Air

&EPA

APTI
Course 415
Control of Gaseous Emissions

Student Workbook

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Notice

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Availability

This document is issued by the Manpower and Technical Information Branch, Control Programs Development Division, Office of Air Quality Planning and Standards, USEPA. It was developed for use in training courses presented by the EPA Air Pollution Training Institute and others receiving contractual or grant support from the Institute. Other organizations are welcome to use the document.

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Others may obtain copies, for a fee, from the National Technical Information Service (NTIS), 5825 Port Royal Road, Springfield, VA 22161.

Sets of slides and films designed for use in the training course of which this publication is a part may be borrowed from the Air Pollution Training Institute upon written request. The slides may be freely copied. Some films may be copied; others must be purchased from the commercial distributor.

Course Description

This course is a four-day lecture course dealing with the sources and control methods associated with gaseous air pollutants. The course presents the fundamental concepts of the operation of gaseous emission control equipment for stationary sources. The lessons include a description of equipment operation, control equipment operating parameters that affect efficiency, and examples of equipment types used in selected industrial applications. Lecture topics include a discussion of the principles of absorption, adsorption, combustion, and condensation. Problem sessions are held in which the student calculates equipment efficiencies and determines if equipment design meets minimum engineering specifications.

How to Use This Workbook

This workbook is to be used during the course offering. It consists of two parts: the first contains a chapter corresponding to each of the fourteen lessons, and the second contains five sets of problems.

Each chapter includes a listing of the lesson goal, the lesson objectives, any special references in Part 1 that might be helpful to you, and several pages of black-and-white line-art reproductions of selected lecture slides. The reproductions are intended to follow generally the slide presentations given in the lecture. However, the instructor may on occasion change the order or present new material not included in the workbook. It is therefore recommended that the student take notes throughout the course and not rely on the graphic reproductions as representing the total course content.

Part 2 of this workbook consists of five problem sets. Each set contains several problems and any graphs or figures that you will need to work the problems.

Table of Contents

*The solution is included.

Figures

*The solution is included.

Nomenclature

SI

a	surface area available for absorption per unit volume of tower, ft^2/ft^3	m^2/m^3
A	area, ft^2	m^2
AHP	air horsepower, hp	kW
BHP	brake horsepower, hp	kW
C_p	specific heat, Btu/lb°F	J/kg °C
$\overline{C}_p$	average specific heat, Btu/lb °F	J/kg °C
c	concentration	
C_s	saturation capacity of adsorber (weight %)	
C	empirical constant in BET equation	
d_t	diameter, ft	m
D	bed depth (adsorber), ft	m
D	diffusivity, ft^2/sec	m^2/s
E	efficiency	
f	percent of flooding	
F	absorbed packing factor	
ΔF	free energy change, Btu/mol	J/mol
g_c	gravitational constant, lb ft^2/lb$_f$ sec^2	kg m/N s^2
G	gas flow rate, lb/min	kg/min
G	superficial gas flow rate lb/min ft^2	kg/min m^2
G_m	gas molar flow rate, lb mol/min	kg mol/min
H	Henry's Law constant, atm/mol fraction	kPa/mol fraction
H	enthalpy, Btu/lb	J/g
H_c	heat of combustion, Btu/ft^3 of fuel	J/m^3
H_s	sensible heat, Btu/lb	J/g
H_v	latent heat of vaporization, Btu/lb	J/g
HV_G	gross heating value, Btu/ft^3	J/m^3
HV_N	net heating value, Btu/ft^3	J/m^3
H_A	available heat, Btu/ft^3	J/m^3
H_{OG}	height of a transfer unit based on overall gas phase, ft	m
H_{OL}	height of a transfer unit based on overall liquid phase, ft	m
h_r	system resistance, in. of water	cm of water
k_ℓ	individual mass transfer coefficient based on liquid phase, lb mol/hr ft^2 atm	kg mol/h m^2 kPa
k_s	individual mass transfer coefficient based on gas phase, lb mol/hr ft^2 atm	kg mol/h m^2 kPa
K_G	overall mass transfer coefficient based on gas phase, lb mol/hr ft^2 atm	kg mol/h m^2 kPa
K_L	overall mass transfer coefficient based on liquid phase, lb mol/hr ft^2 atm	kg mol/h m^2 kPa

L	liquid flow rate, lb/min	kg/min	
L'	superficial liquid flow rate lb/min ft^2	kg/min m^2	
L$_m$	liquid molar flow rate lb mol/min	kg mol/min	
m	slope of a line		
$\dot{m}$	mass flow rate, lbs/hr	kg/h	
MW	molecular weight, lb mol	g mol	
M$_{ar}$	mass of theoretical air per unit mass of fuel combusted		
N$_{OG}$	number of transfer units based on overall gas coefficient		
N$_{OL}$	number of transfer units based on overall liquid coefficient		
N	fan speed, rpm		
N$_A$	mass flux, lb mol/min ft^2	kg mol/min m^2	
P	total pressure, psia	kPa	
P$_b$	barometric or atmospheric pressure, psia	kPa	
p	partial pressure, psia	kPa	
p^o	vapor pressure, psia	kPa	
P$_s$	gage or static pressure, psia	kPa	
P	power, hp	kW	
Q	volumetric flow rate, cfm	m^3/min	
q	heat rate, Btu/hr	J/h	
R	ideal gas constant		
Re	Reynolds number		
T	temperature, °F	°C	
ΔT_m	mean temperature difference, °F	°C	
U	heat transfer coefficient, Btu/hr/ft^2	kJ/h/m^2	
V	volume, ft^3	m^3	
v	velocity, ft/sec	m/s	
V$_{ar}$	volume of theoretical air required to combust a unit volume of fuel		
X	mol fraction in liquid phase		
Y	mol fraction in gas phase		
Z	packed tower height, ft	m	
ϱ	density, lb/ft^3	kg/m^3	
τ	shearing stress, lb$_f$/ft^2	kPa/m^2	
ν	kinematic viscosity, ft^2/sec	m^2/s	
μ	viscosity, centipoise	mPa·s	
Θ	residence time, sec	s	
ϕ	ratio of specific gravity of water to solvent		
ϵ	flooding correlation ordinate		

Part 1
Lessons

Chapter 1
Course Goal and Objectives

Course Goal

The goal of Course 415 is to present characteristics and operating features of gaseous air pollutant emission control devices. Upon completion of the course, you will be able to evaluate the gaseous emission control characteristics of emission control equipment shown in plans filed with a governmental air pollution control agency for a permit to construct or modify an air pollution source. You will also be able to evaluate the gaseous emission control characteristics of operating air pollutant sources.

Course Objectives

At the end of this course, you should be able:
1. To use the ideal gas law, laws pertaining to temperature, pressure and volume corrections, the properties of viscosity, specific heat and the Reynolds number in gaseous emissions control calculations.
2. To calculate gross Heat value, available heat, and fuel requirements for incineration.
3. To evaluate (given sets of design plans for flares, catalytic reactors, and incinerators) in terms of equipment efficiency, problems which may impair efficiency, and appropriateness of the control technique for the particular source.
4. To evaluate (given sets of design plans for contact and surface condensers in terms of vapor and odor control efficiency, problems which may impair efficiency, and appropriateness of the control technique for the particular source.
5. To calculate material balances and conditions of equilibrium for an absorption system.
6. To evaluate (given plans for absorption systems) in terms of emission control efficiency, the suitability of absorption media, the effect of varying physical conditions on the operation of the absorption system and the appropriateness of the control technique for the particular source.
7. To describe the main methods used to control nitrogen oxide emissions from combustion sources.
8. To describe the main methods used to control sulfur oxide emissions from combustion sources.

9. To evaluate (given sets of plans for adsorption control systems) in terms of gaseous emissions removal efficiency, saturation capacity of the adsorption bed, bed regeneration processes and appropriateness of the control technique for the particular source.

