |
| W'     |       | 0.738 |       | 0.617    |       | 0.795 |       |
| W      | 1.25  |       | 0.79  |          | 0.612 |       | 0.864 |
| V'     |       | 0.512 |       |          |       | 0.605 |       |
| V      | 0.94  |       | 0.635 |          | 0.72  |       | 0.564 |
| U'     |       | 0.645 |       | 0.61     |       | 0.63  |       |
| U      | 1.12  |       | 0.589 |          | 0.615 |       | 0.769 |
| T'     |       | 0.641 |       | 0.676    |       | 0.587 |       |
| T      | 1.56  |       | 0.576 |          | 1.17  |       | 0.666 |
| S'     |       | 0.682 |       | 0.808    |       | 0.555 |       |
| S      | ----- |       | 1.71  |          | ----- |       | 0.90  |
| R'     |       | 0.759 |       | 0.625    |       | 0.90  |       |
| R      |       |       | 1.32  |          | 1.11  |       |       |
| Ave.   | 1.34  | 0.741 | 1.044 | 0.728    | 0.982 | 0.647 | 0.943 |

Liquid Rate: 33.9 G.P.M.

Gas Rate: 628 C.F.M.

Gas Conc.: 57.6% by Vol.



CO<sub>2</sub> absorption. Beckman ph meter was used in tetrating these solutions to a ph of 9.0. The amount of barium hydroxide required to raise the fresh water to the tower to a ph of 9.0 was determined for each run and the proper correction applied to the tetration calculation. The resulting data together with the operating conditions of water rate, vapor rate, temperature, etc., are given under the section for data and correlation.

The ethyl alcohol-air absorption runs were made by asperating alcohol into the suction of the fan taking care that the asperation rate was constant and that the alcohol saturation point of the air was never exceeded. The 62 samples of alcohol water solution were analized for alcohol by the density method using a chainomatic Westphal balance. Due account was taken of the temperature and the density of the alcohol free water charged to the tower. The data for the alcohol-air runs are also included in the following section for data and correlation.

#### Data and Correlation

Although numerous runs were made the following three runs are typical of the results obtained.



TABLE V

Run No. 5, CO<sub>2</sub> Divide by 1000 for Wt. %

(Refer to Drawing #8)

| COLUMN | ROW   |       |       |       |       |       |       |
|--------|-------|-------|-------|-------|-------|-------|-------|
|        | A     | B     | C     | D     | E     | F     | G     |
| Z"     |       |       | 0.093 |       | 0.096 |       |       |
| Z'     |       | 0.045 |       | 0.047 |       | 0.088 |       |
| Z Z    | 0.075 |       | 0.066 |       | 0.025 |       | ----- |
| Y'     |       | 0.033 |       | 0.032 |       | 0.03  |       |
| Y      | 0.007 |       | ----- |       | 0.079 |       | 0.042 |
| X'     |       | 0.026 |       | 0.095 |       | 0.011 |       |
| X      | 0.022 |       | 0.005 |       | 0.008 |       | 0.035 |
| W'     |       | ----- |       | ----- |       | 0.002 |       |
| W W    | 0.045 |       | 0.14  |       | 0.084 |       | 0.012 |
| V'     |       | 0.01  |       |       |       | 0.023 |       |
| V      | 0.03  |       | 0.122 |       | 0.11  |       | 0.009 |
| U'     |       | 0.009 |       | 0.006 |       | 0.073 |       |
| U      | 0.057 |       | ----- |       | 0.007 |       | 0.01  |
| T'     |       | 0.004 |       | 0.013 |       | 0.007 |       |
| T      | 0.075 |       | 0.054 |       | 0.027 |       | 0.001 |
| S'     |       | 0.013 |       | 0.073 |       | 0.000 |       |
| S      | 0.104 |       | 0.067 |       | 0.053 |       | 0.006 |
| R'     |       | 0.027 |       | 0.025 |       | 0.017 |       |
| R      |       |       | 0.057 |       | 0.019 |       |       |
| Ave.   | 0.052 | 0.018 | 0.067 | 0.036 | 0.051 | 0.029 | 0.014 |

Liquid Rate: 29.9 G.P.M.

Gas

Gas Rate: 1470 C.F.M.

Gas Conc.: Laboratory Air



TABLE VI

Run No. 4, CO<sub>2</sub>. Divide by 1000 for Wt. %

(Refer to Drawing #3)

| COLUMN | A     | B     | C     | D     | E     | F     | G     |
|--------|-------|-------|-------|-------|-------|-------|-------|
| Z"     |       |       | 0.423 |       | 0.302 |       |       |
| Z'     |       | 0.355 |       | 0.330 |       | 0.253 |       |
| Z      | 0.378 |       | 0.325 |       | 0.394 |       | 0.281 |
| Y'     |       | 0.309 |       | 0.412 |       | 0.304 |       |
| Y      | 0.374 |       | 0.412 |       | 0.394 |       | 0.325 |
| X'     |       | 0.312 |       | 0.501 |       | 0.345 |       |
| X      | 0.299 |       | 0.260 |       | 0.389 |       | 0.337 |
| W'     |       | 0.374 |       | 0.436 |       | 0.350 |       |
| W      | 0.363 |       | 0.664 |       | 0.289 |       | 0.299 |
| V'     |       | 0.278 |       |       |       | 0.355 |       |
| V      | 0.360 |       | 0.615 |       | 0.400 |       | 0.299 |
| U'     |       | 0.360 |       | 0.376 |       | 0.353 |       |
| U      | 0.391 |       | 0.364 |       | 0.484 |       | 0.26  |
| T'     |       | ----- |       | 0.394 |       | 0.322 |       |
| T      | 0.460 |       | 0.328 |       | 0.294 |       | 0.291 |
| S'     |       | 0.299 |       | 0.360 |       | 0.305 |       |
| S      | 0.520 |       | 0.379 |       | 0.389 |       | ----- |
| R'     |       | 0.309 |       | 0.274 |       | 0.304 |       |
| R      |       |       | 0.299 |       | 0.274 |       |       |
| Ave.   | 0.393 | 0.325 | 0.408 | 0.385 | 0.361 | 0.321 | 0.299 |

