

PROBLEM WORKBOOK

Control of Gaseous Emissions

Conducted by the
AIR POLLUTION TRAINING INSTITUTE



The Control of Gaseous Emissions Workbook has been prepared specifically for the trainees attending the course and should not be included in reading lists or periodicals as generally available.

United States Environmental Protection Agency
Office of Air and Water Programs
Control Programs Development Division
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Section I

Examination

DIRECTIONS: There are three parts to this examination. Circle the "best answer" to each question or problem on the Answer Sheet. There is one and only one "best answer" to each question or problem. When you have completed the examination, turn in only the Answer Sheet.

Part I Multiple Choice

(Each question is worth 2 points)

1. The principle commercial adsorbent used for adsorption of organic vapors or gases is:
 - a. Silica Gel
 - b. Alumina
 - c. Zeolite
 - d. Carbon

2. The principle advantage of catalytic combustion over furnace combustion is that oxidation is accomplished at a much lower:
 - a. Flow Rate
 - b. H/C Ratio
 - c. Gross Heating Value
 - d. Temperature
 - e. Pressure

3. A rule of thumb for non-catalytic afterburner operation ranges between _____ and _____ seconds at between _____ and _____ °F.
 - a. 0.1 - 0.3 ; 1000 - 1200
 - b. 1.0 - 5.0 ; 1000 - 1200
 - c. 0.1 - 1.5 ; 1000 - 1700
 - d. 5.0 - 10.0; 1000 - 1700

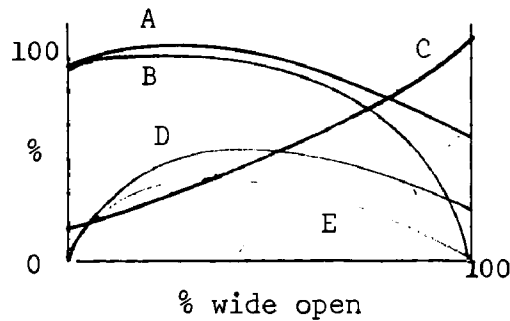
4. A rule of thumb for catalytic afterburner operating temperatures ranges between _____ and _____ °F.
- a. 200 - 400
 - b. 400 - 850
 - c. 600 - 1000
 - d. 1000 - 1200
5. The representation of adsorption data at a constant temperature which indicates the amount adsorbed versus the partial pressure of the adsorbate is called an _____.
- a. Isobar
 - b. Isostere
 - c. Isotherm
 - d. Isokinetic
6. The process by which the large surface area of an adsorbent is created is known as _____.
- a. Regeneration
 - b. Atomization
 - c. Desorption
 - d. Activation
7. The two basic types of fans or blowers are _____ and _____.
- a. Induced draft, forced draft
 - b. Propellor, axial
 - c. Centrifugal, axial
 - d. Radial, reciprocating
8. During gas adsorption, as the temperature of the system increases, the amount of material adsorbed _____.
- a. Increases
 - b. Decreases
 - c. Remains constant

9. The mole fraction of one component of a multi-component solution is defined as:

- a. The number of moles in the solution.
- b. The number of moles of that component in the solution divided by the number of moles of the other components in the solution.
- c. The number of moles of that component in the solution divided by the total number of moles of all the components in the solution.
- d. The weight of that component in the solution divided by the total weight of the solution.

10. In the following diagram of fan curves, Curve "A" represents _____, Curve "C" represents _____, and Curve "E" represents _____.

- a. Horsepower; total pressure; static pressure
- b. Mechanical efficiency; static pressure; horsepower
- c. Total pressure; horsepower; static efficiency
- d. Static pressure; horsepower; mechanical efficiency



11. Dalton's Law of partial pressures is commonly represented by the following equation:

- a. $PV = nRT$
- b. $P_i = P_T y_i$
- c. $P_i = H_i x_i$
- d. $P_i = P_i x_i$

12. For an ideal gas mixture, the mole fraction and the volume fraction are _____ .

- a. Functions of the void fraction
- b. Identical
- c. Unrelated
- d. Both equal to the weight fraction

13. The variables which control absorption equilibrium are:

- a. Temperature
- b. Pressure
- c. Concentrations of the contaminant in the gas and liquid phases
- d. All of the above
- e. None of the above

14. A rule of thumb for flare operation indicates that a sooty emission will occur with:

- a. A premixed air-fuel system
- b. Blue flame combustion
- c. A H/C ratio > 0.28
- d. A H/C ratio < 0.28

15. The equation describing the column packed height for a gas scrubber is commonly represented by the following equation:

a. $P_i = H_i x_i$

b. $Z = H_{OG} \times N_{OG}$

c. $H_{OG} = \left[\frac{G}{K_G^a (1 - y_i)_{olm}} \right]_{ave.}$

d. $N_{OG} = \int_{y_{i2}}^{y_{i1}} \frac{(1 - y_i)_{olm} dy_i}{(1 - y_i)(y_i - y_i^*)}$

16. The Mass Transfer Zone (MTZ) for an adsorber may be defined as follows:
- a. That zone in an adsorption bed where the adsorbate exists in the highest loading on the adsorbent.
 - b. That portion of the length of an adsorption bed which is only partially saturated and progresses in a downstream direction through the bed.
 - c. That portion of the adsorbent bed where the Coefficient of Diffusion is the greatest.
 - d. None of the above.
17. The basic difference between a regenerative and a non-regenerative adsorption system is that the regenerative type is usually _____ , while the non-regenerative type is usually _____ .
- a. A thick bed; a thin bed.
 - b. For low concentrations; for high concentrations.
 - c. Activated carbon; activated alumina.
 - d. Heated; cooled.

Part II True-False

(Each question is worth 2 points)

- 1. The fan laws apply to fans from the same homologous series at the same point of rating.
- 2. The regeneration time for an adsorber in an adsorption system may be considerably less than the adsorption phase of the operation cycle.
- 3. In combustion processes the available heat for useful heating purposes is usually identical to the gross heating value of the fuel.

4. The volumes delivered by similar fans at the same rpm vary directly as the square of the fan blade diameter.
5. The Mass Transfer Zone (MTZ) for an adsorption system may theoretically be longer than the adsorption bed itself.
6. The heat of physical adsorption is usually about equal to the latent heat of vaporization of the adsorbate.
7. The relative direction of gas to liquid flow in a packed tower is usually cocurrent rather than countercurrent.

Part III Problems

- 4 pts. 1. If Henry's Law constant for CO_2 in the CO_2 -Air-Water-System is 1420 (atm/mole fraction) at 78°F , what is the partial pressure of CO_2 when the mole fraction of CO_2 in the liquid is 0.0005?
- a. 7.1
 - b. 0.028
 - c. 0.71
 - d. 0.28
- 4 pts. 2. Given the following information for a packed countercurrent gas scrubber, determine the outlet liquid concentration, x_1 .

Gas Flow Rate: 10 lb. moles/hr.ft²

Liquid Flow Rate: 40 lb. moles/hr. ft²

mole fraction of contaminant in inlet gas: $y_1 = 0.02$

mole fraction of contaminant in outlet gas: $y_2 = 0.004$

mole fraction of contaminant in inlet liquid: $x_2 = 0$

- a. 0.400
- b. 0.004
- c. 0.064
- d. 0.640

- 4 pts. 3. 49,000 BTU/hr. are transferred in an air preheater, calculate the outlet temperature of the air stream using the following information:

For air, $C_p = 0.245$ BTU/lb. °F

Air Flow Rate = 1000 lb./hr.

Air Inlet Temperature = 200°F

- a. 220°F
- b. 440°F
- c. 400°F
- d. 600°F

- 10 pts. 4. Type G II carbon was used in a two-foot adsorption bed for solvent recovery. In this application the carbon capacity was 36%, the MTZ was two inches, and the heel was 2.2%. Determine the working charge.

- a. 34.5%
- b. 32.3%
- c. 36.7%
- d. 33.8%

- 10 pts. 5. Determine the scfm of dry natural gas (Gross Heating Value, $HV_G = 1200$ BTU/scf) required to heat 3790 scfm of a contaminated gas stream (assume air) from 200°F to 1500°F. Assume no excess air and no heat losses.

- a. 156
- b. 137
- c. 92
- d. 81

- 10 pts. 6. Fan A at 1622 rpm has a blade diameter of 46 inches, delivers 15,120 cfm, and requires 45.9 bhp. If Fan B operates at 1600 rpm, has a blade diameter of 50 inches, delivers a gas having the same density as for Fan A, and is from the same homologous series as Fan A, what is the power requirement for Fan B?

- a. 66.8 bhp
- b. 58.1 bhp
- c. 49.2 bhp
- d. 69.6 bhp

7. Under the following conditions, determine the packed height of a countercurrent packed scrubber using a contaminant-free liquid rate (assume water) of $(55.5 \text{ lb.moles/hr.ft}^2)$:

Gas Flow Rate: $500 \text{ (lb/hr.ft}^2\text{)}$ or, $17.2 \text{ (lb.moles/hr.ft}^2\text{)}$

Inlet contaminant gas mole fraction, $y_1 = 0.020$

Outlet contaminant liquid mole fraction, $x_1 = 0.0059$

Slope of equilibrium line, $m = 0.972$

Packing "B"

HINT: First, use a material balance to find y_2 .

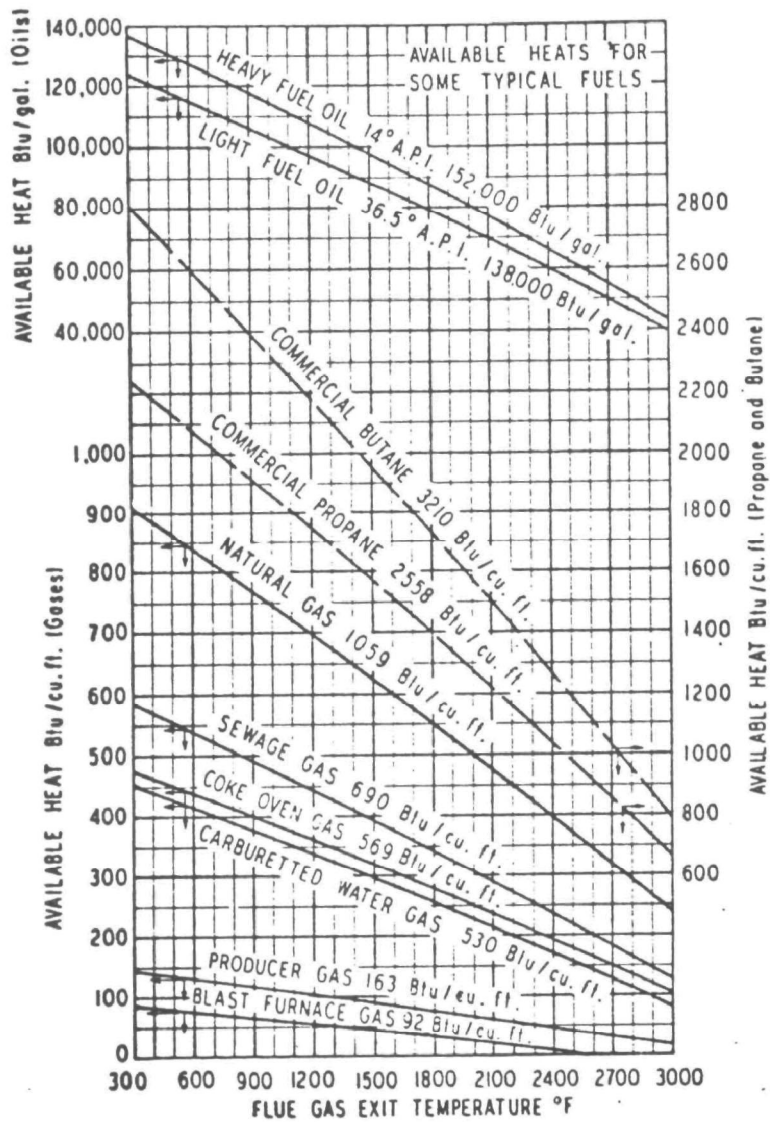
- a. 4.7 ft.
- b. 5.5 ft.
- c. 7.1 ft.
- d. 8.0 ft.

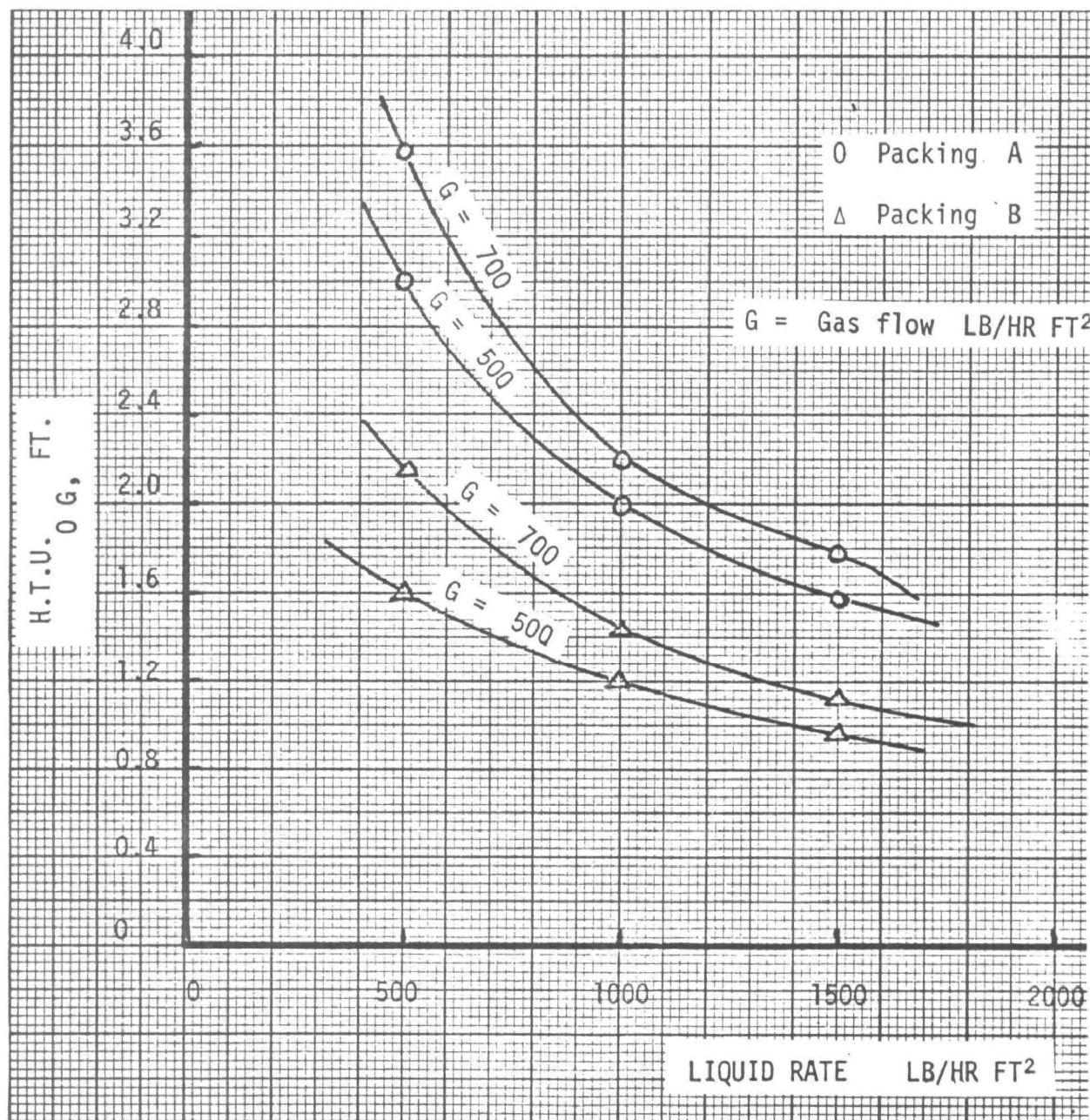
ENTHALPIES OF COMBUSTION GASES

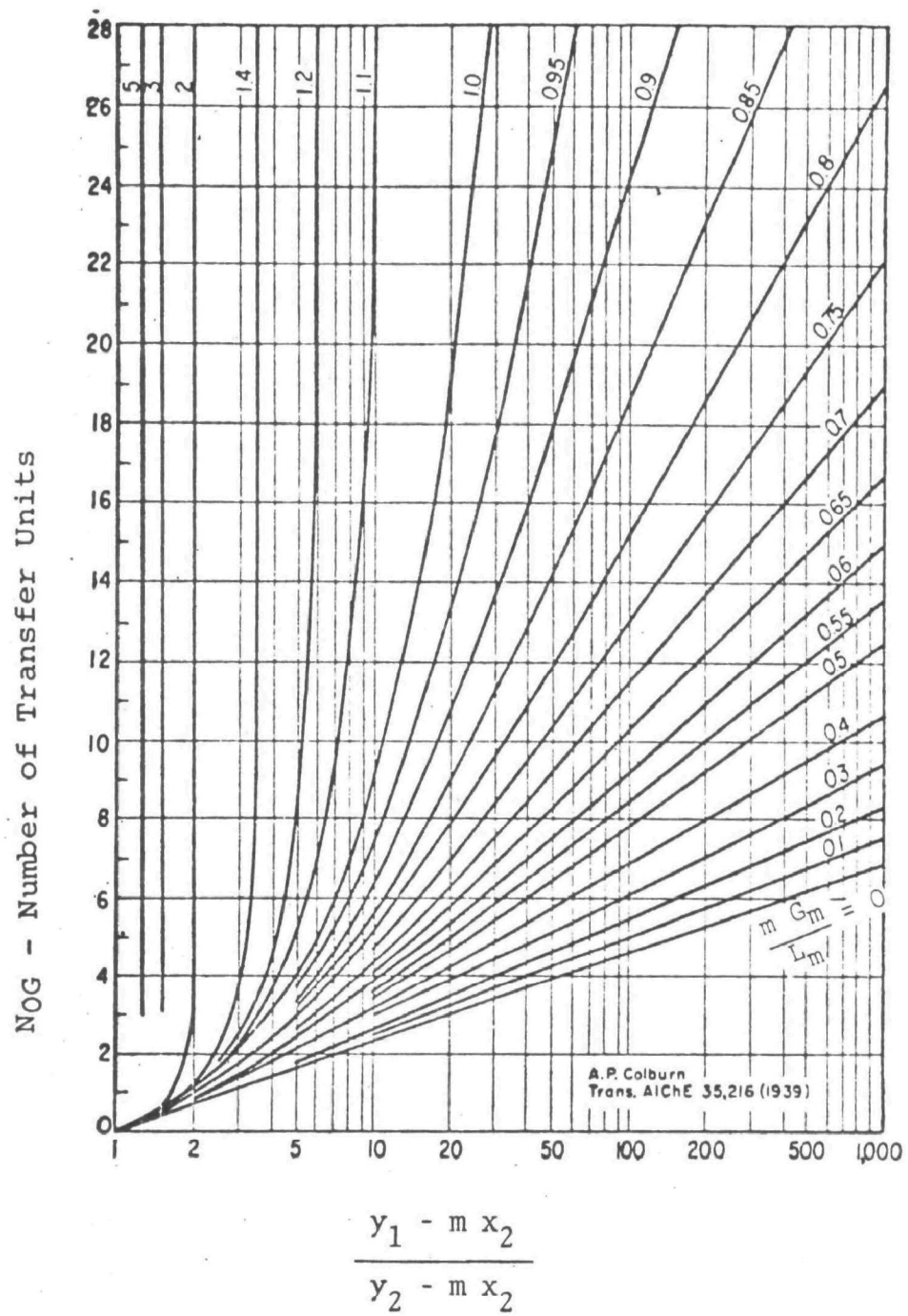
Btu/lb.mole

°F	N ₂	AIR M.W. 28.97	CO ₂	H ₂ O
32	0	0	0	0
60	194.9	194.6	243.1	224.2
77	312.2	312.7	392.2	360.5
100	473.3	472.7	597.9	545.3
200	1,170	1,170	1,527	1,353
300	1,868	1,870	2,509	2,171
400	2,570	2,576	3,537	3,001
500	3,277	3,289	4,607	3,842
600	3,991	4,010	5,714	4,700
700	4,713	4,740	6,855	5,572
800	5,443	5,479	8,026	6,460
900	6,182	6,227	9,224	7,364
1,000	6,929	6,984	10,447	8,284
1,200	8,452	8,524	12,960	10,176
1,500	10,799	10,895	16,860	13,140
2,000	14,840	14,970	23,630	18,380
2,500	19,020	19,170	30,620	23,950
3,000	23,280	23,460	37,750	29,780

* Kobe, Kenneth A., and Long, Ernest G., "Thermochemistry for the Petroleum Industry," *Petroleum Refiner*, Vol. 28, No. 11, November, 1949, page 129, table 9.







Section II

Combustion

TABLE 1

Combustion Constants

No.	Substance	Formula	Molecular Weight	Lb per Cu Ft	Cu Ft per Lb	Sp Gr Air = 1.0000	Heat of Combustion				For 100% Total Air Moles per mole of Combustible or Cu Ft per Cu Ft of Combustible Required for Combustion						For 100% Total Air Lb per Lb of Combustible Required for Combustion						
							Btu per Gross (High)	Cu Ft Net (Low)	Btu per Gross (High)	Lb Net (Low)	O ₂	N ₂	Air	CO ₂	H ₂ O	N ₂	O ₂	N ₂	Air	CO ₂	H ₂ O	N ₂	
1	Carbon*	C	12.01	.....	...	...	...	...	14,093	14,093	1.0	3.76	4.76	1.0	..	3.76	2.66	8.86	11.53	3.66	..	8.86	26.41
2	Hydrogen	H ₂	2.016	0.0053	187.723	0.0696	325	275	61,100	51,623	0.5	1.88	2.38	.	1.0	1.88	7.94	26.41	34.34	..	8.94	26.41	..
3	Oxygen	O ₂	32.000	0.0846	11.819	1.1053	...	...	.....	...	...	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
4	Nitrogen (atm)	N ₂	28.016	0.0744	13.443	0.9718	...	...	.....	.....	...	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
5	Carbon monoxide	CO	28.01	0.0740	13.506	0.9672	322	322	4,347	4,347	0.5	1.88	2.38	1.0	...	1.88	0.57	1.90	2.47	1.57	.	1.90	..
6	Carbon dioxide	CO ₂	44.01	0.1170	8.548	1.5282	...	...	.....	...	...	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Paraffin series																							
7	Methane	CH ₄	16.041	0.0424	23.565	0.5543	1013	913	23,879	21,520	2.0	7.53	9.53	1.0	2.0	7.53	3.99	13.28	17.27	2.74	2.25	13.28	..
8	Ethane	C ₂ H ₆	30.067	0.0803	12.455	1.0488	1792	1641	22,320	20,432	3.5	13.18	16.68	2.0	3.0	13.18	3.73	12.39	16.12	2.93	1.80	12.19	..
9	Propane	C ₃ H ₈	44.092	0.1196	8.365	1.5617	2590	2385	21,661	19,944	5.0	18.82	23.82	3.0	4.0	18.82	3.63	12.07	15.70	2.99	1.63	12.07	..
10	n-Butane	C ₄ H ₁₀	58.118	0.1582	6.321	2.0665	3370	3113	21,308	19,680	6.5	24.47	30.97	4.0	5.0	24.47	3.58	11.91	15.49	3.03	1.55	11.91	..
11	Isobutane	C ₄ H ₁₀	58.118	0.1582	6.321	2.0665	3363	3105	21,257	19,629	6.5	24.47	30.97	4.0	5.0	24.47	3.58	11.91	15.49	3.03	1.55	11.91	..
12	n-Pentane	C ₅ H ₁₂	72.144	0.1904	5.252	2.4872	4016	3709	21,091	19,517	8.0	30.11	38.11	5.0	6.0	30.11	3.55	11.81	15.35	3.05	1.50	11.81	..
13	Isopentane	C ₅ H ₁₂	72.144	0.1904	5.252	2.4872	4008	3716	21,052	19,478	8.0	30.11	38.11	5.0	6.0	30.11	3.55	11.81	15.35	3.05	1.50	11.81	..
14	Neopentane	C ₅ H ₁₂	72.144	0.1904	5.252	2.4872	3993	3693	20,970	19,396	8.0	30.11	38.11	5.0	6.0	30.11	3.55	11.81	15.35	3.05	1.50	11.81	..
15	n-Hexane	C ₆ H ₁₄	86.169	0.2274	4.398	2.9704	4762	4412	20,940	19,403	9.5	35.76	45.26	6.0	7.0	35.76	3.53	11.74	15.27	3.06	1.46	11.74	..
Olefin series																							
16	Ethylene	C ₂ H ₄	28.051	0.0746	13.412	0.9740	1614	1513	21,644	20,295	3.0	11.29	14.29	2.0	2.0	11.29	3.42	11.39	..	3.14	1.29	11.39	..
17	Propylene	C ₃ H ₆	42.077	0.1110	9.007	1.4504	2336	2186	21,041	19,691	4.5	16.94	21.44	3.0	3.0	16.94	3.42	11.39	14.81	3.14	1.29	11.39	..
18	n-Butene	C ₄ H ₈	56.102	0.1480	6.756	1.9336	3084	2885	20,840	19,496	6.0	22.59	28.59	4.0	4.0	22.59	3.42	11.39	14.81	3.14	1.29	11.39	..
19	Isobutene	C ₄ H ₈	56.102	0.1480	6.756	1.9336	3068	2869	20,730	19,382	6.0	22.59	28.59	4.0	4.0	22.59	3.42	11.39	14.81	3.14	1.29	11.39	..
20	n-Pentene	C ₅ H ₁₀	70.128	0.1852	5.400	2.4190	3836	3586	20,712	19,363	7.5	28.23	35.73	5.0	5.0	28.23	3.42	11.39	14.81	3.14	1.29	11.39	..
Aromatic series																							
21	Benzene	C ₆ H ₆	78.107	0.2060	4.852	2.6920	3751	3601	18,210	17,480	7.5	28.23	35.73	6.0	3.0	28.23	3.07	10.22	13.30	3.38	0.69	10.22	..
22	Toluene	C ₇ H ₈	92.132	0.2431	4.113	3.1760	4484	4284	18,440	17,620	9.0	33.88	42.88	7.0	4.0	33.88	3.13	10.40	13.53	3.34	0.78	10.40	..
23	Xylene	C ₈ H ₁₀	106.158	0.2803	3.567	3.6618	5230	4980	18,650	17,760	10.5	39.52	50.02	8.0	5.0	39.52	3.17	10.53	13.70	3.32	0.85	10.53	..
Miscellaneous gases																							
24	Acetylene	C ₂ H ₂	26.036	0.0697	14.344	0.9107	1499	1448	21,500	20,776	2.5	9.41	11.91	2.0	1.0	9.41	3.07	10.22	13.30	3.38	0.69	10.22	..
25	Naphthalene	C ₁₀ H ₈	128.162	0.3384	2.955	4.4208	5854	5654	17,298	16,708	12.0	45.17	57.17	10.0	4.0	45.17	3.00	9.97	12.96	3.43	0.56	9.97	..
26	Methyl alcohol	CH ₃ OH	32.041	0.0846	11.820	1.1052	868	768	10,259	9,078	1.5	5.65	7.15	1.0	2.0	5.65	1.50	4.98	6.48	1.37	1.13	4.98	..
27	Ethyl alcohol	C ₂ H ₅ OH	46.067	0.1216	8.221	1.5890	1600	1451	13,161	11,929	3.0	11.29	14.29	2.0	3.0	11.29	2.08	6.93	9.02	1.92	1.17	6.93	..
28	Ammonia	NH ₃	17.031	0.0456	21.914	0.5961	441	365	9,668	8,001	0.75	2.82	3.57	..	1.5	3.32	1.41	4.69	6.10	..	1.59	5.51	..
SO ₂ :																							
29	Sulfur*	S	32.06	..	.....	.	..	...	3,983	3,983	1.0	3.76	4.76	1.0	..	3.76	1.00	3.29	4.29	2.00	..	3.29	..
30	Hydrogen sulfide	H ₂ S	34.076	0.0911	10.979	1.1898	647	596	7,100	6,545	1.5	5.65	7.15	1.0	1.0	5.65	1.41	4.69	6.10	1.88	0.53	4.69	..
31	Sulfur dioxide	SO ₂	64.06	0.1733	5.770	2.2640	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
32	Water vapor	H ₂ O	18.016	0.0476	21.017	0.6215	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
33	Air	..	28.9	0.0766	13.063	1.0000	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..

*Carbon and sulfur are considered as gases for molal calculations only.

Note: This table is reprinted from *Fuel Flue Gases*, 1941 Edition, courtesy of American Gas Association.

All gas volumes corrected to 60 F and 30 in. Hg dry.

TABLE 2 — ENTHALPIES OF COMBUSTION GASES *

Btu/lb.mole

°F	N ₂	AIR M.W. 28.97	CO ₂	H ₂ O
32	0	0	0	0
60	194.9	194.6	243.1	224.2
77	312.2	312.7	392.2	360.5
100	473.3	472.7	597.9	545.3
200	1,170	1,170	1,527	1,353
300	1,868	1,870	2,509	2,171
400	2,570	2,576	3,537	3,001
500	3,277	3,289	4,607	3,842
600	3,991	4,010	5,714	4,700
700	4,713	4,740	6,855	5,572
800	5,443	5,479	8,026	6,460
900	6,182	6,227	9,224	7,364
1,000	6,929	6,984	10,447	8,284
1,200	8,452	8,524	12,960	10,176
1,500	10,799	10,895	16,860	13,140
2,000	14,840	14,970	23,630	18,380
2,500	19,020	19,170	30,620	23,950
3,000	23,280	23,460	37,750	29,780

* Kobe, Kenneth A., and Long, Ernest G., "Thermochemistry for the Petroleum Industry," *Petroleum Refiner*, Vol. 28, No. 11, November, 1949, page 129, table 9.

TABLE 3 — MEAN MOLAL HEAT CAPACITIES OF GASES ABOVE 0°F *

$$t = ^\circ\text{F} \quad \bar{C}_p = \text{Btu}/(\text{lbmole})(^\circ\text{F})$$

t	N ₂	O ₂	H ₂ O	CO ₂	H ₂	CO	CH ₄	SO ₂	NH ₃	HCl	NO	AIR
0	6.94	6.92	7.93	8.50	6.86	6.92	8.25	9.9'	8.80	6.92	7.1	6.94
200	6.96	7.03	8.04	9.00	6.89	6.96	8.42	10.0	8.85	6.96	7.2	6.97
400	6.98	7.14	8.13	9.52	6.93	7.00	9.33	10.3	9.05	7.01	7.2	7.01
600	7.02	7.26	8.25	9.97	6.95	7.05	10.00	10.6	9.40	7.05	7.3	7.07
800	7.08	7.39	8.39	10.37	6.97	7.13	10.72	10.9	9.75	7.10	7.3	7.15
1000	7.15	7.51	8.54	10.72	6.98	7.21	11.45	11.2	10.06	7.15	7.4	7.23
1200	7.23	7.62	8.69	11.02	7.01	7.30	12.13	11.4	10.43	7.19	7.5	7.31
1400	7.31	7.71	8.85	11.29	7.03	7.38	12.78	11.7	10.77	7.24	7.6	7.39
1600	7.39	7.80	9.01	11.53	7.07	7.47	13.38	11.8	.....	7.29	7.7	7.48
1800	7.46	7.88	9.17	11.75	7.10	7.55	.....	12.0	.....	7.33	7.7	7.55
2000	7.53	7.96	9.33	11.94	7.15	7.62	.....	12.1	.....	7.38	7.8	7.62
2200	7.60	8.02	9.48	12.12	7.20	7.68	.....	12.2	.....	7.43	7.8	7.69
2400	7.66	8.08	9.64	12.28	7.24	7.75	.....	12.3	.....	7.47	7.9	7.75
2600	7.72	8.14	9.79	12.42	7.28	7.80	.....	12.4	.....	7.52	8.0	7.81
2800	7.78	8.19	9.93	12.55	7.33	7.86	.....	12.5	.....	7.57	8.0	7.86
3000	7.83	8.24	10.07	12.67	7.38	7.91	.....	12.5	.....	7.61	8.1	7.92
3200	7.87	8.29	10.20	12.79	7.43	7.95	.....	.....	.....	.....	...	7.96
3400	7.92	8.34	10.32	12.89	7.48	8.00	.....	.....	.....	.....	...	8.01
3600	7.96	8.38	10.44	12.98	7.53	8.04	.....	.....	.....	.....	...	8.05
3800	8.00	8.42	10.56	13.08	7.57	8.08	.....	.....	.....	.....	...	8.09
4000	8.04	8.46	10.67	13.16	7.62	8.11	.....	.....	.....	.....	...	8.13
4200	8.07	8.50	10.78	13.23	7.66	8.14	.....	.....	.....	.....	...	8.16
4400	8.10	8.54	10.88	13.31	7.70	8.18	.....	.....	.....	.....	...	8.19
4600	8.13	8.58	10.97	13.38	7.75	8.20	.....	.....	.....	.....	...	8.22
4800	8.16	8.62	11.08	13.44	7.79	8.23	.....	.....	.....	.....	...	8.26

* Williams, E. T., and Johnson, R. C., Stoichiometry for Chemical Engineers,
(New York: Mc Graw-Hill Book Company, 1958), page 321.