Chapter 2
Review of the Basics

Lesson Goal

To explain the meaning of numerous symbols and basic concepts that are used when performing gaseous emission control calculations.

Lesson Objectives

Upon completion of this lesson, you should be able to:
1. Define the following in general terms.
   a. Pressure—gage, barometric, absolute
   b. Temperature—Celsius, Farenheit, Kelvin, Rankin
   c. Density
   d. Ideal Gas Law
   e. Molecular weight
   f. Raoult's and Henry's laws
   g. Gas viscosity
   h. Reynolds Number
2. Calculate pressure, temperature, and volume changes of gases.
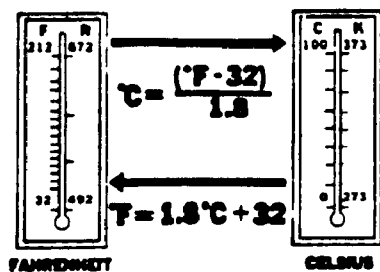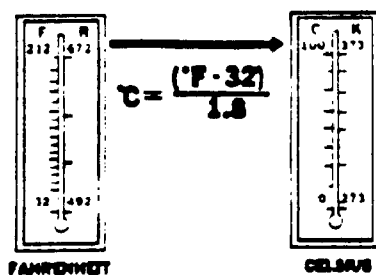3. Calculate the Reynolds Number.
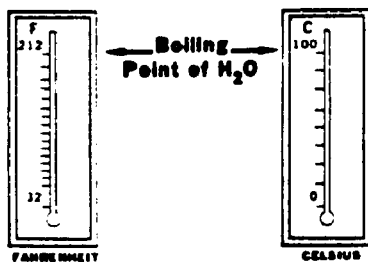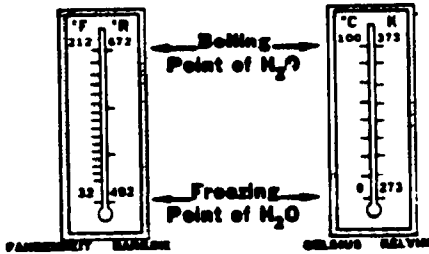
References

1. APTI Course 415 Student Manual.

REVIEW OF GAS PROPERTIES AND LAWS

PROPERTIES OF GASES

- Temperature
- Pressure
- Density
- Molecular Weight
- Viscosity

Boiling Point of H_2O

FAHRENHEIT   CELSIUS

$$°C = \frac{(°F - 32)}{1.8}$$

FAHRENHEIT   CELSIUS

$$°C = \frac{(°F - 32)}{1.8}$$

$$°F = 1.8°C + 32$$

FAHRENHEIT   CELSIUS

TEMPERATURE SCALES

Boiling Point of H_2O

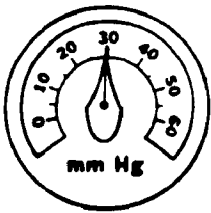Freezing Point of H_2O

BAROMETRIC OR ATMOSPHERIC PRESSURE

P_b

Measured in mm of mercury or atmospheres

GAGE PRESSURE

p_g

The difference between system pressure and atmospheric pressure

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ABSOLUTE PRESSURE

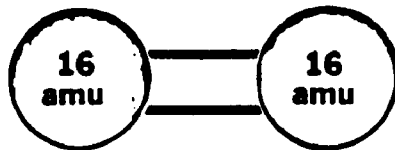$$P_{ABS} = P_b + p_g$$

P_b = barometric pressure

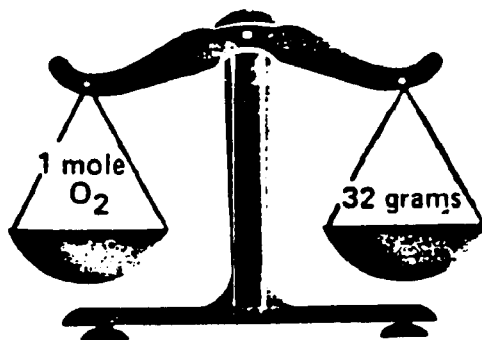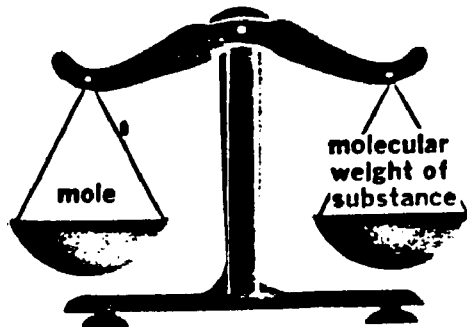p_g = gage pressure (positive or negative value)

DENSITY

$$\varrho = \frac{mass}{volume}$$

O_2 (one molecule)

16 amu — 16 amu

sum of all atomic weights = molecular weight

= 32 amu

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mole — molecular weight of substance

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1 mole O_2 — 32 grams

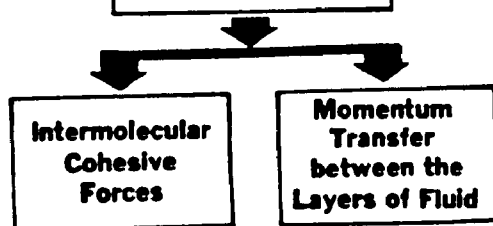
$$M_{mix} = \frac{n_1M_1 + n_2M_2 + ...n_xM_x}{n_t}$$

M_{mix} = molecular weight of gas mixture

n = number of moles of each component

M = molecular weight of each component

Viscosity

Intermolecular Cohesive Forces

Momentum Transfer between the Layers of Fluid

VISCOSITY =
fluid resistance to flow

Low Viscosity   High Viscosity
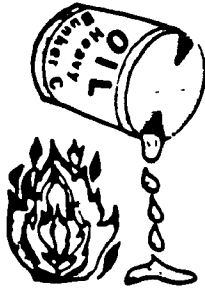
HEATED LIQUID = lower viscosity

Gas   Gas

KINEMATIC VISCOSITY

$$\nu = \frac{\mu}{\varrho}$$
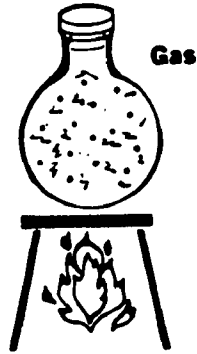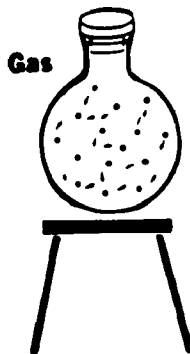
ν = kinematic viscosity
μ = absolute viscosity
ϱ = density

BEHAVIOR OF GASES

- Ideal Gas Law
- Van der Waals Law
- Dalton's Law
- Henry's Law
- Reynolds Number

CHARLES LAW	BOYLES LAW	AVOGADRO'S LAW
$P \propto T$	$P \propto \frac{1}{V}$	$V \propto n$
• constant pressure and moles	• constant temperature and moles	• constant temperature and pressure

$$PV = nRT$$

n = number of moles

R = Ideal Gas Constant

$$V = \frac{nRT}{P} = \quad \begin{array}{l} n = 1 \text{ mole} \\ R = .08205 \\ T = \text{standard temperature} = \\ \qquad 298.16 \text{ K} \\ P = \text{standard pressure} = \\ \qquad 1 \text{ atm} \end{array}$$

$$V = \frac{1 \,(.08205)(298.16K)}{1 \text{ atm}}$$

$$V = 24.46 \text{ liters at EPA STP}$$

VAN DER WAALS EQUATION

$$\left(P + \frac{a}{V^2}\right)(V - b) = RT$$

P = pressure
V = volume
R = Ideal gas constant
T = temperature
a = constant
b = constant

