AECD-4277

MASTER

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
ENGINEERING PRACTICE SCHOOL
CARBIDE AND CARBON CHEMICALS DIVISION
Union Carbide and Carbon Corporation

SECRET
SECURITY INFORMATION

[redacted]

Changed to unclassified
H. L. Hanewell

By A.R. Maxwell Date 4-17-59

MEMORANDUM | KT-117
EPS Y-158 | November 17, 1951

TO: T. H. Pigford

FROM: J. W. Barlow (leader), F. H. Jones, and R. H. Reuther

SUBJECT: Loop-Type Liquid-Gas Separator

DISTRIBUTION:

1. J. O. Bradfute
2. C. B. Graham
3. F. R. McQuilkin
4. I. Spiewak

5-8. Y-12 Central Files
9. J. B. Sykes (K-25 RC)
10-13. J. B. Sykes (Files)
14-17. M.I.T. Practice School

I. INTRODUCTION

In liquid-type homogeneous reactors, bubbles of gas are formed as a result of fission and radiation. The fission-produced gas is mostly xenon, which has a fairly large neutron-capture cross section. The other gases consist of hydrogen and oxygen formed as a result of the decomposition of water by radiation. If the gas bubbles are not removed from the system, they may quite rapidly affect the stability of the reactor by capturing neutrons and by changing the effective volume of the reactor core.

In the 1000-kw. homogeneous reactor now being constructed, gas bubbles will be removed by the action of a vortex flow developed within the reactor core. The vortex is formed by feeding the fuel solution tangentially into the core and removing it from the top center, perpendicular to the inlet stream. Centrifugal forces associated with this vortex flow cause the gas bubbles to collect in a narrow needle-like column at the center of the core. This column of gas is then drawn out through the inner pipe of two concentric pipes, the liquid fuel being removed through the outer pipe.

SECRET
SECURITY INFORMATION

Larger homogeneous reactors now being proposed will require considerably more power to generate a vortex of sufficient intensity to remove the gases. For this reason other types of liquid-gas separators located outside of the core are being investigated. An external separator investigated by previous workers was a scroll-type separator which induced a vortex into the fuel stream (3). The scroll-type separator removed essentially all of the gas bubbles with some fuel; however, pressure drop across the unit was quite high. In order to obtain separation with a smaller pressure drop, a simple loop-type separator was suggested. This paper is a study of the separating qualities of such a loop separator.

A loop-type separator consists essentially of a single coil of pipe or tubing inserted into the fuel stream. In passing through the loop, a mixture of gas and liquid will be acted upon by centrifugal forces which concentrate the gas on the inner surface of the loop. Extraction taps located on this inner surface permit removal of this gas layer.

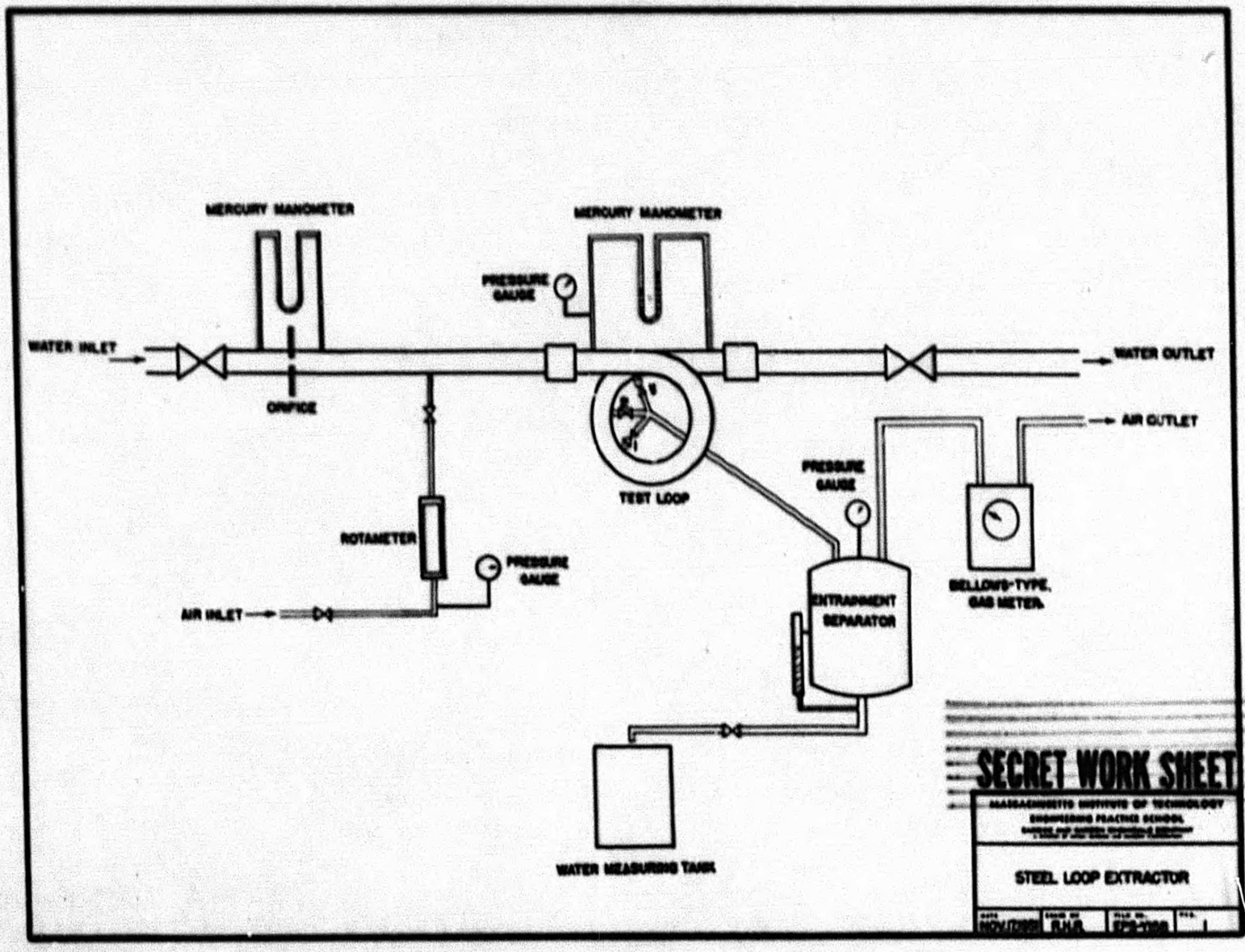
Work was begun on this project October 29, 1951, and completed November 17, 1951.

II. RESULTS

The major portion of this investigation was concerned with the study of a steel test loop of 13 in. diameter at the center line placed in both a horizontal and a vertical position (see Figure 1 for vertical loop arrangement). The loop had an elliptical cross section with three extraction taps located on the inner surface at 225, 270, and 315 degrees from the entrance to the loop. All data were taken for a water-flow rate of 100 gal./min. and at air-flow rates ranging from 0.2 to 1.0 g./sec. The water temperature was 58°F.

Since the density of air is negligibly small compared to that of water, the separating qualities of the equipment will depend primarily upon the volume occupied by the air in the water stream rather than on the mass. For this reason the data are presented in terms of the percent by volume of air in the inlet stream. The percent extraction or removal of the air is based on the mass, however.