Liquid Rate: 36.3 G.P.M.

Gas Rate: 933. C.F.M.

Gas Conc.: 17.5% by vol.



TABLE VIII

Run No. 8, Alcohol

Concentration (Wt.%)

(Refer to Drawing #8)

| COLUMN               | ROW   |       |       |       |       |       |       |
|----------------------|-------|-------|-------|-------|-------|-------|-------|
|                      | A     | B     | C     | D     | E     | F     | G     |
| Z"                   |       |       | 1.35  |       | 1.25  |       |       |
| Z'                   |       | 1.16  |       | 1.37  |       | ----- |       |
| Z                    | 1.175 |       | 1.175 |       | 1.84  |       | 1.60  |
| Y'                   |       | 1.26  |       | 1.30  |       | 1.80  |       |
| Y                    | 1.25  |       | 1.60  |       | ----- |       | 2.75  |
| X'                   |       | 1.475 |       | 1.88  |       | 2.29  |       |
| X                    | 2.10* |       | 1.88  |       | 2.02  |       | 2.36  |
| W'                   |       | 1.58  |       | 2.13  |       | ----- |       |
| W                    | 1.27  |       | 1.88  |       | 2.42  |       | 2.29  |
| V'                   |       | 1.05* |       |       |       | 2.41  |       |
| V                    | 1.39  |       | 1.89  |       | ----- |       | 2.475 |
| U'                   |       | 1.54  |       | 2.27  |       | 2.58  |       |
| U                    | 1.26  |       | 1.80  |       | 2.30  |       | 2.54  |
| T'                   |       | 1.59  |       | 1.98  |       | 2.36  |       |
| T                    | 1.22  |       | 1.64  |       | 2.09  |       | 2.08  |
| S'                   |       | 1.38  |       | 1.88  |       | 2.11  |       |
| S                    | 1.14  |       | 1.14  |       | 1.76  |       | 1.94  |
| R'                   |       | 1.22  |       | ----- |       | ----- |       |
| R                    |       |       | 1.14  |       | 1.59  |       |       |
| *Not used in average |       |       |       |       |       |       |       |
| Ave.                 | 1.24  | 1.40  | 1.55  | 1.83  | 1.91  | 2.26  | 2.25  |

Liquid Rate: 9.6 G.P.M.

Gas Rate: 1980 C.F.M.

Gas Conc.: 7.9% by Vol.



TABLE VII

Run No. 6, CO<sub>2</sub>. Divide by 1000 for Wt. %

(Refer to Drawing #8)

| COLUMN         | A     | B     | C     | ROW<br>D | E     | F     | G     |
|----------------|-------|-------|-------|----------|-------|-------|-------|
| Z <sup>n</sup> |       |       | 1.70  |          | 1.815 |       |       |
| Z <sup>i</sup> |       | 1.19  |       | 0.65     |       | 0.548 |       |
| Z              | 1.67  |       | 1.34  |          | 1.15  |       | 1.44  |
| Y <sup>i</sup> |       | 0.775 |       | 1.16     |       | 0.53  |       |
| Y              | 1.39  |       | 1.14  |          | 0.91  |       | 1.26  |
| X <sup>i</sup> |       | 0.775 |       | 0.68     |       | 0.623 |       |
| X              | 1.46  |       | 0.671 |          | 0.74  |       | 1.08  |
| W <sup>i</sup> |       | 0.738 |       | 0.617    |       | 0.795 |       |
| W              | 1.25  |       | 0.79  |          | 0.612 |       | 0.864 |
| V <sup>i</sup> |       | 0.512 |       |          |       | 0.605 |       |
| V              | 0.94  |       | 0.635 |          | 0.72  |       | 0.564 |
| U <sup>i</sup> |       | 0.645 |       | 0.61     |       | 0.63  |       |
| U              | 1.12  |       | 0.589 |          | 0.615 |       | 0.769 |
| T <sup>i</sup> |       | 0.641 |       | 0.676    |       | 0.587 |       |
| T              | 1.56  |       | 0.576 |          | 1.17  |       | 0.666 |
| S <sup>i</sup> |       | 0.682 |       | 0.808    |       | 0.555 |       |
| S              | ----- |       | 1.71  |          | ----- |       | 0.90  |
| R <sup>i</sup> |       | 0.759 |       | 0.625    |       | 0.90  |       |
| R              |       |       | 1.32  |          | 1.11  |       |       |
| Ave.           | 1.34  | 0.741 | 1.044 | 0.728    | 0.982 | 0.647 | 0.943 |

Liquid Rate: 33.9 G.P.M.

Gas Rate: 628 C.F.M.

Gas Conc.: 37.6% by Vol.