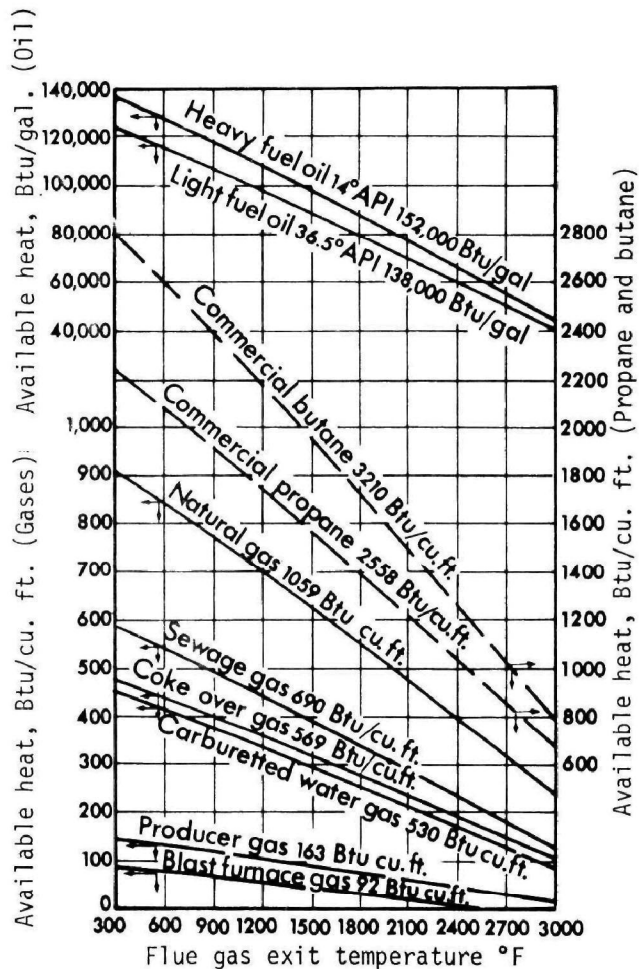
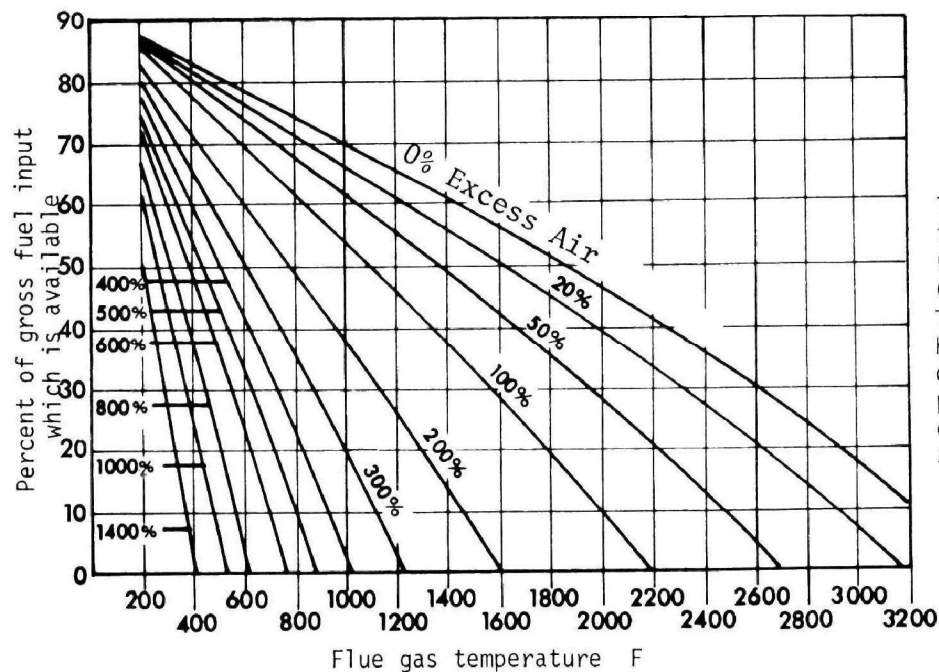


Figure 1. AVAILABLE HEATS FOR SOME TYPICAL FUELS⁽¹⁾ (Refer to 60°F)



This chart is only applicable to cases in which there is no unburned fuel in the products of combustion. The average temperature of the hot mixture just beyond the end of the flame may be read at the point where the appropriate % excess air curve intersects the zero available heat line.

Figure 2. GENERALIZED AVAILABLE HEAT CHART FOR ALL FUELS AT VARIOUS FLUE GAS TEMPERATURES AND VARIOUS EXCESS COMBUSTION AIR⁽¹⁾ (Refer to 60°F)

COMPREHENSIVE COMBUSTION PROBLEM

PART 1

For a natural gas of the following composition, find the gross heating value by using the data given in Table 1. The dry natural gas is delivered at 60°F.

Natural Gas Analysis
(Volume or Mole Fraction)

N ₂	0.0515
CH ₄	0.8111
C ₂ H ₆	0.0967
C ₃ H ₈	0.0351
C ₄ H ₁₀	0.0056
	<hr/> 1.0000

22,601.6 BTU/lb

PART 2

For the natural gas specified above, determine the available heat at 1200°F by two methods. Method a. should utilize Table 2, and Method b. should use Figure 1.

Method b
2670 BTU/lb

PART 3

For the natural gas previously specified, calculate the rate of auxiliary fuel required to heat 5000 scfm of contaminated air from 200°F to 1200°F. Two methods of calculation should be used. Method a. should utilize the enthalpy data given in Table 2, and Method b. should use the mean heat capacity data of Table 3.

The contaminated gas stream will be assumed to be air.

The assumption of no heat loss will be made for the control device.

PART 4

What are the dimensions of an afterburner treating the contaminated gas stream described in PART 3?

PART I -- SOLUTION*

1. The natural gas analysis was given in volume fractions. Therefore, for each standard cubic foot of natural gas there is 0.0515 scf of nitrogen, 0.8111 scf of methane, and etc.

2. From Table 1, fill in the following gross heats of combustion:

	Gross Heat of Combustion (Btu/scf)
N ₂	_____
CH ₄	_____
C ₂ H ₆	_____
C ₃ H ₈	_____
C ₄ H ₁₀	_____

3. The gross heating value for natural gas is:

$$HV_G = (0.8111)(1013) + (0.0967)(1792) + (0.0351)(2590) + (0.0056)(3370)$$

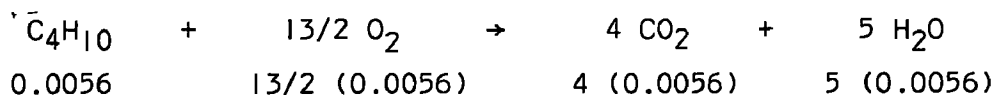
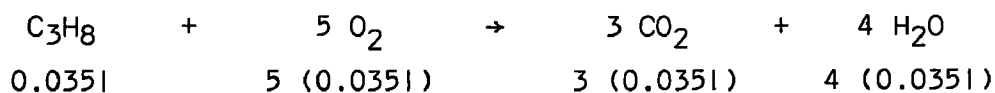
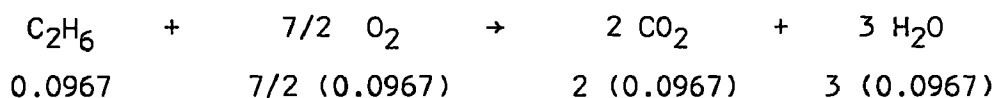
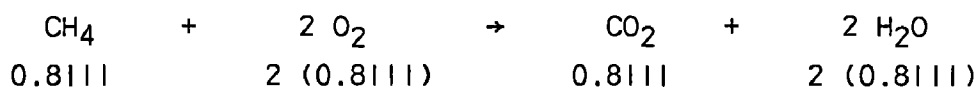
$$HV_G = \text{_____ Btu/scf natural gas}$$

*Answers are on page 29.

PART 2 -- SOLUTION

Method a.

1. Balanced chemical combustion equations are written for each component of the natural gas. Based on (either) one mole or one standard cubic foot of natural gas, the required amount of each constituent is written under that constituent in each equation.



2. Calculate the number of standard cubic feet for each of the following constituents of combustion:

O_2	_____	scf/scf natural gas
CO_2	_____	scf/scf natural gas
H_2O	_____	scf/scf natural gas
N_2^*	_____	scf/scf natural gas

* Assuming the natural gas is burned with air (21% O₂ and 79% N₂), the total amount of nitrogen in the products of combustion is the sum of that N₂ in the natural gas (0.0515 scf) and that amount traveling with the required O₂ ($\frac{79}{21} \times \text{scf O}_2$).

3. How many cubic feet of products are there per scf of natural gas burned (assuming that a stoichiometric quantity of air is used)?

$$\frac{\text{scf CO}_2}{\text{scf Gas}} + \frac{\text{scf H}_2\text{O}}{\text{scf Gas}} + \frac{\text{scf N}_2}{\text{scf Gas}} = \frac{\text{scf Products}}{\text{scf Gas}}$$

4. The available heat (HA_T) at any temperature is the gross heating value (HV_G) minus the amount of heat required to take products of combustion to that temperature (Σ ΔH):

$$HA_T = HV_G - \Sigma \Delta H$$

For the natural gas, the HV_G at 60°F is 1105 Btu/scf. It is therefore necessary to find Σ ΔH for the products of combustion. Enthalpies of combustion gases are given in Table 2, and the latent heat of vaporization of water at 60°F is 1060 Btu/lb.

$$\Delta H_{\text{CO}_2} = \frac{1.1322 (\text{scf CO}_2/\text{scf Gas}) (12960 - 243) (\text{Btu/lb. mole})}{379 (\text{scf CO}_2/\text{lb. mole})}$$

$$\Delta H_{\text{CO}_2} = \text{_____} (\text{Btu/scf Gas})$$

$$\Delta H_{\text{N}_2} = \frac{8.2246 (\text{scf N}_2/\text{scf Gas}) (8452 - 195) (\text{Btu/lb. mole})}{379 (\text{scf N}_2/\text{lb. mole})}$$

$$\Delta H_{\text{N}_2} = \text{_____} (\text{Btu/scf Gas})$$

First the liquid water must be vaporized, and then the vapor is heated to 1200°F.

$$\Delta H_\lambda = \frac{1060 (\text{Btu/lb. H}_2\text{O}) 18 (\text{lb. H}_2\text{O/lb. mole}) 2.0807 (\text{scf H}_2\text{O/scf Gas})}{379 (\text{scf H}_2\text{O/lb. mole})}$$

$$= \text{_____} (\text{Btu/scf Gas})$$

$$\Delta H_{H_2O} = \frac{2.0807 \text{ (scf } H_2O/\text{scf Gas})(10176-224)(\text{Btu/lb. mole})}{379 \text{ (scf } H_2O/\text{lb. mole})}$$

$$\Delta H_{H_2O} = \underline{\hspace{2cm}} \text{ (Btu/scf Gas)}$$

$$\Sigma \Delta H = \Delta H_{CO_2} + \Delta H_{N_2} + \Delta H_{\lambda} + \Delta H_{H_2O}$$

$$\Sigma \Delta H = \underline{\hspace{2cm}} \text{ (Btu/scf Gas)}$$

$$HA_{1200^{\circ}F} = HV_G - \Sigma \Delta H$$

$$HA_{1200^{\circ}F} = 1105 - \Sigma \Delta H$$

$$HA_{1200^{\circ}F} = \underline{\hspace{2cm}} \text{ (Btu/scf natural gas)}$$

Part 2 -- Solution

Method b.

1. Use Figure 1 and the following equation:

$$\left[\frac{HA_T}{HV_G} \right]_{\text{fuel in Fig. 1}} = \frac{HA_T}{HV_G}$$

2. The unknown is $HA_{1200^\circ F}$ for a natural gas with an HV_G of 1105 Btu/scf. From Figure 1 for a natural gas with an HV_G of 1059 Btu/scf the $HA_{1200^\circ F}$ is 695 Btu/scf natural gas.

$$3. \quad HA_{1200^\circ F} = HV_G \times \left[\frac{HA_{1200^\circ F}}{HV_G} \right]_{\text{Fuel in Fig. 1}}$$

$$HA_{1200^\circ F} = 1105 \times \frac{695}{1059}$$

$$HA_{1200^\circ F} = \underline{\hspace{2cm}} \quad (\text{Btu/scf natural gas})$$

PART 3 -- SOLUTION

Method a.

1. From Table 2 the enthalpy of air at 200°F and 1200°F is listed as 1170 and 8524 Btu/lb. mole respectively.

2. The heat rate required to heat 5000 scfm from 200°F to 1200°F is given as follows:

$$Q \text{ (Btu/min)} = \frac{5000 \text{ (scfm)} \times (8524 - 1170) \text{ (Btu/lb. mole)}}{379 \text{ (scf/lb. mole)}}$$

$$Q = \underline{\hspace{2cm}} \text{ Btu/min}$$

3. If the amount of available heat per scf of natural gas is 725 Btu/scf (refer to PART 2), what is the natural gas rate that is required to heat 5000 scfm of air from 200°F to 1200°F?

$$\text{Natural Gas Rate} = \frac{97,000 \text{ Btu/min}}{725 \text{ Btu/scf}}$$

$$\text{Natural Gas Rate} = \underline{\hspace{2cm}} \text{ scfm}$$

Part 3 -- Solution

Method b.

1. From Table 3 the \bar{C}_{p200} for air is 6.97 (Btu/lb.mole F°) and the \bar{C}_{p1200} for air is 7.31 (Btu/lb.mole F°).

2. Using the following equation, the heat required to heat 5000 scfm from 200°F to 1200°F is calculated.

$$Q = m [\bar{C}_{p_{t_2}} (t_2 - t_b) - \bar{C}_{p_{t_1}} (t_1 - t_b)]$$

$$Q = m [(7.31)(\text{Btu/lb.mole}^\circ\text{F}) \times (1200 - 0)(F^\circ) - 6.97 (\text{Btu/lb.mole}^\circ\text{F}) \times (200 - 0) F^\circ]$$

$$Q = m [\quad (\text{Btu/lb.mole})]$$

$$m = \frac{5000 (\text{scfm})}{379 (\text{scf/lb.mole})}$$

$$m = \quad \text{lb. mole/min.}$$

$$Q = \quad \text{Btu/min.}$$

3. If the amount of available heat per scf of natural gas is 725 Btu/scf (refer to PART 2), what is the natural gas rate that is required to heat 5000 scfm of air from 200°F to 1200°F?

$$\text{Natural Gas Rate} = \frac{\quad \text{Btu/min}}{\quad \text{Btu/scf}}$$

$$\text{Natural Gas Rate} = \quad \text{scfm}$$

PART 4 -- SOLUTION

1. Assuming the natural gas flow rate is 135 scfm, what is the volumetric rate of products of combustion? (Remember from PART 2 that there are 11.44 scf of products for scf of natural gas burned.)

$$11.44 \text{ (scf/scf gas)} \times \text{_____ (scfm gas)} = \text{_____ scfm}$$

2. The total flue gas flow rate is the total of the contaminated gas stream flow rate and the flow rate of the products of combustion.

$$\text{_____ scfm} + \text{_____ scfm} = \text{_____ scfm}$$

3. What is the flue gas flow rate at 1200°F in cubic feet per second?

$$6544 \text{ cfm} \times \frac{1}{60 \text{ sec/min}} \times \frac{(1200 + 460) (^{\circ}\text{R})}{(60 + 460) (^{\circ}\text{R})} = \text{_____ cfs}$$

4. Assuming a linear gas velocity of 20 fps, what is the diameter of the afterburner?

$$\text{Area} = \frac{\pi D^2}{4} = \text{_____ (cfs)} / \text{_____ fps} = \text{_____ (ft)}^2$$

$$D = \sqrt{\frac{17.4 \text{ (ft}^2) \times 4}{\pi}} = \text{_____ ft.}$$

5. Assuming a length-to-diameter design ratio of 2.0, how long should the afterburner be?

$$2.0 \times \text{_____ ft.} = \text{_____ ft.}$$

6. What is the residence time for the gases in the afterburner?

$$\text{Residence Time} = \frac{\text{Length}}{\text{Linear Gas Velocity}}$$

$$\text{Residence Time} = \text{_____ ft.} / \text{_____ fps}$$

$$\text{Residence Time} = \text{_____ sec.}$$

7. Is the residence time calculated in (6.) acceptable with respect to the minimum residence time for air pollution control? (Assume that the minimum design criteria for this afterburner application requires the gases to be at 1200°F for 0.3 second.)

A N S W E R S

PART 1

- No. 2 1013, 1792, 2590, 3370
No. 3 1105

PART 2

Method a.

- No. 2 2.1726, 1.1322, 2.0807, 8.2246
No. 3 1.1322, 2.0807, 8.2246, 11.4375
No. 4 38, 179, 105, 55, 377, 728

Method b.

- No. 3 725

PART 3

Method a.

- No. 2 97,000
No. 3 133.8

Method b.

- No. 2 7378; 13.2; 97,500
No. 3 97,500; 725; 134.5

PART 4

- No. 1 135, 1544
No. 2 1544, 5000, 6544
No. 3 348
No. 4 348, 20, 17.4, 4.71
No. 5 4.71, 9.42
No. 6 9.42, 20, 0.47
No. 7 Yes

C-11

Theoretical Flame Temperature

Calculate the theoretical flame temperature of a gas stream with the following analysis (volumetric):

CO ₂	10%
CO	10%
O ₂	5%
N ₂	75%

The gas stream enters the afterburner at 200°F at a flow rate of 6350 cfm.

The heat of combustion of CO at 60°F is 121,745 (Btu/lb. mole).

Mean heat capacity data are available in Table 3. Assume that for the given concentrations the system is within the flammability range.

SOLUTION*

1. Calculate the flow rate in standard cfm (at 60°F).

$$6550 \text{ cfm} \times \frac{(460 + 60) ^\circ\text{R}}{(460 + 200) ^\circ\text{R}} = \underline{\hspace{2cm}} \text{ scfm}$$

2. Calculate the number of lb. moles of each constituent in the gas stream per minute.

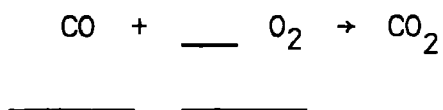
$$n_{\text{CO}_2} = \frac{5000 \text{ (scf)} \times 0.10 \text{ (scf CO}_2\text{/scf)}}{379 \text{ (scf/lb. mole)}} = 1.32 \text{ lb. mole CO}_2$$

$$n_{\text{CO}} = \underline{\hspace{2cm}} \text{ lb. moles CO}$$

$$n_{\text{O}_2} = \underline{\hspace{2cm}} \text{ lb. moles O}_2$$

$$n_{\text{N}_2} = \underline{\hspace{2cm}} \text{ lb. moles N}_2$$

3. Write the balanced chemical equation for the oxidation of carbon monoxide and write the number of lb. moles of reactants available under each reactant.



4. Is there enough oxygen present for the reaction to theoretically go to completion or must additional air be added?
5. If you determined that no additional oxygen is theoretically required, you are correct.

*Answers are on page 35.

6. In order to calculate the theoretical flame temperature, the combustion process must be carried out (on paper) in such a manner as to use the available data:

- Cool all the gases from 200°F to 60°F.
- React the materials at 60°F.
- By using the heat available from (a) and (b), heat the products to the final flame temperature.

7. The above procedure can be written in the following form as a heat balance: results (6a) + results(6b) = results(6c) or,

$$[\sum n_i \bar{C}_{pi}] (200 - 60) + n \Delta H_{\text{comb. } 60^\circ} = [\sum n_i \bar{C}_{pi}] (t - 60)$$

8. Evaluate $[\sum n_i \bar{C}_{pi}] (200 - 60)$ for all the gases.

	n_i (lb. mole)	\bar{C}_{pi} (From Table 3) (Btu/lb. mole F°)
CO ₂	1.32	9.00
CO	1.32	6.96
O ₂	0.66	7.03
N ₂	9.90	6.96

$$\sum n_i \bar{C}_{pi} = \underline{\hspace{2cm}} \text{ (Btu/F}^\circ\text{)}$$

$$[\sum n_i \bar{C}_{pi}] (140) = 13,246 \text{ Btu}$$

9. Evaluate $n \Delta H_{\text{comb. } 60^\circ\text{F}}$.

$$[\underline{\hspace{2cm}} \text{ (lb. mole)} \times 121,745 \text{ (Btu/lb. mole)}] = 160,703 \text{ Btu}$$

10. The equation from Part 7 may now be rewritten:

$$173,949 = [\sum n_i \bar{C}_{pi}] (t - 60)$$

This equation must be solved by trial and error for t .

11. Evaluate $[\sum n_i \bar{C}_{pi}] (t - 60)$ when $t = 1800^\circ\text{F}$.

	n_i (lb. mole)	\bar{C}_{pi} (From Table 3) (Btu/lb. mole)
CO ₂	2.64	_____
CO	0	_____
O ₂	0	_____
N ₂	9.90	_____

$$\sum n_i \bar{C}_{pi} = \text{_____ (Btu/F}^\circ\text{)}$$

$$[\sum n_i \bar{C}_{pi}] (1800 - 60) = 182,481 \text{ Btu}$$

This is too high, assume 1700°F .

12. Evaluate $[\sum n_i \bar{C}_{pi}] (t - 60)$ when $t = 1700^\circ\text{F}$.

	n_i (lb. mole)	\bar{C}_{pi} (From Table 3) (Btu/lb. mole)
CO ₂	2.64	_____
N ₂	9.90	_____

$$\sum n_i \bar{C}_{pi} = \text{_____ (Btu/F}^\circ\text{)}$$

$$[\sum n_i \bar{C}_{pi}] (1700 - 60) = 171,030 \text{ Btu}$$

This is close enough, therefore the flame temperature is 1700°F .

13. If a closer approximation for t is desired, the equation in (10) can be solved for t :

$$[\sum n_i \bar{C}_{pi}] (t - 60) = 173,949$$

$$t = \frac{173,949}{\sum n_i \bar{C}_{pi}} + 60$$

$$t = 1728 \text{ } ^\circ\text{F}$$

The flame temperature can now be solved for explicitly because the mean heat capacities can be considered to be approximately the same at 1728°F as at 1700°F.

ANSWERS

1. 5000
2. 1.32, 0.66, 9.90
3. $\frac{1}{2}$
1.32, 0.66
4. There is enough oxygen.
8. 94.6
9. 1.32
11. 11.75, 7.55, 7.88, 7.46
104.874
12. 11.64, 7.43
104.287

PLAN REVIEW OF A CATALYTIC AFTERBURNER

Plans have been submitted for a catalytic afterburner. The afterburner is to be installed to incinerate a 3000 cfm contaminated gas stream discharged from a direct-fired paint baking oven at 350°F. The following table summarizes the data taken from the plans.

Exhaust Flow Rate from Oven at 350°F	3000 cfm
Exhaust Gas Temperature from Oven	350 °F
Solvent Emission to Afterburner	0.3 lb./min.
Final Temperature in Afterburner	1000 °F
Gross Heating Value of Natural Gas	1100 Btu/scf
Total Heat Requirement	26884 Btu/min
Natural Gas Requirement	35.0 scfm
Furnace Volume	46.0 ft ³
Exhaust Flow Rate from Afterburner at 1000°F	6530 cfm
Gas Velocity Through Catalyst Bed	8.6 fps
No. of Type A 19 x 24 x 3 ³ / ₄ in. Catalyst Elements	4

The following information and rules of thumb may be required in order to review the plans for the catalytic afterburner.

- a. Heat will be recovered from the afterburner effluent, but that process will not be considered in this problem.
- b. Catalytic afterburner operating temperatures of approximately 950°F have been found sufficient to control emissions from most process ovens.
- c. Preheat burners are usually designed to increase the temperature of the contaminated gases to the required catalyst discharge gas temperature without regard to the heating value of the contaminants (especially if considerable concentration variation occurs).

- d. A 10 per cent heat loss is usually a reasonable estimate for an afterburner.
- e. The properties of the contaminated effluent may usually be considered identical to those of air.
- f. A design value for heat release rates for catalytic afterburners is 50,000 (Btu/hr.ft³).
- g. The catalyst manufacturer's literature suggests a superficial gas velocity through the catalyst element of 10 fps.

SOLUTION *

In order to review these plans, the following questions must be answered.

1. Is the operating temperature adequate for sufficient control?

The plans indicate a combustion temperature of _____°F; this is acceptable when compared to the _____°F rule of thumb.

2. Is the fuel requirement adequate to maintain the operating temperature?

- a. Calculate the number of lb,moles/min of gas to be heated from 350°F to 1000°F.

$$3000 \text{ (cfm)} \times \frac{(460 + 60)^\circ\text{R}}{(460 + 350)^\circ\text{R}} = \text{_____ scfm}$$

$$\text{_____ (scfm)} \times \frac{1 \text{ lb. mole}}{379 \text{ scf}} = \text{_____ lb. moles/min.}$$

- b. Use data for air from a table of enthalpy data (Table 2) to find the heat requirement to heat the gas stream (air) from 350°F to 1000°F.

$$\text{_____ (lb. moles/min)} \times (\text{_____} - \text{_____})(\text{Btu/lb. mole}) = 24196 \text{ Btu/min.}$$

- c. Calculate the total heat requirement, remembering the 10% heat loss rule of thumb.

$$\text{Total Heat Requirement} = 24196 \div 0.90$$

$$\text{Total Heat Requirement} = \text{_____ Btu/min}$$

*Answers are on page 41.

- d. Calculate the heat available at 1000°F by using Figure 1 and assuming theoretical air.

$$\frac{HA_{1000^{\circ}F}}{HV_G} = \left[\frac{HA_{1000^{\circ}F}}{HV_G} \right] \text{ Fuel in Fig. 1}$$

$$HA_{1000^{\circ}F} = 1100 \left[\frac{\quad}{1059} \right]$$

$$HA_{1000^{\circ}F} = 774 \text{ Btu/scf natural gas}$$

- e. By using (c) and (d), determine the natural gas requirement and compare it with that given on the data sheet.

$$\text{Natural Gas Requirement} = \frac{\text{Total Heat Requirement}}{\text{Available Heat in Fuel}}$$

$$\text{Natural Gas Requirement} = \frac{\quad \text{Btu/min}}{\quad \text{Btu/scf}}$$

$$\text{Natural Gas Requirement} = 34.7 \text{ scfm}$$

3. Is the catalyst section sized properly?

- a. Determine the total volumetric gas rate at the afterburner conditions (1000°F).

- (1) One scf of natural gas yields 11.45 scf of combustion products.

$$\text{Volume of Combustion Products } 1000^{\circ}F =$$

$$= 11.45 (\text{scf/scf gas}) \times \quad (\text{scfm gas}) \times \frac{(460 + \quad)^{\circ}R}{(460 + \quad)^{\circ}R}$$

$$\text{Volume of Combustion Products } 1000^{\circ}F = \quad \text{cfm}$$

(2) Volume of Contaminated Gases 1000°F =

$$\text{_____ (scfm)} \times \frac{(460 + 1000)^{\circ}\text{R}}{(460 + 60)^{\circ}\text{R}}$$

Volume Contaminated Gases 1000°F = _____ cfm

(3) Total Volumetric Gas Rate 1000°F = Volume of Combustion

Products 1000°F + Volume of Contaminated Gases 1000°F .

\therefore Total Volumetric Gas Rate 1000°F = _____ cfm + _____ cfm

Total Volumetric Gas Rate 1000°F = 6530 cfm

- b. How many $19 \times 24 \times 3^{3/4}$ in. catalyst elements are required if a linear gas velocity of 10 fps (or 600 fpm) is used?

$$\text{No. of Elements} = \frac{\text{_____ (cfm)} \times 144 (\text{in.}^2/\text{ft.}^2)}{\text{_____ (fpm)} \times 19 (\text{in.}) \times 24 (\text{in.})}$$

No. of Elements = 3.44

It is seen that four elements have been specified; this is a conservative design allowing a slightly slower gas flow through the elements.

ANSWERS

1. 1000, 950
2. a. 1925
1925, 5.08
b. 5.08, 6984, 2222
c. 26884
d. 745
e. 26884, 774
3. a. (1) 35, 1000, 60
1125
(2) 1925, 5405
(3) 1125, 5405
b. 6530, 600

Section III

Adsorption

Heat of Adsorption

This problem is an exercise in plotting data and calculating the heat of adsorption using the Clausius - Clapeyron equation. This equation is usually stated as follows:

$$\frac{d(\ln p)}{d(1/T)} = - q/R$$

Where

p = equilibrium adsorption pressure in mm Hg.

T = absolute temperature in °K

q = heat of adsorption in $\frac{\text{cal}}{\text{g mole}}$

R = ideal gas law constant = $2 \frac{\text{cal}}{^\circ\text{K g mole}}$

We will plot an NH_3 adsorption isostere from the NH_3 isotherms given in Figure 1. An adsorption isostere is a representation of equilibrium data relating pressure and temperature for a constant volume of material adsorbed per gram of carbon.

Calculate the heat of adsorption for adsorbing 35 cc of NH_3 per gram of carbon. The system temperature is 0°C and the pressure is 760 mm Hg.

Solution

1. Use Figure 2 to convert T to $1/T$.
2. The Clausius - Clapeyron equation tells us that if we plot $\ln p$ vs $1/T$ we will get a straight line with a slope $- q/R$.
3. Complete the following table.

Data for 35 cc NH_3 adsorbed per gram carbon

p (mm Hg)	7	30	115	675
T (°K)	249.5	273	303	353
$1/T$ (1/°K)	0.004			

(answer is on next page)

Answer to (3)

Data for Adsorption Isostere
(35 cc NH_3 adsorbed per gram
carbon)

P (mm Hg)	15	40	122	725
T ($^{\circ}\text{K}$)	249.5	273	303	353
1/T ($1/^{\circ}\text{K}$)	.004	.00366	.0033	.00284

4. The next steps are to plot the values of p and 1/T on the semi-log graph paper provided (Figure 3) and to draw the best straight line. Recall that we can plot $\ln p$ by plotting the value p on the log scale.

5. Our objective here is to obtain a value of the slope $d(\ln p)/d(1/T)$. We need to recall what $d \ln p$ is in terms of p. Since we are plotting values of p on a log scale, $d \ln p$ is really a very small increment of $\ln p$ or $(\ln p_2 - \ln p_1)$.

For example, $\ln 10 - \ln 5 = 2.303 - 1.610 = 0.692$

or $\ln 10 - \ln 5 = \ln 10/5 = \ln 2 = 0.692$

Calculate the slope $\frac{d \ln p}{d(1/T)}$ which is $\frac{\ln p_2 - \ln p_1}{1/T_2 - 1/T_1} = \frac{\ln P_2/P_1}{1/T_2 - 1/T_1}$.

Do this in the space below and use the values $p_2 = 600$ mm Hg and $p_1 = 200$ mm Hg.