Tables I and II, given in Appendix B, show the test results for the loop in both a horizontal and a vertical position. In addition to the above-mentioned parameters, the tables include the operating pressure for which the air volume was calculated, the percent of input water which was removed with the extracted air, the pressure drop across the loop, and the pressure differential between the loop and the entrainment separator.


MERCURY MANOMETER
MERCURY MANOMETER
PRESSURE GAUGE
WATER INLET
WATER OUTLET
ORIFICE
AIR OUTLET
PRESSURE GAUGE
TEST LOOP
ROTAMETER
PRESSURE GAUGE
AIR INLET
ENTRAINMENT SEPARATOR
BELLOWS-TYPE, GAS METER
WATER MEASURING TANK
SECRET WORK SHEET
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
ENGINEERING PRACTICE SCHOOL
STEEL LOOP EXTRACTOR

Figures 2, 3, and 4 are plots of the percent of air extracted versus the percent volume of air in the inlet stream under various conditions of operation. These plots show certain significant trends. First, it can be seen that over 90% of the air could be extracted under most conditions, except for the case where the pressure differential between the loop and the entrainment separator was only 5.5 lb./sq. in. In general, the extraction increased as this pressure differential increased.

With the loop in a horizontal position, it is to be noted that the extraction was always several percent greater than in the vertical position. In the region below 2.5% volume of air in the inlet stream, the extraction invariably dropped off, in some cases to below 80%.

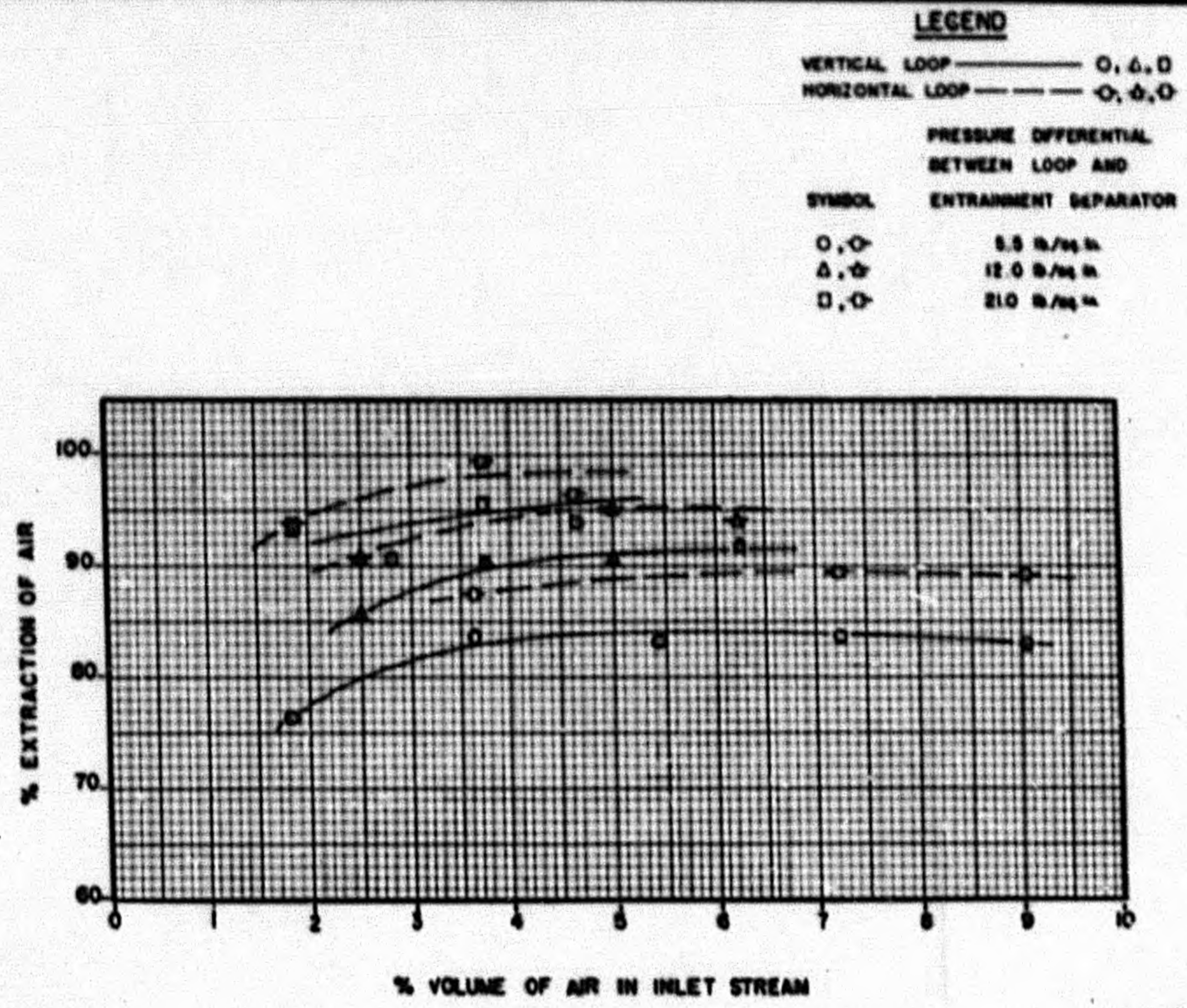
As shown in Appendix C, the absolute values of the data are only reliable to within 9%. Since the various trends are seen to be fairly consistent, however, the errors involved are not believed to have affected these trends appreciably.

The water entrained by the extracted air varied from 0.5 to 5.2% of the water input. The minimum entrainment occurred at the lowest pressure differential between loop and entrainment separator in the case where only one tap was open. The maximum entrainment occurred at the greatest pressure differential when all the taps were open.

During all the runs, the pressure drop across the test loop was between 0.4 and 1.0 lb./sq. in. With no taps open and no air in the system, the pressure drop was at its maximum. Based on empirical data of pressure drops through curved pipes (1), the predicted pressure drop was 1.1 lb./sq. in.

Two other types of loops were also investigated in this study. A Pyrex 7-in. center-to-center loop was used, but because the taps were too small only about 35% of the air could be extracted. This loop ruptured under the strains imposed on it at the higher pressures From this piece of equipment, however, it was noted that essentially all the bubbles reached the inside surface of the loop at an angle of 270° from the inlet. This value compared favorably with the 244° as calculated from F. N. Peebles' equations (as cited in a report by Spievak (2), see Appendix D). A corresponding value of 113° was calculated for the steel loop, and by applying the correction factor found with the Pyrex loop, a value of 125° was obtained as being the probable actual value. Since the first tap on the steel loop was located at 225°, no check on this predicted value could be ascertained from the data.

The other extractor used consisted of two Pyrex loops connected in series. No data were obtained from this piece of equipment because the taps were inserted at the wrong locations during its construction.