DALTON'S LAW

$$Y_A = \frac{p_A}{P_T}$$

Y_A = volume fraction of A
p_A = partial pressure of A
P_T = total pressure

RAOULT'S LAW

$$p_A = X_A p_A^c$$

p_A = partial pressure of A
X_A = mole fraction of A in solution
p_A^c = vapor pressure of pure A

HENRY'S LAW

$$p_A = \mathcal{H} X_A$$

REYNOLDS NUMBER

$$Re = \frac{Dv\varrho}{\mu}$$

Re = Reynolds number ϱ = gas density
D = diameter of duct μ = gas viscosity
v = gas velocity

REYNOLDS NUMBER RANGE - PIPE FLOW
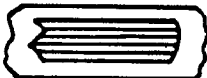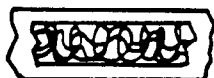
Re < 2000	Re > 2500
Laminar Flow	Turbulent Flow

GASES

Properties	Behavior
• Temperature	• Ideal Gas Law
• Pressure	• Van der Waals Law
• Density	• Dalton's Law
• Molecular Weight	• Henry's Law
• Viscosity	• Reynolds Number

Chapter 3

Concepts of Combustion as an Emission Control Method

Lesson Goal

To review the basic concepts of combustion and to illustrate some basic heat calculations.

Lesson Objectives

Upon completion of this lesson, you should be able to:
1. Define a combustion reaction.
2. List the 4 variables involved with combustion of any fuel.
   a. Time
   b. Temperature
   c. Turbulence
   d. Oxygen
3. Balance a simple chemical equation for a combustion reaction.
4. Describe the difference between yellow flame combustion and blue flame combustion.
   a. Fuel/air mixture
   b. Type of fuel used
   c. Burning characteristics
5. Write a balanced generalized equation for combustion of carbon fuels.
6. Calculate the amount of air needed for combustion of a unit amount of a given fuel.
7. Define the terms commonly used in working combustion problems.
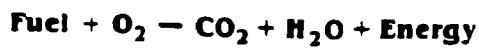8. Calculate the available heat for a given fuel.

References

1. APTI Course 415 Student Manual.

BASIC PRINCIPLES OF COMBUSTION

COMBUSTION REACTION

$$Fuel + O_2 \rightarrow CO_2 + H_2O + Energy$$

FACTORS AFFECTING COMBUSTION

$$O_2$$
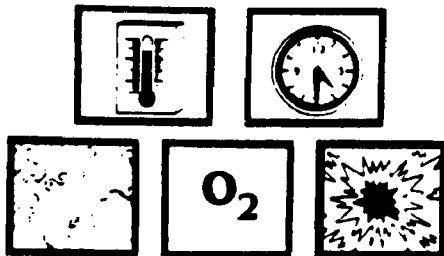
TEMPERATURE

- minimum ignition temperature
- increase in temperature accelerates reaction rate

TIME

- residence time
- $\Theta = V/Q$

TURBULENCE

- mixing of air and fuel

O_2 OXYGEN

- completeness of combustion depends upon amount of oxygen

- $CH_4 + O_2 \rightarrow C + 2H_2O + Energy$

- $CH_4 + 2O_2 \rightarrow CO_2 + H_2O + Energy$

FLAMMABILITY / EXPLOSIBILITY

- Upper Explosive Limit (UEL)

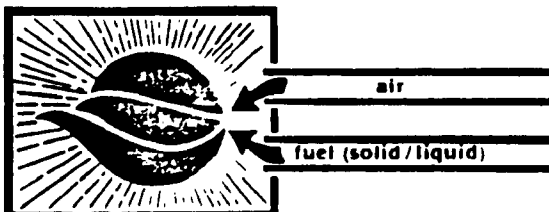- Lower Explosive Limit (LEL)
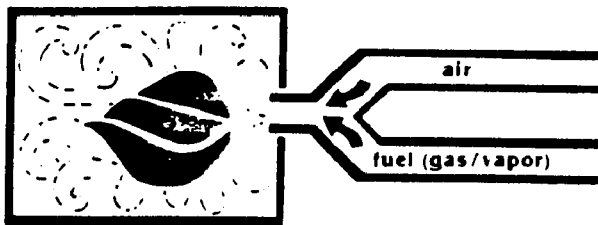
MECHANISMS OF COMBUSTION

Yellow Flame   Blue Flame   Water-Gas Reaction
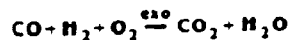
YELLOW FLAME COMBUSTION

air

fuel (solid / liquid)

3-3

BLUE FLAME COMBUSTION

WATER-GAS REACTION

$$C + 2H_2O \overset{endo}{=} CO + 2H_2 + \tfrac{1}{2}O_2$$

$$CO + H_2 + O_2 \overset{exo}{=} CO_2 + H_2O$$

STOICHIOMETRY

- determination of oxygen needed for complete combustion of a fuel — theoretical amount .

EXAMPLE OF A STOICHIOMETRIC CALCULATION

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + Energy$$
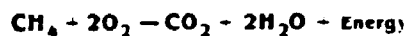
$$\frac{2 \text{ moles } O_2}{1 \text{ mole fuel}} \times \frac{1 \text{ mole air}}{.209 \text{ mole } O_2} = \frac{9.57 \text{ moles air}}{1 \text{ mole fuel}}$$

$$\frac{9.57 \text{ moles air}}{1 \text{ mole fuel}} \times \frac{379 \text{ scf air}}{1 \text{ mole air}} \times \frac{1 \text{ mole fuel}}{379 \text{ scf fuel}} =$$

$$\frac{9.57 \text{ scf air}}{1 \text{ scf fuel}}$$

GENERALIZED STOICHIOMETRIC EQUATION

$$C_xH_yS_zO_w + (x + \tfrac{y}{4} + z - \tfrac{w}{2})O_2$$
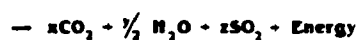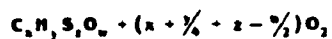
$$\longrightarrow xCO_2 + \tfrac{y}{2} H_2O + zSO_2 + \text{Energy}$$

EXCESS AIR

$$\%EA = \frac{\%O_2 - 0.5\,(\%CO)}{0.264\,(\%N_2) - \left[\%O_2 - 0.5\,(\%CO)\right]}$$

THERMOCHEMICAL RELATIONS

- total heat present
- heats produced by combustion

TOTAL HEAT PRESENT

Heat Content (H)	
Sensible Heat (H_s)	Latent Heat of Vaporization (H_V)

HEATS PRODUCED BY COMBUSTION

Gross Heating Valve (HV_G)	
Available Heat (H_A)	Heat Loss in Exit Flue Gas

HEAT BALANCE

HEAT BALANCE diagram showing air and fuel inputs at T_1, flue gas (q_1), available heat (q_a) output at T_2, within system boundary.
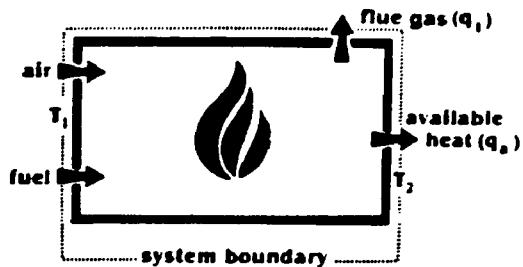
HEAT CONTENT (ENTHALPY)
Btu / lb

$$H = C_p(T - T_0)$$

Where:

C_p = specific heat, Btu/lb °F

T = temperature of gas, °F

T_0 = reference temperatures, °F

ENTHALPY FROM A TEMPERATURE CHANGE

$$H = \left[C_{p_2}(T_2 - T_0) - C_{p_1}(T_1 - T_0)\right]$$

Where:

T_1 = initial temperature
T_2 = final temperature
C_p = defined at T_2 or T_1, respectively

AVERAGE SPECIFIC HEAT

$$H = \bar{C}_p(T_2 - T_1)$$

Where:

$\bar{C}_p$ = average specific heat value between T_1 and T_2

HEAT RATE REQUIRED TO CHANGE THE TEMPERATURE OF A GAS
Btu / hr

$$q = \dot{m}\,\Delta H$$

Where:

$\dot{m}$ = mass flow rate, lb/hr

(no phase change or heat loss in the system)

HEAT RATE REQUIRED
TO CHANGE THE TEMPERATURE
OF A GAS

$$q = \dot{m}\left[C_{p_2}(T_2 - T_0) - C_{p_1}(T_1 - T_0)\right]$$

or

$$q = \dot{m}\,\overline{C}_p(T_2 - T_1)$$

Chapter 4
Stack Gas Afterburners

Lesson Goal

To provide you with an understanding of the basic concepts of waste gas incineration and heat recovery.
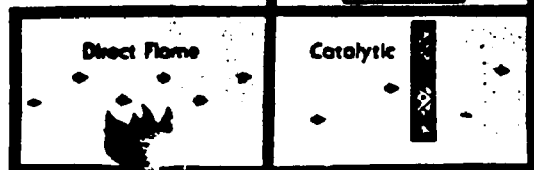
Lesson Objectives

Upon completion of this lesson, you should be able to:
1. List three methods used to incinerate gaseous air pollutants.
2. Identify the conditions necessary for efficient combustion of organic materials in a direct flame incinerator—including the effect of gas conditioning, temperature, and residence time.
3. Explain the operation of at least two types of direct flame incinerators—explaining the purpose of baffles, multijets, and distributed burners.
4. Identify the conditions necessary for the efficient combustion of organic materials in catalytic incinerators—including the effect of catalysts, temperature, and residence time.
5. Discuss the advantages and disadvantages associated with catalytic incineration.
6. Discuss the problems inherent in using process or heating boilers for incineration.
7. Diagram at least two types of methods used for heat recovery.
8. Discuss the advantages, problems, and limitations associated with primary and secondary heat recovery.
9. Discuss how a choice would be made in applying a heat recovery system—discussing relative costs.
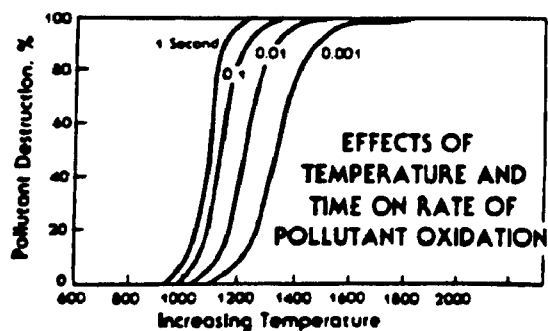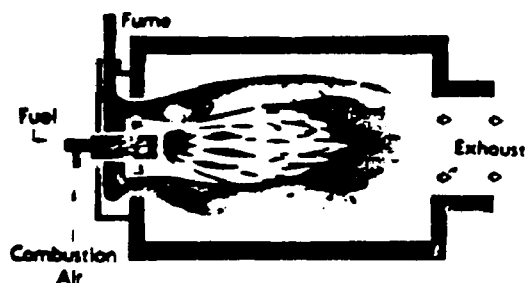
References

1. National Technical Information Services (NTIS). 1972. *Afterburner Systems Study*. PB-212560.
2. Environmental Protection Agency (EPA). 1977. *Controlling Pollution from the Manufacturing and Coating of Metal Products: Metal Coating Air Pollution Control*. Technology Transfer Publication. EPA-625/3-77-009.

INCINERATION
THERMAL OXIDATION
AFTERBURNING

Process Boiler

Direct Flame

Catalytic

DIRECT FLAME INCINERATION

Fume

Fuel

Combustion Air

Exhaust

EFFECTS OF
TEMPERATURE AND
TIME ON RATE OF
POLLUTANT OXIDATION

Pollutant Destruction, %

1 Second   0.1   0.01   0.001

600 800 1000 1200 1400 1600 1800 2000
Increasing Temperature

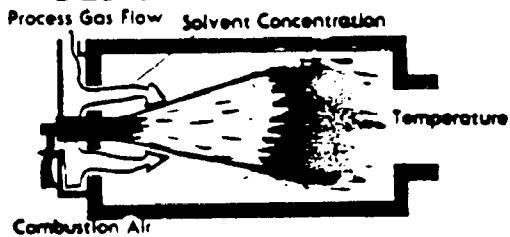## TYPICAL AFTERBURNER OPERATING TEMPERATURES

Coil Coating ————— 1200° – 1500° F

Point Bake Ovens — 1100° – 1500° F

Petroleum Refining – 1300° – 2000° F

Printing ————— 1300° – 1500° F

Wire Enameling —— 1300° – 1400° F

4-2

DESIGN RANGES

Temperature   1300° — 1500° F

Detention   0.3 — 0.5 seconds
Time

DESIGN PARAMETERS

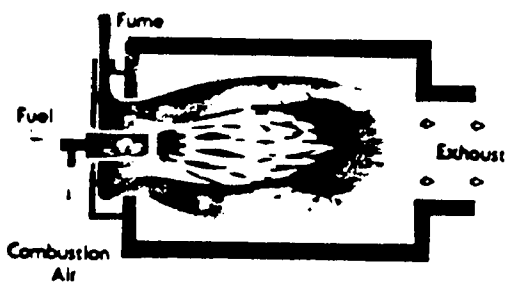Process Gas Flow   Solvent Concentration   Temperature

Combustion Air

THERMAL DESIGN FACTORS

Efficiency increases with:

- operating temperature
- detention time
- initial hydrocarbon concentration
- flame/solvent contact
- good mixing
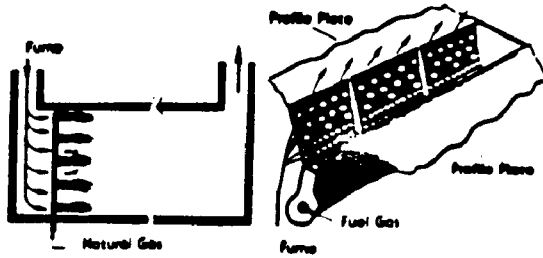- CO removal
   (at temperatures >1300°F)

DISCRETE BURNER

Fume

Fuel

Combustion Air

Exhaust

BAFFLED MIXING DEVICES

Fume

Fuel Air

Fume

DISTRIBUTED BURNERS

MULTIJET BURNER

CATALYTIC INCINERATION

700 - 900 °F
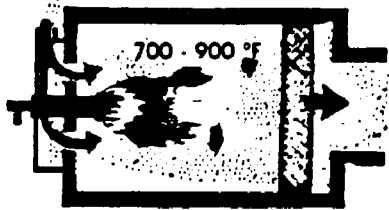
PRINCIPLES OF OPERATION

Diffusion

Adsorption

Reaction

Desorption

Diffusion and Mixing
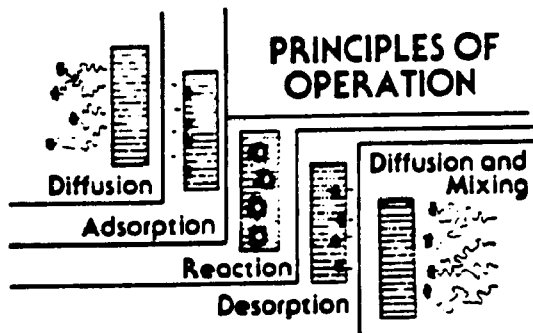
ADVANTAGES OF CATALYTIC INCINERATION

- lower operating temperatures
- lower auxiliary fuel needs
- lower construction materials cost