(answer is on next page)

Answer to (5)

$$\frac{d \ln p}{d (1/T)} = \frac{\ln p_2/p_1}{1/T_2 - 1/T_1} = \frac{\ln 600/200}{.00278 - .00314} = \frac{1.100}{-.00036}$$

$$\frac{d \ln p}{d (1/T)} = - 3050$$

6. Calculate the value of q in units of cal/g mole.

$$\frac{d \ln p}{d (1/T)} = - q/R$$

$$- q/R = -3050 \quad \text{and } R = 2 \text{ cal/g mole } ^\circ\text{K}$$

$$\text{then } q = 2 \times 3050 = \text{——— cal/g mole}$$

(answer is on next page)

7. Use the ideal gas law ($PV = n RT$) to calculate the number of gram moles of NH_3 in 35 cc.

$$P, \text{ atm}; V, \text{ liters}; n, \text{ g moles}; T, ^\circ\text{K}; R = .08205 \frac{\text{atm liters}}{\text{g moles } ^\circ\text{K}}$$

$$n = \frac{PV}{RT} = \frac{\text{atm pressure} \times \text{liters } \text{NH}_3}{.08205 \times ^\circ\text{K}}$$

$$n = \frac{(\quad)(\quad)}{.08205 (\quad)}$$

$$n = (\quad)$$

(answer is on next page)

8. Now calculate the heat released by the adsorption of 35cc of NH_3 per gram of carbon.

$$q = 6100 \times 0.00156 = (\quad) \text{ cal}$$

(answer is on next page)

Answer to (6)

$$q = 6100 \text{ cal/g mole}$$

Answer to (7)

$$n = \frac{(1) \quad (.035)}{(.08205) (273)}$$

$$n = 0.00156 \text{ g moles NH}_3$$

Answer to (8)

$$q = 9.52 \text{ cal}$$

Figure 1. NH_3 ADSORPTION ISOTHERM ON CARBON

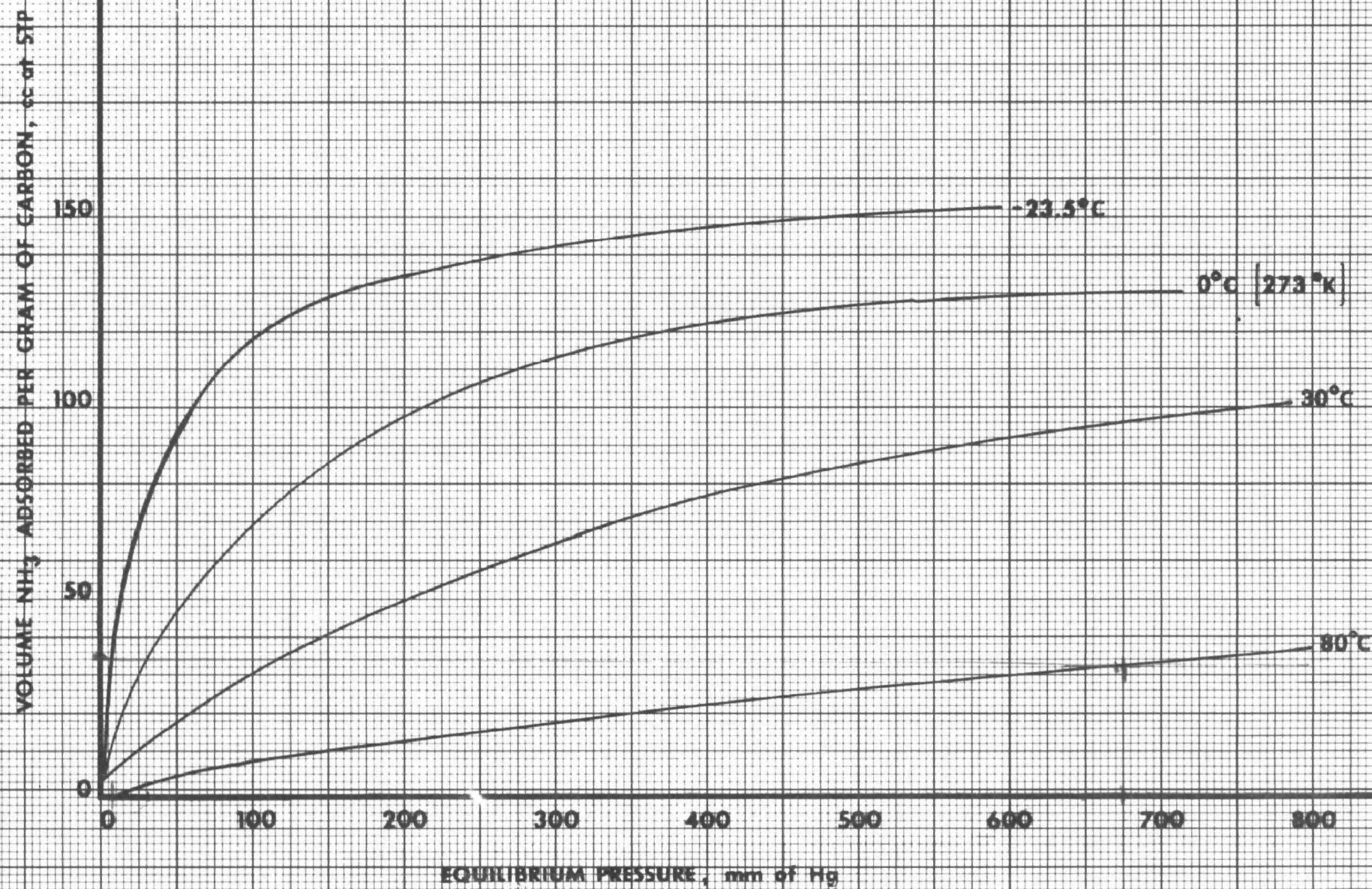


FIGURE 2.

PLOT OF T vs $1/T$ IN $^{\circ}\text{K}$

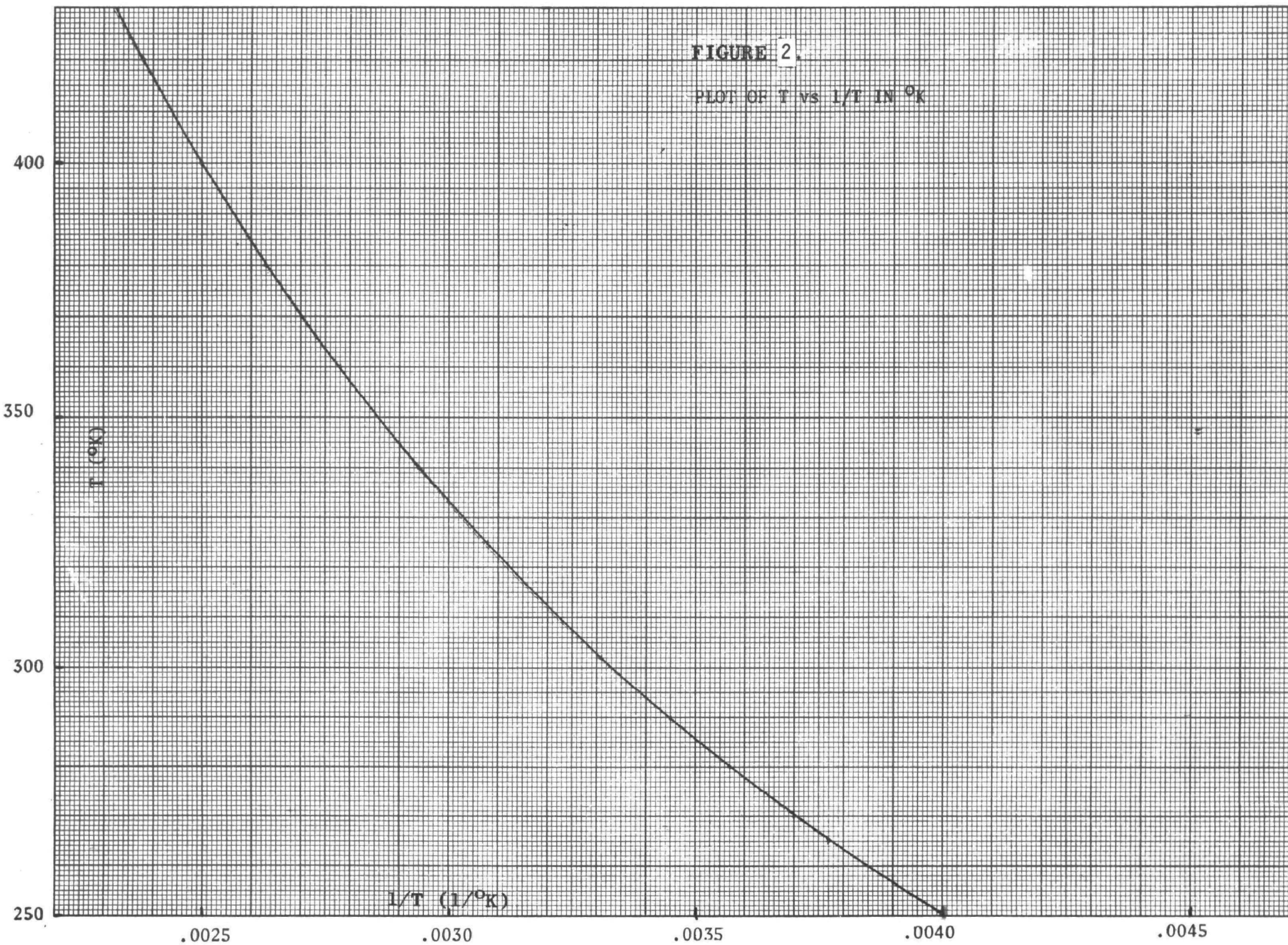


FIGURE 3.
ADSORPTION ISOSTERE

EQUILIBRIUM PRESSURE p (mm Hg)

$1/T$ ($1/^\circ K$)

.0030

.0035

.0040

AD-II

Surface Area Determination

Using the NH_3 adsorption isotherm at -23.5°C and the following BET equation, calculate the surface area of the carbon.

$$V = \frac{V_m C x}{(1-x) [1 + (C-1) x]} \quad \text{where } x = p/p_s; V_m = \text{Volume of } \text{NH}_3 \text{ adsorbed per gram of carbon when surface is covered by one layer of } \text{NH}_3 \text{ molecules.}$$

By rearranging the previous equation, the following equation is obtained:

$$\frac{x}{V(1-x)} = \frac{C-1}{V_m C} x + \frac{1}{V_m C}$$

Figure 1 is given, and p_s , the saturation equilibrium pressure, is given as 1216 mm Hg.

Tabulate the following values: p , x , $1-x$, V , and $\frac{x}{V(1-x)}$.

Using Figure 2 plot x vs. $x/V(1-x)$. Find the intercept ($1/V_m C$) and the slope ($(C-1)/V_m C$), and solve for V_m .

The following information may be important:

The area occupied by one NH_3 molecule is 13 \AA^2 .

p is expressed in mm Hg.

V is expressed in cubic centimeters, cc.

Avogadro's number = $6.028 \times 10^{23} \frac{\text{molecules}}{\text{g mole}}$

1 Angstrom = $1 \text{ \AA} = \frac{1}{10,000} \mu = \frac{1}{10^8} \text{ cm} = 10^{-8} \text{ cm}$

$(\text{ \AA})^2 = 10^{-16} \text{ cm}^2$

$R = 82.057 \frac{\text{atm. cc}}{\text{g mole } ^\circ\text{K}}$

Solution

1. By using the given value of p_s and Figure 1 calculate values of $x = p/p_s$ for specific values of volume adsorbed V . Enter these values in the table below.

p	x	$1-x$	V	$\frac{x}{V(1-x)}$
9	0.0074	0.9926	25	.000298
24	.0197	.9803	50	.0004
46	.0375	.9625	75	.00052
70	.0501	.9499	100	.00068
120	.0730	.9270	125	.00092

(answer is on next page)

2. Plot this data in the form of x vs $\frac{x}{V(1-x)}$ on Figure 2.

Obtain the intercept which is equal to $\frac{1}{V_m C}$ and the slope which is equal to $\frac{C-1}{V_m C}$.

$$\frac{1}{V_m C} = (\quad)$$

$$\frac{C-1}{V_m C} = (\quad)$$

(answer is on next page)

3. Solve these equations for V_m by substitution.

(work space is on next page)

Answer to (1)

p	x	1-x	V	$\frac{x}{V(1-x)}$
9	0.00740	0.9926	25	.000298
22	0.01809	0.9819	50	.000368
45	0.03700	0.9630	75	.000512
78	0.06414	0.9359	100	.000685
128	0.10526	0.8947	125	.000941

Answer to (2)

$$\frac{1}{V_m C} = 0.00027$$

$$\frac{C-1}{V_m C} = 0.0064$$

(answer to (3) is on next page)

Answer to (3)

$$\frac{1}{V_m C} = 0.00027 \text{ and } \frac{C-1}{V_m C} = 0.0064$$

$$\frac{C-1}{V_m C} / \frac{1}{V_m C} = C-1 = \frac{0.0064}{0.00027}$$

$$C-1 = 23.7$$

$$C = 24.7$$

Substitution into $\frac{1}{V_m C}$ gives:

$$V_m = \frac{1}{C \times 0.00027} = \frac{1}{24.7 \times 0.00027}$$

$$V_m = 150 \frac{\text{cc NH}_3}{\text{g carbon}}$$

4. Now we are ready to convert this volume of ammonia to an equivalent area which we must assume is the surface area of the carbon. The ammonia molecule has a molecular area of 13 \AA^2 (Angstrom Units)². We must visualize these molecules as covering the surface in a close packed monolayer. Calculating the surface area is as simple as counting the molecules of ammonia and multiplying by the area of each molecule.

First we will count the ammonia molecules. Use the ideal gas law to calculate the gram moles of NH_3 in the 150 cc (V_m). Then use Avogadro's number to calculate the total number of molecules. Avogadro's number, remember, is the number of molecules in a gram mole of a substance.

In the ideal gas law, $PV = nRT$, what values of P , T , and V must be used?

$$P = \underline{\hspace{2cm}}, T = \underline{\hspace{2cm}}, V = \underline{\hspace{2cm}}$$

(answer is on next page)

5. $n = \frac{PV}{RT}$

$$n \frac{\text{g moles NH}_3}{\text{g carbon}} = \frac{(\hspace{1cm}) \text{ atm } (\hspace{1cm}) \text{ cc/g carbon}}{82.06 \frac{\text{atm cc}}{\text{g moles } ^\circ\text{K}} (\hspace{1cm}) ^\circ\text{K}}$$

$$=$$

(answer is on next page)

6. Now we can "count" the molecules by using Avogadro's number.

$$\frac{\text{number molecules NH}_3}{\text{gram carbon}} = n \left(\frac{\text{g moles NH}_3}{\text{g carbon}} \right) \times \text{Avogadro's number} \left(\frac{\text{number molecules}}{\text{g mole}} \right)$$

$$\frac{\text{number molecules NH}_3}{\text{g carbon}} = (\hspace{2cm}) \times (\hspace{2cm})$$

(answer is on next page)

Answer to (4)

We must use those values that apply to the calculation of V_m .

$P = 1$ atm pressure

$T = -23.5^\circ\text{C}$ (249.5°K)

$V = V_m, \text{cc/g carbon}$

Answer to (5)

$$n = \frac{(1) \times (150)}{(82.06) \times (249.5)} = 7.3 \times 10^{-3} \frac{\text{g mole NH}_3}{\text{g carbon}}$$

Answer to (6)

$$\frac{\text{number molecules NH}_3}{\text{g carbon}} = 7.3 \times 10^{-3} \times 6.028 \times 10^{23}$$

$$\frac{\text{number molecules NH}_3}{\text{g carbon}} = 4.40 \times 10^{21}$$

7. The surface area of the carbon is easily calculated by adding the cross-sectional area of all the NH_3 molecules. The only complication of this simple operation is that the cross-sectional area of the molecules is in square Angstrom units but the area of the carbon is normally quoted in square centimeters.

Note: $1 (\text{\AA})^2 = 10^{-16} \text{ cm}^2$

Surface Area of carbon = number NH_3 molecules \times cross section area per NH_3 molecule

$$\text{Area carbon} = (\quad) \text{ molecules} \times (\quad) \frac{\text{cm}^2}{\text{molecule}}$$

=

(answer is on next page)

Answer to (7)

$$\text{Area carbon} = 4.40 \times 10^{21} \text{ molecules} \left(13 \times 10^{-16} \right) \frac{\text{cm}^2}{\text{molecule}} \text{NH}_3$$

$$\text{Area carbon} = 5.7 \times 10^6 \frac{\text{cm}^2}{\text{g carbon}}$$

FIGURE 1.

NH_3 Adsorption Isotherm on Carbon

Temperature = 23.5°C

Vol. NH_3 adsorbed per gram of carbon, cc @ STP

pressure (p), mm Hg

200

150

100

50

0

0

100

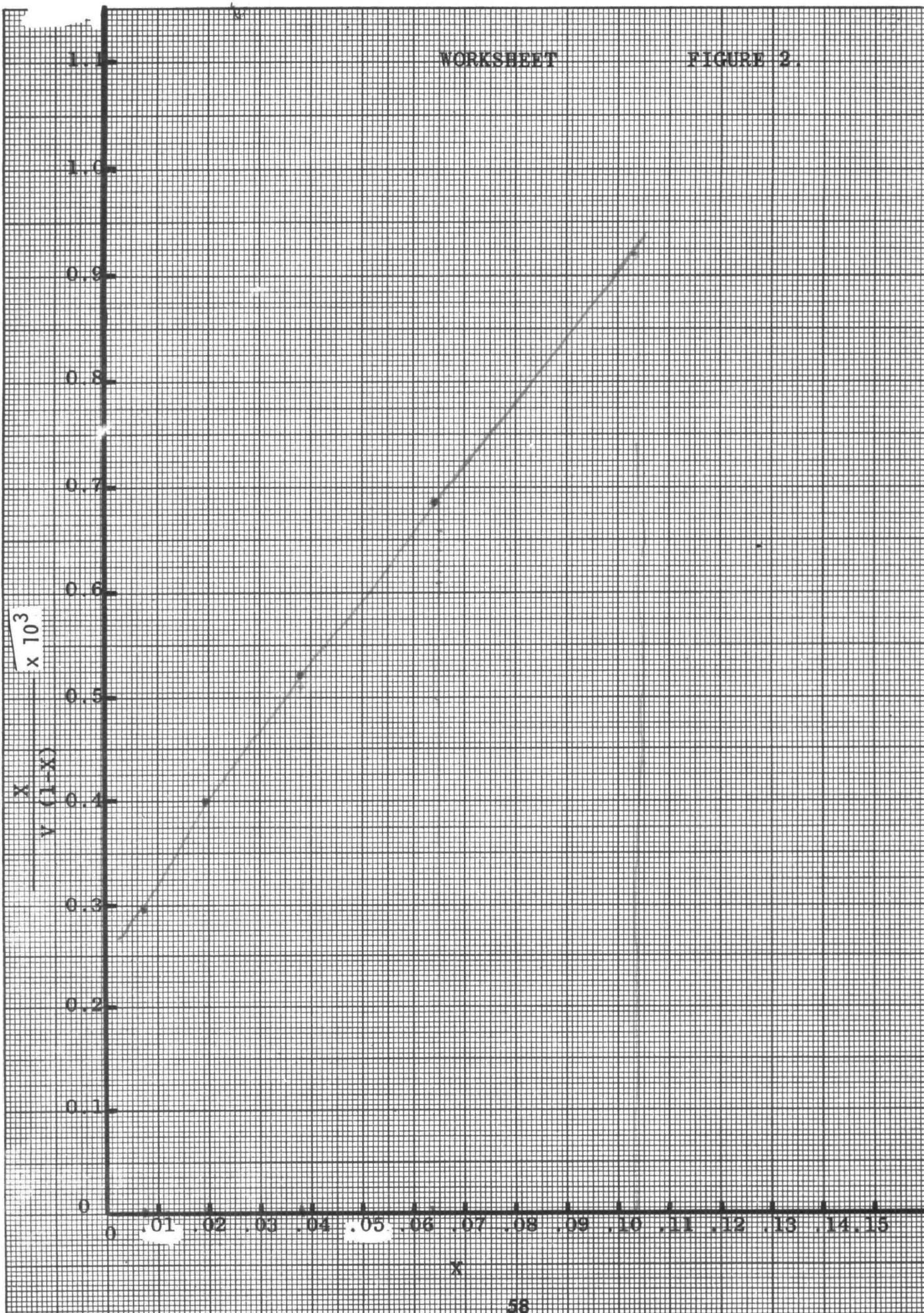
200

300

400

500

600



Adsorption Dynamics

The breakthrough capacities were obtained on a test board using 4 x 6 mesh pelleted carbon in bed depths of 4" and 9" removing benzene vapor at an inlet concentration of 2000 ppm by volume and 100 fpm superficial gas velocity.

$$D_1 = 4'' \text{ bed} \quad C_1 = 15.00 \text{ g benzene/100 g carbon}$$

$$D_2 = 9'' \text{ bed} \quad C_2 = 17.77 \text{ g benzene/100 g carbon}$$

1. Use the following equation to calculate the saturation capacity, C_s :

$$C_s = \frac{C_2 D_2 - C_1 D_1}{D_2 - D_1}$$

2. Substitute C_s into the following equation to find the MTZ length:

$$MTZ = \frac{1}{1-x} D_1 \left[1 - \frac{C_1}{C_s} \right]$$

The benzene adsorption breakthrough curve is symmetrical and "S" shaped, yielding at $x = 0.5$. This implies 50% saturation in the MTZ.

3. Calculate the temperature rise of the above described carbon bed using the following equation:

$$\Delta t = \frac{6.1}{(S_g/C) \times 10^5 + 0.51 (S_A/W)}$$

$$C = 2000 \text{ ppm}$$

$$S_g = 0.021 \text{ BTU/(ft}^3 \text{ } ^\circ\text{F)}$$

$$S_A = 0.25 \text{ BTU/(lb } ^\circ\text{F)}$$

Since W is not known correctly until the temperature of the bed is known, the result has to be obtained by successive approximations.

Δt is first calculated for t , where W is equal to C_s from the previous calculations. A new W for temperature $t + \Delta t$, is obtained from the adsorption isobar.

For the type of carbon used and benzene vapor, the adsorption isobar is such that a 10°C temperature rise results in a 10 percent loss of capacity. (Example: If W is 40% at 20°C it will be 36% at 30°C)

Answers to AD-III

$$1. \quad C_s = \frac{17.77 (9) - 15.00 (4)}{9-4} = 20.0 \frac{\text{g benzene}}{100 \text{ g carbon}}$$

$$2. \quad \text{MTZ} = \left[\frac{1}{1 - 0.5} \right]^2 \left(\frac{1-15}{20} \right) = 2.0 \text{ inches}$$

$$3. \quad \Delta t = \frac{6.1}{(0.021/2000) \times 10^5 + 0.51 (0.25/20)}$$

$$\Delta t = 5.8^\circ\text{F} = 3.2^\circ\text{C}$$

The resulting Δt should cause a negligible loss in capacity. No additional trials are necessary.

AD-IV

Adsorption System

A solvent recovery system was designed to recover benzene from an air stream having a concentration of 1316 ppm. This represents a vapor concentration of 1.0% Relative Saturation at 26°C which is the temperature of the carbon. The plant capacity has increased; the question now regards the need to enlarge the capacity of the adsorption unit by adding another adsorber, changing the type of carbon, or changing the adsorption cycle.

The new load on the system is estimated to be a 75% increase in benzene. The properties of carbons available are as follows:

Carbon properties	I	II
Apparent Density Lbs/ft ³	23	26
Particle Size U.S. Standard Sieve	4 x 6	4 x 6

Information on the existing system is given below:

Carbon used: Type II
Gas Velocity: 100 fpm (STP)
Air Volume: 12,000 CFM
Bed area: 120 ft²
Bed depth: 24 inches
Carbon charge per adsorber: 5832 lbs.
Working charge, wt. per cent: 31.0 lb. benzene/100 lb. carbon
Working charge, pounds of solvent: 1808 lbs.
Steam solvent ratio of 3:1
Bed pressure drop: 7.2 inches w.g.
Adsorbent temperature: 26°C
Residual charge of benzene: 2.2%
Standard Temperature and Pressure (STP): 0°C and 760 mm Hg

Determine:

1. Benzene vapor content at 1% Relative Saturation @ 26°C.
2. Benzene vapor content at the new concentration (75% increase).
3. Carbon capacities for carbons I and II at each benzene concentration.
4. The break through carbon loading at new condition.
5. The working charge at new condition.
6. Whether to alter the system.
7. What changes take place in the unit due to the new conditions.

SOLUTION

1. Calculate the benzene vapor content of the gas in lbs per cu. ft. at 1% Relative Saturation using the formula $W = \frac{MPV}{RT}$ (P:mm Hg, V: ft³, T: 539 °R, R: 555 $\frac{\text{mm Hg ft}^3}{\text{lb mole } ^\circ\text{R}}$).

At first we will calculate the benzene vapor content at 100% RS and then at 1% RS. Note that the vapor pressure of benzene at 26°C is 100 mm Hg, and that the molecular weight of benzene is 78.11.

$$\frac{W}{V} \text{ lb/ft}^3 = \frac{M \left(\frac{\text{lbs Benzene}}{\text{lb mole}} \right) \times P \text{ (mm Hg)}}{R \left(\frac{\text{mm Hg ft}^3}{\text{lb mole } ^\circ\text{R}} \right) \times T \text{ (} ^\circ\text{R)}}$$

$$\frac{W}{V} = \frac{(\quad) \frac{\text{lbs}}{\text{lb mole}} \times (\quad) \text{ mm Hg}}{(\quad) \frac{\text{mm Hg ft}^3}{\text{lb mole } ^\circ\text{R}} \times (\quad) ^\circ\text{R}}$$

$$\frac{W}{V} = (\quad) \text{ lbs/ft}^3 \text{ @ 100\% RS}$$

$$\frac{W}{V} = (\quad) \text{ lbs/ft}^3 \text{ @ 1\% RS} \quad \text{(answer is on next page)}$$

2. Next we want to adjust the data to correspond to 75% increase in pollutant concentration. This 75% increase will be a multiplying factor of _____.

(answer is on next page)

3. What will be the new benzene concentration after we multiply by this factor?

Benzene concentration at 1% RS x factor = Benzene conc. at new condition.

$$\underline{\hspace{2cm}} \times \underline{\hspace{2cm}} = \underline{\hspace{2cm}} \quad \text{(answer is on next page)}$$

4. Next you must obtain the carbon capacities from Figure 1 for each benzene concentration or % R S.

Answer to (1)

$$W/V = (78.11) (100) / (555) (539)$$

$$W/V = 0.0261 \text{ lbs/ft}^3 \text{ @ 100\% RS}$$

$$W/V = .000261 \text{ lb/ft}^3 \text{ @ 1\% RS}$$

Answer to (2)

Factor will be 1.75 or $100\% + 75\% = 175\%$

Answer to (3)

$$.000261 \frac{\text{lb}}{\text{ft}^3} \times 1.75 = .000457 \frac{\text{lb}}{\text{ft}^3}$$

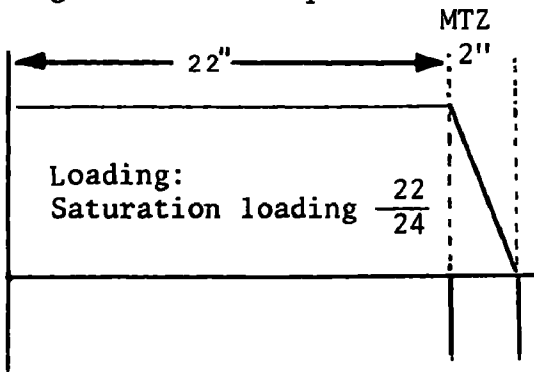
(# 4 cont.)

Concentration of Benzene	Carbon Type I	Capacities wt % Type II
1.0% RS	39.0	34.5
1.75% RS	—	—

(answer is on next page)

5. Now that we have the saturation capacity we can calculate the adsorber charge at breakthrough. To do this we will assume that the MTZ length is, as calculated previously, 2 inches, and that the average concentration in the MTZ is 1/2 Saturation charge.

This diagram should help.



$$\frac{\text{Loading MTZ: Saturation loading } (\frac{2}{24})}{2}$$

Answer to (4)		
	Carbon Capacity, wt %	
	Type I	Type II
1.0% RS	39.0	34.5
1.75% RS	41.5	36.0

(# 5 cont.)

The breakthrough charge is the sum of these two:

$$\underline{\hspace{2cm}} + \underline{\hspace{2cm}} = \underline{\hspace{2cm}} \text{ \% or lbs benzene}$$

100 lb carbon

(answer is on next page)

6. Now calculate the working charge. The working charge is the difference between the breakthrough charge and the "heel" or residual charge.

$$\text{Working charge} = \underline{\hspace{2cm}} - \underline{\hspace{2cm}} = \underline{\hspace{2cm}} \text{ \% or lbs Benzene}$$

100 lb carbon

(answer is on next page)

7. The question now is - do we need to alter the system to handle the additional load on the system ?

 yes

 no

(answer is on next page)

8. The next question concerns what changes do occur in the system. Check those factors which you think will change in the adsorber.

 Pressure drop

 Regeneration time

 Adsorption time

(answer is on next page)

Answer to (5)

$$36 \left(\frac{22}{24} \right) + 18 \left(\frac{2}{24} \right) = 34.5\% \text{ or } \frac{1 \text{ lb Benzene}}{100 \text{ lb carbon}}$$

Answer to (6)

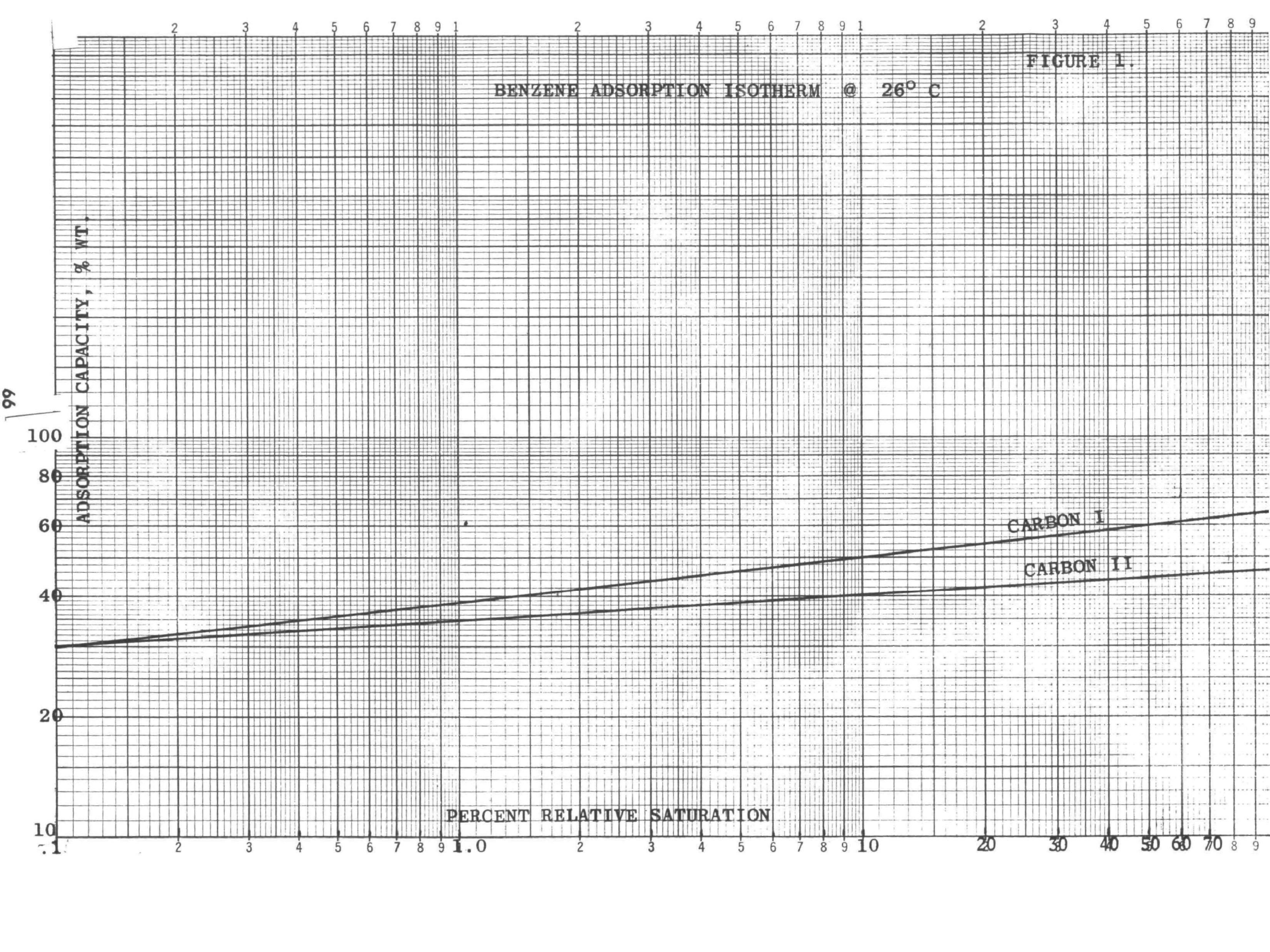
$$\text{Working charge} = 34.5 - 2.2 = 32.3\% \text{ or } \frac{1 \text{ lb Benzene}}{100 \text{ lb carbon}}$$

Answer to (7)

No, since the new working charge is still greater than the 31.0 percent as designed.

Answer to (8)

Adsorption time will be shortened and as a result the time between regeneration will shorten. The actual regeneration time may not be shortened however.



Design Problem

An electrolytic process generates 5000 CFM of high pressure (1500 psi) hydrogen with contaminants consisting of oil vapor and Mercury vapor.

Temp: 38°C

Hg inlet concentration: 7.5 ppm (Volume)

RH: 50%

Oil vapor concentration: 1 ppm (Volume)

Given Figures 1-4, select a carbon, size an adsorber for 6 months life using a 20% safety factor, and calculate the pressure drop across the bed.

Carbon Type	Density
G215 (10 x 20)	30 lbs/ft ³
G352 (10 x 20)	27 lbs/ft ³

Since regeneration of this carbon will be far more complicated than a steam regeneration we will not consider a multiple bed unit. Carbon replacement will be made at the breakthrough time.

Solution

1 First inspect the adsorption curves and select a carbon you feel is most suitable for the adsorption of mercury vapors.

a Consider the effects of aging on the capacity of the carbon. Calculate the percent reduction at breakthrough for each conditioning experiment.

b For carbon aged 20 days @ 65°C, 50% RH (Figure 2):

% Reduction =

c For carbon aged 30 days @ 30°C, 100% RH (Figure 2):

% Reduction =

(answer is on next page)

d The reduction expected would then be between 15% and 30%. A 20% reduction would be a good estimate. This will be in addition to the suggested safety factor of 20%, suggested in the statement of the problem.

e Notice that Figure 1 indicates the effect of added Iodine on mercury adsorption. Select the most suitable carbon from this figure, and from Figure 3.