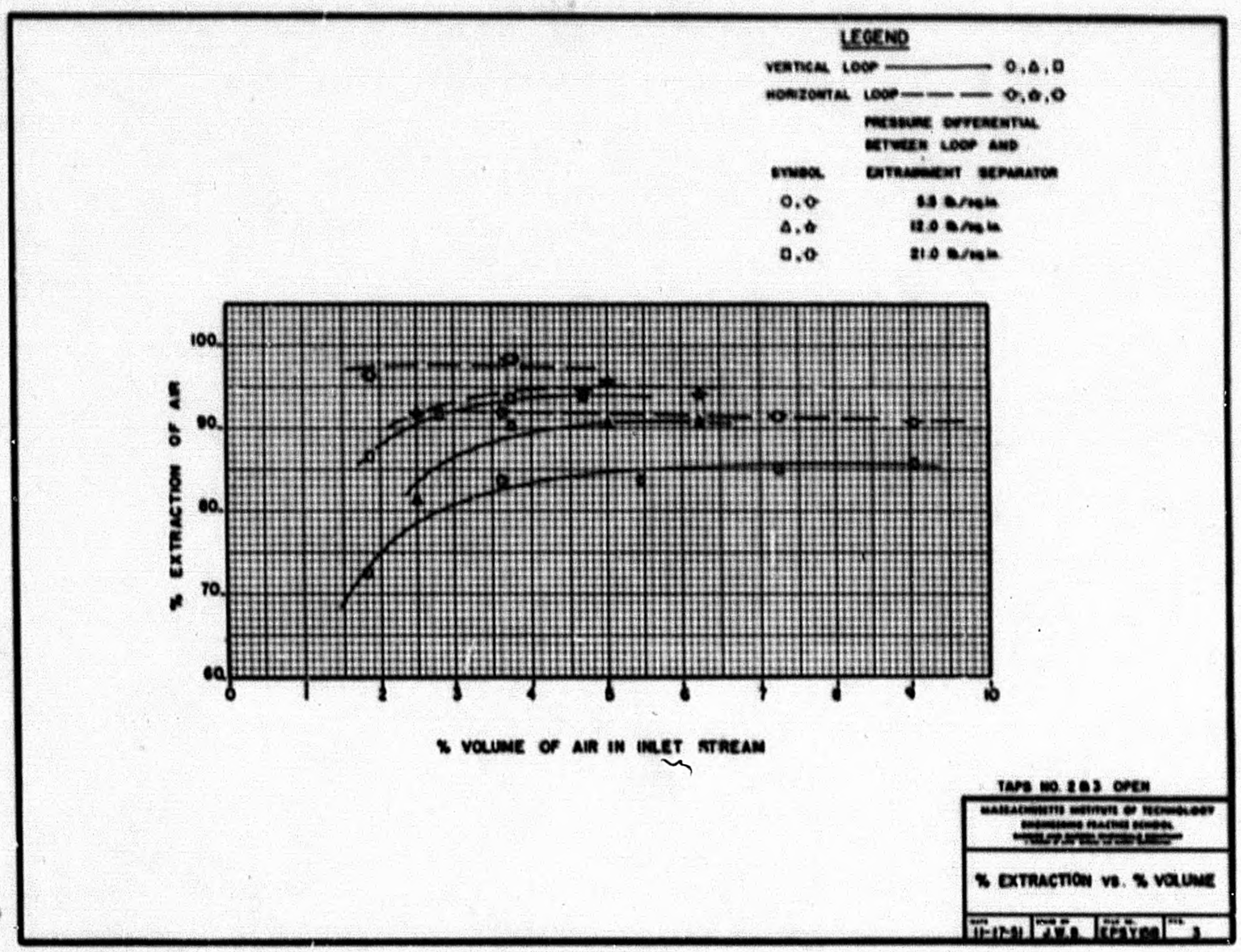


TAPS NO. 1,2,&3 OPEN

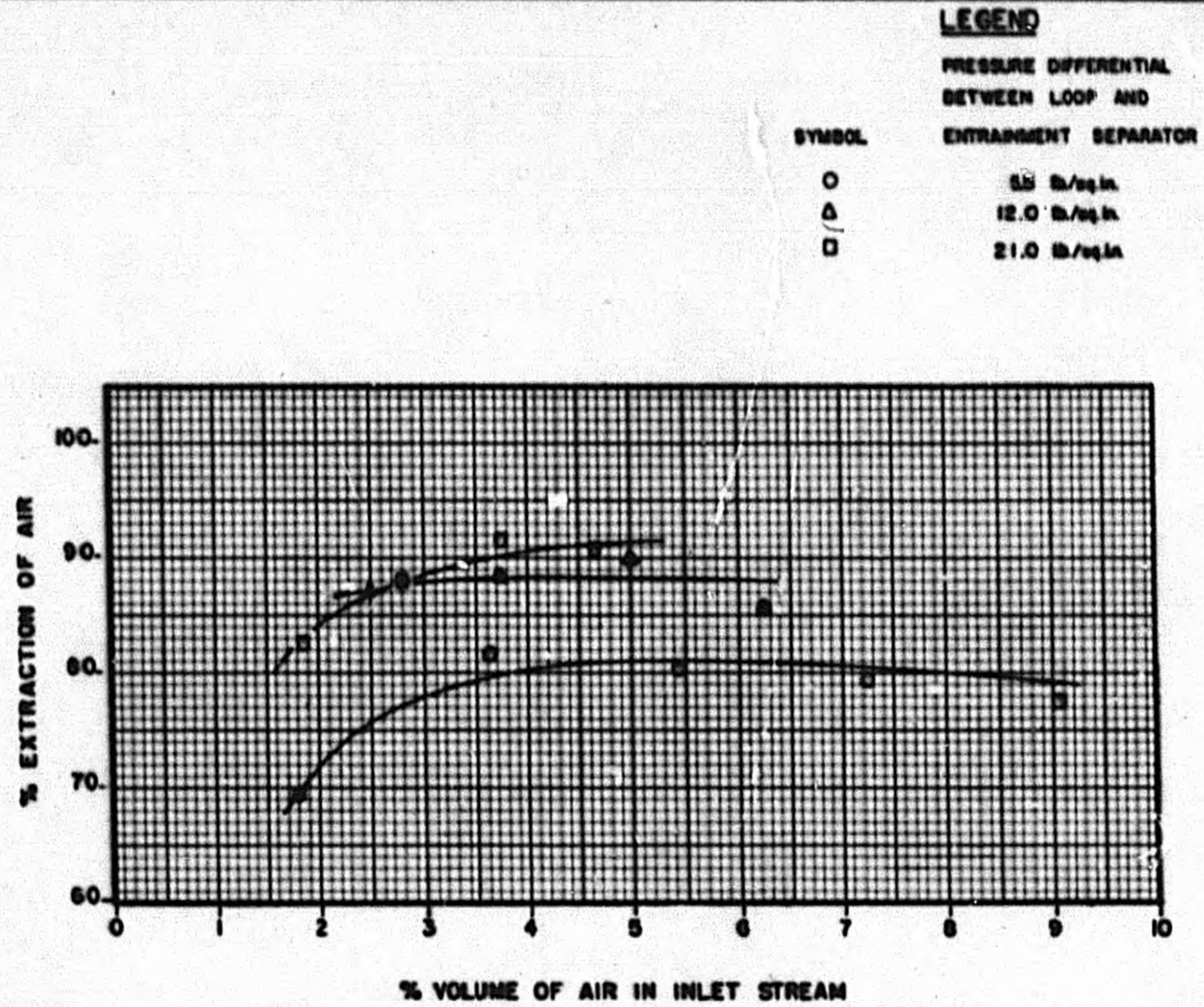
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
ENGINEERING PRACTICE SCHOOL