DISADVANTAGES OF CATALYTIC INCINERATION

- particulate fouling
- thermal aging
- catalyst poisoning

PLATINUM CATALYST POISONS

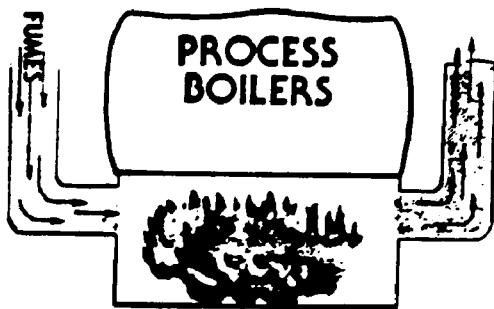| Fast	Slow	High Temp.
P	Zn	(>1100°F)
Bi	Pb	Fe
As	Sn	Cu
Sb		
Hg		

DISADVANTAGES OF CATALYTIC INCINERATION

- particulate fouling
- thermal aging
- catalyst poisoning
- suppressants

PLATINUM CATALYST SUPPRESSANTS

- Sulfur
- Halogens

action is reversible
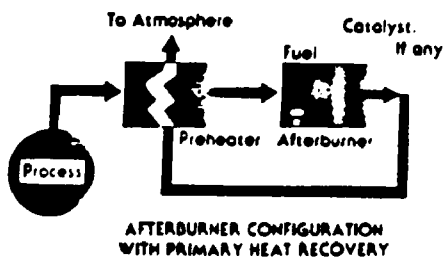
PROCESS BOILERS

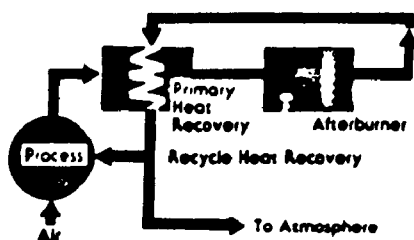## CONDITIONS FOR INCINERATION USE

- sufficient residence time
- no dependency
- low fuel/oxygen rate
- unaltered flame and radiation patterns
- non-fouling or acid fumes

Contaminated Waste Gas → Catalyst. if any → To Atmosphere

Fuel   Afterburner

Process
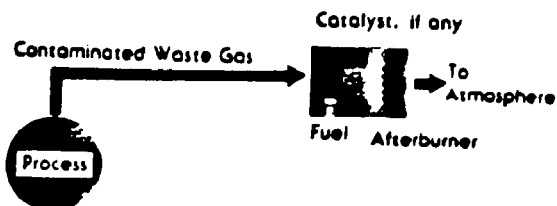
AFTERBURNER CONFIGURATION
WITHOUT HEAT RECOVERY

To Atmosphere   Catalyst. If any

Fuel

Preheater   Afterburner

Process

**AFTERBURNER CONFIGURATION
WITH PRIMARY HEAT RECOVERY**

Primary Heat Recovery   Afterburner

Process

Recycle Heat Recovery

Air   To Atmosphere

**AFTERBURNER CONFIGURATION WITH
PRIMARY HEAT RECOVERY
AND DIRECT RECYCLE HEAT RECOVERY**

AFTERBURNER CONFIGURATION WITH PRIMARY AND SECONDARY HEAT RECOVERY

RECUPERATIVE HEAT RECOVERY DEVICE

REGENERATIVE HEAT RECOVERY DEVICE (Reeco)
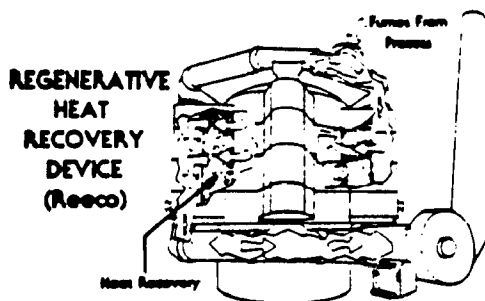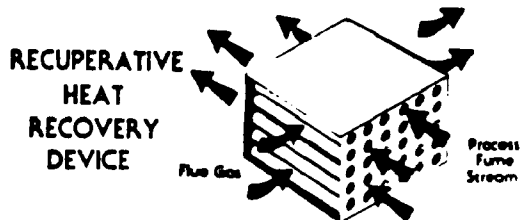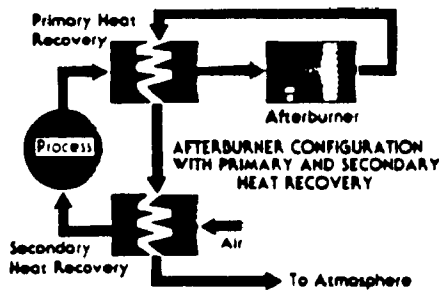
TUBULAR HEAT EXCHANGER SYSTEMS

- Effectiveness ratio, E
    1. Stage   50% max.
    2. Stage   62% max.
    3. Stage   85% max

- Limitation
    Easily fouled
    Structural failures
    Chemical interactions with fume components
    Corrosion

AFTERBURNER PROCESS HEAT RECOVERY

NOTE: Final Temperature of flue gas = 350°F

Fume stream used for oxygen supply

4-7

CAPITAL COST OF INCINERATION

ANNUAL VARIABLE COST OF INCINERATION
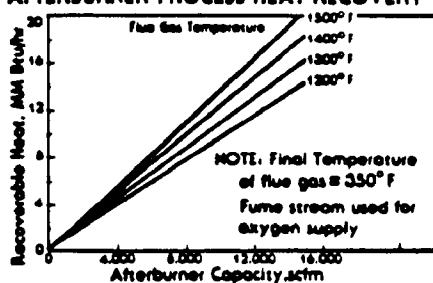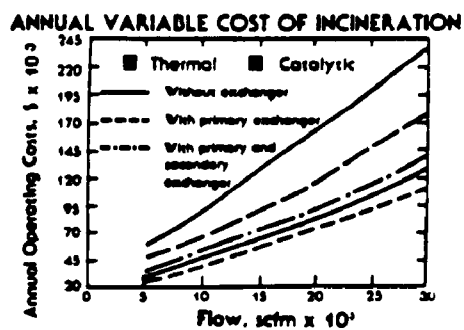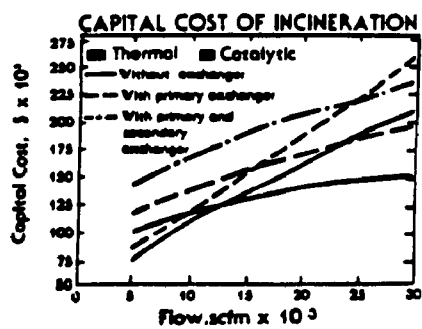
Chapter 5
Principles of Absorption

Lesson Goal

To familiarize you with the basic concepts involved in the transfer of mass from the gas phase to the liquid phase.

Lesson Objectives

Upon completion of this lesson, you should be able to:
1. Describe the following in general terms.
   a. Solute
   b. Carrier gas
   c. Absorbent
2. Illustrate the steps involved in the absorption of a gaseous molecule.
3. Describe both the two-film and Higbee penetration theories.
4. Differentiate between liquid and gas phase controlling resistances.
5. Use Henry's and Dalton's Laws to draw an equilibrium diagram.

References

1. APTI Course 415 Student Manual.
2. Bethea, R. M. 1978. *Air Pollution Control Technology, An Engineering Analysis Point of View*. NY., NY.: Van Nostrand Reinhold Co.
3. Buonicore, A. J., and Theodore, L. 1975. *Industrial Control Equipment for Gaseous Pollutants*, volume I. Cleveland, OH.: CRC Press Inc.
4. Treybal, R. E. 1968. *Mass Transfer Operations*. NY., NY.: McGraw Hill Book Co.