Carbon _____ having _____ % I₂

(answer is on next page)

2 The next step is to size the adsorber using the carbon you selected. The problem requires a 20% safety factor to be used. This factor can be applied only to the carbon required, not to the gas flow rate since this would affect pressure drop calculations.

a If the adsorption bed is to last six months we must calculate the total pounds of mercury to be removed in that period.

(1.) The total gas volume to be treated is:

$$5000 \frac{\text{ft}^3}{\text{min}} \times 60 \frac{\text{min}}{\text{Hr}} \times 24 \frac{\text{Hr}}{\text{day}} \times \frac{183 \text{ days}}{6 \text{ mo.}} = (\quad) \frac{\text{ft}^3}{6 \text{ mo.}}$$

(answer is on next page)

(2.) The Hg concentration is 7.5 ppm (volume). Now calculate the volume of Hg vapor in the gas.

$$\text{Hg (vol)} = \frac{7.5}{10^6} \times (\quad) \frac{\text{ft}^3}{6 \text{ mo.}} = (\quad) \frac{\text{ft}^3 \text{ Hg}}{6 \text{ mo.}}$$

(answer is on next page)

Answer to (1- b&c)

$$1-b \quad \% \text{ Reduction} = \left(\frac{490 - 420}{490} \right) 100 = 14.3\%$$

$$1-c \quad \% \text{ Reduction} = \left(\frac{490 - 340}{490} \right) 100 = 30.6\%$$

Answer to (1-e)

You should have selected carbon G352 having 15% I_2 .

Answer to (2-a(1))

$$5000 \times 60 \times 24 \times 183 = 1.318 \times 10^9 \text{ ft}^3 / 6 \text{ mo.}$$

Answer to (2-a(2))

$$\frac{7.5}{10^6} \times (1.318 \times 10^9) = 9882 \frac{\text{ft}^3 \text{ Hg}}{6 \text{ mo.}}$$

3 From Figure 3, note that the breakthrough time for G352 with 15% I_2 is 800 minutes.

- a We can introduce the 20% factor for carbon conditioning at this point by reducing the breakthrough time by 20%. The breakthrough time becomes: () min. \times () = () min.

(answer is on next page)

- b Next calculate the treated volume of gas during this breakthrough period for the laboratory data on Figure 3 for carbon G352. Remember we have adjusted the breakthrough time for conditioning the carbon.

Flow rate (ml/min) \times breakthrough time (min) = gas volume treated (ml)

$$() \text{ ml/min} \times () \text{ min} = () \text{ ml}$$

(answer is on next page)

- c Now you can calculate the volume of mercury vapor captured on each gram of carbon.

$$\frac{(\text{ppm Hg in H}_2) \times (\text{Vol. H}_2)}{(10^6) \times (\text{grams carbon tested})} = () \frac{\text{ml Hg vapor}}{\text{g carbon}}$$

(answer is on next page)

Answer to (3-a)

800 min. breakthrough time.

$800 \times 0.80 = 640$ minutes for conditioned carbon.

This is 10 hours and 40 minutes.

Answer to (3-b)

$$64000 \text{ ml/min} \times 640 \text{ min.} = 4.1 \times 10^7 \text{ ml}$$

Answer to (3-c)

$$\frac{7.5 \text{ ppm} \times 4.1 \times 10^7 \text{ ml H}_2}{10^6 \times 42 \text{ gram carbon}} = 7.3 \frac{\text{ml Hg vapor}}{\text{g carbon}}$$

d Express the volume of Hg vapor to be adsorbed (refer 2-a-(2)) as ml.

$$(\quad) \text{ cu ft Hg} \times 28,316 \frac{\text{ml}}{\text{cu ft}} = (\quad) \text{ ml Hg vapor}$$

(answer is on next page)

4 Now calculate the grams of carbon required. To do this assume that the length of the MTZ (mass transfer zone) is insignificant. A rough estimate would place it at about 0.375 inches.

$$a \quad \frac{(\quad) \text{ ml Hg vapor}}{(\quad) \frac{\text{ml Hg}}{\text{g carbon}}} = (\quad) \text{ g carbon}$$

(answer is on next page)

b Calculate the pounds of carbon.

$$1 \text{ lb carbon} = \frac{(\quad) \text{ g carbon}}{454 \text{ g/lb}} = (\quad) \text{ lb carbon}$$

(answer is on next page)

5 With a flow rate of only 5000 CFM we can use a thick bed of carbon and still use little power for moving the gas. The bed depth selected is 10 feet.

Answer to (3-d)

$$9882 \times 28,316 = 280 \times 10^6 \text{ ml Hg vapor}$$

Answer to (4-a)

$$\frac{(280 \times 10^6 \text{ ml Hg})}{(7.3) \frac{\text{ml Hg}}{\text{g carbon}}} = (38.2 \times 10^6) \text{ g carbon}$$

Answer to (4-b)

$$\frac{38.2 \times 10^6}{454} = 8.42 \times 10^4 \text{ lbs carbon}$$

a Calculate the volume of the carbon in the system.

$$(\text{Vol.}) \text{ ft}^3 = \left(\frac{\quad}{\quad} \right) \frac{\text{lb carbon}}{\text{lb/ft}^3} = (\quad) \text{ ft}^3$$

(answer is on next page)

b Now calculate the area of the carbon bed for a 10 ft bed depth. Introduce the 20% safety factor here on the volume of carbon in the adsorber.

$$(\text{Area}) \text{ ft}^2 = \frac{1.2 (\quad) \text{ ft}^3}{(\quad) \text{ ft depth}} = (\quad) \text{ ft}^2$$

(answer is on next page)

6 The superficial gas velocity is needed to determine the pressure drop across the adsorption bed.

$$^a (\text{gas velocity}) \text{ ft/min} = \left(\frac{\quad}{\quad} \right) \frac{\text{CFM}}{\text{ft}^2} = (\quad) \text{ ft/min.}$$

(answer is on next page)

b Now determine the pressure drop for 10 x 20 mesh carbon from Figure 4.

$$\Delta P = (\quad) \text{ in H}_2\text{O/inch carbon}$$

For the carbon bed, the pressure drop is:

$$\Delta P_{\text{Bed}} = (\quad) \frac{\text{in H}_2\text{O}}{\text{in carbon}} \times (\quad) \text{ in carbon}$$

$$\Delta P_{\text{Bed}} = (\quad) \text{ in H}_2\text{O} \quad (\text{answer is on next page})$$

Answer to (5-a)

$$\frac{8.42 \times 10^4 \text{ lb carbon}}{27 \text{ lb/ft}^3} = 3.12 \times 10^3 \text{ ft}^3$$

Answer to (5-b)

$$\frac{(1.2) (3120) \text{ ft}^3}{10 \text{ ft}} = 375 \text{ ft}^2$$

Answer to (6-a)

$$\frac{5000 \text{ CFM}}{375 \text{ ft}^2} = 13.3 \text{ ft/min.}$$

Answer to (6-b)

$$\Delta P_{\text{Bed}} = (0.275) \frac{\text{in H}_2\text{O}}{\text{in carbon}} \times 120 \text{ in carbon} = 33.0 \text{ in H}_2\text{O}$$

FIGURE I

CARBON BED

2.75 INCHES ID

0.75 INCHES DEEP

85 mls CARBON

40 grams

TEMP. 38°C

Hg CONC. 7.5 PPM (vol)

RH 50%

FLOW RATE 64,000 ml/min

RESIDENCE TIME 0.08 SEC

MERCURY VAPOR OUTLET CONCENTRATION, PPM

0.30

0.25

0.20

0.15

0.10

0.05

0.0

I, INSTANTANEOUS
BREAKTHROUGH
G 215

II, G215
+ 5% I₂

III, G 215
+ 10% I₂

IV, G 215
+ 15% I₂

100

300

500

700

800

BREAKTHROUGH TIME, MINUTES

FIGURE 2

CARBON BED

2.75 INCHES ID TEMP. 38°C
0.75 INCHES DEEP Hg INLET CONC. 7.5 PPM (vol)
85 ml CARBON RH 50%
40 g FLOW RATE 64,000 ml/min
 RESIDENCE TIME 0.08 SEC

CARBON G215 + 15% I₂

I UNAGED

II AGED 20 days @ 65°C
50% RHIII AGED 30 days @ 30°C
100% RH

MERCURY VAPOR OUTLET CONCENTRATION, PPM

0.30

0.25

0.20

0.15

0.10

0.05

0

200

300

400

500

BREAKTHROUGH TIME, MINUTES

700

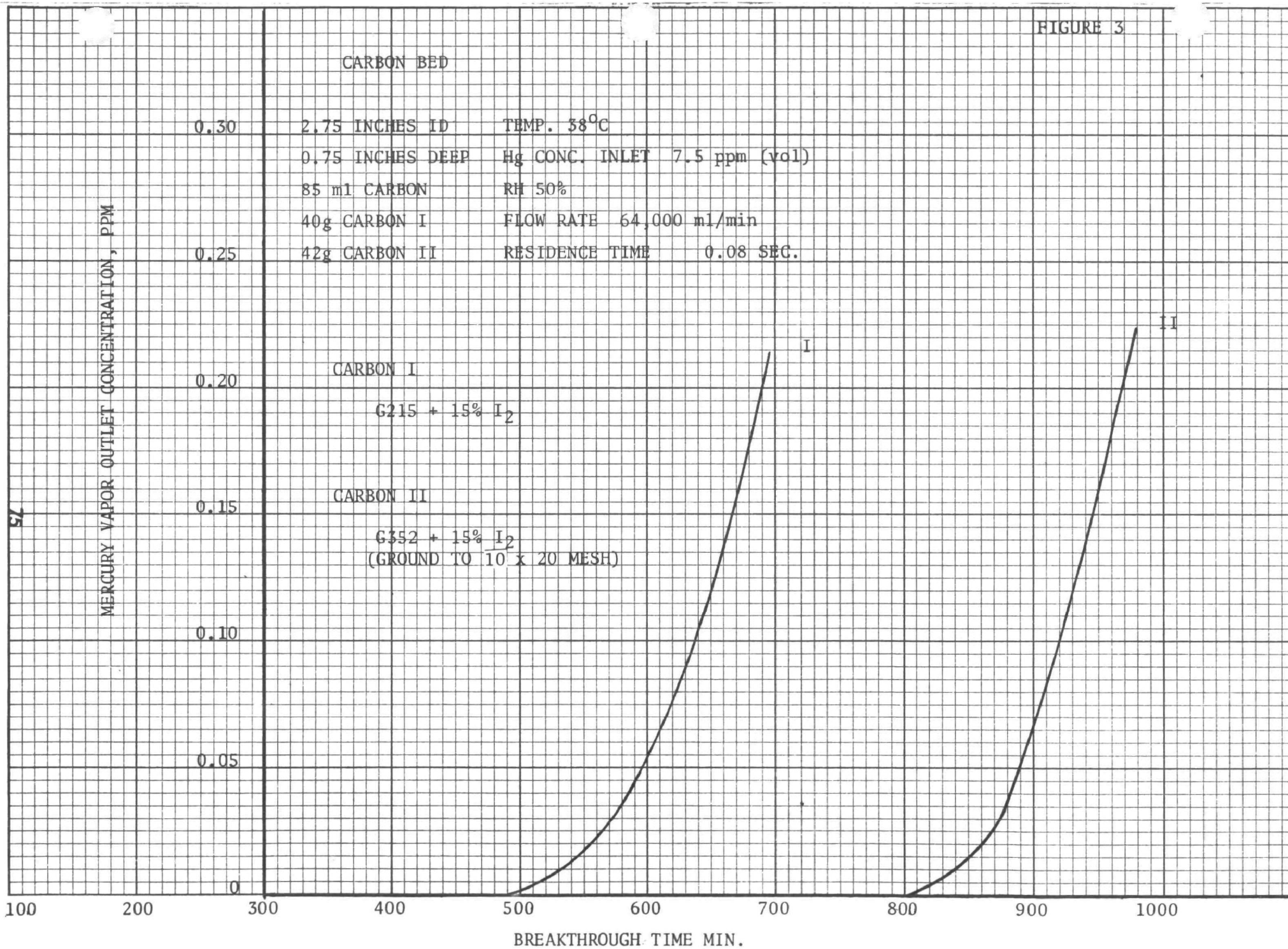
800

III

II

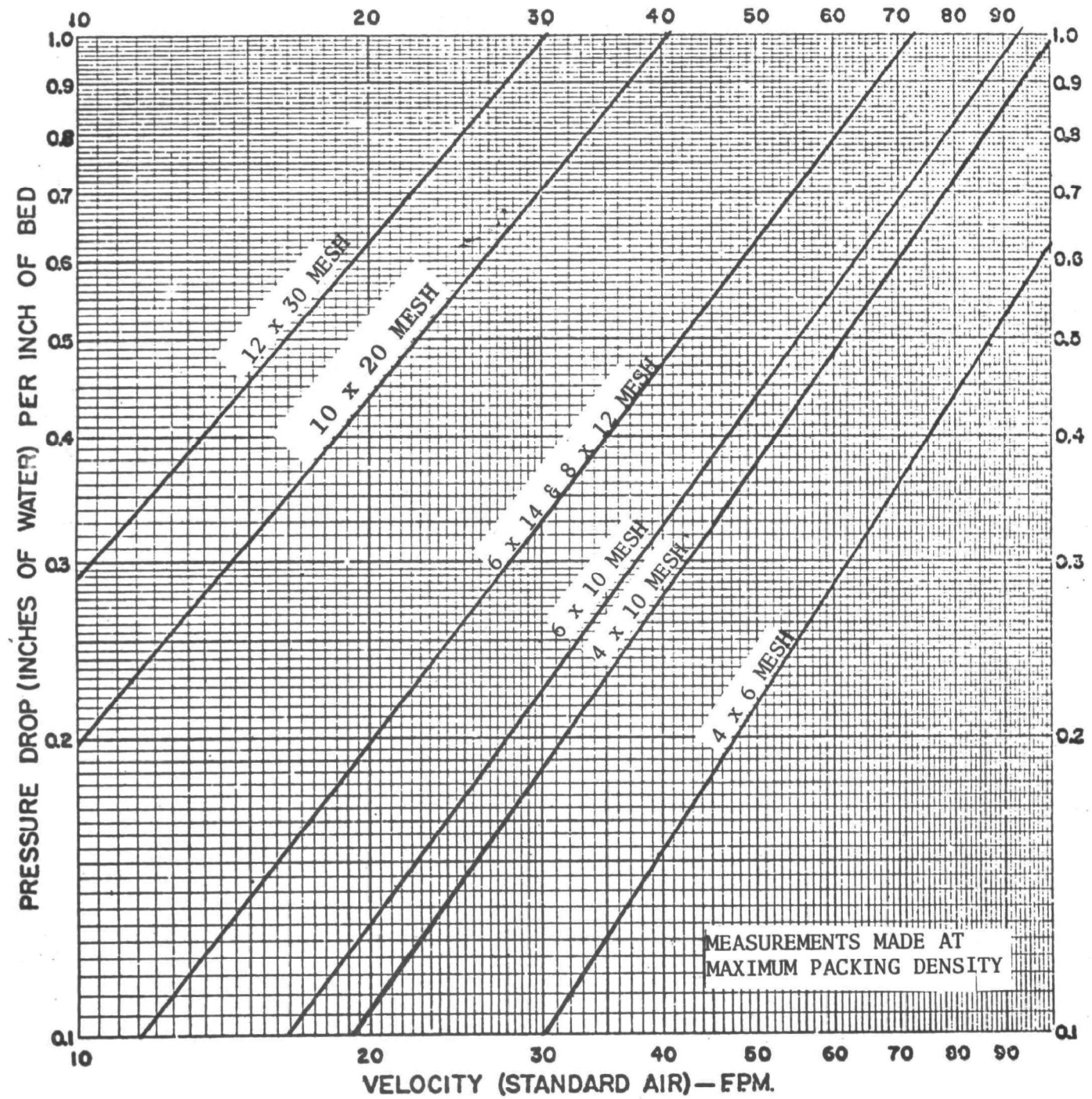
I

FIGURE 3



ACTIVATED CARBON
PRESSURE DROP CURVES

FIGURE 1



Design Problem

The exhaust from a coating operation amounts to 12,000 CFM of gas containing:

7 lbs/hour of 2-nitro propane
 22 lbs/hour of MEK, methyl ethyl ketone
 90 lbs/hour of MIBK, methyl isobutyl ketone

The temperature will vary between 70°F and 95°F, averaging 82.5°F (28°C). The pressure is atmospheric. The blower is capable of developing 10 inch w.g. There is no visible evidence of solvent droplets or particulate carry over.

	V.P., mm Hg	Mol. WT.	B.P., °C
2-NP	20.0	89.09	120.3
MEK	115.0	72.10	76.6
MIBK	9.0	100.16	118.0

Solution

- Using the ideal gas law, determine the saturation concentration for each component at 28°C.

Saturation concentration:

$$\frac{W}{V} = \frac{\text{lbs solvent}}{\text{cu ft}} = \frac{MP}{RT}$$

W = weight solvent in gas, lb.

V = volume, ft³

M = molecular weight of solvent, lb./lb mole

T = absolute temperature, °R

P = vapor pressure of solvent component, mm Hg

R = 555 (mm Hg ft³)/(lb moles °R)

$$\text{for 2-NP} \quad \frac{W}{V} = \frac{(\quad) \times (\quad)}{555 \times 543} = (\quad) \frac{\text{lbs}}{\text{ft}^3}$$

$$\text{for MEK} \quad \frac{W}{V} = \frac{(\quad) \times (\quad)}{555 \times 543} = (\quad) \frac{\text{lbs}}{\text{ft}^3}$$

$$\text{for MIBK} \quad \frac{W}{V} = \frac{(\quad) \times (\quad)}{555 \times 543} = (\quad) \frac{\text{lbs}}{\text{ft}^3}$$

(answer is on next page)

Answer to (1)

$$2\text{-NP} \quad \frac{W_i}{V} = \frac{89.09 \times 20.0}{555 \times 543} = 5.91 \times 10^{-3} \text{ lb/ft}^3$$

$$\text{MEK} \quad \frac{W}{V} = \frac{72.1 \times 115}{555 \times 543} = 2.75 \times 10^{-2} \text{ lb/ft}^3$$

$$\text{MIBK} \quad \frac{W_i}{V} = \frac{100.2 \times 9.0}{555 \times 543} = 2.99 \times 10^{-3} \text{ lb/ft}^3$$

2. The next step is to determine the actual concentration of each solvent from the stated solvent flow rates.

For example, 2-NP is emitted at 7 lbs/hour:

$$\frac{7 \text{ lbs 2-NP/hr.}}{12,000 \text{ CFM} \times 60 \text{ Min/hour}} = (9.72 \times 10^{-6}) \text{ lb/ft}^3$$

Now calculate the values for MEK and MIBK.

$$\left(\frac{\quad}{\quad} \right) \text{ lbs MEK/hr.} \div \left(\frac{\quad}{\quad} \right) \text{ CFM} \left(\frac{\quad}{\quad} \right) \text{ min/hour} = (\quad) \text{ lb/ft}^3$$

$$\left(\frac{\quad}{\quad} \right) \text{ lbs MIBK/hr.} \div \left(\frac{\quad}{\quad} \right) \text{ CFM} \left(\frac{\quad}{\quad} \right) \text{ min/hour} = (\quad) \text{ lb/ft}^3$$

(answer is on next page)

3. Now you can calculate the percent relative saturation, %RS, of each solvent component.

$$\%RS, (2\text{-NP}) = \frac{\text{actual concentration}}{\text{saturation concentration}} \times 100$$

$$= \frac{(\quad)}{(\quad)} \times 100 =$$

$$\%RS, (\text{MEK}) = \frac{(\quad)}{(\quad)} \times 100 =$$

$$\%RS, (\text{MIBK}) = \frac{(\quad)}{(\quad)} \times 100 =$$

(answer is on next page)

4. At these concentrations 3 carbons show the following equilibrium (isothermal) capacities at 28°C. These capacities are given in wt. % units.

	Carbon I	II	III
2-NP	45	42	40
MEK	27.0	27.0	32
MIBK	35.0	37.0	33
Surface Area	1600 m ² /g	1400 m ² /g	1200 m ² /g
Bulk density	23 lbs/cu.ft.	26 lbs/cu.ft.	29 lbs/cu.ft.

Answer to (2)

$$\text{MEK} \quad \frac{22}{12,000 \times 60} = (3.05 \times 10^{-5}) \text{ lb/ft}^3$$

$$\text{MIBK} \quad \frac{90}{12,000 \times 60} = (1.25 \times 10^{-4}) \text{ lb/ft}^3$$

Answer to (3)

$$\% \text{RS (2-NP)} = \frac{9.72 \times 10^{-6}}{5.91 \times 10^{-3}} \times 100 = 0.164\%$$

$$\% \text{RS (MEK)} = \frac{3.05 \times 10^{-5}}{2.75 \times 10^{-2}} \times 100 = 0.111\%$$

$$\% \text{RS (MIBK)} = \frac{1.25 \times 10^{-4}}{2.99 \times 10^{-3}} \times 100 = 4.17\%$$

Look at the capacities each carbon has for the solvents and select a carbon.
Check your selection:

_____ Carbon I
_____ Carbon II
_____ Carbon III

Give your reason here:

(answer is on next page)

5. Laboratory tests run on the solvent mixture supplied the following information for Type II carbon:

At a gas velocity of 100 FPM, a working capacity of 11.0% is obtained using a 3:1 steam-solvent ratio.

At a gas velocity of 80 FPM, a working capacity of 14.0% is obtained using a 4:1 steam-solvent ratio.

Does increasing the steam: solvent ratio increase or decrease the cycle time available for adsorption? Why?

_____ Increase

_____ Decrease

(answer is on next page)

Answer to (4)

Carbon II should be selected since it has the highest capacity for the component present in the highest concentration which is MIBK. Breakthrough would occur first with this component.

Answer to (5)

Increases. The higher steam to solvent ratio reduces the "heel" or residual solvent on the carbon. This increases the working charge which increases the time of the adsorption step for the cycle. The additional steam required also increases the time of the regeneration step.

6. The remainder of the problem is to size the adsorbers required to remove:
- ~~460~~ a. 640 lbs solvent mixture
b. 1020 lbs solvent mixture
- per regeneration using the 100 FPM value for (a.) and the 80 FPM value for (b.).

7. Determine the adsorbent volume for a gas velocity of 100 FPM.

a The working capacity is _____% (see part 5).

(answer is on next page)

b Calculate the pounds of carbon required.

$$0.11 \frac{\text{lbs solvent}}{\text{lb carbon}} = \frac{460}{x} \frac{640 \text{ lbs solvent}}{\text{lbs carbon}}$$

x = () lbs carbon

(answer is on next page)

c What is the pressure drop per inch of 4 x 6 mesh carbon (see Figure 1)?

$$\Delta p = () \frac{\text{in H}_2\text{O}}{\text{in carbon}}$$

(answer is on next page)

d Calculate the bed depth for the previously specified 10 in H₂O pressure drop.

$$\text{Bed depth} = \frac{\Delta P_{\text{Bed}} \text{ in H}_2\text{O}}{\Delta P \text{ in H}_2\text{O/in carbon}} = () = () \text{ in carbon}$$

(answer is on next page)

e Calculate the cross-sectional area of the adsorber and the diameter for 100 FPM and 640# solvent adsorbed.

Answer to (7-a)

Working capacity is 11% for 100 FPM.

Answer to (7-b)

$$x = \frac{640}{0.11} = 5810 \text{ lbs carbon}$$

Answer to (7-c)

$$\Delta p = 0.62 \frac{\text{in H}_2\text{O}}{\text{in carbon}} @ 100 \text{ FPM } 4 \times 6 \text{ mesh}$$

Answer to (7-d)

$$\text{Bed depth} = \frac{10}{0.62} = 16 \text{ inches carbon}$$

$$\text{Area} = \frac{\text{volume}}{\text{depth}} = \frac{\text{lbs carbon/bulk density carbon}}{\text{depth of carbon}}$$

$$\text{Area} = \frac{(\quad / \quad)}{(\quad)} = (\quad) \text{ ft}^2$$

(answer is on next page)

f Now calculate the diameter of a cylindrical adsorber having this area.

$$\text{Diameter} = \sqrt{\frac{\text{Area} \times 4}{\pi}} = \sqrt{\frac{167 \times 4}{\pi}}$$

$$\text{Diameter} = \sqrt{\quad} = (\quad) \text{ ft}$$

(answer is on next page)

8. Determine the same values for 80 FPM and 1020 lb solvent adsorbed. This time go through all the calculations, then check the answers on page 83.

a The working capacity is _____ %.

b lbs of carbon required:

$$(\quad) \frac{\text{lbs solvent}}{\text{lb carbon}} = \frac{(\quad) \text{ lbs solvent}}{x \text{ lbs carbon}}$$

$$x = (\quad) \text{ lbs carbon}$$

c Pressure drop per inch of 4 x 6 mesh carbon:

$$\Delta p = (\quad) \frac{\text{in H}_2\text{O}}{\text{in carbon}}$$

$$\text{d Bed depth} = \frac{(\quad) \text{ in H}_2\text{O across bed}}{(\quad) \text{ in H}_2\text{O/in carbon}} = (\quad) \text{ in carbon}$$

Answer to (7-e)

$$\text{Area} = \frac{5810 \text{ lbs carbon}/26 \text{ lbs/ft}^3}{(16/12) \text{ ft carbon}} = 167 \text{ ft}^2$$

Answer to (7-f)

$$\text{Diameter} = \sqrt{212.5} = 14.58 \text{ ft}$$

e Cross-sectional area of adsorber:

$$\text{Area} = \frac{(\quad) \text{ lbs carbon in bed}/(\quad) \text{ carbon bulk density}}{(\quad) \text{ carbon bed depth}}$$

$$\text{Area} = (\quad) \text{ ft}^2$$

(answer is on next page)

f Diameter of cylindrical adsorber:

$$\text{Diameter} = \sqrt{\frac{\text{Area} \times 4}{\pi}} = \sqrt{\frac{(\quad) 4}{\pi}}$$

$$\text{Diameter} = (\quad) \text{ ft}$$

(answer is on next page)

Answer to part (8)

a Working capacity is 14% for 80 FPM.

b lb carbon required:

$$0.14 = \frac{1020}{x}; x = 7290 \text{ lbs carbon}$$

c Δp per inch of 4 x 6 mesh carbon @ 80 FPM:

$$\Delta p = 0.44 \text{ in H}_2\text{O/inch carbon}$$

d Bed depth = $\frac{10 \text{ in H}_2\text{O}}{0.44 \text{ in H}_2\text{O/in carbon}} = 22.7 \text{ in carbon}$

e Cross-sectional area:

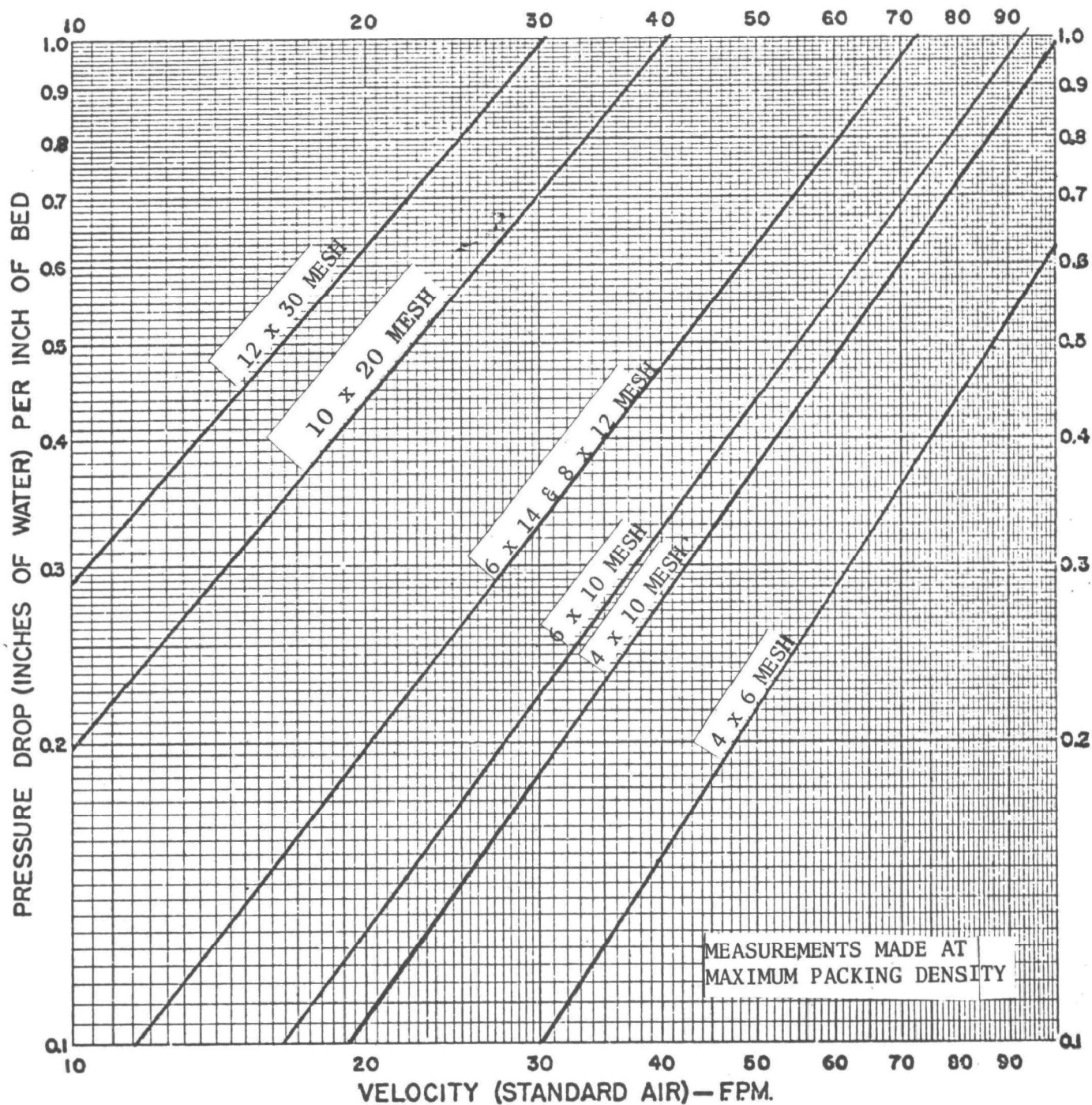
$$\text{Area} = \frac{(7290/26)}{(22.7/12)} = 148 \text{ ft}^2$$

f Diameter of cylindrical adsorber:

$$\text{Diameter} = \sqrt{\frac{148 \times 4}{\pi}} = \sqrt{189} = 13.7 \text{ ft}$$

ACTIVATED CARBON PRESSURE DROP CURVES

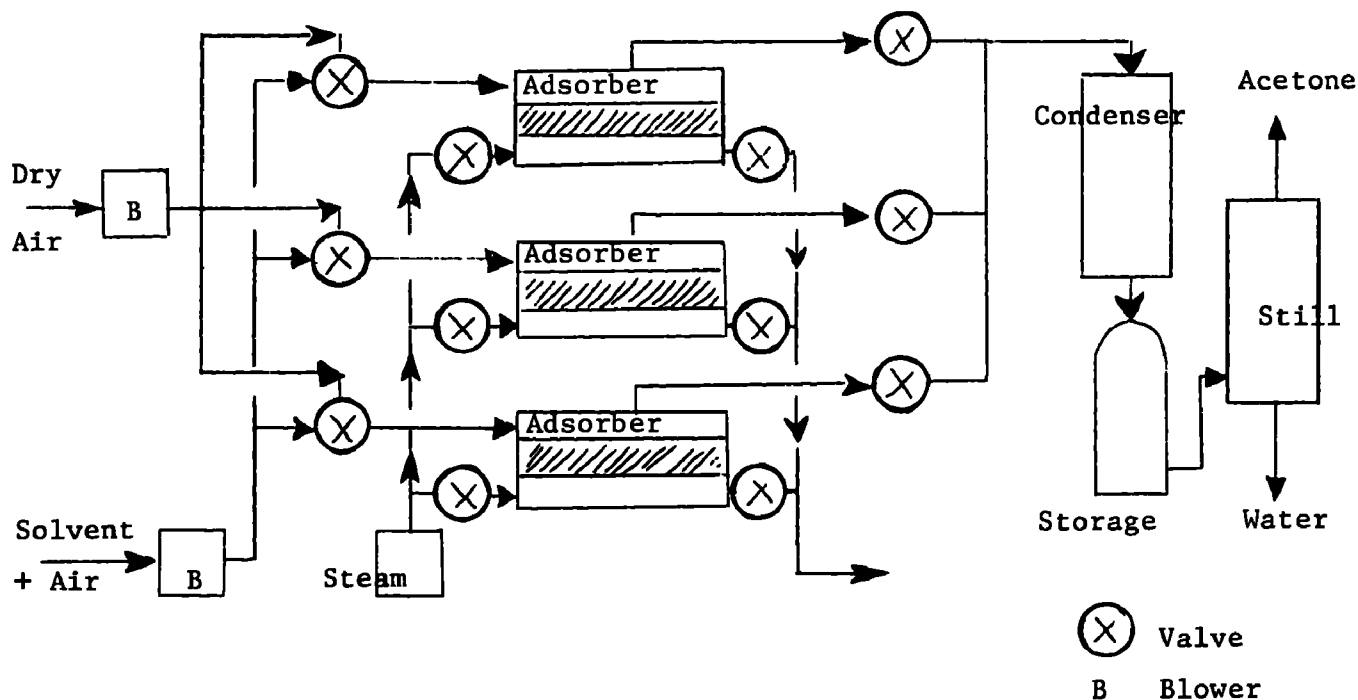
FIGURE 1



Plan Review of an Adsorption System

This solvent recovery plant must recover acetone from an air stream having a volume flow of 30,000 CFM, containing 0.15% (volume) acetone. This solvent recovery plant operates 24 hours per day, 365 days per year. The permit to construct this unit has been applied for and you are asked to review the plans for the adsorption system.