% EXTRACTION VS. % VOLUME

11-17-51 | J.W.B. | EPSY150 | 2



LEGEND
VERTICAL LOOP
HORIZONTAL LOOP
SYMBOL
PRESSURE DIFFERENTIAL BETWEEN LOOP AND ENTRAINMENT SEPARATOR
5.5 lb./sq.in.
12.0 lb./sq.in.
21.0 lb./sq.in.
% EXTRACTION OF AIR
60
70
80
90
100
0
1
2
3
4
5
6
7
8
9
10
% VOLUME OF AIR IN INLET STREAM
TAPS NO. 2 & 3 OPEN
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
ENGINEERING PRACTICE SCHOOL
% EXTRACTION VS. % VOLUME
11-17-51



TAP NO. 2 OPEN

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
ENGINEERING PRACTICE SCHOOL

% EXTRACTION vs. % VOLUME
VERTICAL LOOP

11-17-51	J W B	EPS-Y-158	4

III. DISUCSSION OF RESULTS

In the design of the test loop, two factors were considered: (1) the pressure drop across the loop and (2) the flow pattern of the air bubbles. A correlation by H. Richter (1) showed that the ratio of the radius of curvature of center line to pipe radius which would give the minimum equivalent length of straight pipe for copper pipe was 5.0. The only glass loop available which approached this desired ratio was one having a diameter of 2 in. and a radius curvature of 3.5 in. The actual pressure drop encountered in this section was slightly less than the value predicted by Richter's relation, being less than 1 lb./sq. in.

The flow pattern of air bubbles for this loop was calculated by means of Peebles' correlations (2). These calculations predicted that the bubbles would form a uniformly thick layer after traversing 244° of the loop for a water flow rate of 100 gal./min. Since this uniform layer was observed to form in 270°, Peebles' relations proved to be satisfactory for this design.

Because the glass loop failed structurally under high pressure, a 13-in. steel loop was constructed. The extraction taps were located well beyond the region where the air bubbles were calculated to have all reached the inner surface. In the investigation with the steel loop, an efficiency of greater than 90% was obtainable under most conditions. With modifications the efficiency could be increased. The limiting factor of the apparatus investigated was the tap size. The diameter of the taps used was only 1 in. Since the width of the bubble layer on the inside surface of the loop exceeded the area covered by the tap, it appears that complete removal of air bubbles could not be obtained with the test apparatus used.

The slight increase in extraction efficiency noted with the loop in a horizontal position may be attributed to the fact that any buoyancy effects on the bubbles encountered in the vertical arrangement will be considerably reduced.

The importance of the degree of entrainment of water by the extracted air depends on the use of the separator. The main purpose for using a compact separator of the loop type instead of a simple settling tank is to cut down the holdup in the system, which is of considerable interest in a reactor. In the larger reactors being proposed, even a 1% entrainment would require the use of additional separators of large capacity. Therefore, any modifications which could eliminate entrainment without appreciably affecting the extraction are to be desired.

Even with entrainment, however, it merely becomes necessary to feed the entrained liquid back into the system at some point of lower pressure than at the extraction loop.

IV. CONCLUSIONS AND RECOMMENDATIONS

From the test data on the loop separator investigated, it is concluded that:

1. In the range of flows where the gas occupies from 2 to 10% of the total volume flow, such a separator can extract over 90% of the gas.

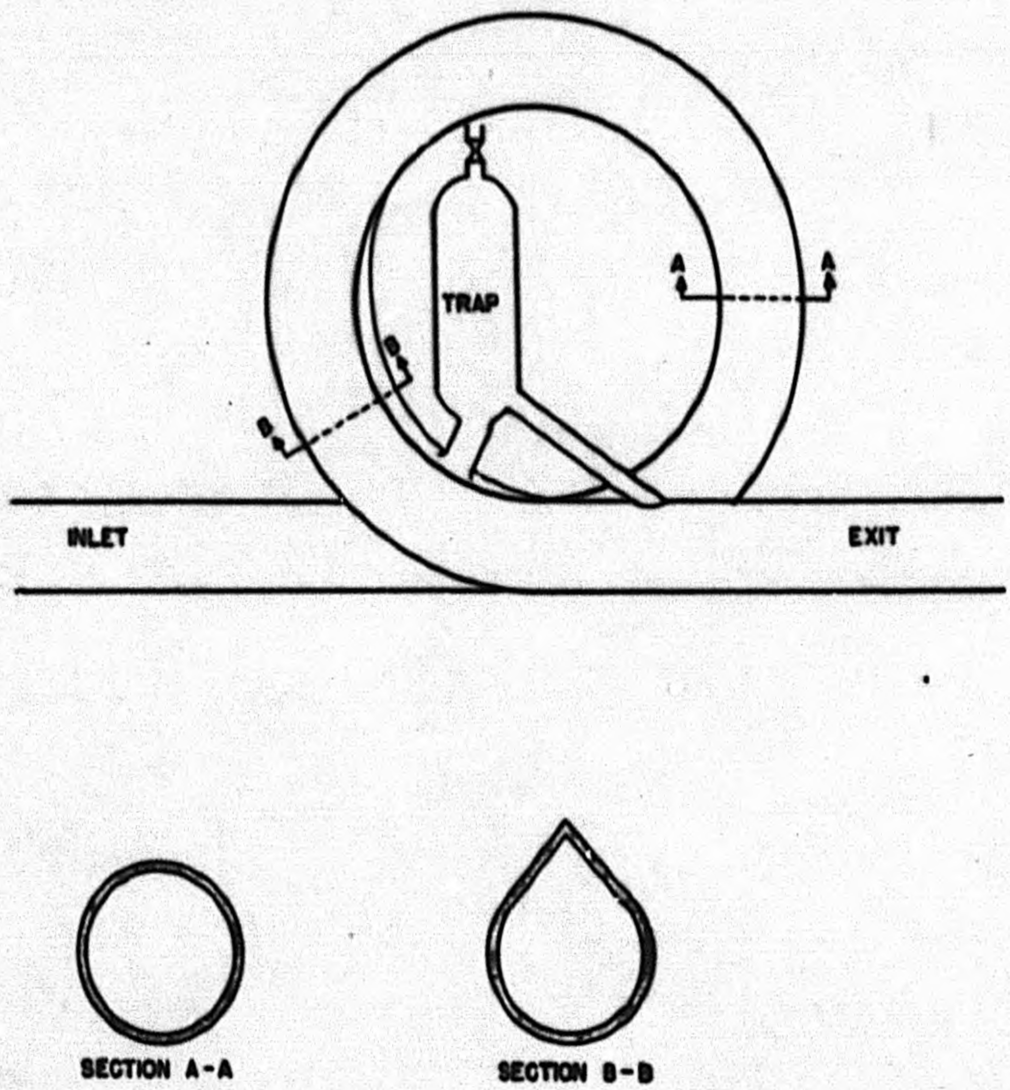
2. Pressure drop through the loop is very small and can be calculated with reasonable accuracy by methods available in the literature (1).