BASIC ABSORPTION SYSTEM
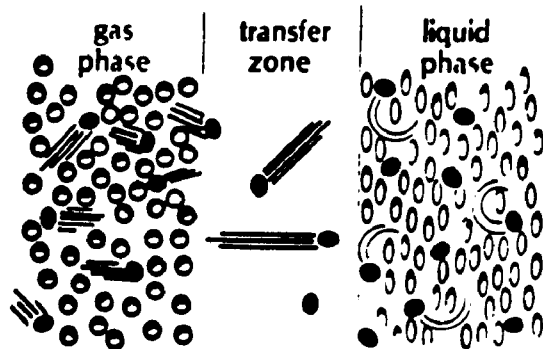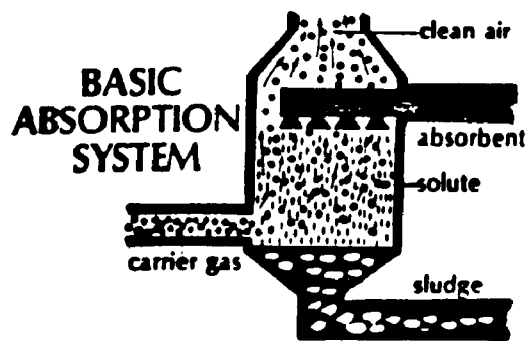
$$\text{mole fraction} = \frac{\text{moles of solute}}{\text{moles of solute} + \text{moles of solvent}}$$

LIQUID PHASE MOLE FRACTION

$$X_A = \frac{\text{mole A}}{\text{mole A} + \text{mole } H_2O}$$

GAS PHASE MOLE FRACTION

$$Y_A = \frac{\text{moles A}}{\text{moles A} + \text{moles air}}$$

DALTON'S LAW

$$Y = \frac{p_A}{P_{tot}}$$

HENRY'S LAW

$$p_A^* = \mathcal{H} X_A$$

DALTON'S LAW   HENRY'S LAW

$$Y = \frac{p_A}{P_{tot}} \qquad Y = \mathcal{H} X_A$$

where
$$\mathcal{H} = \frac{\text{mole fraction in gas}}{\text{mole fraction in liquid}}$$

PRE-EQUILIBRIUM

$$p_{AG} \quad \xleftarrow{\text{forward}} \quad c_{AL}$$
reverse
net transfer

EQUILIBRIUM

forward

p_{AG} ← reverse → c_{AL}

no net transfer

gas bulk phase   liquid bulk phase

gas bulk phase   liquid bulk phase

gas film : liquid film

p_{AG}

partial pressure driving force p_{AI}

$p_{AG} - p_{AI}$ c_{AI} $c_{AI} - c_{AL}$

concentration driving force c_{AL}
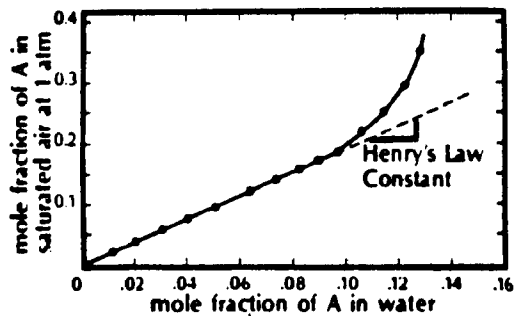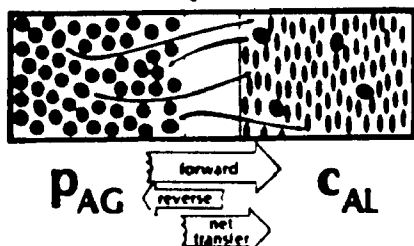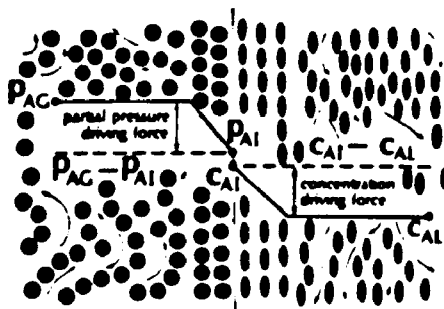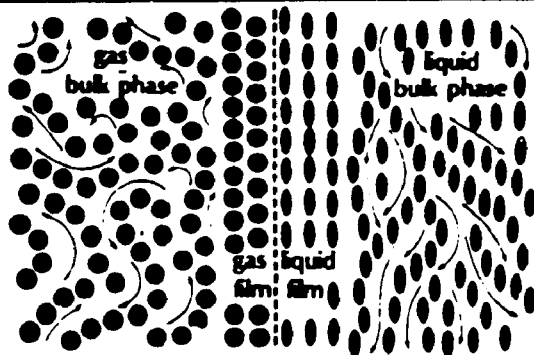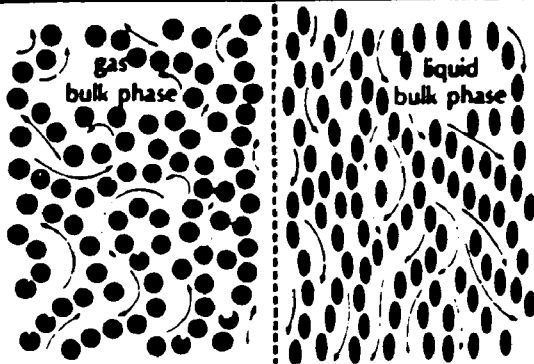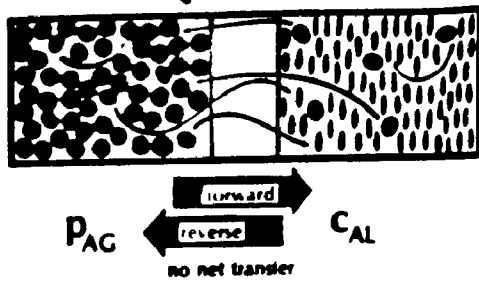
MASS FLUX
(INDIVIDUAL)

$$N_A = k_g(p_{AG} - p_{AI})$$

$$N_A = k_l(c_{AI} - c_{AL})$$

MASS FLUX
(OVERALL)

$$N_A = K_G(p_{AG} - p^*)$$

$$N_A = K_L(c^* - c_{AL})$$
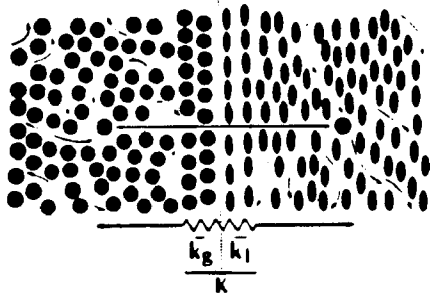
$$\frac{1}{K_G} = \frac{1}{k_g} + \frac{\mathcal{H}}{k_l}$$

$$\frac{1}{K_L} = \frac{1}{k_l} + \frac{1}{\mathcal{H}k_g}$$

GAS PHASE CONTROLLED	LIQUID PHASE CONTROLLED
• contaminant is very soluble in liquid	• contaminant is relatively insoluble in liquid
• diffusion through gas phase is rate controlling step	• diffusion through liquid phase is rate controlling step

HIGBEE PENETRATION THEORY

gas | liquid
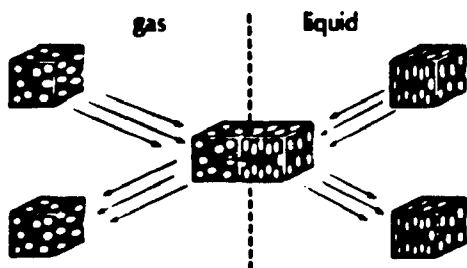
$$k_g = \frac{2}{RT} \sqrt{D_g / \pi \Theta}$$

$$k_l = 2 \sqrt{D_l / \pi \Theta}$$

Where:

$D =$ diffusivity

$\Theta =$ contact time

$R =$ ideal gas constant

TYPICAL ABSORPTION TRANSFER
COEFFICIENT PLOT
(from vendor literature)

Given Condition:
* tower diameter
* packing height
* inlet gas concentration
* outlet liquid concentration
* liquid temperature
* packing type

Chapter 6
Review of Absorption Design Principles

Lesson Goal

To familiarize you with the main criteria used in designing a packed tower absorber.