The diagram for this unit is presented here. Note that the solvent separation is done by a distillation process which will be reviewed separately.



The available information is summarized:

1. Air flow: 30,000 CFM @ 1 ATM
2. Air temperature: 20°C (293°K or 527°R)
3. Concentration of acetone in air: 0.15% (volume)
4. Operation: 24 hours per day, 365 days per year
5. Carbon charge per adsorber: 15,000 lbs. Carbon "B", (4 X 6 mesh)
6. Adsorber diameter: 18 feet (254.1 ft²)
7. Adsorption bed depth: 1.96 feet
8. Vapor pressure acetone @ 20°C: 170 mm Hg
9. Blower: centrifugal straight blade
60 inch wheel diameter
180 HP motor, 1600 RPM
10. Plant steam available, minimum, 5,000 lbs (5 PSIG) per hour
11. Two of the three adsorbers are in the adsorption phase at all times.

In reviewing these plans you will check:

1. The time to run each adsorber to breakthrough.

2. The lbs. of steam required to regenerate the carbon.
3. The size of the blower.

1. The first step is to check the adsorption time per adsorber.

- a First we must calculate the saturation loading of the carbon bed and the fraction of the carbon saturated.
- b The relative saturation of acetone in the air stream is expressed as follows:

$$RS = \frac{\text{partial pressure acetone in air}}{\text{saturation partial pressure of acetone @ } 20^{\circ}\text{C}}$$

This is usually expressed as the percent relative saturation by multiplying RS by a factor of 100.

$$\% RS = \left(\frac{760 \times .0015}{170} \right) \times 100 = 0.67 \%$$

- c Determine the saturation capacity of carbon B for acetone at the calculated % RS from Figure 3.

Saturation capacity = ()% wt (answer is on next page)

This is an ideal capacity, but in reality we can adsorb only 75-85% of the saturation capacity at break through because the mass transfer zone (MTZ) is less than saturated.

- d Now we must know the length of the MTZ. Why?

In order to calculate adsorber length?

(answer is on next page)

In order to calculate adsorber run time?

In order to calculate the break through solvent loading?

e The length of the MTZ is supplied by the carbon manufacturer based upon laboratory data (see Figure 5). The MTZ length is a function of gas velocity, time, adsorbate concentration, temperature of gas and carbon, system pressure, and type and size of the carbon. In this case the length of the MTZ is 2 inches.

f Now we can calculate the breakthrough capacity as follows:
Breakthrough capacity =

$$[(\text{Ave. loading in MTZ}) \times (\text{MTZ length})] + [(\text{Saturation loading}) \times (\text{bed length} - \text{MTZ length})]$$

bed length

$$\text{Breakthrough capacity} = \frac{\left[\left(\frac{.23}{2} \right) () \right] + \left[(0.23) (1.96 -) \right]}{()}$$

$$\text{Breakthrough capacity} = \frac{\left[(0.115) () \right] + \left[() () \right]}{()}$$

$$\text{Breakthrough capacity} = \frac{() + ()}{()} = () \frac{\text{lbs Acetone}}{\text{lb carbon}}$$

(answer is on next page)

Answer to (c)

Saturation capacity = 23% wt

Answer to (d)

In order to calculate the carbon breakthrough loading. The adsorber length is fixed, and the run time depends upon the solvent loading on the carbon.

g Next we calculate the working capacity of the carbon. The working capacity of the carbon is lower than the saturation capacity or the breakthrough capacity and results from unrecoverable solvent in the carbon and from a lower packing density than laboratory specifications. Based upon previous experience, the unrecoverable solvent or (heel) is 2% wt, and the lower capacity due to lower packing density is estimated to be 3% wt.

The working capacity is then calculated as follows:

$$\% \text{ W. C.} = (\text{Break capacity}) \% - (\text{heel}) \% - 3\%$$

$$\% \text{ W. C.} = 22\% - 2.0\% - 3.0\% = () \% \quad (\text{answer is on next page})$$

h Calculate the mass flow rate of the acetone.

$$30,000 \text{ CFM air} \times \frac{15 \text{ cu ft acetone}}{10,000 \text{ cu ft air}} = () \frac{\text{cu ft acetone}}{\text{min}}$$

The ideal gas law is used to calculate the mass flow rate.

$$W = \frac{(P)(V)(MW)}{(R)(T)} = \frac{() \text{ ATM} \times () \text{ cu ft/min} \times () \text{ lb/mole}}{() \frac{\text{ATM cu ft}}{\text{lb mole } ^\circ\text{R}} \times () ^\circ\text{R}}$$

$$W = () \text{ lb/min}$$

(answer is on next page)

Answer to (f)

$$\text{Breakthrough capacity} = \frac{\left[\frac{(.23)(0.166)}{2} \right] + [(0.23)(1.96 - 0.166)]}{(1.96)}$$

$$\text{Breakthrough capacity} = \frac{[(0.115)(0.166)] + [(0.23)(1.794)]}{(1.96)}$$

$$\text{Breakthrough capacity} = \frac{(0.0190) + (0.413)}{(1.96)} = 0.2204 \quad \text{Or } 22\%$$

Answer to (g)

$$\% \text{ W. C.} = 17\%$$

Answer to (h)

$$30000 \text{ CFM air} \times \frac{15 \text{ cu ft acetone}}{10000 \text{ cu ft air}} = (45) \frac{\text{cu ft acetone}}{\text{min}}$$

$$W = \frac{(1)(45)(58)}{(0.73)(527)} = (6.77) \text{ lb acetone/min}$$

i Now we calculate the adsorption time per adsorption bed.

NOTE: 2 adsorbers on stream, each cleaning 1/2 the total gas volume

$$\frac{15,000 \text{ lb carbon}}{\text{adsorber}} \times () \frac{\text{lb acetone}}{\text{lb carbon}} \times () \frac{\text{min}}{\text{lb acetone}} = () \text{ minutes}$$

(answer is on next page)

j For regeneration of each adsorption bed we will have how much time to complete the regeneration cycle?

() hours (answer is on next page)

The time for regeneration should be less than 1/2 the time for breakthrough.

Answer to (i)

$15,000 \times 0.17 \times 2/6.77 = 753$ minutes
This is 12.55 hours or 12 hrs 33 min.

Note: Each adsorber carries
1/2 the flow.

Answer to (j)

If your answer is 6.275 hours or 6 hours 16 minutes you are correct.

k The steam should be supplied during the first 3 hours of the regeneration cycle. Why not supply the steam for the full 6 hours and 16 minutes? What else must be done before returning the adsorption bed to the adsorb cycle?

(answer is on next page)

2. Now calculate the total pounds of steam required to regenerate the carbon bed using Figure 4.

- a Since the percent working charge is about 17% we can refer to Figure 4 and obtain the steam requirement for carbon B.

$$\frac{\text{lb steam required}}{\text{lb solvent removed}} =$$

(answer is on next page)

- b Now we can calculate the lbs of steam required.

$$\text{lb steam} = \frac{2.4 \text{ lb steam}}{\text{lb solvent}} \times \frac{.17 \text{ lb acetone}}{\text{lb carbon}} \times (\quad) \text{ lb carbon}$$

$$= (\quad) \text{ lbs steam} \quad (\text{answer is on next page})$$

- c If we wish to reduce the required lbs of steam we would change the amount of "heel" on the carbon. By deciding to operate with a lower working charge we increase the percent "heel" and require less steam.

Answer to (k)

Before returning the adsorber to the adsorb cycle we must:

1. remove moisture from the carbon
2. reduce the temperature of the carbon

Both are accomplished by blowing air through the hot, moisture-laden carbon bed.

Answer to (a)

If you answered 2.4 you are correct. If not, look again at Figure 4.

Answer to (b)

$$\text{lb steam} = \frac{2.4 \text{ lb steam}}{\text{lb solvent}} \times \frac{.17 \text{ lb Acetone}}{\text{lb carbon}} \times 15,000 \text{ lb carbon} = 6120 \text{ lb steam}$$

d How would this increase of the percent _____ increase
"heel" affect the adsorption time? _____

_____ decrease

e How would this affect the regeneration time (assuming a constant steam supply rate)?

_____ increase

_____ decrease (answer is on next page)

f The regeneration time depends upon the steam supply rate to heat the carbon plus the time to cool the carbon to the operating temperature. This is not usually a critical factor. Four hours is usually ample time to regenerate the largest adsorber bed, but we may allow a longer time depending upon available steam and breakthrough time.

3. The last step is to check the pressure drop across the adsorber bed to determine blower capacity.

a Calculate the superficial velocity through the adsorber bed.

$$N_s \text{ (fpm)} = \text{volume flow (CFM)} \div \text{adsorber area (ft}^2\text{)}$$

$$= (\quad) \text{ CFM} \div (\quad) \text{ ft}^2$$

$$= (\quad) \text{ fpm}$$

(answer is on next page)

b Use Figure 1 to determine the pressure drop per inch of bed depth. Then calculate the pressure drop across the bed.

Answer to (d) & (e)

If you answered "decrease" in both cases you are correct. What we have done is to decrease the effective size of the system.

Answer to (a)

$$N_s \text{ (fpm)} = 15,000 \text{ cfm} \div 254.1 \text{ ft}^2 = 59 \text{ fpm}$$

$$\begin{aligned} (\quad) \text{ (in H}_2\text{O/in of bed)} \times 12 \text{ (in/ft)} \times (\quad) \text{ (ft/bed)} &= \\ &= (\quad) \text{ (in H}_2\text{O/bed)} \quad \text{(answer is on page 94)} \end{aligned}$$

c The next logical step is to check the fan or blower size based upon the calculated pressure drop. This is easily checked using the fan multi rating table (Figure 2) and the "fan laws".

- (1.) We will use information for the 15,120 cfm fan.
Summarizing the fan conditions from the multirating table:

$$\begin{aligned} V_{t1} &= 15,120 \text{ cfm} \\ D_1 &= 46 \text{ in.} \\ N_1 &= 1622 \text{ rpm} \\ P_1 &= 45.9 \text{ bhp} \\ h_{r1} &= 7.0 \text{ in. H}_2\text{O} \end{aligned}$$

- (2.) The fan laws are as follows:

$$(a.) V_t = k D^3 N \quad \text{or}$$

$$V_{t2} = V_{t1} \left[\frac{D_2}{D_1} \right]^3 \left[\frac{N_2}{N_1} \right]$$

$$(b.) h_r = k D^2 N^2 \rho \quad \text{or}$$

$$h_{r2} = h_{r1} \left[\frac{D_2}{D_1} \right]^2 \times \left[\frac{N_2}{N_1} \right]^2$$

$$(c.) P = k D^5 N^3 \rho \quad \text{or}$$

$$P_2 = P_1 \left[\frac{D_2}{D_1} \right]^5 \left[\frac{N_2}{N_1} \right]^3$$

(3.) Summarizing the specifications for the proposed fan.

$$D_2 = 60 \text{ in.}$$

$$N_2 = 1600 \text{ rpm}$$

$$V_{t2} \text{ must be } \geq 30,000 \text{ cfm}$$

$$h_{r2} \text{ must be } \geq 6.5 \text{ in. H}_2\text{O}$$

$$P_2 \text{ must be } \leq 180 \text{ bhp}$$

(4.) Calculate the volumetric flow for the proposed fan using the proper equation from (3c(2)(a)) above.

$$\begin{aligned} V_{t2} &= V_{t1} \left[\frac{D_2}{D_1} \right]^3 \left[\frac{N_2}{N_1} \right] \\ &= (\quad) \left[\quad \right]^3 \left[\quad \right] \\ &= (\quad) \text{ cfm} \end{aligned}$$

Does this meet the requirement?

☐ Yes ☐ No (answer is on page 94)

(5.) Calculate the static pressure, h_r , for the proposed fan using the proper equation from (3c(2)(b)).

$$\begin{aligned} h_{r2} &= h_{r1} \left[\frac{D_2}{D_1} \times \frac{N_2}{N_1} \right]^2 \\ h_{r2} &= (\quad) \left[\left(\quad \right) \times \left(\quad \right) \right]^2 \\ h_{r2} &= (\quad) \text{ in. H}_2\text{O} \end{aligned}$$

Does this meet the requirement?

☐ Yes ☐ No

(6.) If we need only 6.5 in. H₂O pressure drop, how will we control the pressure?

- a. Install a valve in the duct to the adsorber?
- b. Recycle the gas through the blower at a controlled rate?

(answer is on next page)

(7.) Calculate the horsepower required by the proposed fan using the proper equation from (3c(2)(c)).

$$P_2 = P_1 \left[\frac{D_2}{D_1} \right]^5 \left[\frac{N_2}{N_1} \right]^3$$

$$P_2 = (\quad) \left[\quad \right]^5 \left[\quad \right]^3$$

$$P_2 = (\quad) \text{ bhp}$$

Does this meet the requirement?

☐ Yes

☐ No

(answer is on next page)

4. You have now completed all the calculations necessary to review the plans for this adsorber. The actual approval is subject to engineering judgement as to whether the data supplied or assumptions made are valid, or whether the design is conservative. This problem is difficult to simulate in an exercise, but it is the main problem in a real situation when plans have been submitted for review.

Based upon the calculations made in this problem would you conclude that this design is:

☐ critical?

☐ conservative?

☐ ridiculous?

Do you approve this plan for a construction permit? ☐ yes, ☐ no.

(answer is on next page)

Answer to (3-b)

$$(0.277) \times (12) \times (1.96) = 6.5 \text{ in H}_2\text{O/bed}$$

Answers to (3c(4)-(7))

$$(4) \quad (15,120) \quad \left[\frac{60}{46} \right]^3 \left[\frac{1600}{1622} \right] = 33,100 \text{ cfm}$$

yes

$$(5) \quad (7.0) \quad \left[\frac{60}{46} \times \frac{1600}{1622} \right]^2 = 11.6 \text{ in. H}_2\text{O}$$

yes

(6) Recycling gas through the blower is the usual control method since the blower can operate most efficiently at constant speed and constant power.

$$(7) \quad (45.9) \quad \left[\frac{60}{46} \right]^5 \left[\frac{1600}{1622} \right]^3 = 166 \text{ bhp.}$$

yes

Answers to (4)

conservative

yes

ACTIVATED CARBON PRESSURE DROP CURVES

FIGURE 1

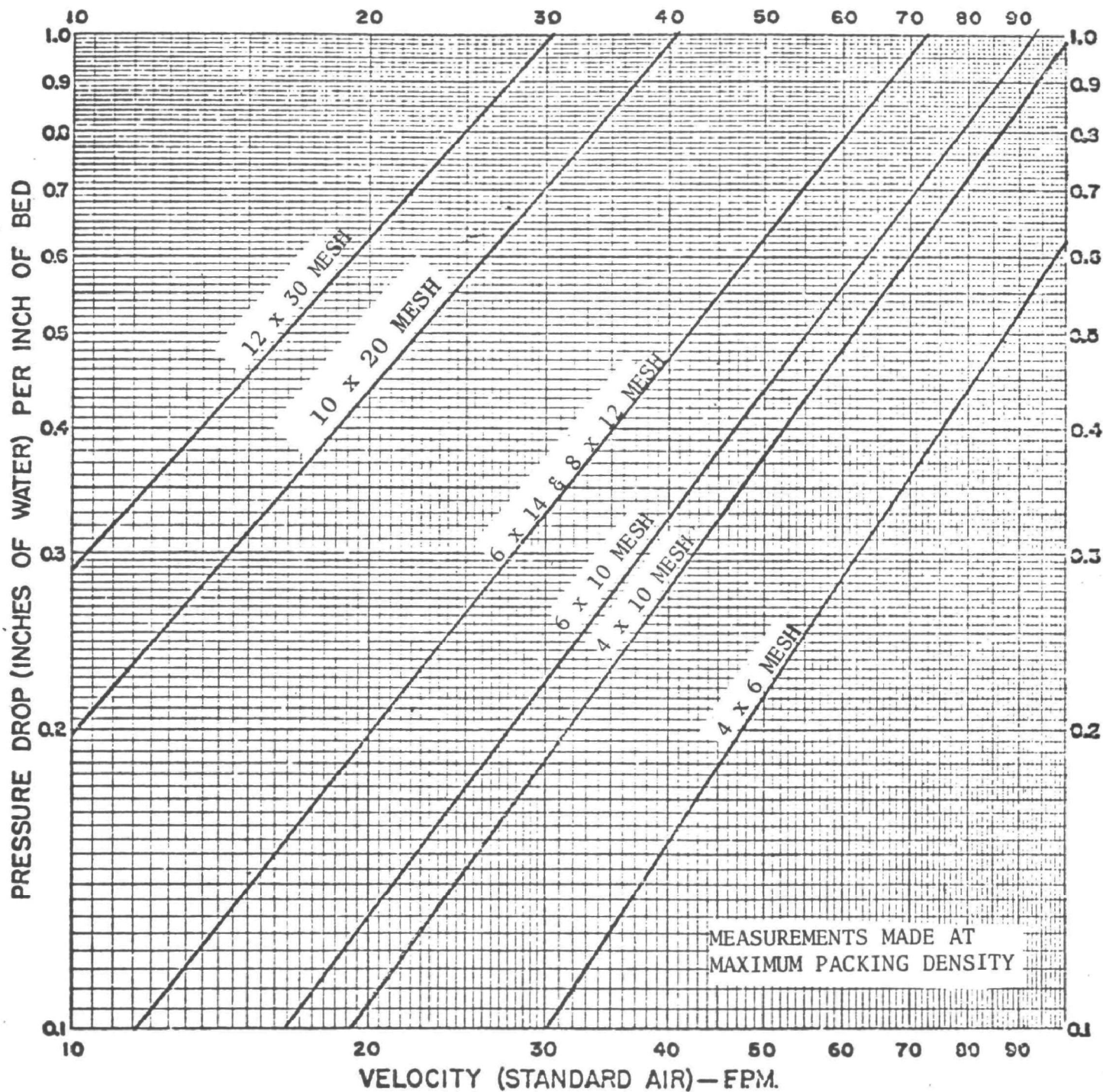
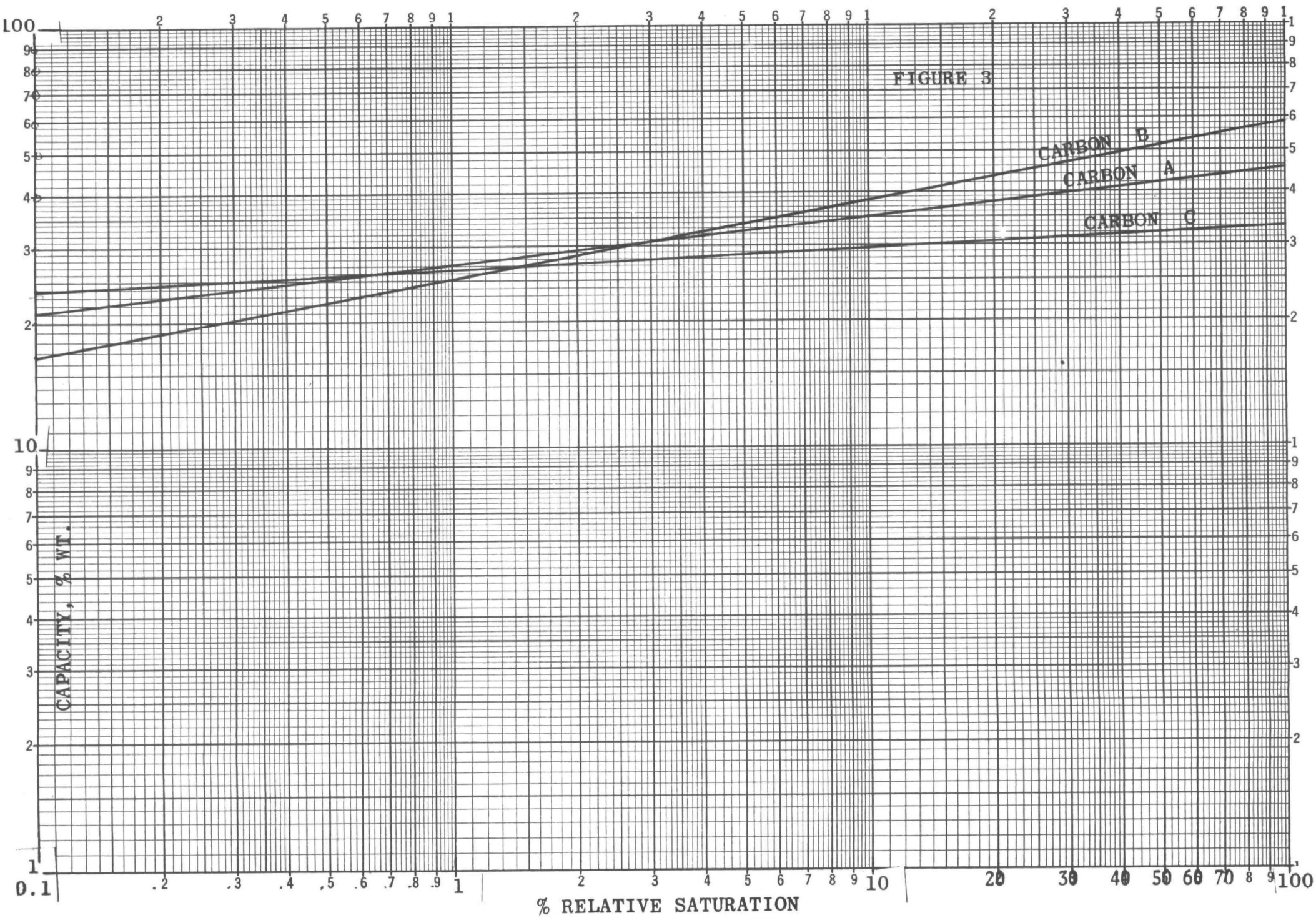


FIGURE 2

TYPICAL FAN MULTIRATING TABLE

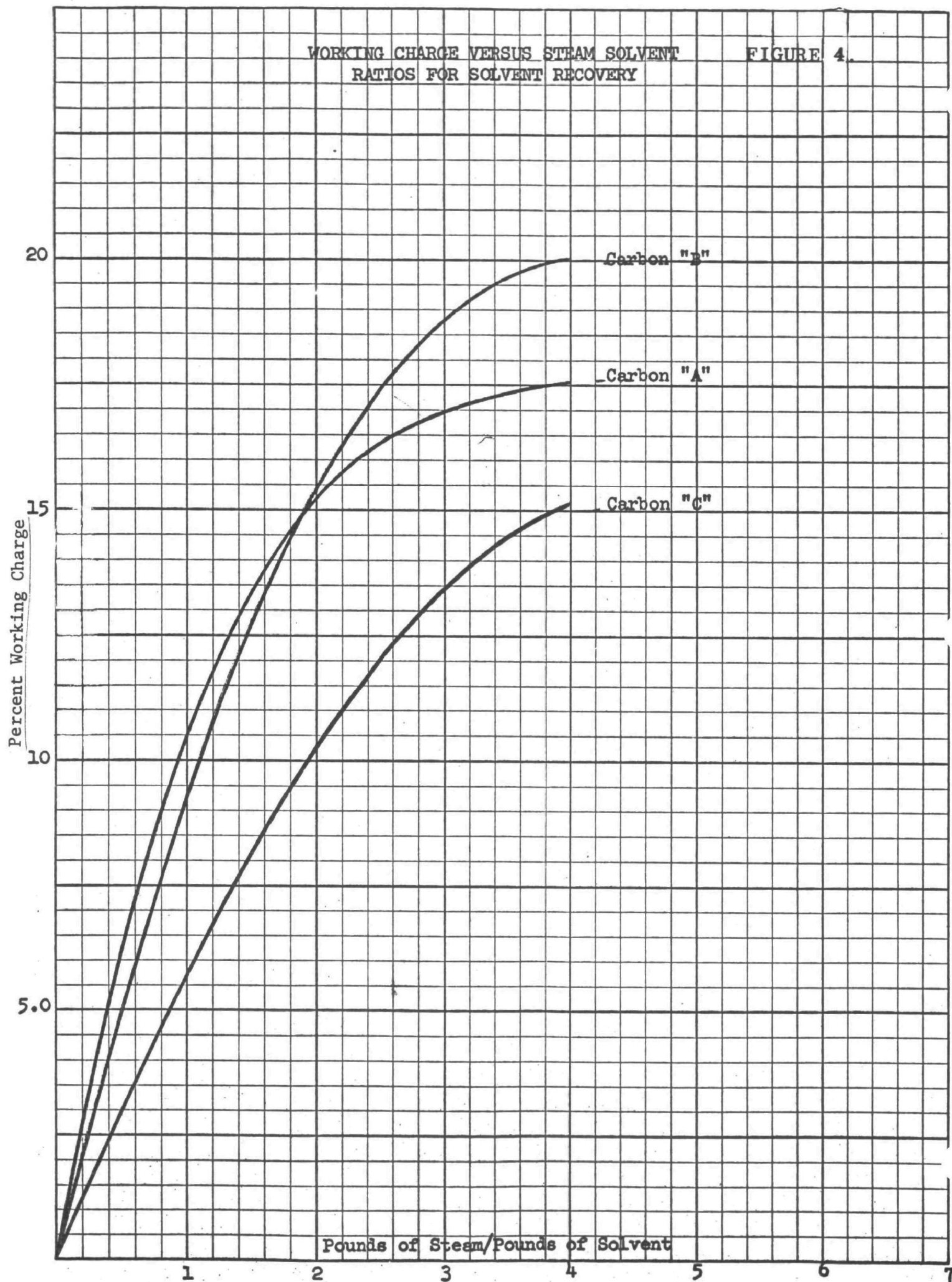
Volume, cfm	Outlet velocity, fpm	Velocity pressure, in. WC	1 in. SP		2 in. SP		3 in. SP		4 in. SP		5 in. SP		6 in. SP		7 in. SP		8 in. SP		9 in. SP	
			rpm	bhp	rpm	bhp	rpm	bhp	rpm	bhp	rpm	bhp	rpm	bhp	rpm	bhp	rpm	bhp	rpm	bhp
2,520	1,000	0.063	437	0.63	595	1.27	728	2.00	837	2.66										
3,120	1,200	0.090	459	0.85	610	1.55	735	2.30	842	3.10										
3,530	1,400	0.122	483	1.05	626	1.87	746	2.72	847	3.57	943	4.60								
4,030	1,600	0.160	513	1.33	642	2.18	759	3.17	858	4.12	950	5.21	1,030	6.29						
4,530	1,800	0.202	532	1.61	666	2.56	774	3.63	876	4.63	964	5.82	1,040	6.92	1,125	8.18				
5,040	2,000	0.250	572	2.00	688	2.97	797	4.12	890	5.30	976	6.50	1,052	7.75	1,134	8.96	1,208	10.15	1,270	11.67
5,540	2,200	0.302	603	2.36	712	3.43	816	4.66	910	5.93	999	7.38	1,068	8.60	1,145	9.93	1,210	11.18	1,279	12.82
6,040	2,400	0.360	637	2.79	746	3.99	840	5.33	926	6.73	1,017	8.17	1,088	9.50	1,160	10.88	1,230	12.25	1,288	13.92
6,550	2,600	0.422	670	3.27	762	4.62	866	6.05	954	7.83	1,032	9.08	1,095	10.50	1,171	11.98	1,245	13.50	1,298	15.10
7,060	2,800	0.489	708	3.81	795	5.32	892	6.72	963	8.78	1,050	9.97	1,125	11.60	1,188	13.06	1,257	14.70	1,310	16.48
7,560	3,000	0.560	746	4.42	833	6.05	920	7.70	993	9.32	1,068	11.00	1,142	12.75	1,210	14.28	1,277	15.98	1,328	17.80
8,060	3,200	0.638			866	6.96	943	8.71	1,020	10.40	1,097	12.10	1,168	14.02	1,228	15.50	1,292	17.36	1,340	19.15
8,560	3,400	0.721			900	7.93	964	9.80	1,053	11.48	1,120	13.30	1,188	15.35	1,248	16.93	1,310	19.00	1,360	20.90
9,070	3,600	0.808					1,010	11.00	1,078	12.70	1,148	14.65	1,213	16.70	1,270	18.42	1,335	20.75	1,380	22.60
9,570	3,800	0.900					1,038	12.25	1,108	14.15	1,170	14.90	1,240	18.80	1,292	19.46	1,355	22.35	1,405	24.40
10,080	4,000	0.998					1,162	13.60	1,138	15.40	1,200	17.35	1,270	19.70	1,320	21.70	1,380	23.15	1,430	26.40
10,580	4,200	1.100							1,168	16.90	1,230	19.05	1,283	21.50	1,348	23.50	1,405	26.10	1,450	28.45
11,100	4,400	1.210							1,198	18.58	1,258	20.55	1,322	22.50	1,373	25.40	1,430	27.95	1,478	30.60
11,600	4,600	1.310							1,232	20.30	1,290	22.50	1,355	23.80	1,405	27.40	1,450	30.15	1,500	32.90
12,100	4,800	1.450							1,270	21.00	1,321	24.40	1,383	25.65	1,432	29.60	1,482	32.40	1,528	35.20
12,600	5,000	1.570							1,301	24.20	1,355	26.40	1,410	28.80	1,462	31.80	1,513	34.60	1,555	37.80
15,120	6,000	2.230													1,622	45.90	1,670	49.00	1,702	51.50

For straight blade centrifugal blower having 46 inch diameter



WORKING CHARGE VERSUS STEAM SOLVENT
RATIOS FOR SOLVENT RECOVERY

FIGURE 4.



SOOTHSAYER CONSULTING LABORATORY

"We guarantee the answer you want"

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Anywhere, U.S.A.

Test Performed: Measurement of length of MTZ

Material Tested: Carbon "B"

Test Number: B-17

Conditions:

Carbon bed depth	62.0 cm, 2.0 feet
Saturation capacity	26% @ 20°C
Temperature of test	20°C
Breakthrough capacity	24.9% calculated from test

Calculations:

$$\text{Breakthrough Capacity} = \frac{\frac{1}{2} \left[\begin{array}{c} \text{Saturation} \\ \text{Capacity} \end{array} \right] \left[\begin{array}{c} \text{MTZ} \\ \text{Length} \end{array} \right] + \left[\begin{array}{c} \text{Saturation} \\ \text{Capacity} \end{array} \right] \left[\begin{array}{c} \text{Bed} \\ \text{Length} \end{array} - \begin{array}{c} \text{MTZ} \\ \text{Length} \end{array} \right]}{\text{Bed Length}}$$

$$0.249 = \frac{\frac{1}{2} (.26) (\text{MTZ}) + 0.26 (62.0 - \text{MTZ})}{62.0 \text{ cm}}$$

$$\text{MTZ} = 5.3 \text{ cm}$$

$$\text{MTZ} = 2.09 \text{ in}$$

Section IV

Absorption

AB-I

Basic Concepts

The following data are from Perry's Chemical Engineering Handbook, Fourth Edition, Page 14-6.

WEIGHTS OF HCl PER 100 WEIGHTS OF H ₂ O	HYDROGEN CHLORIDE (HCl) PARTIAL PRESSURE OF HCl, mm Hg @ 68°F
25.0	0.205
19.05	0.0428
13.64	0.0088
8.70	0.00178
7.32	0.000928
4.17	0.00024
2.04	0.000044

TABLE 1.

The information in this table is to be transformed to other units, as indicated in Table 2. Atmospheric pressure is assumed to be 760 mm. Hg, and the temperature is assumed to be 68°F.

SOLUTION *

1. Convert the partial pressure data to volume fractions by dividing by the total pressure (760 mm.). Remember Dalton's law of partial pressures.

*Answers are on page 106.