3. The size of loop and location of extraction taps can be designed with the aid of pertinent equations developed by Peebles (2). These equations predicted the location of a uniformly thick layer of air on the inner surface of the loop within 90% of the observed location.

4. Additional modifications will be necessary if it is desired to eliminate entrainment of water or improve the extraction of gas flows which occupy less than 2.0% of the total volume flow.

Based on these conclusions, it is recommended that an improved design be made and tested. Such a design could have incorporated in it the features depicted in Figure 5. These include the addition of a trap at the tap opening which could be designed to return the entrained liquid to the system at the loop. This method was suggested by J. O. Bradfute, a member of ORNL, and would entail having a separate liquid return line entering the stream just after the loop where it will not be re-entrained.

A second modification, also depicted in Figure 5, should improve the separation at gas flows less than 2.0% of the total volume flow. This modification would be in the cross-sectional shape of the loop, and entails creating a V-shaped channel which would collect even the smallest air streams.



SECRET WORK SHEET

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
ENGINEERING PRACTICE SCHOOL
CARBIDE AND CARBON CHEMICALS COMPANY

PROPOSED TEST LOOP

DATE	DRAWN BY	FILE NO.	FIG.
17 May 51	F.H. Jones	[illegible]	5

V. PROCEDURE

Since the percent extraction of air was the primary item to be investigated in this work, it was necessary to calibrate the inlet air rotameter against the bellows-type gas meter used in measuring the extracted air. This cross calibration was then checked against a wet-test meter and by actually collecting the metered air in a water-filled bottle of known capacity. The orifice plate manometer in the water line was calibrated by measuring collected amounts of metered water and by using a Neptune water meter.

To test the different loop sections, air was metered into the water stream at flow rates from 0.2 to 1.0 g./sec. The water flow was maintained at 100 gal./min. Various combinations of extraction taps were then opened, and the extracted air and water were separated in a small tank whose water level was maintained constant with the aid of a valve (see Figure 1). The upstream pressure was varied from 6.0 to 25.0 lb./sq. in. (gauge), and the pressure differential between the stream and separating tank was varied from 5.5 to 21.0 lb./sq. in.

The following items were recorded:

- Air input, g./sec.
- Air extracted, g./sec.
- Water flow rate, gal./min.
- Water extracted with air, gal./min.
- Upstream pressure, lb./sq. in. (gauge)
- Pressure drop across test loop, in. Hg
- Pressure differential between loop and separation tank, lb./sq. in.

Original test data are located in Data Notebook No. 1879, pages 17-26, on file at the M.I.T. Engineering Practice School, Oak Ridge, Tennessee.

VI. APPENDIX

A. APPARATUS

A schematic diagram of the apperatus is shown in Figure 1. A rotameter was used to measure the amount of air fed to the system. Needle valves preceding and following this rotameter were inserted to maintain the inlet air pressure at 60 lb./sq. in. (gauge). A 1.8125-in. orifice plate was placed in the 2-in. water line so that the water flow rate could be measured by means of a calibrated mercury manomoter.

The test sections consisted of the following:

1. a 7-in. Pyrex glass loop with a 2-in. I.D.,

2. a 13-in. steel loop with an elliptical cross-section 1.25 by 2.25 in., and

3. a 7-in. double loop section with a 2-in. I.D.

Extraction taps located on the inner surfaces were inserted at equi-spaced points to remove the collected air bubbles and to enable an investigation of the effect of tap location.

TABLE I -- VERTICAL LOOP

Run	Taps Open	Inlet Water Pressure	Pressure Drop Across Loop	Pressure Drop Between Loop and Separator	Volume of Air in Feed	Air Input Extracted	Water Input Extracted with Air
		lb/sq.in. (gauge)	lb./sq. in.	lb./sq. in.	percent	percent	percent
1	1, 2, 3	6.00	1.03	5.5	9.06	83.0	1.36
2	1, 2	6.25	1.03	5.5	9.06	83.5	0.83
3	2, 3	6.25	1.03	5.5	9.06	85.7	1.22
4	2	6.25	1.03	5.5	9.06	77.5	0.51
5	1, 2, 3	6.25	1.03	5.5	7.25	83.7	1.39
6	1, 2	6.25	1.03	5.5	7.25	83.3	1.12
7	2, 3	6.00	1.03	5.5	7.25	85.1	1.31
8	2	6.25	1.03	5.5	7.25	79.5	0.56
9	1, 2, 3	6.00	1.03	5.5	5.44	83.1	1.72
10	1, 2	6.00	1.03	5.5	5.44	84.8	1.05
11	2, 3	6.00	1.03	5.5	5.44	83.8	1.48
12	2	6.00	1.03	5.5	5.44	80.3	0.73
13	1, 2, 3	6.00	1.03	5.5	3.62	83.7	2.04
14	1, 2	6.00	1.03	5.5	3.62	84.2	1.07
15	2, 3	6.00	1.03	5.5	3.62	83.7	1.62
16	2	6.00	1.03	5.5	3.62	81.7	0.84
17	1, 2, 3	6.00	1.03	5.5	1.81	76.3	2.13
18	1, 2	6.00	1.03	5.5	1.81	74.5	1.55
19	2, 3	6.00	1.03	5.5	1.81	72.5	1.85
20	2	6.00	1.03	5.5	1.81	69.5	1.02
21	1, 2, 3	15.0	0.74	12.0	6.25	92.0	2.32
22	1, 2	15.0	0.74	12.0	6.25	91.5	2.22
23	2, 3	15.0	0.74	12.0	6.25	90.8	2.88
24	2	15.0	0.74	12.0	6.25	85.8	1.08
25	1, 2, 3	15.0	0.74	12.0	5.00	90.6	3.78
26	1, 2	15.0	0.74	12.0	5.00	94.8	2.08
27	2, 3	15.0	0.74	12.0	5.00	90.6	2.93
28	2	15.0	0.74	12.0	5.00	90.0	1.32
29	1, 2, 3	15.0	0.74	12.0	3.75	90.2	3.36
30	1, 2	15.0	0.74	12.0	3.75	91.4	2.40
31	2, 3	15.0	0.74	12.0	3.75	90.2	3.42
32	2	15.0	0.74	12.0	3.75	88.5	1.62
33	1, 2, 3	15.0	0.74	12.0	2.50	85.7	4.20
34	1, 2	15.0	0.74	12.0	2.50	94.1	2.58
35	2, 3	15.0	0.74	12.0	2.50	81.3	3.30
36	2	15.0	0.74	12.0	2.50	87.2	1.74
37	1, 2, 3	25.0	0.49	21.0	4.67	94.0	4.50
38	1, 2	25.0	0.49	21.0	4.67	92.6	3.84
39	2, 3	25.0	0.49	21.0	4.67	94.0	3.76
40	2	25.0	0.49	21.0	4.67	90.9	2.22
41	1, 2, 3	25.0	0.49	21.0	3.73	95.6	4.50
42	1, 2	25.0	0.49	21.0	3.73	93.7	3.60
43	2, 3	25.0	0.49	21.0	3.73	93.7	4.06
44	2	25.0	0.49	21.0	3.73	91.7	2.34
45	1, 2, 3	26.5	0.49	21.0	2.80	90.9	5.03
46	1, 2	26.5	0.49	21.0	2.80	90.0	4.20
47	2, 3	26.5	0.49	21.0	2.80	91.8	4.55
48	2	26.5	0.49	21.0	2.80	88.0	2.52
49	1, 2, 3	26.5	0.49	21.0	1.87	93.5	5.03
50	1, 2	26.5	0.49	21.0	1.87	84.0	----
51	2, 3	26.5	0.49	21.0	1.87	86.8	4.52
52	2	26.5	0.49	21.0	1.87	82.5	2.82