Lesson Objectives

Upon completion of this lesson, you should be able to:
1. Perform material balance calculations for an absorber.
2. Draw an operating line to determine minimum L/G ratio.
3. Determine minimum tower diameter.
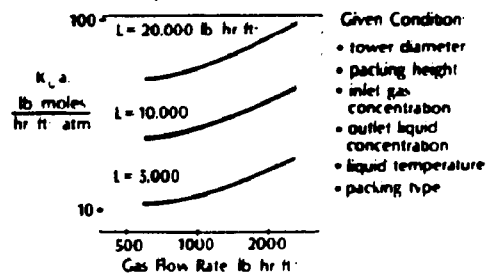4. Calculate the number of transfer units for the special case of straight equilibrium line.
5. Calculate the height of packing required to achieve the desired efficiency for a given absorber.

References

1. APTI Course 415 Student Manual.
2. Bethea, R. M. 1978. *Air Pollution Control Technology, An Engineering Analysis Point of View.* NY., NY.: Van Nostrand Reinhold Co.
3. Buonicore, A. J., and Theodore L. 1975. *Industrial Control Equipment for Gaseous Pollutants,* volume I. Cleveland, OH.: CRC Press Inc.
4. Cheremisinoff, P. N., and Young, R. 1977. *Air Pollution and Control Design Handbook,* part 2. NY., NY.: Marcel Dekker, Inc.
5. Environmental Protection Agency (EPA). 1973. *Air Pollution Engineering Manual.* AP-40. 2nd ed. RTP, NC.
6. Treybal, R. E. 1968. *Mass Transfer Operations.* NY., NY.: McGraw Hill Book Co.
7. Zenz, F. A. 1972. Designing Gas-Absorption Towers. *Chem. Engr.* 79:120-138.

REVIEW OF ABSORPTION DESIGN PRINCIPLES

FACTORS AFFECTING SOLUBILITY
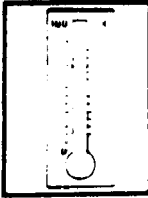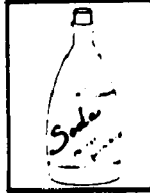
● Temperature   ● Pressure

ABSORBERS

Packed Tower   Plate Tower   Spray Tower

OPERATING CRITERIA

Inlet Liquid
● temperature
● composition

Inlet Gas
● flow rate (cfm)
● composition
● temperature
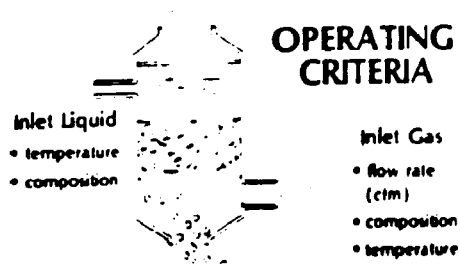
DESIGN REVIEW

- Liquid Flow (L/G ratio)
- Tower Diameter
- Height of Packing

**LIQUID
FLOW
RATE
(L/G ratio)**

G_{m_2} Y_2

**MATERIAL
BALANCE**

L_{m_2}

X_2

G_{m_1}

Y_1
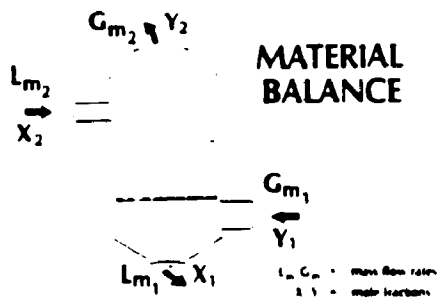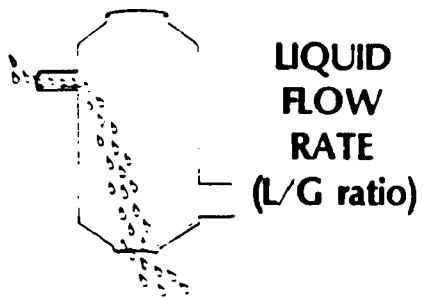
L_{m_1} X_1

IN = OUT

$$G_{m_1}Y_1 + L_{m_2}X_2 = G_{m_2}Y_2 + L_{m_1}X_1$$

Where:

G_m = gas mass flow rate (lb moles/min)
L_m = liquid mass flow rate (lb moles/min)

Rewriting the equation, we get:

$$G_m(Y_1 - Y_2) = L_m(X_1 - X_2)$$

$$Y_1 - Y_2 = \frac{L_m}{G_m}(X_1 - X_2)$$

SYSTEM OPERATING LINE
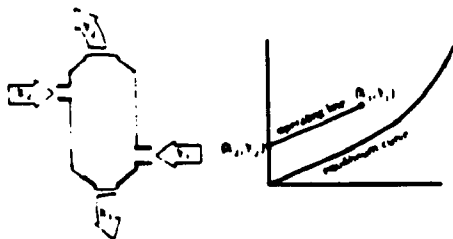
6-3

EQUILIBRIUM DIAGRAM

mole fraction in gas

Y_1

(X_2,Y_2) A

B

(X_{max},Y_1)

X_{max}

mole fraction in liquid

MINIMUM OPERATING LINE

mole fraction in gas

Y_1

(X_2,Y_2) A

minimum $\frac{L}{G}$

B

(X_{max},Y_1)

X_{max}

mole fraction in liquid

ACTUAL OPERATING LINE

Y_1

(X_2,Y_2) A

$\frac{L}{G}$

C (X_1,Y_1)

B

(X_{max},Y_2)

X_1

EXAMPLE PROBLEM 3.3

$Y_2 = .003$

$L = ?$

$X_2 = 0.0$

exhaust gas flow rate $= 3,000$ acfm

$Y_1 = .03$

$X_1 = ?$
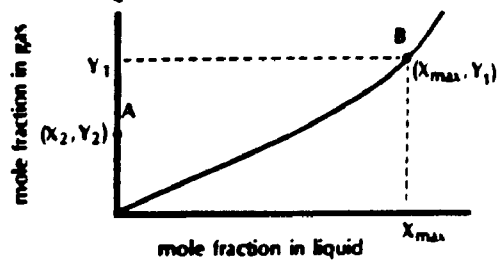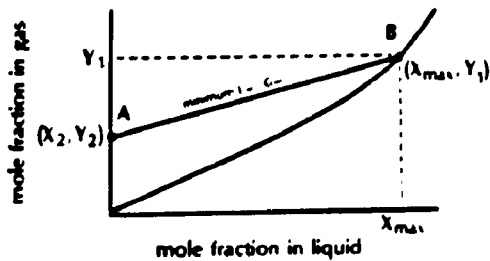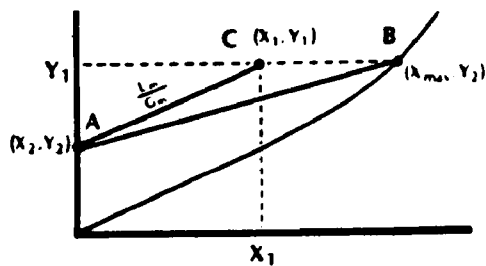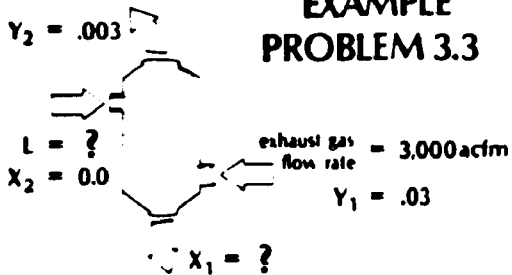
EQUILIBRIUM DIAGRAM $SO_2 - H_2O$