- a. Volume fraction is converted to volume % by multiplying by 100. This is done in Column (3).
- b. Is volume per cent of a gas the same as mole per cent of a gas? If the answer is yes, write "Mole % of HCl in the Gas" in above Column (3) in the space provided.
2. Next convert the liquid concentration of HCl in Column (1) to mole units.
 - a. Use the molecular weight of HCl to convert the weight of HCl to moles.
 - b. Molecular weight HCl is 36.46. The units are expressed as either grams/gram mole or lbs./lb. mole.
3. Now determine the moles of water in the (100 parts) referred to in Column (1).
 - a. Molecular weight water is 18.0.
 - b. Total moles of water is $100 \div 18.0$.
 - c. The total moles of water and HCl is then $(100 \div 18.0) + \text{moles HCl}$.
 - d. This is calculated in Column (5) by adding the moles water to the moles HCl from Column (4).
4. The mole per cent of HCl in the liquid can now be determined by dividing the moles HCl by the total moles liquid or Moles HCl/ Moles Liquid.
 - a. This is Column (4) divided by Column (5).
 - b. Calculate the Mole % of HCl in the Liquid and enter in Column (6).
5. Plot the values for Mole % gas (y) and Mole % liquid (x) on the graph provided (Figure 1). From this plot of the data, does it appear that Henry's Law applies? Yes _____ No _____
6. Plot the data on Figure 2. Does Henry's Law apply here? Yes _____ No _____

HYDROGEN CHLORIDE (HCl) EQUILIBRIUM DATA

(1) WEIGHTS OF HCl PER 100 WEIGHTS OF H ₂ O	(2) PARTIAL PRESSURE HCl mm. Hg @ 68°F	(3) (Y) $\frac{\text{COL (2)} \times 100}{760 \text{ mm. Hg}}$	(4) MOLES HCl IN MIXTURE $\text{COL (1)} \div 36.461$	(5) MOLES H ₂ O IN MIXTURE + MOLES HCl IN MIXTURE $(100 \div 18.0) + \text{COL (4)}$	(6) MOLE % OF HCl IN LIQUID $\frac{\text{COL (4)}}{\text{COL (5)}} \times 100$ (X)
25.1	0.205	0.0269	0.685	5.55 + 0.685 = 6.235	11.0
19.05	.0428	.00563	.522	6.072	8.596
13.64	.0088	.00118	.374	5.92	6.307
8.70	.00178	.00234	.239	5.79	4.118
7.32	.000928	.001221	.201	5.75	3.484
4.17	.00024	.00031	.114	5.67	2.017
2.04	.000044	.000058	.056	5.61	.997

TABLE 2.

$$X = \frac{25}{36.5} = \frac{100 \div 25}{100 \div 36.5} = \frac{4}{2.66}$$

FIGURE 1

MOLE PERCENT HCl IN GAS

0.020

0.015

0.01

0.005

0

2

4

6

8

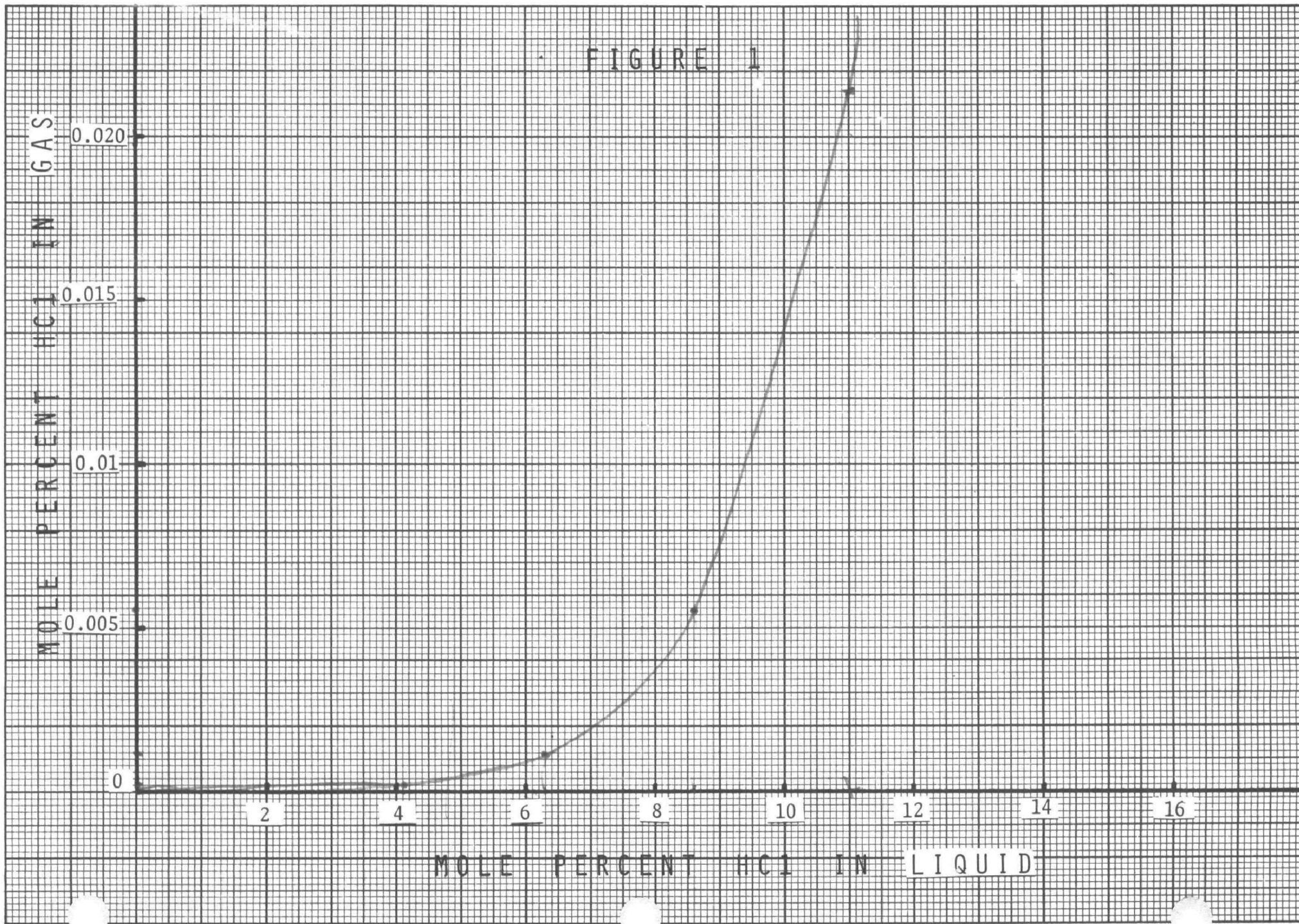
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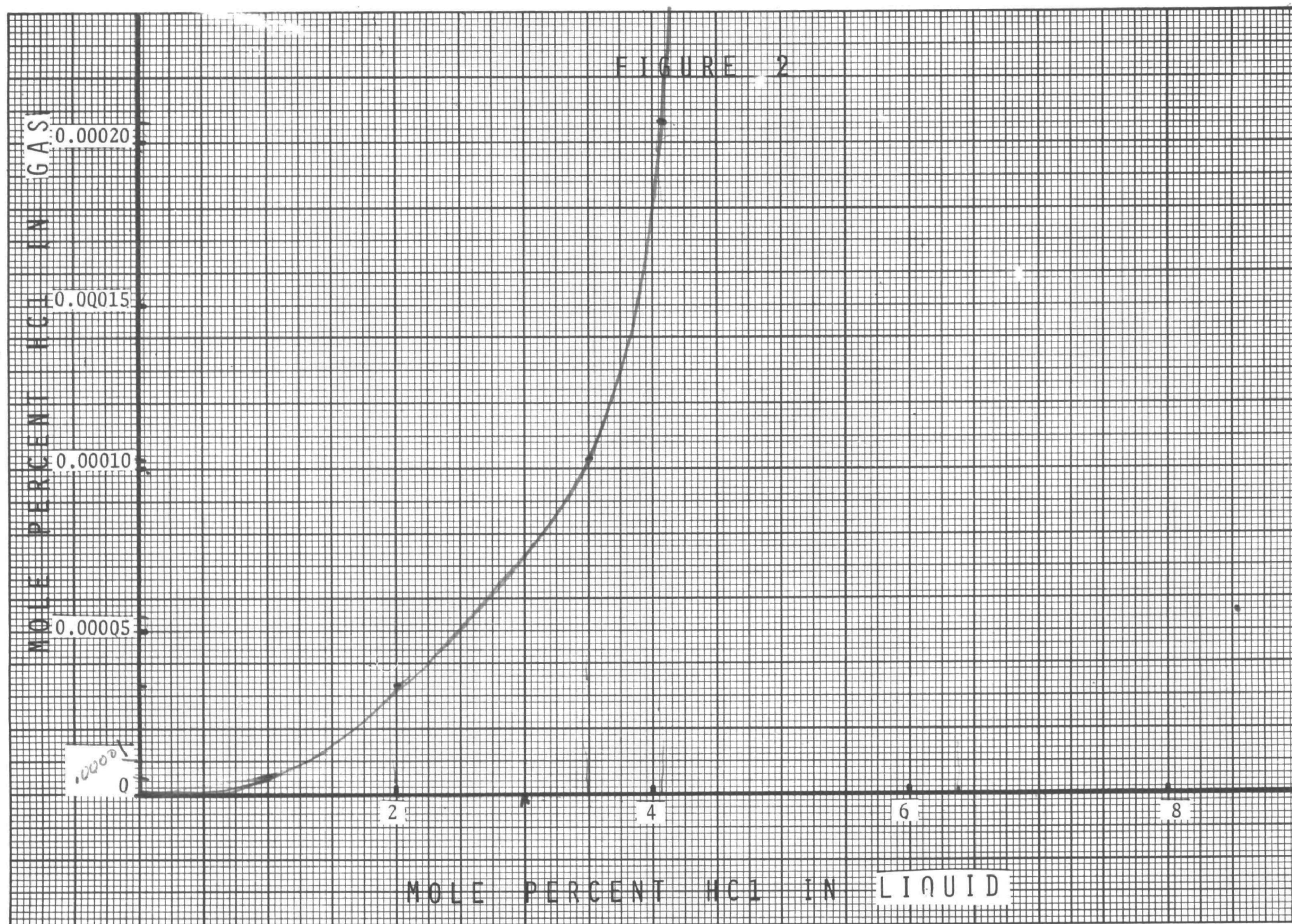
12

14

16

MOLE PERCENT HCl IN LIQUID





ANSWERS

1b. Yes

4.	Col. (2)	Col. (3)	Col. (4)	Col. (5)	Col. (6)
	0.205	0.0269	0.685	6.235	11.0
	0.0428	0.00564	0.521	6.071	8.6
	0.0088	0.00115	0.374	5.924	6.3
	0.00178	0.000234	0.238	5.788	4.1
	0.000928	0.000122	0.201	5.751	3.5
	0.000240	0.0000316	0.114	5.664	2.0
	0.000044	0.00000578	0.056	5.606	1.0

5. NO

6. NO

Material Balance

You are given the basic data for an absorption system to be used for scrubbing ammonia (NH_3) from air with water. The water rate will be $300 \text{ lb}/(\text{hr ft}^2)$ and the gas rate will be $250 \text{ lb}/(\text{hr ft}^2)$ at 72°F . The equilibrium data for the ammonia-air system is shown in the following table.

EQUILIBRIUM DATA NH_3 - WATER 72°F 1 ATM PRESSURE							
P_e mm Hg Equilibrium Pressure	3.4	7.4	9.1	12.0	15.3	19.4	23.5
Concentration of NH_3 # NH_3 /100 # H_2O	0.5	1.0	1.2	1.6	2.0	2.5	3.0

PERRY'S HANDBOOK FOURTH EDITION 1963

The air to be scrubbed has 1.5% wt. NH_3 at 72°F and 1 atmosphere pressure and is to be vented with 95% of the ammonia removed. The inlet scrubber water will be ammonia free.

The exercise in this problem is to:

- Plot the equilibrium data in mole fraction units. ✓
- Calculate the material balance and plot the operating line on the equilibrium plot.
- Set up the mass flux equations for both the gas and liquid driving forces.

SOLUTION*

A. Convert the equilibrium data to mole fraction units.

1. Remember that in an ideal gas mixture the partial pressure of a gas is equal to its volume fraction in the gas mixture. This is Dalton's Law. The volume fraction is also the mole fraction for an ideal gas mixture. Since the atmospheric or system pressure (P) is 760 mm Hg, the volume fraction or mole fraction of NH_3 for a partial pressure (p_e) of 3.4 mm Hg is:

$$\frac{p_e}{P} = \frac{3.4}{760} = 0.00447$$

Calculate the remaining gas mole fraction values and enter in Table I.

GAS	GAS	LIQUID	LIQUID
p_e mm Hg	Mole Fraction Y	$\frac{\text{lbs. NH}_3}{100 \text{ lbs. H}_2\text{O}}$	Mole Fraction X
3.4	0.00447	0.5	0.0052
7.4	.00974	1.0	.0105
9.1	.01197	1.2	.0125
12.0	.01579	1.6	.0166
15.3	.02013	2.0	.0207
19.4	.02553	2.5	.0258
23.5	.03092	3.0	.0308

Table I.

*Answers are on page 114.

2. The factor for converting the liquid concentration data to mole fraction units depends upon the molecular weights of the substances.

For a liquid concentration of 0.5 $\frac{\text{LBS. NH}_3}{100 \text{ LBS. H}_2\text{O}}$ the calculation is as follows:

$$\text{mole fraction NH}_3 \text{ in H}_2\text{O} = \frac{\text{lb. moles of NH}_3}{\text{Total lb. moles of solution}} \quad \text{or,}$$

$$\text{mole fraction NH}_3 \text{ in H}_2\text{O} = \frac{\frac{0.5}{\text{M.W. NH}_3}}{\frac{0.5}{\text{M.W. NH}_3} + \frac{100}{\text{M.W. H}_2\text{O}}}$$

NOTE: M.W. NH_3 = 17.03 (use 17.0)

M.W. H_2O = 18.01 (use 18.0)

M.W. Air = 28.95 (use 29.0)

Calculate the liquid mole fraction values and enter in Table I.

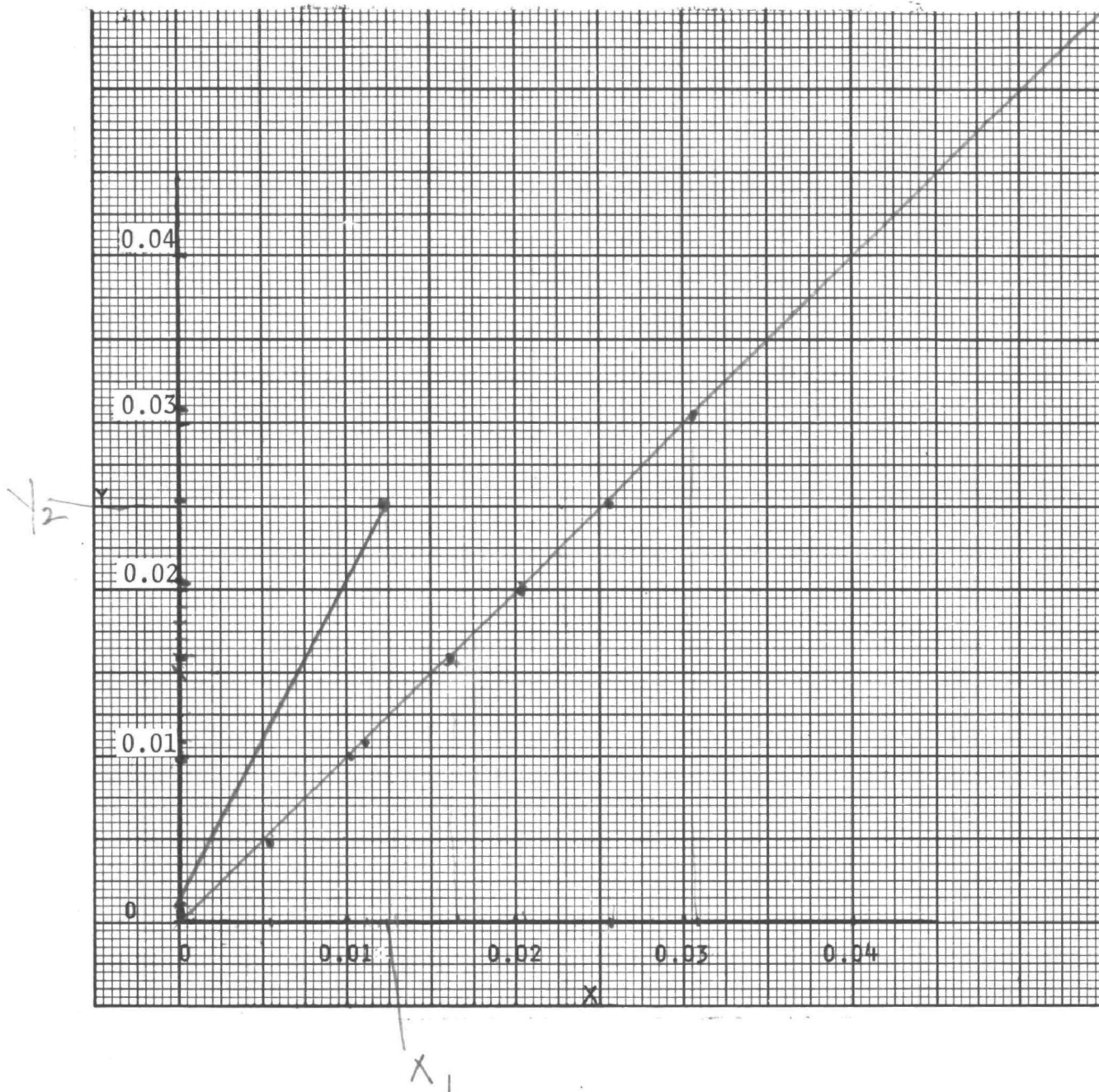
- B. Plot the mole fraction values on the following graph. Liquid concentrations should be plotted on the x-axis and gas concentrations on the y-axis.

1. Does the plot indicate that Henry's Law applies?

YES or NO? yes

2. Why?

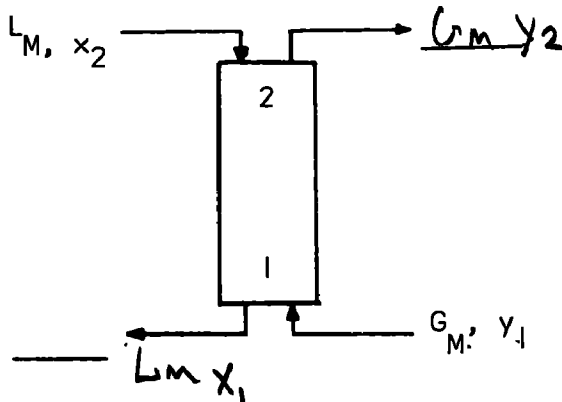
straight line



3. Calculate the slope of the equilibrium line.

$$\text{Slope} = \frac{\Delta y}{\Delta x} = \frac{0.01}{0.012} = \underline{\hspace{2cm}}$$

C. Label the following schematic of the system.



D. Calculate the outlet liquid concentration using the material balance. It is assumed that for air pollution applications L_M and G_M are essentially constant throughout the column.

$$L_M (x_1 - x_2) = G_M (y_1 - y_2)$$

All values should be expressed in LB. Mole units or mole fraction units:

x_1 = outlet NH_3 concentration in liquid = ?

y_1 = inlet NH_3 concentration in gas = _____ *

y_2 = outlet NH_3 concentration in gas = _____ *

x_2 = inlet NH_3 concentration in liquid = _____ *

L_M = Liquid flow, LB Moles/(Hour Ft²) = ?

G_M = Gas flow, LB Moles/(Hour Ft²) = ?

* NOTE: The concentration units which were given in wt. % must be converted to mole fraction units.

Solve for x_1

$$1. \quad L_M = \frac{300 \text{ LB. H}_2\text{O}/(\text{Hr. Ft}^2)}{18 \frac{\text{LB. H}_2\text{O}}{\text{LB. Mole H}_2\text{O}}} = \underline{16.5} \frac{\text{LB. Moles H}_2\text{O}}{\text{Hour Ft}^2}$$

$$2. \quad G_M = \frac{250 \text{ LB. Air}/(\text{Hr. ft}^2)}{29.0 \frac{\text{LB. Air}}{\text{LB. Mole Air}}} = \underline{8.6} \frac{\text{LB. Moles Air}}{\text{Hour ft}^2}$$

$$3. \quad x_1 = \frac{G_M}{L_M} (y_1 - y_2) + x_2$$

$$4. \quad x_1 = \frac{8.6}{16.5} (.025 - .0025) + 0$$

$$5. \quad x_1 = \underline{.0124} \frac{\text{LB. Moles NH}_3}{\text{LB. Mole Liquid}}$$

E. Plot the inlet and outlet concentrations on the graph, Fig. 1., i.e. plot points x_1 , y_1 and x_2 , y_2 .

1. Connect them with a line. This is called the operating line. The operating line defines a boundary for operating conditions within the absorption unit. The operating line states the concentrations for adjacent streams throughout the column.

2. Any line on a coordinate system such as this graph may be expressed as an equation.

a. Write the equation for this straight line explicit for Δy or $(y_1 - y_2)$.

NOTE: Remember the material balance equation!

b. What is the value for the slope of the operating line? _____

F. Indicate the gas phase concentration driving force between the operating line and the equilibrium line for the gas inlet conditions.

1. The driving force in the gas phase is expressed as a function of the inlet ammonia concentration (y_1) and the concentration of ammonia in equilibrium with the outlet liquid (y^*).

$$\text{driving force} = (y_1 - y^*)$$

2. Identify the gas phase driving force on the graph.

G. The mass flux, $N_A \frac{\text{lb. moles}}{\text{Hr. ft}^2}$ can be expressed as a function of the driving force and the mass transfer coefficient (K_G).

1. This is analogous to Ohm's Law.

$$\text{FLOW (I)} = \text{Driving Force (E)}/\text{Resistance (R)}$$

2. The reciprocal of the mass transfer coefficient is analogous to electrical resistance. The mass transfer coefficient is therefore analogous to (electrical) conductance.

$$\therefore \text{Mass Flow } (N_A) = K_G \times (\text{driving force})$$

$$N_A = K_G (y_1 - y^*)$$

3. What are the units of K_G ?

H. Write the similar equation for the liquid phase driving force and the liquid mass transfer coefficient K_L at the same point of reference on the graph as was used for the gas driving force.

$$1. \text{ Mass Flow } (N_A) = K_L \times (\text{driving force})$$

$$N_A = K_L (x^* - x_1)$$

2. Identify the liquid phase driving force on the graph.

ANSWERS

A.	1.	Gas	2.	Liquid
		Mole Fraction, y		Mole fraction, x
		0.00447		0.0052
		0.00973		0.0105
		0.0120		0.0125
		0.0158		0.0167
		0.0201		0.0206
		0.0255		0.0258
		0.0309		0.0307

- B. 1. Yes
 2. The equilibrium data describe a straight line.
 3. 1.0

- C. G_m , y_2
 L_m , x_1

- D. 0.0253, 0.0013, 0
 1. 16.67
 2. 8.62
 4. 0.517, 0.0253, 0.0013, 0
 5. 0.0124

- E. 2. a. $\Delta y = m\Delta x = 1.93 \Delta x$
 b. 1.93

- G. 3. $\frac{\text{lb. moles}}{\text{hr. ft}^2}$ or $\frac{\text{lb. moles}}{\text{hr. ft}^2 \text{ mole fraction}}$ or $\frac{\text{lb. moles}}{\text{hr. ft}^2 \text{ atm.}}$

INFORMATION NECESSARY FOR REVIEWING ABSORBER PLANS

1. Equipment Description

- a. Drawings
- b. Specifications
- c. Make, Model, Size

2. Process Description

- a. Flow diagram
- b. Chemical compositions of all streams
- c. Temperatures
- d. Volumes
- e. Gas velocities through equipment
- f. Flow rates for materials entering and leaving the equipment
- g. Pressure drop data for the equipment

3. Design Information

- a. Data used in the design
 - (1) Equilibrium data
 - (2) Mass transfer or height of a transfer unit data
 - (3) Number of transfer unit data
- b. Calculations made in the design and selection of the equipment

4. Description of Gas Mover

- a. Make, Model, Size, Speed, Capacity
- b. Cubic feet per minute to be handled
- c. Static pressure
- d. Motor description

Procedure for Reviewing Absorber Plans

1. Study the chemical feasibility of the scrubbing system.
2. Perform a material balance to determine the emission quantities.
3. Compare emissions with standards or laws.
 - a. If comparision indicates a violation: deny
 - b. If comparision is favorable: proceed to 4.
4. Calculate tower diameter.
5. Evaluate column's performance by calculating:
 - a. Height of tower, or
 - b. Number of transfer units, or
 - c. Outlet emission concentration
6. Compare 4. and 5. with submitted information.
7. Recommendation for approval or denial.
8. Plan Review Air Mover

Packed Tower

XYZ Company has submitted plans for a H_2S scrubber. Hydrogen sulfide is to be removed from a waste air discharge by scrubbing the gas stream with a triethanolamine — water solution in a packed absorption tower at atmospheric pressure.

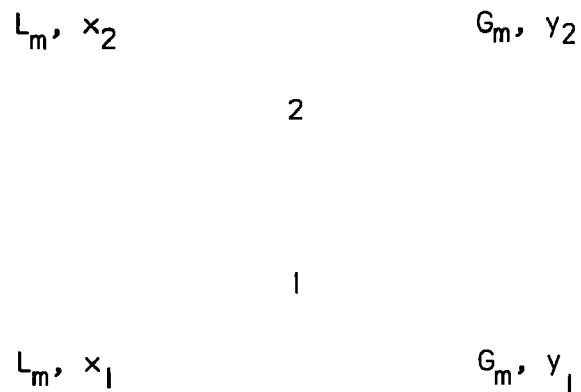
Specification sheets indicate that the gas and liquid flow rates are $290 \text{ lb}/(\text{Hr} \cdot \text{ft}^2)$ and $40 \text{ lb. moles}/(\text{Hr} \cdot \text{ft}^2)$, respectively. The inlet liquid is indicated to be contaminant free. XYZ Company pilot plant data indicate that Henry's Law applies ($m = 2.0$) and the H_{OG} is 1.94 ft .

From your preliminary calculations you have determined that the scrubber must reduce the H_2S from $17 \text{ lb}/(\text{Hr} \cdot \text{ft}^2)$ to $0.64 \text{ lb}/(\text{Hr} \cdot \text{ft}^2)$.

Is the 12 foot tower (which the XYZ Co. proposes) adequate?

SOLUTION*

1. Draw and label a schematic of the tower:



2. Convert all units to a lb. mole basis:

$$\text{M.W. H}_2\text{S} = 34 \text{ lb/lb. mole}$$

$$\text{M.W. Air} = 29 \text{ lb/lb. mole}$$

$$G_m = 290 \frac{\text{lb.}}{\text{Hr. ft}^2} \times \frac{1}{\text{M.W. Air}} = \frac{10}{\text{Hr. ft}^2} \frac{\text{lb. moles}}{\text{Hr. ft}^2}$$

$$L_m = 40 \frac{\text{lb. moles}}{\text{Hr. ft}^2}$$

$$y_1 = 17 \frac{\text{lb. H}_2\text{S}}{\text{Hr. ft}^2} \times \frac{1}{\text{M.W. H}_2\text{S}} \times \frac{1}{G_m} = \underline{\hspace{2cm}}$$

$$y_2 = 0.64 \frac{\text{lb. H}_2\text{S}}{\text{Hr. ft}^2} \times \frac{1}{\text{M.W. H}_2\text{S}} \times \frac{1}{G_m} = \underline{\hspace{2cm}}$$

$$x_2 = \underline{\hspace{2cm}}$$

*Answers are on page 121.

3. By using a material balance, find x_1 :

$$L_m (x_1 - x_2) = G_m (y_1 - y_2)$$

$$x_1 = \frac{G_m}{L_m} (y_1 - y_2) + x_2$$

$$x_1 = \underline{\hspace{2cm}}$$

4. By using the Colburn Chart, find the N_{OG} :

$$x_2 = \underline{\hspace{2cm}}$$

$$m = \underline{\hspace{2cm}}$$

$$y_1 = \underline{\hspace{2cm}}$$

$$y_2 = \underline{\hspace{2cm}}$$

$$L_m = \underline{\hspace{2cm}}$$

$$G_m = \underline{\hspace{2cm}}$$

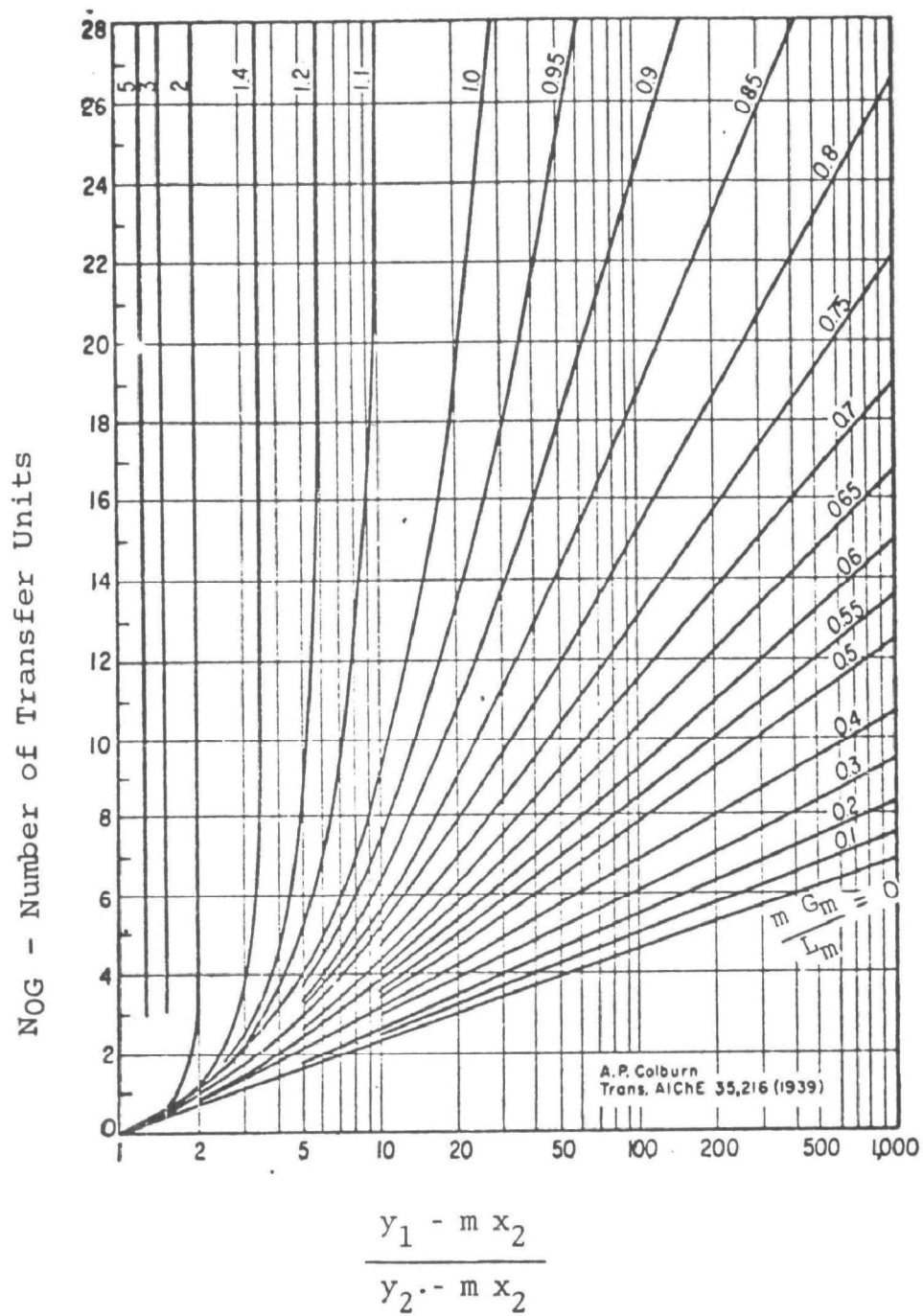
$$\frac{m G_m}{L_m} = \underline{\hspace{2cm}}$$

$$\frac{y_1 - m x_2}{y_2 - m x_2} = \underline{\hspace{2cm}}$$

$$\therefore N_{OG} = \underline{\hspace{2cm}}$$

5. $Z = N_{OG} \times H_{OG}$

$$Z = \underline{\hspace{2cm}} \text{ ft}$$



Colburn's Chart Permits an Easy Solution for N_{OG}.

ANSWERS

2. 10

0.05

0.00188

0

3. 0.012

4. 0, 2.0, 0.05, 0.00188, 40, 10, 0.5, 26.6, 5.1

5. 9.9 Yes, the 12 foot design is adequate.

AB-IV

Packed Tower

Pollution Unlimited, Inc. has submitted plans for a packed ammonia scrubber on 1575 cfm air stream containing 2% NH_3 . The emission regulation is 0.1% NH_3 .