TABLE II -- HORIZONTAL LOOP

Run	Taps Open	Inlet Water Pressure	Pressure Drop Across Loop	Pressure Drop Between Loop and Separator	Volume of Air in Feed	Air Input Extracted	Water Input Extracted with Air
		lb/sq.in. (gauge)	lb./sq. in.	lb./sq. in.	percent	percent	percent
53	1, 2, 3	6.50	0.74	6.0	9.06	89.1	1.51
54	1, 2	6.50	0.74	6.0	9.06	88.5	1.40
55	2, 3	6.50	0.74	6.0	9.06	90.7	1.26
56	1, 2, 3	6.50	0.74	6.0	7.25	89.4	1.62
57	1, 2	6.50	0.74	6.0	7.25	89.4	1.44
58	2, 3	6.50	0.74	6.0	7.25	91.5	1.44
59	1, 2, 3	6.50	0.74	6.0	3.62	87.5	2.00
60	1, 2	6.50	0.74	6.0	3.62	86.8	1.68
61	2, 3	6.50	0.74	6.0	3.52	92.0	1.80
62	1, 2, 3	15.0	0.49	12.0	6.25	94.0	3.00
63	1, 2	15.0	0.49	12.0	6.25	92.5	2.62
64	2, 3	15.0	0.49	12.0	6.25	94.0	2.64
65	1, 2, 3	15.0	0.49	12.0	5.00	95.0	3.12
66	1, 2	15.0	0.49	12.0	5.00	93.7	2.58
67	2, 3	15.0	0.49	12.0	5.00	95.6	2.82
68	1, 2, 3	15.0	0.49	12.0	2.50	90.7	3.60
69	1, 2	15.0	0.49	12.0	2.50	87.5	3.16
70	2,3	15.0	0.49	12.0	2.50	92.0	3.18
71	1, 2, 3	25.0	0.39	21.0	4.67	96.3	4.56
72	1, 2	25.0	0.39	21.0	4.67	92.5	3.96
73	2, 3	25.0	0.39	21.0	4.67	94.5	3.90
74	1, 2, 3	25.0	0.39	21.0	3.73	99.7	4.68
75	1, 2	25.0	0.39	21.0	3.73	94.4	4.08
76	2, 3	25.0	0.39	21.0	3.73	98.3	3.97
77	1, 2, 3	25.0	0.39	21.0	1.87	93.5	5.16
78	1, 2	25.0	0.39	21.0	1.87	85.3	4.57
79	2, 3	25.0	0.39	21.0	1.87	96.2	4.20
80	2	25.0	0.39	21.0	1.87	88.0	3.00
81	3	25.0	0.39	21.0	1.87	86.5	2.64

C. ERROR ANALYSIS

The precision of the rotameter calibration against the bellows gas meter was ± 0.05 g./sec. The precision of the measurements of extracted air was ± 1.5%. For an air input of 0.600 ± 0.050 g./sec., the extracted air was about 0.530 ± 0.008 g./sec.

$$\frac{\Delta\left(\frac{\text{extracted air}}{\text{inlet air}}\right)}{\frac{\text{extracted air}}{\text{inlet air}}} = \pm\left[\frac{\Delta(\text{inlet air})}{\text{inlet air}} + \frac{\Delta(\text{extracted air})}{\text{extracted air}}\right]$$

$$= \pm\left[\frac{0.050}{0.600} + \frac{0.008}{0.530}\right]$$

$$= \pm\ 0.098$$

$$\therefore\ \frac{\Delta(\text{extracted air})}{\text{inlet air}} = \pm\ 0.098\left(\frac{0.530}{0.600}\right)$$

$$= \pm\ 0.086$$

$$\therefore\ \text{percent extraction} = \left[\frac{\text{extracted air}}{\text{inlet air}} + \frac{\Delta(\text{extracted air})}{\text{inlet air}}\right]100$$

$$= (88.3 \pm 8.6)\%$$

Note: This error analysis is not made for a particular run, but represents the order of magnitude of error encountered in each run.

D. SAMPLE CALCULATIONS

1. Calculation of Pressure Drop in 13-in. Test Loop

Using Fanning Equation for pressure drop (1):

$$\Delta P = \left(\frac{32\ v^2 f L_s}{144\ \pi^2 \rho_1 g_c D_p^5}\right) \text{lb./sq. in.} \tag{1}$$

$$D_p = \frac{4(2.25)(1.25)(2)}{(1.021)(4)(12)(3.5)}$$

$= 0.131$ ft., since loop has an elliptical cross section.

$$N_R = \frac{\rho V_t D_p}{\mu} = \frac{62.4(14.5)(0.131)}{8.8 \times 10^{-4}}$$

$= 135{,}000$

$\therefore\ f = 0.0050$

Using Richter's correlation for equivalent lengths for curved pipes (1):

$$L_e = 0.0202\ X\alpha^{1.10}(N_R)^{0.032} \tag{2}$$

Where X is a factor depending on the ratio R_L/R_p
$X = 1.55$

$\therefore\ L_e = (0.0202)(1.55)(360)^{1.1}(135{,}000)^{0.032}$

$= 29.5$ Diameters

$L_s \doteq L_e D_p = 0.131(29.5)$

$= 3.86$ ft.

$$\therefore\ \Delta P = \frac{32(13.9)^2(0.0050)(3.86)}{144\ \pi^2(62.4)(32.2)(0.131)^5}$$

$= 1.10$ lb./sq. in.

The actual pressure drop = 0.491 in. Hg

= 0.491 (2)

= 0.98 lb./sq. in.

2. Design Calculation of Position in Test Loop Where Gas Layer is of Uniform Thickness (2)

The pertinent equations for gas velocity as presented by F. N. Peebles in a report not issued are

$$u = 1.146\left[\frac{8\,V_t^{\,2}(\rho_1 - \rho_2)}{3\,R_L\,\rho_1}\right]^{1/6}\left[\frac{\gamma}{\rho_1}\right]^{1/2}\left[\frac{g_c^{\,2/3}}{R_B}\right]^{1/2} \qquad (3)$$

in the range where

$$\left(\frac{1}{R_B}\right)\left(\frac{2.01}{g_c^{\,0.25}}\right)\left[\frac{\mu^4}{\rho_1\gamma^3 g_c^{\,2}}\right]^{0.036}\left[\frac{\gamma g_c}{\rho_1}\right]^{0.75} \leq u \leq \left(\frac{1.594}{g_c^{\,0.25}}\right)\left(\frac{\gamma g_c}{\rho_1}\right)^{0.75}\left(\frac{1}{R_B}\right),$$

and

$$u = 0.825\left[\frac{8\,V_t^{\,2}(\rho_1 - \rho_2)}{3\,R_L\,\rho_1}\right]^{1/3}\left[\frac{\gamma}{\rho_1}\right]^{1/4}\left(g_c^{\,1/6}\right) \qquad (4)$$

in the range where

$$u \geq 1.594\, g_c^{\,1/2}\left(\frac{\gamma}{\rho_1}\right)^{3/4}\left(\frac{1}{R_B}\right).$$

Since the bubble size to be encountered was not known prior to operation, equation (4) was used where the limiting bubble size is

$$R_B \geq \left(\frac{1}{u}\right)\left[1.594\sqrt{32.2}\left(\frac{5.08 \times 10^{-3}}{62.4}\right)^{3/4}\right] \geq \frac{0.00773 \text{ ft.}}{u}$$

Using the average value of velocity:

$$V_t^{\,2} = \frac{Q^2}{A^2}$$

$$= \frac{Q^2}{\pi^2 R_p^{\,4}} \qquad (5)$$

Substituting equation (5) in equation (4) and neglecting ρ_2 in comparison with ρ_1:

$$u = 0.825\left(\frac{8}{3}\right)^{1/3}\left(\frac{Q^2}{\pi^2 R_p^4 R_L}\right)^{1/3}\left(\frac{\gamma}{\rho_1}\right)^{1/4} (g)^{1/6}$$

$$= 1.142\left(\frac{Q}{\pi R_p^2 \sqrt{R_L}}\right)^{2/3}\left(\frac{\gamma}{\rho_1}\right)^{1/4} (g)^{1/6}$$

$$= \frac{1.142}{\pi^{2/3}}\left(\frac{5.08 \times 10^{-3}}{62.4}\right)^{1/4} (32.2)^{1/6}\left(\frac{Q}{R_p^2 \sqrt{R_L}}\right)^{2/3}$$

$$= 0.090\left(\frac{Q}{R_p^2 \sqrt{R_L}}\right)^{2/3} \text{ ft./sec.} \qquad (6)$$

The time for a bubble to travel across the pipe from the outer surface to the inner surface is given by

$$\theta_B = \frac{D}{u}$$

The time for the stream to complete one loop is

$$\theta_L = \frac{2\pi R_L}{V_t} = \frac{2\pi^2 R_L R_p^2}{Q}$$

Therefore, the angle traversed before a uniform gas layer is collected is

$$\alpha_B = \frac{360^\circ\, \theta_B}{\theta_L} = \frac{360\, D}{0.090}\left(\frac{R_p^2 \sqrt{R_L}}{Q}\right)^{2/3}\left(\frac{Q}{2\pi^2 R_L R_p^2}\right)$$

$$= 202.5\left(\frac{D^3 Q}{R_L^2 R_p^2}\right)^{1/3} \text{ degrees} \qquad (7)$$

In the case of the single-loop Pyrex section:

$D = 2R = 0.166$ ft.

$Q = 0.223$ cu. ft./sec.

R_L = 0.292 ft.

R_p = 0.0833 ft.

$$\therefore u = 0.090\left[\frac{0.223}{(0.0833)^2\sqrt{0.292}}\right]^{2/3}$$

$$= 1.37 \text{ ft./sec.}$$

$$\alpha_B = 202.5\left[\frac{(0.166)^3(0.223)}{(0.292)^2(0.0833)^2}\right]^{1/3}$$

$$= 244^\circ$$

Actual observed value of $\alpha_B = 270^\circ$.

$$R_B \geq \frac{(0.00773)(12)}{1.37} = 0.0677 \text{ in.}$$

In the case of the steel-loop section,

D = 0.104 ft.

R_L = 0.542 ft.

$R_p = \frac{1}{24}\sqrt{1.25(2.25)} = 0.070$ ft.

$$\therefore u = 0.090\left[\frac{0.223}{(0.070)^2\sqrt{0.542}}\right]^{2/3}$$

$$= 1.41 \text{ ft./sec.}$$

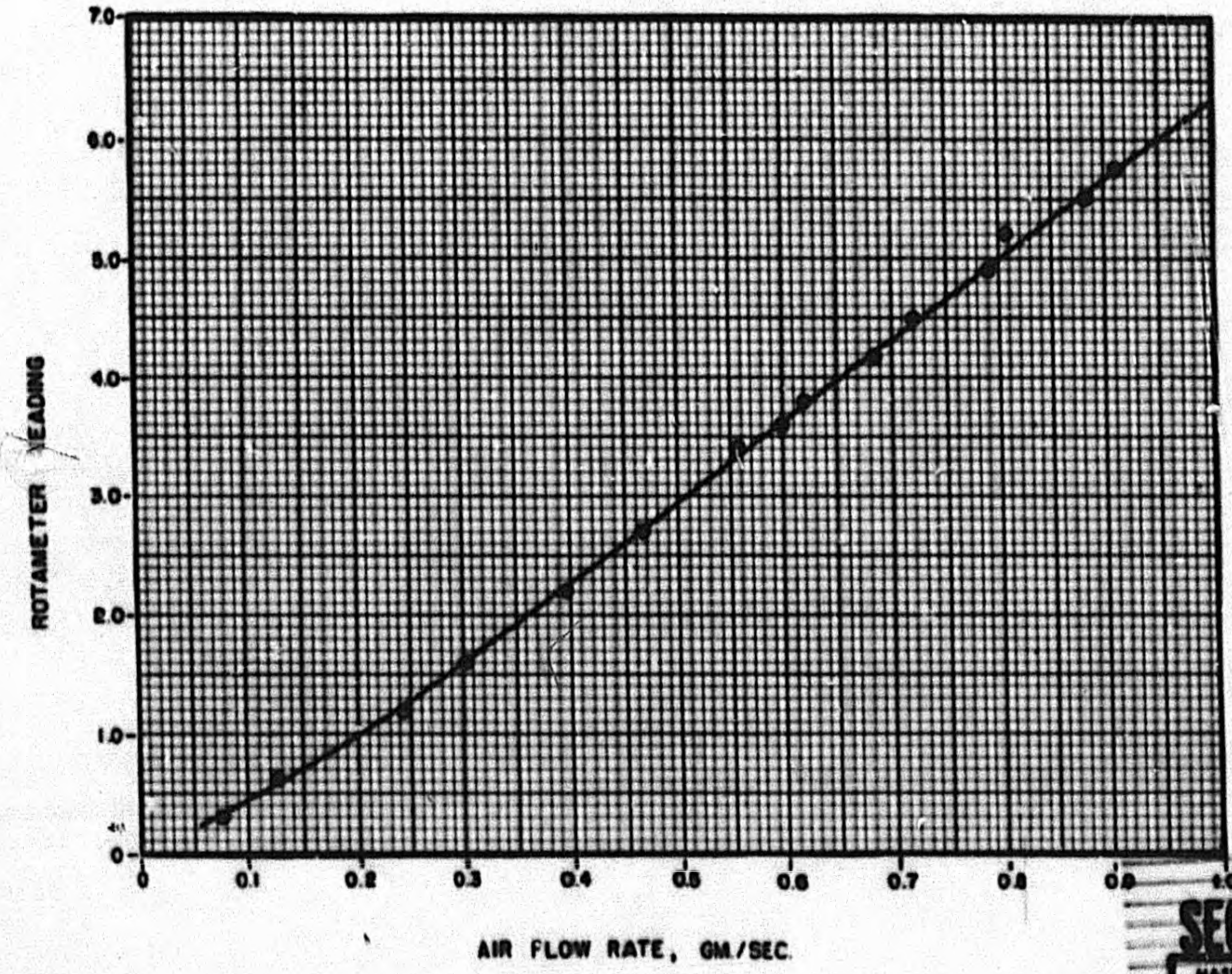
$$\alpha_B = 202.5\left[\frac{(0.104)^3(0.223)}{(0.542 \times 0.070)^2}\right]^{1/3}$$