The following information is provided:

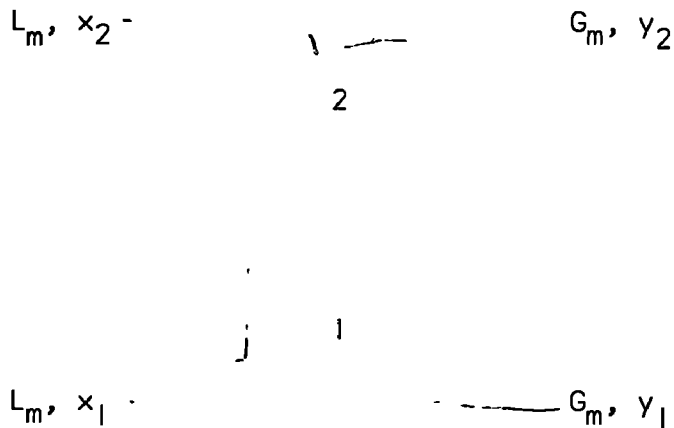
1. Tower Diameter - 3.57 feet
2. Packed Height of Column - 8 feet
3. Gas and liquid temperature - 75°F
4. Operating Pressure - 1.0 atm.
5. Ammonia-free liquid flow rate - 1000 lb/(hr.ft²)
6. Gas flow rate - 1575 cfm
7. Inlet NH_3 gas concentration - 2.0 volume %
8. Outlet NH_3 gas concentration - 0.1 volume %
9. Figure 1
10. Packing 'A' is used
11. Air density - 0.0743 lb/ft³
12. Molecular weight air - 29 lb/lb mole
13. Henry's Law constant - $m = 0.972$
14. Molecular weight water - 18 lb/lb mole

You remember approving plans for a nearly identical scrubber for Pollution Unlimited, Inc. in 1968. After consulting your old files you find all the conditions were identical — except the gas flow rate was 1121 cfm.

What is your recommendation?

SOLUTION *

1. Draw and label a schematic of the tower:



2. Calculate the cross-sectional area of the tower:

$$A = \frac{\pi D^2}{4} = \underline{10} \text{ ft}^2$$

3. Calculate the gas molar flow rate:

$$G_m = \frac{15.75 \text{ ft}^3/\text{min} \times 60 \text{ min/hr} \times 0.2743 \text{ lb/ft}^3}{10 \text{ ft}^2 \times 29 \text{ lb/lb. mole}}$$

$$G_m = \underline{2.22} \frac{\text{lb. mole}}{\text{hr. ft}^2}$$

4. Calculate the liquid molar flow rate:

$$L_m = 1000 \frac{\text{lb.}}{\text{hr. ft}^2} \times \frac{1}{18 \text{ lb./lb. mole}}$$

$$L_m = \underline{55.6} \frac{\text{lb. mole}}{\text{hr. ft}^2}$$

*Answers are on page 128.

5. Determine N_{OG} graphically from Figure 2:

$$\begin{aligned} x_2 &= \frac{0}{.972} \\ m &= \frac{.02}{.001} \\ y_1 &= \frac{.02}{.001} \\ y_2 &= \frac{.001}{.001} \\ L_m &= \frac{55.5}{.001} \\ G_m &= \frac{24.2}{.001} \end{aligned}$$

$$\frac{m G_m}{L_m} = \frac{(.972)(24.2)}{55.5} = .43$$

$$\frac{y_1 - m x_2}{y_2 - m x_2} = \frac{.02}{.001} = 20$$

$$\therefore N_{OG} = \underline{4.3}$$

6. a. For the previously specified gas flow rate, liquid flow rate, and packing type, what is the best H_{OG} (see Figure 1)?

$$H_{OG} = \underline{2.2}$$

- b. What is the packed height needed to do the job?

$$Z = N_{OG} \times H_{OG}$$

$$Z = \underline{4.3} \times \underline{2.2}$$

$$Z = \underline{9.46}$$

7. Part (b) tells us that the packed column height necessary to give 4.3 transfer units 9.47 feet. The plans which Pollution Unlimited submitted specified a packed column height of 8 feet. What is your recommendation?

_____ Approve

_____  Deny

8. Company officials ask if there is any modification which would allow the scrubber to operate. They plead that because of a prior shut down of an adjacent gas cleaning operation, this scrubber already exists in the specified location and would only require minor piping changes to be put on stream.

From your experience thus far, and by inspection of Figure 1, list process modifications and rank them in probable order of increasing feasibility.

a. *no. 1. 6' tower*

b. *no. 2. 8' tower*

c. *5' tower with 10' packing*

d. *use 1' packing*

9. Instead of buying a taller tower or new, more efficient packing, we will investigate manipulating the liquid flow rate in order to attain the desired separation.

Calculate the tower height needed for each L rate:

L	$\frac{m G_m}{L_m}$	N_{OG}	H_{OG}	Z, ft.
1000	0.423	4.3	2.2	9.47
1200	<i>0.35</i>	<i>4</i>	<i>2</i>	<i>8</i>
1400	<i>0.302</i>	<i>3.6</i>	<i>1.8</i>	<i>7.9</i>
1600	<i>0.264</i>	<i>3.2</i>	<i>1.7</i>	<i>6.1</i>

From these calculations we see that the liquid rate must be increased to 1200 lb/(hr. ft²) for the 8' tower to perform according to specifications. If a safety factor is to be incorporated into the recommendation, the liquid rate must be increased beyond this value.

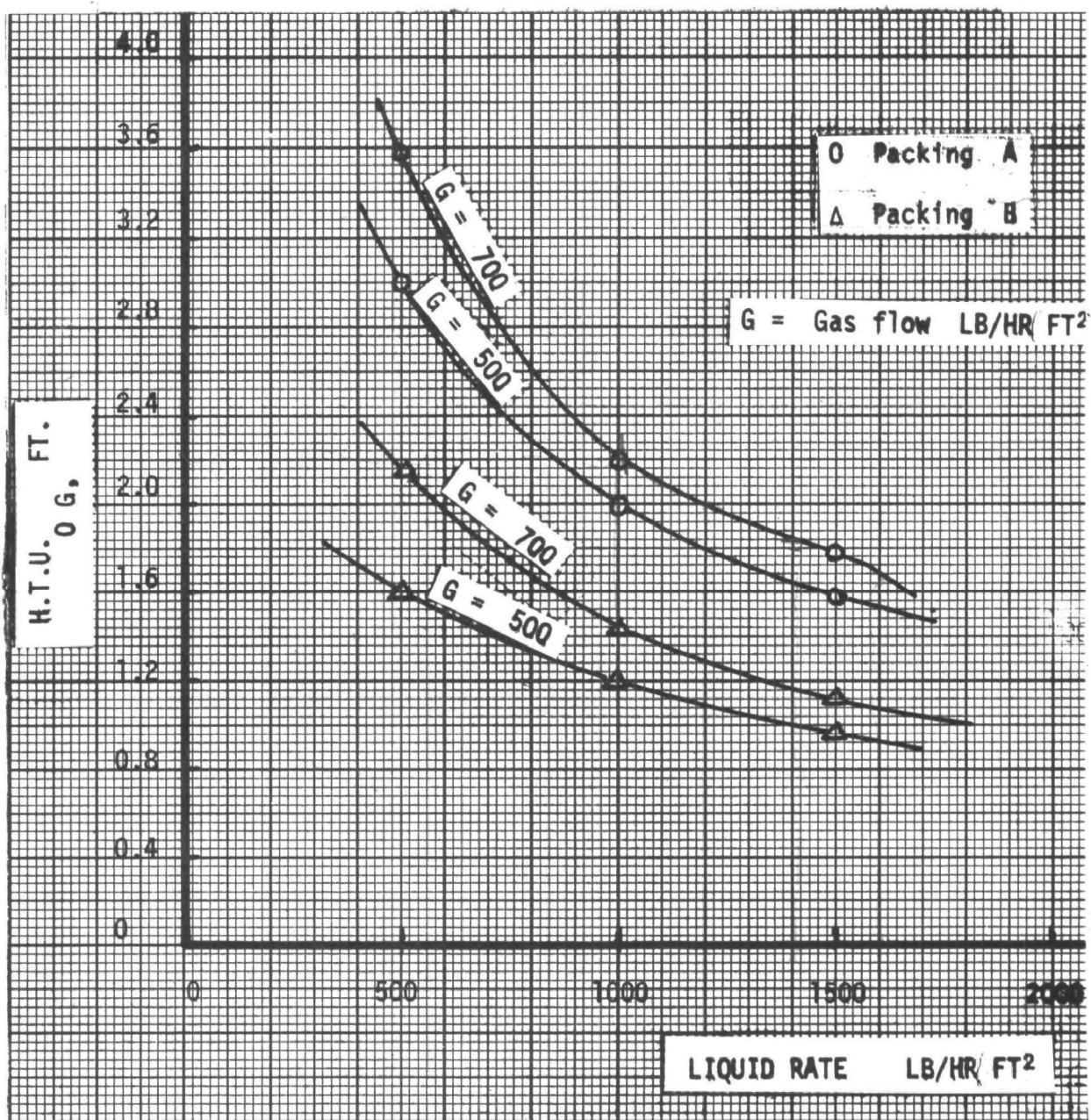


Fig. 1

Air - Ammonia - Water System
 Ref: Perry's Chemical Engineer's Handbook
 pg. 18-43 Fig. 18-82.

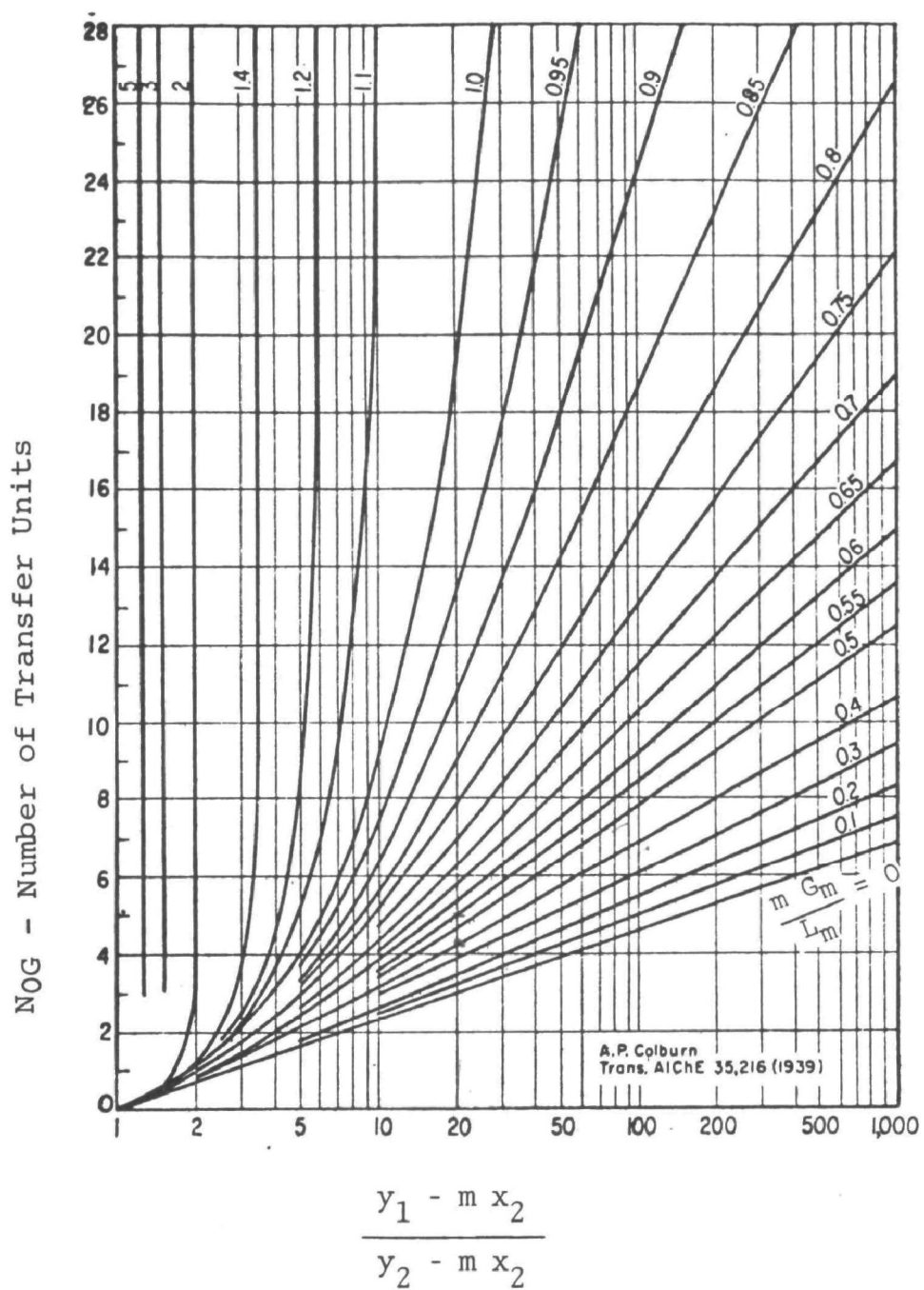


Fig. 2

Colburn's Chart Permits an Easy Solution for N_{OG} .

ANSWERS

2. 10.0
3. 1575, 0.0743, 10.0, 29
24.2
4. 18
55.6
5. 0, 0.972, 0.02, 0.001, 55.6, 24.2, 0.423, 20, 4.3
6. a. 2.2
b. 4.3, 2.2, 9.47
7. Deny
8. a. Engineer a new scrubbing system (buy a new tower).
b. Lengthen existing tower.
c. Increase liquid flow rate.
d. Purchase new packing.

9. $\frac{m G_m}{L_m}$	N_{OG}	H_{OG}	Z
0.423	4.3	2.2	9.47
0.353	4.0	2.0	8.00
0.302	3.9	1.85	7.21
0.265	3.75	1.70	6.38

1200

AB-V

Spray Tower



A steel pickling operation emits HCl fumes (hydrochloric acid) of 300 ppm average with peak values of 500 ppm for 15% of the time. The air flow is a constant 25,000 cfm at 75°F and 1 atm pressure. Regulations limit emissions to no more than 25 ppm HCl at any time. Only sketchy information was submitted with the scrubber permit application. The plans show a 14-foot diameter counter current water spray tower.

By using the following rules of thumb, determine if the spray unit is satisfactory.

1. Gas velocity through the tower is not to exceed 3 ft/sec.
2. For HCl, Henry's Law does not apply.
3. For a very soluble gas (Henry's Law constant close to zero), the number of transfer units (N_{OG}) can be determined by the following equation:

$$N_{OG} = \ln \frac{y_1}{y_2}$$

where y_1 = concentration of inlet gas

y_2 = concentration of outlet gas

4. In a spray tower, the number of transfer units (N_{OG}) for the first or top spray will be about 0.7. Each lower spray will have only about 60% of the (N_{OG}) of the spray above it. This is due to the mixing of liquids with that from upper sprays and back mixing of liquids and gases. The final spray, if placed in the inlet duct, adds no height and has 0.5 N_{OG} .
5. The spray sections of a tower are normally spaced at three foot intervals.

SOLUTION *

1. Calculate the diameter of the tower. We do this using the gas velocity (ft/sec) and the gas flow rate (cu. ft/sec).

First, set up the equation for the gas velocity.

$$\text{velocity} = \frac{\text{gas flow rate}}{\text{area of cross section}}$$

Remember that the area of the cross section is a function of the tower diameter.

$$\text{Area} = \frac{\pi D^2}{4}$$

$$3 \text{ ft/sec} = \frac{25,000/60 \text{ ft}^3/\text{sec}}{\pi \frac{D^2}{4}}$$

What are the units of D? _____

Solve for D.

$$D = \sqrt{\frac{25,000/60}{3 \pi/4}} = \underline{\hspace{2cm}}$$

2. Calculate the Number of Transfer Units required.

$$N_{OG} = \ln y_1/y_2 = \ln \underline{\hspace{1cm}} / \underline{\hspace{1cm}} = \ln \underline{\hspace{2cm}}$$

Remember, we need the natural log of the ratio of the concentrations. This can be obtained directly from the \ln_e scales of your slide rule, or calculated by $\ln_e = 2.303 \log_{10}$, or from natural log tables. Take your pick!

*Answers are on page 133.

$$N_{OG} = \frac{\quad}{\quad} \quad \text{transfer units}$$

3. Now, determine the number of transfer units provided by a tower with several spray sections (take 5 or more). Remember, each lower spray has only 60% the efficiency of the section above it.

Spray Section	N_{OG}	
Top	0.700	(this is a starter)
2nd		
3rd		
4th		
5th		
Inlet		
<hr/>		
TOTAL	<hr/>	

Remember, we need only enough spray sections to get the **required** N_{OG} .

4. Calculate the efficiency of a spray tower with as many spray sections as you chose to give it (based on your answer to part 3). That is, calculate the outlet concentration with the relationship:

$$N_{OG} = \ln \frac{y_1}{y_2} = \underline{\hspace{2cm}}$$

You should have no trouble with this calculation now.

$$\frac{y_1}{y_2} = \text{anti } \ln_e N_{OG}$$

$$\frac{y_1}{y_2} = x = \underline{\hspace{2cm}}$$

$$y_2 = \frac{y_1}{x} = \underline{\hspace{2cm}}$$

5. Does this meet the specification?

ANSWERS

1. ft., 13.3
2. 500, 25, 20
3.0
3. 0.420, 0.252, 0.151, 0.091, 0.500
2.114
4. 2.114
8.3
60 ppm
5. NO

APPENDIX C: HYPOTHETICAL AVAILABLE HEATS FROM NATURAL GAS

Burners for combustion devices such as afterburners frequently use the oxygen present in the contaminated effluent stream. An example would be a natural gas-fired afterburner that takes in 60 percent of its combustion air from the atmosphere, and 40 percent from an air containing contaminated effluent stream.

One step in checking afterburner design is the calculation of the natural gas flow rate required to raise an effluent stream to a given temperature. A calculation such as this normally makes use of the available heat from natural gas. Available heat is the amount of heat remaining after the products of combustion from a cubic foot of natural gas are raised to the afterburner temperature. Available heat from natural gas is shown in Table D7.

If the afterburner gas burner takes a portion of the combustion air from the effluent stream, then the calculation of the gas flow rate becomes a trial-and-error procedure. By the method of hypothetical available heats given here, the trial-and-error solution is eliminated.

The natural gas used in illustrating this calculation procedure requires 10.36 cubic feet of air for theoretical combustion of 1 cubic foot of gas (Los Angeles area natural gas). Products of complete combustion evolved from this process are carbon dioxide, water, and nitrogen. If the combustion of 1 cubic foot of natural gas is thought of as taking place at 60°F, then a portion of the heat released by combustion must be used to raise the products of combustion from 60°F to the temperature of the device. The remaining heat is called available heat. This quantity represents the heat from natural gas that can be used to do useful work in the combustion device, such as heating an effluent stream in an afterburner.

Consider a gas-fired afterburner adjusted to provide a fraction, X , of theoretical air through the burner. If the contaminated effluent contains air, then the remaining air for combustion, $1-X$, is taken from the effluent stream. This means that a smaller quantity of effluent has to be heated by the natural gas, since a portion of the effluent is involved in the combustion reaction. Thus, a burner taking combustion air from an effluent stream can be fired to raise the temperature of the effluent at a natural gas input lower than that of a burner firing with all combustion air taken from the atmosphere.

Let the heat content of an effluent stream, at the desired final temperature, be H Btu/lb. Since 10.36 cubic feet of air is required for combustion of 1 cubic foot of natural gas, the weight of air taken from the effluent would be

$$W = (10.36)(1-X)(\rho) \quad (C1)$$

The heat contents of this secondary combustion air would be

$$Q = WH = (10.36)(1-X)(\rho)(H) \quad (C2)$$

where

W = weight of combustion air from the effluent per cubic foot of natural gas, lb/ft³ natural gas

H = heat content of the effluent at the required temperature, Btu/lb

X = fraction of theoretical combustion air, furnished as primary air through burner

ρ = density of air at 60°F
= 0.0764 lb/ft³.

Since Q Btu per cubic foot of natural gas is not required to heat the effluent, it can be added to the available heat, A , at the afterburner temperature, or

$$A' = A + Q \quad (C3)$$

where

A' = hypothetical available heat, Btu/ft³ natural gas

Q = heat content of secondary combustion air from equation C2.

Equation C3 is given in terms of temperature in the following equations:

Temperature, °F	Hypothetical available heat, Btu/ft ³ natural gas
600	871 + 104 (1-X)
700	846 + 124 (1-X)
800	821 + 144 (1-X)
900	798 + 167 (1-X)
1,000	773 + 185 (1-X)
1,100	747 + 206 (1-X)

HYPOTHETICAL AVAILABLE HEATS FROM NATURAL GAS

1,200	721 + 227 (1-X)
1,300	693 + 249 (1-X)
1,400	669 + 270 (1-X)
1,500	643 + 292 (1-X)
1,600	615 + 314 (1-X)
1,700	590 + 336 (1-X)
1,800	562 + 358 (1-X)

X = fraction of theoretical air furnished as the burner's primary air.

Hypothetical available heats are given in Table C1 for varying temperatures and percentages of primary air.

The use of this concept is illustrated in the following examples.

Example C1:

An afterburner is used to heat an effluent stream to 1,200°F by using 1×10^6 Btu/hr. The burner is installed and adjusted so that 60% of the theoretical combustion air is furnished through the burner, and the remainder is taken from the effluent. Determine the required natural gas rate.

1. The percent primary air is 60%, the required temperature is 1,200°F, the hypothetical available heat from Table C1 is 812 Btu/ft³ of gas.
2. Burner flow rate = $10^6/812 = 1,230$ cfh gas.

3. The gases in the afterburner will consist of:

- a. Products of combustion from 1,230 cfh natural gas with theoretical air - $1,230 \times 11.45$ scfh,
- b. the portion of the effluent not used for combustion air = effluent volume rate - $(1,230)(10.36)(1-X)$.

Example C2:

An afterburner is used to heat an effluent stream to 1,200°F by using 1×10^6 Btu/hr. The burner is installed and adjusted so that all the combustion air is taken from the effluent stream. Determine the natural gas rate.

This is equivalent to the burner's operating at 0% primary air.

1. At 1,200°F the hypothetical available heat is 948 Btu/ft³ for 0% primary air.
2. Burner flow rate = $10^6/948 = 1,058$ cfh.
3. Gases in afterburner will consist of:
 - a. Combustion products from 1,058 cfh natural gas with theoretical air = $1,058 \times 11.45$,
 - b. the portion of the effluent not used for secondary combustion air = effluent volume - $(1,058)(10.36)(1-X)$.

Table C1. HYPOTHETICAL AVAILABLE HEATS

Temp. °F	Hypothetical available heats, Btu/ft ³ gas										100
	% primary air through the burner										
	0	10	20	30	40	50	60	70	80	90	
600	975	965	954	944	933	923	913	902	892	881	271
700	970	958	945	933	921	908	896	883	871	859	296
800	965	950	936	922	907	893	878	864	850	835	
900	965	948	931	915	898	881	865	848	831	814	
1,000	958	939	921	902	884	865	847	828	810	791	
1,100	953	933	912	891	871	850	830	809	788	768	
1,200	948	926	903	880	858	835	812	789	767	744	
1,300	942	917	892	867	842	818	793	768	743	718	
1,400	939	912	885	858	831	804	777	750	723	696	
1,500	935	906	876	847	818	789	760	730	701	672	
1,600	929	897	866	834	803	772	740	709	677	646	
1,700	926	892	859	825	791	758	724	691	657	623	
1,800	920	885	849	813	777	741	706	670	634	598	562

MASS TRANSFER

GAS ABSORPTION THEORY

There are many theories describing the mechanism of mass transfer across an interface. The Lewis and Whitman Two-Film theory assumes a turbulent gas phase and a turbulent liquid phase, between which the turbulence dies out forming a laminar gas film and a laminar liquid film at the gas-liquid interface. The entire resistance to mass transfer is considered to exist in these two films through which the mass transfer is effected by molecular diffusion.

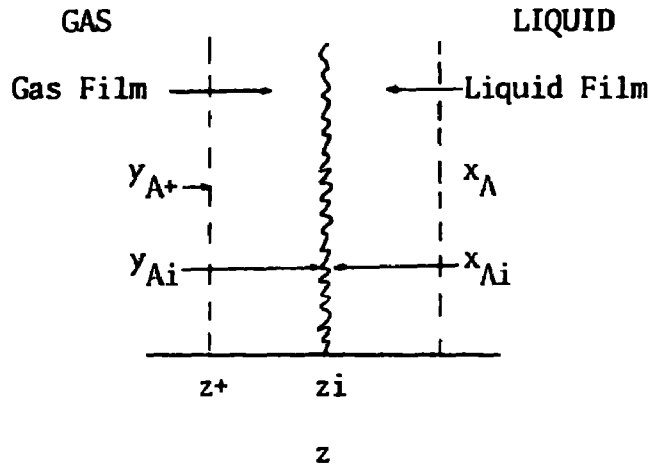


Figure 1.

Schematic of the Gas-Liquid Interfacial Region

For the steady state diffusion of gaseous material A in a binary mixture of A and B:

$$\left[\begin{array}{l} \text{Total flux of} \\ \text{material A with} \\ \text{respect to fixed} \\ \text{axes} \end{array} \right] = \left[\begin{array}{l} \text{Flux from} \\ \text{diffusion} \end{array} \right] + \left[\begin{array}{l} \text{Flux from} \\ \text{bulk flow} \end{array} \right] \quad (1)$$

$$\bar{N}_A = - \rho D_A \frac{dy_A}{dz} + y_A (\bar{N}_A + \bar{N}_B) \quad (1a)$$

$$\text{Let } \gamma = \bar{N}_B / \bar{N}_A$$

Then

$$1 = - \rho \frac{D_A}{\bar{N}_A} \frac{dy_A}{dz} + y_A (1 + \gamma)$$

$$dz = \rho \frac{D_A}{\bar{N}_A} \frac{dy_A}{[y_A (1 + \gamma) - 1]} \quad (2)$$

Integrating across the distance from the gas film to the gas-liquid interface (z_+ to z_i):

$$\int_{z_+}^{z_i} dz = \Delta z = \rho \frac{D_A}{\bar{N}_A} \int_{y_{A+}}^{y_{Ai}} \frac{dy_A}{y_A (1 + \gamma) - 1} \quad (2a)$$

$$\bar{N}_A = \rho \frac{D_A}{\Delta z} \left[\frac{1}{1 + \gamma} \right] \ln \left[\frac{y_{Ai} (1 + \gamma) - 1}{y_{A+} (1 + \gamma) - 1} \right] \quad (3)$$

or in the alternate form of P_A and P ,

$$\bar{N}_A = \frac{P}{RT} \frac{D_A}{\Delta z} \left[\frac{1}{1 + \gamma} \right] \ln \left[\frac{P_{Ai} (1 + \gamma) - P}{P_{A+} (1 + \gamma) - P} \right] \quad (3a)$$

For the specific case of gas absorption, unimolal unidirectional diffusion occurs in the gas (diffusion through a stagnant gas), $\bar{N}_B = 0$, and therefore, $\gamma = 0$. The general expression for the flux of A may be written as follows:

$$\bar{N}_A = \frac{\rho D_A}{\Delta z} \ln \left[\frac{1 - y_{Ai}}{1 - y_{A+}} \right] \quad (4)$$

$$\text{Let } (1 - y_A)_{LM} = \frac{(1 - y_{Ai}) - (1 - y_{A+})}{\ln \left[\frac{1 - y_{Ai}}{1 - y_{A+}} \right]} = \frac{y_{A+} - y_{Ai}}{\ln \left[\frac{1 - y_{Ai}}{1 - y_{A+}} \right]} \quad (5)$$

Then,

$$\bar{N}_A = \frac{\rho D_A}{\Delta z (1 - y_A)_{LM}} (y_{A+} - y_{Ai}) \quad (6)$$

or in terms of P_A and P ,

$$\bar{N}_A = \frac{P D_A}{RT \Delta z (P - P_A)_{LM}} (P_{A+} - P_{Ai}) \quad (6a)$$

It is assumed that local equilibrium prevails at the interface. If the gas and liquid interfacial concentrations can be related by a form of Henry's Law, then:

$$y_{Ai} = m x_{Ai} \quad (7)$$

If the diffusivity is constant, equations (6) and (6a) may approximate the flux at any point as a constant times a concentration driving force:

$$\bar{N}_A = k_g (y_A - y_{Ai}) = k_g' (P_A - P_{Ai}) \quad (8)$$

where

$$k_g = \frac{\rho D_A}{\Delta z (1 - y_A)_{LM}} \quad (8a)$$

and

$$k_g' = \frac{P D_A}{RT \Delta z (P - P_A)_{LM}} \quad (8b)$$

or

$$k_g = P k_g' \quad (8c)$$

The individual gas phase mass transfer coefficient for the transfer of material A, k_g (sometimes written as k_{Ag}), is analogous to the conductance for material A across the laminar gas film.

The expression for mass flux could have just as easily been developed considering the mass flux across the liquid film (since steady state conditions are assumed). Equation (8) would then become:

$$\bar{N}_A = k_e (x_{Ai} - x_A) = k_e' (c_{Ai} - c_A) \quad (9)$$

where

$$k_e = k_e' \rho_e \quad (9a)$$

Interfacial concentrations are difficult if not impossible to measure; the flux equations are therefore written for any point in terms of overall mass transfer coefficients (which account for the resistance in both the gas and liquid films) and overall concentration driving forces.

$$\bar{N}_A = K_g (y_A - y_A^*) \quad (10)$$

or analogously,

$$\bar{N}_A = K_e (x_A^* - x_A) \quad (10a)$$

The expressions relating the individual to the overall mass transfer coefficients are as follows:

$$\frac{1}{K_g} = \frac{1}{k_g} + \frac{m}{k_e} \quad (11)$$

$$\frac{1}{K_e} = \frac{1}{k_e} + \frac{1}{m k_g} \quad (11a)$$

Whenever an overall process consists of several sequential steps, the overall rate of the process may be governed by the rate of the slowest step. If the resistance to mass transfer is high in the gas film relative to the liquid film ($1/k_g \gg m/k_e$), then mass transfer is said to be gas phase controlled and equation (11) becomes:

$$\frac{1}{K_g} \approx \frac{1}{k_g} \quad (11b)$$

Similarly when mass transfer is liquid phase controlling ($1/k_g \ll m/k_e$) equation (11) becomes:

$$\frac{1}{K_g} \approx \frac{m}{k_e} \quad (11c)$$

The same arguments could be applied to equation (11a) with similar equations resulting.

DESIGN CONSIDERATIONS FOR A COUNTERCURRENT CONTACTOR

Let a represent interfacial contact area per unit tower volume.
 Let V represent the empty tower volume.
 Consider a tower of differential height having a unit cross-sectional area (see Figure 2), then,

$$dV = (1) dz = dz$$

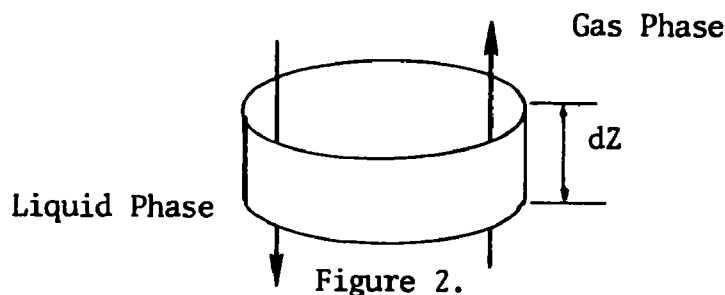


Figure 2.
Differential Element of Tower

and for the differential element,

$$\left[\begin{array}{l} \text{The rate of} \\ \text{transfer of} \\ \text{material A per} \\ \text{unit tower cross} \\ \text{section} \end{array} \right] = \left[\begin{array}{l} \text{Flux of A} \\ \text{(see Eqn. (10))} \end{array} \right] \times \left[\begin{array}{l} \text{Interfacial} \\ \text{area per unit} \\ \text{tower volume} \end{array} \right] \times \left[\begin{array}{l} \text{Tower volume} \\ \text{per unit tower} \\ \text{cross section} \end{array} \right] \quad (12)$$

$$d (G_m y_A) = (\bar{N}_A) (a) (dZ) \quad (12a)$$

If the left side of equation (12a) is expanded,

$$d (G_m y_A) = G_m d y_A + y_A d G_m$$

But from a material balance on the transferring component in the gas phase:

$$d G_m = d (G_m y_A)$$

$$\therefore d G_m = G_m d y_A + y_A d G_m$$

$$\text{and } d G_m = \frac{G_m d y_A}{1 - y_A}$$

$$\text{then, } d (G_m y_A) = \frac{G_m d y_A}{1 - y_A} \quad (13)$$

Substituting equations (10) and (13) into (12a) the following is obtained:

$$\frac{G_m d y_A}{1 - y_A} = K_g (y_A - y_A^*) (a) (dZ) \quad (14)$$

Integrating equation (14) across the tower gives the most general form of the design equation.

$$Z = \int_{y_{A2}}^{y_{A1}} \frac{G_m}{K_g a} \frac{d y_A}{(1 - y_A)(y_A - y_A^*)} \quad (15)$$

Empirical results indicate that k_g and k_L are proportional to $G_m^{0.8}$ and $L_m^{0.8}$. Equations (6) and (8a) suggest that $[G_m/K_g a (1 - y_A)_{LM}]$ should be constant. The average of this term evaluated at the top and bottom of the tower is then taken from the integral:

$$Z = \left[\frac{G_m}{K_g a (1 - y_A)_{LM}} \right]_{ave.} \times \int_{y_{A2}}^{y_{A1}} \frac{(1 - y_A)_{LM} dy_A}{(1 - y_A)(y_A - y_{A*})} \quad (16)$$

Although equation (16) is based on overall gas phase concentrations, an analogous equation can be written based on overall liquid phase concentrations.

$$Z = \left[\frac{L_m}{K_L a (1 - x_A)_{LM}} \right]_{ave.} \times \int_{x_{A1}}^{x_{A2}} \frac{(1 - x_A)_{LM} dx_A}{(1 - x_A)(x_{A*} - x_A)} \quad (16a)$$

Equations (16) and (16a) are of the following form[†]:

$$Z = H_{OG} \times N_{OG} \quad (17)$$

$$Z = H_{OL} \times N_{OL} \quad (17a)$$

Number of Transfer Units

Qualitatively the number of transfer units is a measure of the degree of separation required. Evaluation of the number of transfer units is generally accomplished by a graphical integration of the second term in equation (16), or in equation form,

$$N_{OG} = \int_{y_{A2}}^{y_{A1}} \frac{(1 - y_A)_{LM} dy_A}{(1 - y_A)(y_A - y_{A*})} \quad (18)$$

[†]Although the development of equations is straight forward based on either gas phase or liquid phase concentrations, only the gas phase concentrations will be considered throughout the remainder of this discussion.