$$= 113^\circ$$

Assuming the same size gas bubbles to exist in both the Pyrex and the steel test section, the actual value of α_B in the steel test section would be

$$\alpha_B \text{ (expected)} = 113\left(\frac{270}{244}\right)$$

$$= 125^\circ$$



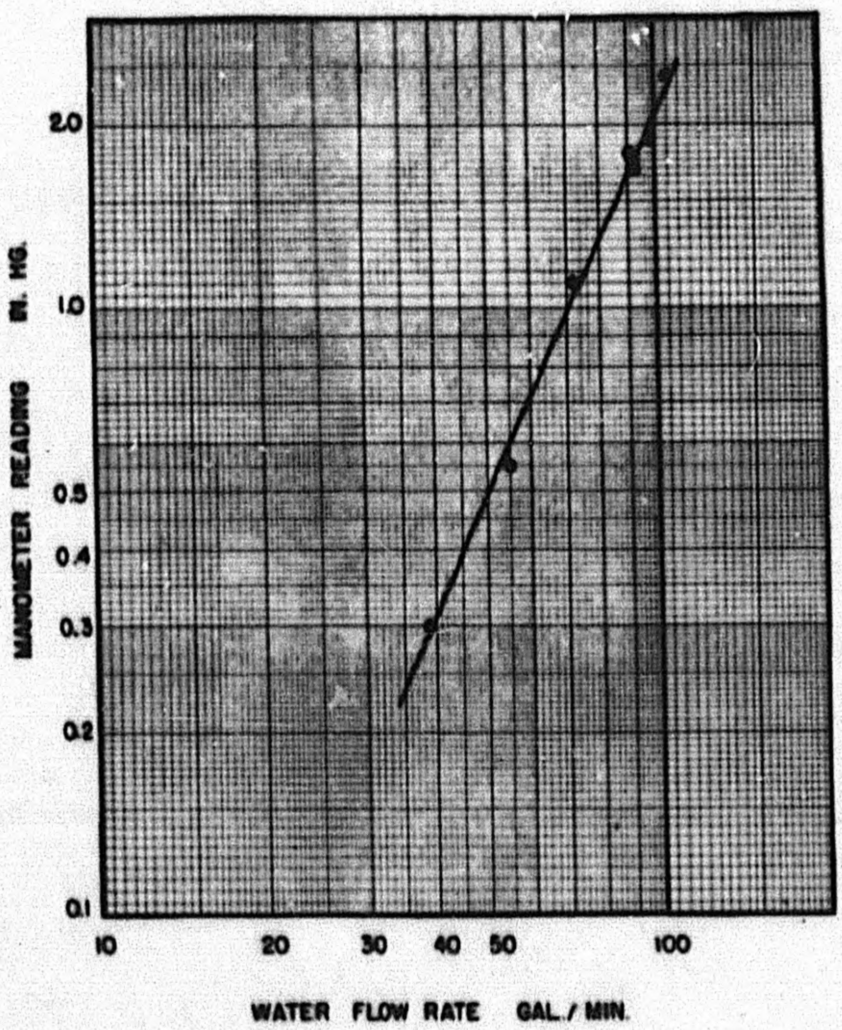
SECRET WORK SHEET

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

ENGINEERING PRACTICE SCHOOL

ROTAMETER CALIBRATION

DATE	DRAWN BY	FILE NO.	FIG.
11-17-51	J.W.S.	EPS-X-158	6



SECRET WORK SHEET

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
ENGINEERING PRACTICE SCHOOL

ORIFICE CALIBRATION

Date	Drawn by	File No.	Fig.
17 Nov 51	J.W.B.	[illegible] Y 158	7

E. TABLE OF NOMENCLATURE

A	cross-sectional area of test loop, sq. ft.
D	distance across pipe (ft.), (equals $2R_p$ for a circular cross section; equals length of minor axis for an elliptical cross section).
D_p	equivalent diameter of loop pipe, ft., (equals $4R_H$).
f	Fanning friction factor for pipes, dimensionless.
g	gravitational acceleration (equals 32.2 ft./(sec.)(sec.).
g_c	conversion factor in Newton's law of motion [equals 32.2 ft. (lb. mass)/(sec.)(sec.)(lb. force)].
L_e	equivalent pipe lengths, ft., (equals L_s/D_p).
L_s	effective length of pipe, ft.
N_R	Reynolds number, dimensionless, [equals $(\rho V_t D_p)/\mu$].
Q	liquid volumetric flow rate, cu. ft./sec.
R_B	bubble radius, ft.
R_H	hydraulic radius, ft., (equals area/wetted perimeter).
R_L	loop radius, ft.
R_p	representative radius of loop pipe, ft., (equals $\sqrt{A/\pi}$).
u	radial gas velocity, ft./sec.
V_t	Tangential liquid velocity, ft./sec., (equals stream velocity).
w	liquid flow rate, lb. mass/sec.
α	angle subtended by loop (equals 360°).
α_B	angle traversed before layer of gas assumes a uniform thickness on the inner surface of the loop.
γ	surface tension (equals 5.08×10^{-3} lb. force/ft. for water at 50°F).
Δ	difference

ΔP pressure drop across test section, lb./sq. in.

θ_B time for bubbles to reach inner surface of loop, sec.

θ_L residence time of liquid in loop, sec.

μ viscosity of liquid (equals 8.8×10^{-4} lb./sec. ft. at $50^\circ F$).

ρ_1 liquid density (equals 62.4 lb./cu. ft.).

ρ_2 gas density [equals 0.13 lb./cu. ft. at 25 lb./sq. in. (absolute) and $60^\circ F$].

X factor in Richter's correlation (1).

F. LITERATURE CITATIONS

1. Perry, J. H., "Chemical Engineers" Handbook", 3rd. ed., pp. 377 to 390, New York, McGraw-Hill Book Company, Inc. (1950).

2. Spiewak, I., "Comparison of Straight Through and Rotary Flow in Fifteen-Foot Spheres", ORNL CF-51-10-87 (October 12, 1951).

3. Spiewak, I., "Preliminary Investigation of Pipe Gas Separators by J. I. Gonzales", unpublished report, ORNL (1951).