For the following conditions, simplifications to equation (18) can be made.

- (1) Contaminant concentration, y_A , is low throughout the contactor. (From the material balance on A for the non-reacting system, one implication is a straight operating line with slope L_m/G_m .)
- (2) Straight equilibrium line with slope m . Condition (1) yields equation (19) which can be evaluated by graphical integration.

$$N_{OG} = \int_{y_{A2}}^{y_{A1}} \frac{(1 - y_A)_{LM} d y_A}{(1 - y_A)(y_A - y_{A}^*)} \cong \int_{y_{A2}}^{y_{A1}} \frac{d y_A}{(y_A - y_{A}^*)} \quad (19)$$

Under conditions (1) and (2), equation (19) can be further simplified to the form,

$$N_{OG} = \frac{1}{1 - \frac{mG_m}{L_m}} \ln \left[\left[1 - \frac{mG_m}{L_m} \right] \frac{(y_{A1} - mx_{A2})}{(y_{A2} - mx_{A2})} + \frac{mG_m}{L_m} \right] \quad (20)$$

This equation is plotted in Figure 3 in the form N_{OG} vs $\ln \left[\frac{(y_{A1} - mx_{A2})}{(y_{A2} - mx_{A2})} \right]$

for different values of $\frac{mG_m}{L_m}$.

This plot, the Colburn Diagram, allows easy solution for N_{OG} .

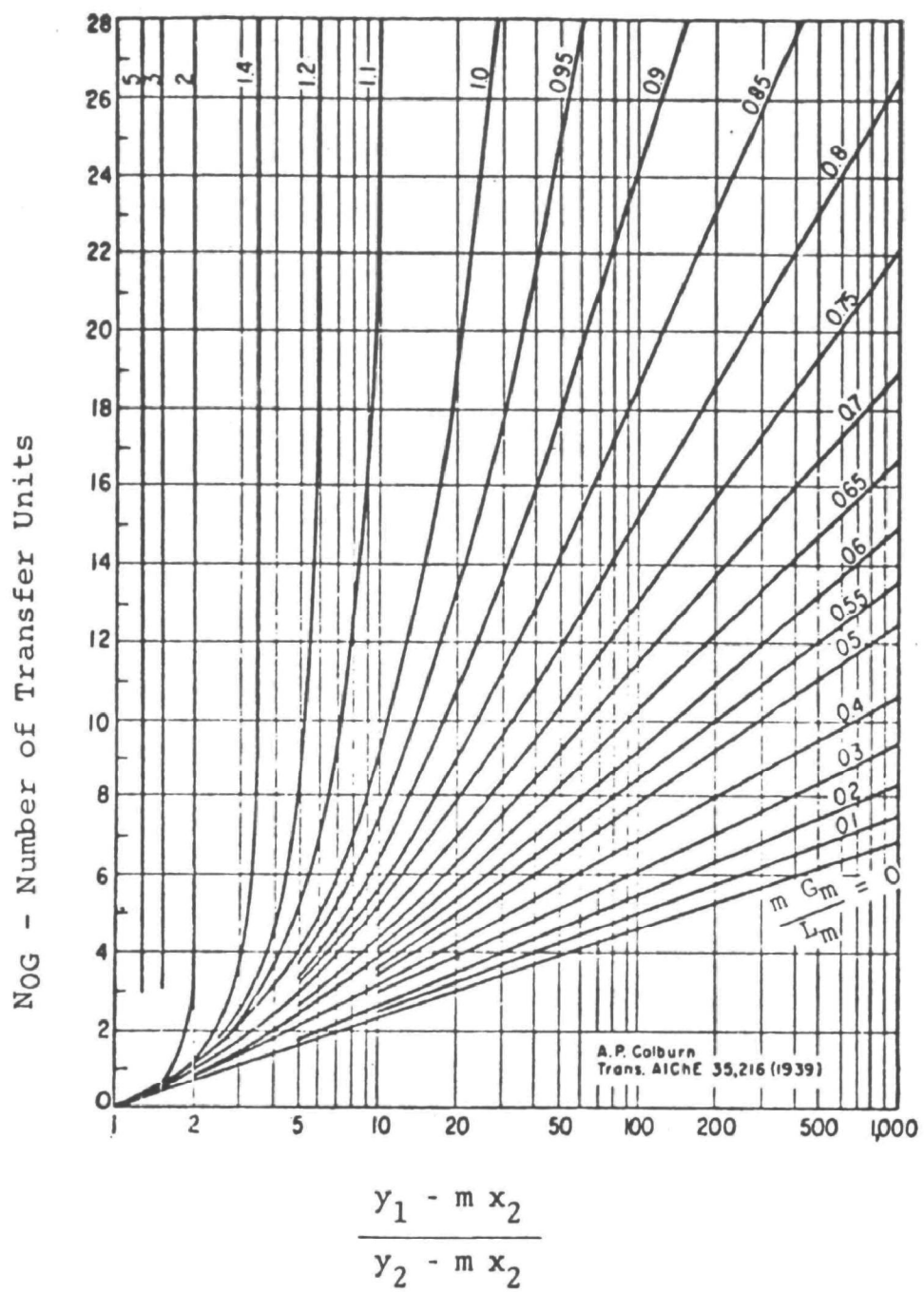


FIGURE 3 COLBURN DIAGRAM

If condition (1) exists and, instead of condition (2), y_A^* approaches zero, as is the case for a very rapid chemical reaction occurring in the liquid phase or for an extremely soluble contaminant ($m \rightarrow 0$), then equation (19) can be simplified as follows:

$$N_{OG} = \int_{y_{A2}}^{y_{A1}} \frac{dy_A}{(y_A - y_A^*)} \cong \int_{y_{A2}}^{y_{A1}} \frac{dy_A}{y_A} = \ln \frac{y_{A1}}{y_{A2}} \quad (21)$$

Application of equation (21) has been referred to as the "Transfer Unit Approach." The underlying assumptions should always be considered before this equation is applied. When equation (21) is applicable, the following results are easily shown:

<u>% Efficiency</u>	<u>N_{OG}</u>
98	4
95	3
86	2
63	1

Height of a Transfer Unit

Qualitatively the height of a transfer unit is a measure of the height of a contactor required to effect a standard separation, and it is a function of the gas flow rate, the liquid flow rate, the type of packing, and the chemistry of the system. In equation form,

$$H_{OG} = \left[\frac{G_m}{K_g a (1 - y_A)} LM \right]_{ave.} \quad (22)$$

This type of information appears in the literature as H_{OG} , $K_g a$, or $k_g a$, $k_l a$ and can be used in previously presented equations for tower design. If the data are not available, pilot plant studies are run or approximations are made.

Individual mass transfer coefficient data can be roughly estimated from available data using the following formula:

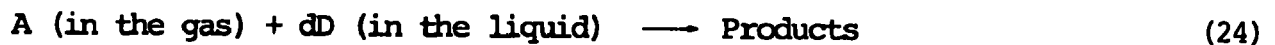
$$\frac{k_\alpha}{k_\beta} \cong \left[\frac{D_\alpha}{D_\beta} \right]^{1/2} \quad (23) \dagger\dagger$$

†† Note that although the Two Film Theory would have predicted an exponent of unity, more sophisticated surface renewal theories and empirical results support the exponent of 0.5 as in equations (23) and (23a). Note also that in order to apply this equation the parameters should all be referring to films of the same phase, with the same thicknesses. If k_α is the mass transfer coefficient for α through a gas film of α and an inert, δ , then k_β should be the similar quantity for β through a gas film of β and δ . D_α and D_β should be the respective gas phase diffusivities for α and β through their mixtures with inert, δ .

For the limiting cases of either gas or liquid phase controlling the rate of mass transfer, height of transfer unit data may be similarly approximated.

$$\checkmark \quad \frac{H_\alpha}{H_\beta} \cong \left[\frac{D_\alpha}{D_\beta} \right]^{1/2} \quad (23a)$$

Consider the following chemical reaction,



For the case where a chemical reaction occurs in addition to physical absorption, the relative rates of chemical reaction versus mass transfer must be considered. When the following condition is met, the special case exists in which mass transfer controls the overall rate of the process, the chemical reaction is extremely rapid, and the reaction zone is located at the gas-liquid interface:

$$\frac{k_D \ell^x D}{d} \geq k_{Ag} y_A \quad (25)$$

When the above condition is met at both ends of the contactor, there is no longer a liquid film resistance, and individual and overall gas phase mass transfer coefficients become approximately equal (refer to equations (11) and (11b)).

$$K_g \cong k_g \quad (26)$$

The appropriate change in design equations (15), (16), or (22) should be made before their application to design. The cases for which equation (25) does not apply are much more complex and will not be considered in this discussion.

Comments

The remaining task of choosing the tower diameter will be left to the design engineer. The methods involved are outlined in the literature and are straightforward based on pressure drop, flooding velocity data, and correlations for the type of packing to be used.

Although the design treatment of this discussion applies only to counter-current contactors, simple modifications are required to extend its applicability to (less efficient) concurrent towers.

Remembering that generally the best efficiency is obtained with counter-current contactors, the air pollution plan review engineer would do well to consider their performance as a bound with which to determine the reasonableness of the stated performance of submitted non-countercurrent designs.

NOMENCLATURE

A	material A, the gaseous contaminant
a	interfacial area per unit tower volume
α	material α
B	material B
β	material β
c	molar concentration, (moles/volume)
D	reactant material D
d	stoichiometric coefficient
\mathcal{D}	diffusivity
\mathcal{D}_A	diffusivity of material A in B
δ	inert material δ
G_m	molar gas flow rate, [moles/(time x tower cross-sectional area)]
γ	ratio of N_A / N_B
H	height of a transfer unit
K	overall mass transfer coefficient
k	individual mass transfer coefficient
L_m	molar liquid flow rate, [moles/(time x tower cross-sectional area)]
m	slope of the equilibrium line when plotted on an x - y diagram
N	number of transfer units
\bar{N}	molar flux, [moles/(time x interfacial area)]
P	total pressure
P	partial pressure
R	ideal gas law constant
ρ	total molar density, (total moles/volume)
T	absolute temperature

V	empty tower volume
x	mole fraction concentration in liquid phase
x *	mole fraction concentration in the liquid which would be in equilibrium with the existing gas at that point in the contactor
y	mole fraction concentration in gas phase
y *	mole fraction concentration in the gas which would be in equilibrium with the existing liquid at that point in the contactor
z	distance through which diffusion occurs
Δz	film thickness, $z_i - z_+$
Z	tower height

Subscripts

A	material A, the gaseous contaminant
α	material α
B	material B
β	material β
D	reactant material D
δ	inert material δ
g	gas
i	located at the interface
LM	log-mean
ℓ	liquid
OG	based on the overall gas phase concentrations
OL	based on the overall liquid phase concentrations

- 1 located at the gas inlet end of a countercurrent contactor
- 2 located at the liquid inlet end of a countercurrent contactor
- + located at the commencement of the laminar gas film

Superscript

based on concentrations expressed in partial pressures for
gases, or molar density for liquids

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415 - CONTROL OF GASEOUS EMISSIONS

Lecture Handout - Condensation and Combustion

by

L. Theodore

Frequently, it becomes necessary to handle a condensable vapor and a noncondensable gas. The most common mixture is, of course, water vapor and air. A mixture of organic vapors and air is another such example; and this mixture can cause pollution problems. Condensers can be used to collect organic emissions discharged to the atmosphere. This is accomplished by lowering the temperature of the gaseous stream although an increase in pressure will produce the same result. There are two basic types of condensers used for control - contact and surface. In contact condensers, the gaseous stream is brought into direct contact with a cooling medium so that the vapors condense and mix with the coolant. The most commonly used unit is the surface condenser (heat exchanger). Here, the vapor and the cooling medium are separated by the exchanger wall. Since high removal efficiencies cannot be obtained with low condensable vapor concentrations, condensers are used as a preliminary unit that can be followed by a more efficient control device such as a reactor, absorber or adsorber.

The phase equilibrium constant is employed in both chemical (combustion) reaction operations and organic removal (condensation) calculations. The phase equilibrium constant for component i , K_i , is defined by

$$K_i = y_i/x_i$$

where

y_i = mole fraction of i in the vapor phase

x_i = mole fraction of i in the liquid phase.

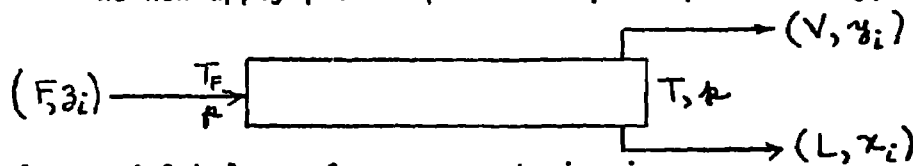
If the vapor phase behaves as an ideal gas and the liquid phase is assumed to be an ideal solution

$$K_i = p^*/p$$

where p^i = vapor pressure of i
 p = total pressure of the system.

This equilibrium constant is therefore seen to be a strong function of temperature and pressure. Numerical values for K can be obtained directly from the attached figure.

We now apply phase equilibrium principles to a typical condenser.



A material balance for component i gives

$$F z_i = L x_i + V y_i$$

where z_i = mole fraction of feed
 F = moles of feed
 L = moles of liquid
 V = moles of vapor

Since

$$K_i = y_i / x_i$$

some manipulation of the above two equations yields

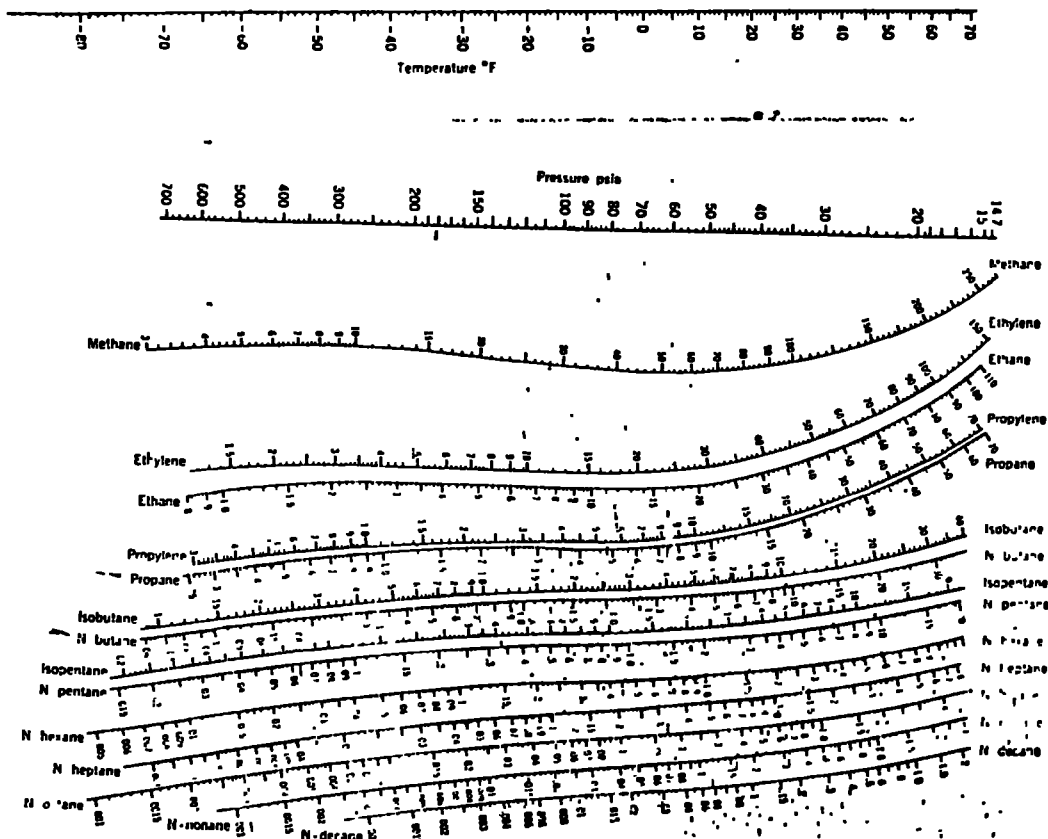
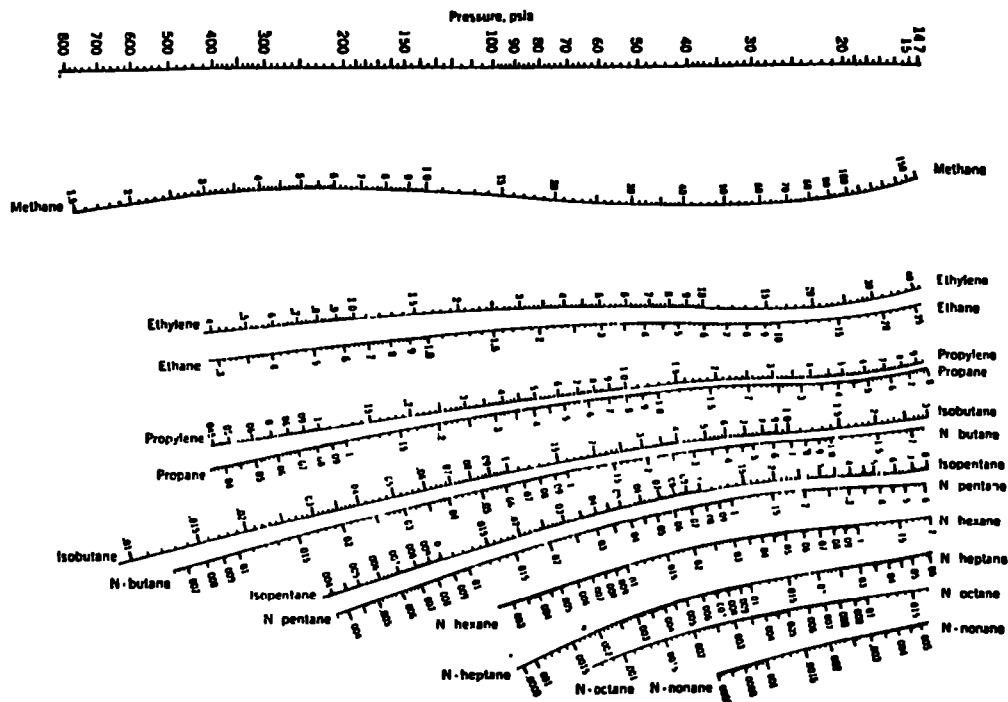
$$y_i = \frac{F z_i}{(L/K_i) + V}$$

We sum this equation to obtain

$$\sum_{i=1}^m y_i = 1.0 = \sum_{i=1}^m \frac{F z_i}{(L/K_i) + V} \quad (1)$$

where m = number of components in the system.

The usual energy (enthalpy) balance calculations can be applied to determine the rate of heat transfer in the condenser. Standard equations are employed to design the heat exchanger.



Example. A 9,700 ft³/min (80°F, 1 atm) process gas stream containing 85% air, 10% heptane, 3.1% hexane, and 1.9% pentane is to be condensed in a unit so that only 0.5% combined hydrocarbons remain in the vapor phase. Determine the temperature and pressure of the unit necessary to carry out this operation. Assume the minimum temperature that can be achieved in the condenser is 20°F.

Solution: Assume all the air remains in the vapor phase since

$$K_{\text{air}} \rightarrow \infty$$

An overall material balance calculation gives

$$F = 1.0$$

$$L = 0.145$$

$$V = 0.855$$

The values of each of the mole fractions in the vapor phase are calculated from Eq. (1). The following table provides the results of a trial and error calculation for the pressure at the minimum temperature:

K@20°F &		
<u>Component</u>	<u>300 psia</u>	<u>y</u>
air	∞	0.995
pentane	0.02	0.00234
hexane	0.0058	0.00120
heptane	0.0021	0.00144
$\Sigma =$		<u>0.99998</u>

The operating conditions are 20°F and 300 psia. The result clearly shows that condensation is not economically feasible for separating light hydrocarbons from air.

Example. A 23,150 ft³/min stream at 530°F and 14.9 psia and containing 60% air, 4% n-octane, 24% n-nonane, and 12% n-decane is to be condensed in a heat exchanger operating with a discharge temperature of 150°F. Calculate the mole fraction of each hydrocarbon in the vapor phase of the exit stream.

Solution. The values of each of the mole fractions in the vapor phase are calculated from Eq. (1) for assumed values of L and V. The following table provides the results of the calculation with V = 0.63 and L = 0.37.

<u>Component</u>	<u>K @ 150°F</u> <u>14.9 psia</u>	<u>y</u>
air	∞	0.953
octane	0.15	0.0129
nonane	0.05	0.0295
decane	0.015	0.005
		<hr/>
		$\Sigma = 1.0004$

The fraction of the inlet hydrocarbons remaining in the vapor phase is therefore

$$\frac{0.03}{0.40} = 0.075 \text{ or } 7.5\%$$

Example. In order to meet recently updated pollution specifications for discharging hydrocarbons to the atmosphere, the pollutants in the gas stream in the ^{1st} previous example must be reduced to 99.5% of its present concentration. Due to economic considerations, it is proposed to meet the above requirement by combusting the hydrocarbons in a thermal reactor operating at 1500°F, rather than further increasing the pressure or decreasing the temperature of the condenser. The gas and methane (fuel) are to be fed to the reactor at 80°F and 1 atm. Calculate fuel requirements and design the proposed reactor.

Solution. The fuel requirements are obtained using the calculational procedures outlined in class. Using the data in the manual and solving the enthalpy balance equation for a reaction (discharge) temperature of 1500°F gives a methane to gas ratio of

$$0.0326; \text{ft}^3 \text{CH}_4/\text{ft}^3 \text{ gas or mole CH}_4/\text{mole gas}$$

We now calculate the volumetric flow rate in the reactor at 1500°F neglecting the volume change associated with both the combustion of the fuel and the hydrocarbons.

$$9,700 \cdot \left(\frac{1960}{540} \right) = 35,200 \text{ cfm}$$

A velocity of 20 ft/sec is suggested in the reactor section. (A slightly higher velocity is usually employed in the burner.) The cross-sectional area required is then

$$\frac{35,200}{(60)(20)} = 29.35 \text{ ft}^2$$

The reactor diameter is therefore 6 ft.

Kinetic considerations dictate the length (and volume) of the reactor. It is common practice to treat a mixture of reactive hydrocarbons in terms of a single hydrocarbon component undergoing a first order irreversible reaction. A reaction velocity constant for the mixture of 7.8 (sec)^{-1} is recommended at this temperature. We employ the plug-flow model, i.e.,

$v_z \frac{dc_A}{dz} = -k_A c_A$, or $Q \frac{dc_A}{dV} = -k_A c_A$
 For 99.5% removal, we have

$$dz = -\left(\frac{v_z}{k_A}\right) \frac{dc_A}{c_A}, \text{ or } dV = -\left(\frac{Q}{k_A}\right) \frac{dc_A}{c_A}$$

Integrating gives

$$L = -\left(\frac{v_z}{k_A}\right) \ln\left(\frac{c_A}{c_{A_0}}\right), \text{ or } V = -\left(\frac{Q}{k_A}\right) \ln\left(\frac{c_A}{c_{A_0}}\right)$$

where

$$\frac{c_A}{c_{A_0}} = \frac{0.005}{1.0} = 0.005$$

Therefore,

$$L = -\left(\frac{20}{7.8}\right)(-5.3), \text{ or } V = -\left(\frac{35,200}{7.8}\right)(-5.3) \\ = 13.6 \text{ ft} \qquad \qquad \qquad = 402 \text{ ft}^3$$

Note that this corresponds to an average residence time of 0.68 sec.

REVIEW OF FANS & BLOWERS

1. TO CALCULATE A SYSTEM CURVE FROM ANY ONE KNOWN OPERATING POINT FOR AN EXHAUST SYSTEM

$$SP_2 = SP_1 \left(\frac{VOL_2}{VOL_1} \right)^2$$

2. TO CALCULATE FAN CHARACTERISTICS FOR ANY SPEED FROM A FAN RATING TABLE FOR 70°F

$$VOL_2 = VOL_1 \left(\frac{RPM_2}{RPM_1} \right)$$

$$SP_2 = SP_1 \left(\frac{RPM_2}{RPM_1} \right)^2$$

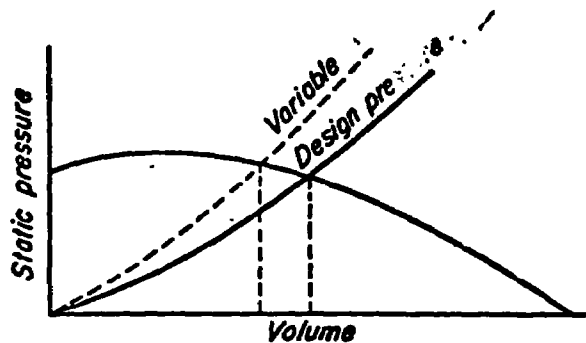
$$HP_2 = HP_1 \left(\frac{RPM_2}{RPM_1} \right)^3$$

3. TO CORRECT FAN CHARACTERISTICS FOR OPERATION AT TEMPERATURES OTHER THAN 70°F

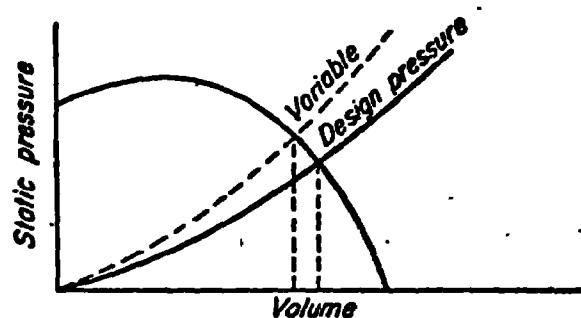
$$CFM_2 = CFM_1$$

$$SP_2 = SP_1 \left(\frac{T_1}{T_2} \right)$$

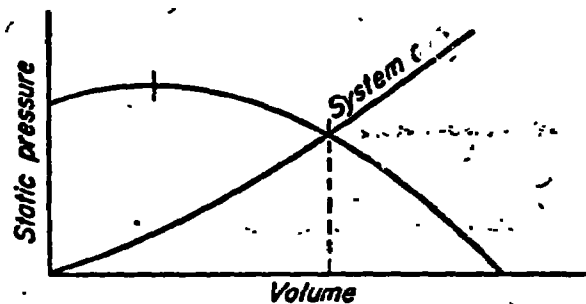
$$HP_2 = HP_1 \left(\frac{T_1}{T_2} \right)$$

**POOR SELECTION**

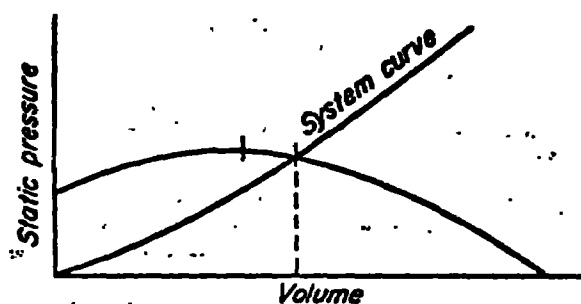
Fan with flat pressure curve gives wide volume variation with pressure change.

**GOOD SELECTION**

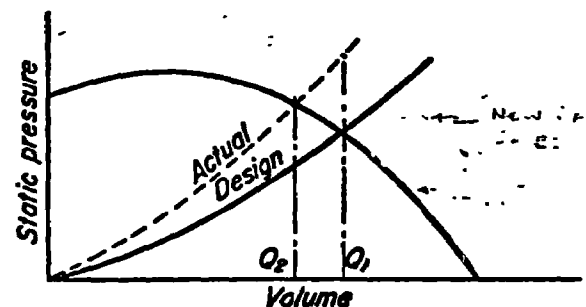
Fan with steep pressure curve gives small volume variation with pressure change.

EFFECT OF FAN CURVE SLOPE**POOR SELECTION**

Small fan used with system curve crossing fan too far to right of peak.
Excessive horsepower
Low efficiency

**GOOD SELECTION**

Large fan used with curve crossing fan curve to right of peak.
Low horsepower
High efficiency

EFFECT OF FAN SIZE

Volume of air delivered less than design flow
To obtain design flow:

increase fan speed $\frac{Q_1}{Q_2}$

increase fan SP $\left(\frac{Q_1}{Q_2}\right)^2$

increase fan BHP $\left(\frac{Q_1}{Q_2}\right)^3$

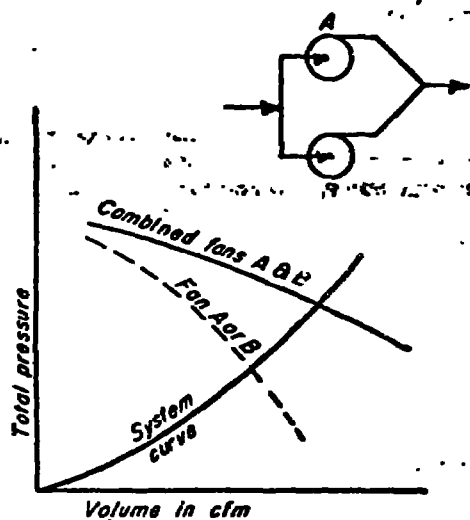
EFFECT OF VARIATION BETWEEN DESIGN AND ACTUAL RESISTANCE

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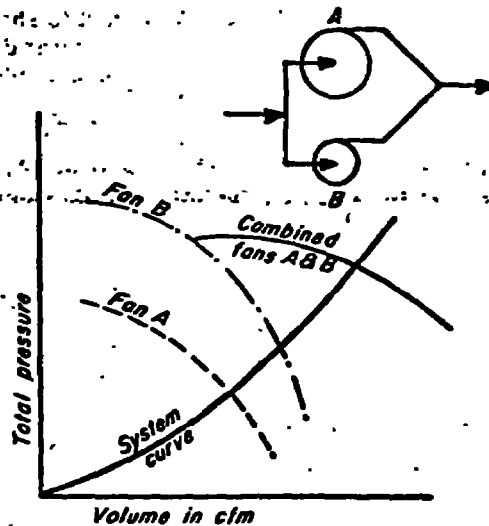
FAN SELECTION

DATE 11-68

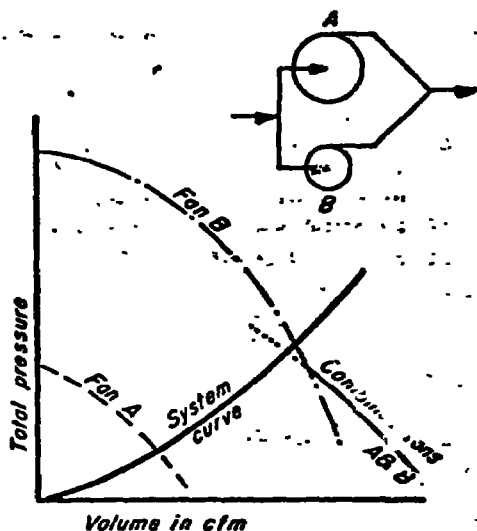
Fig. 10-7



Two identical fans
Recommended for best efficiency



Two different fans
Satisfactory



Two different fans
Unsatisfactory

When system curve does not cross combined fan curve, or crosses projected combined curve before fan B, fan B will handle more air than fans A and B in parallel.

Notes:

1. To establish combined fan curve, the combined air volume, Q_c , is the sum of individual fan air volumes at points of equal pressure.
2. To establish system curve, include losses in individual fan connections.
3. System curve must intersect combined fan curve or higher pressure fan may handle more air alone.

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**FANS
PARALLEL OPERATION**

DATE

1-72

Fig. 10-8