Y, mole fraction SO_2 in air

X, mole fraction SO_2 in water
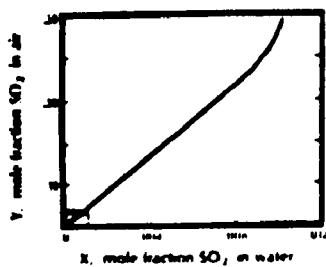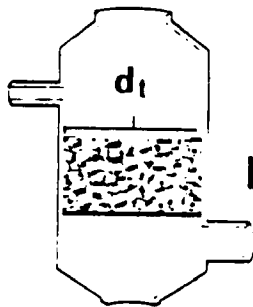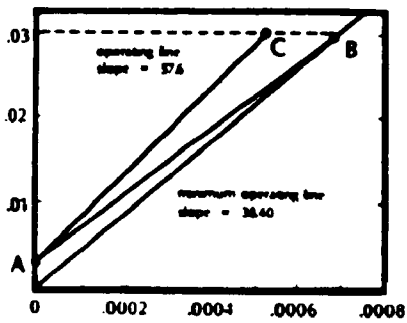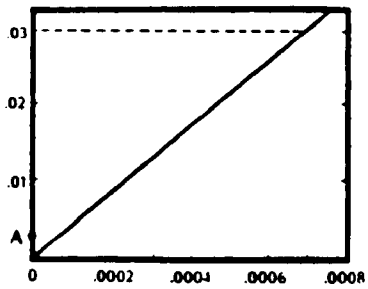
PACKED TOWER DIAMETER

Packed Tower diameter is dependent on:

- gas flow rate
- liquid flow rate
- tower internal design
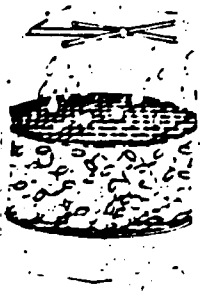
LOADING
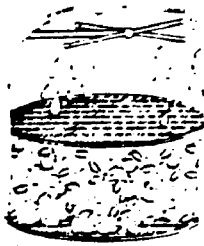
FLOODING

GENERALIZED FLOODING CORRELATION FOR DUMPED PIECES
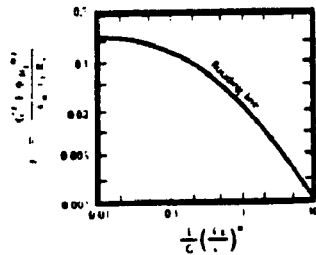
SUPERFICIAL GAS MASS FLOW RATE

$$G' = \sqrt{\frac{\varrho_g \, \varrho_l \, g_c \, \varepsilon}{F \, \Phi \, \mu_l^{0.2}}}$$

G' expressed in lb/min-ft^2

CROSS-SECTIONAL AREA

$$A = \frac{G}{f \, G'}$$

Where:
f = operating percent of flooding
G = actual gas mass flow rate (lb min)
G' = superficial gas mass flow rate (lb min-ft^2)

TOWER DIAMETER

$$d_t = \sqrt{\frac{4A}{\pi}}$$

$$= 1.13 \, A^{0.5}$$

Given:

$$L_m = 434.3 \frac{\text{lb mole } H_2O}{\text{minute}}$$

$$G_m = 7.54 \frac{\text{lb mole air}}{\text{minute}}$$

$$\rho_l = 62.4 \text{ lb ft}^3$$

$$\rho_g = .0732 \text{ lb ft}^3$$

For H_2O: $\Phi = 1.0$ $\mu_l = .8$ centipoise

GENERALIZED FLOODING CORRELATION
FOR DUMPED PIECES
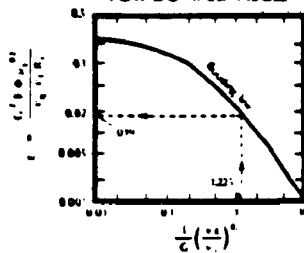
HEIGHT
OF
PACKING — Z
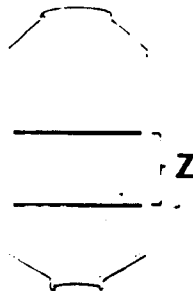
PACKING
HEIGHT
(Z)

$$Z = NTU \times HTU$$
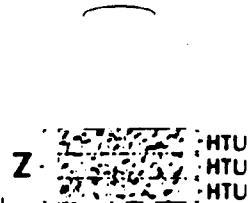
Where:
NTU = number of transfer units
HTU = height per transfer unit

PACKING HEIGHT

$$Z = NTU \times HTU$$

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

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

Where:
OG = overall gas
OL = overall liquid

Chapter 7
Absorption Control Systems

Lesson Goal

To familiarize you with contaminent and absorbent characteristics that affect mass transfer, and to describe the various types of absorption equipment used to control gaseous pollutants.

Lesson Objectives

Upon completion of this lesson, you should be able to:
1. List at least four characteristics of the contaminent gas stream that affect absorber performance.
2. List at least six characteristics considered desirable in an absorbent.
3. Describe the operation of the following types of absorbers.
    a. Spray or baffle tower
    b. Centrifugal scrubber
    c. Venturi scrubber
    d. Plate tower
    e. Packed tower

References

1. APTI Course 415 Student Manual.
2. Bethea, R. M. 1978. *Air Pollution Control Technology, An Engineering Analysis Point of View*. NY., NY.: Van Nostrand Reinhold Co.
3. Cheremisinoff, P. N., and Young, R. 1977. *Air Pollution and Control Design Handbook*, part 2. NY., NY.: Marcel Dekker, Inc.
4. Environmental Protection Agency (EPA). 1973. *Air Pollution Engineering Manual*. AP-40. 2nd ed. RTP, NC.
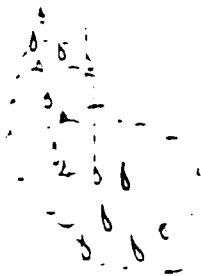
ABSORPTION CONTROL SYSTEMS

FUNCTIONS OF AN ABSORBER

- removal of contaminants
- pretreatment
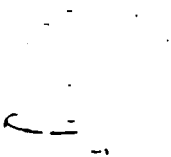
CHARACTERISTICS OF CONTAMINANTS

- concentration
- temperature
- chemical properties
  - solubility
  - pH
- toxicity

DESIRABLE CHARACTERISTICS OF AN ABSORBENT

- high solubility for the contaminant
- low volatility
- low viscosity
- chemical stability

CONTACT METHODS
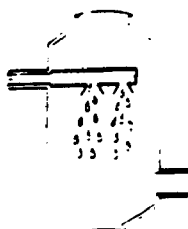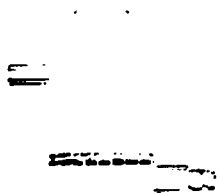
Liquid Dispersal   Gas Dispersal

TYPES OF ABSORBERS

- Spray Towers
- Cyclonic Scrubbers
- Venturi Scrubbers
- Plate Towers
- Packed Towers
- Moving Bed Scrubbers
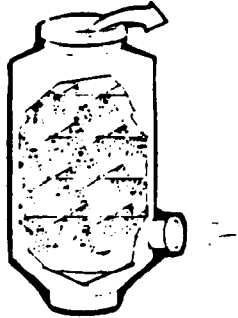
SPRAY TOWER
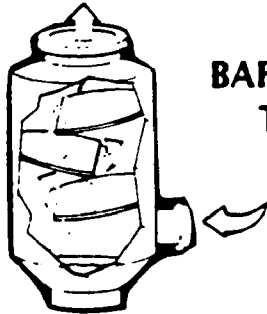
BAFFLE SPRAY TOWER

CYCLONIC SCRUBBER

VENTURI SCRUBBER
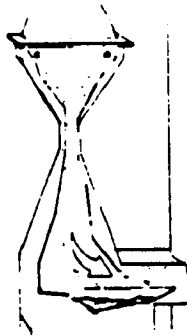
**SPRAY
VENTURI
SCRUBBER**
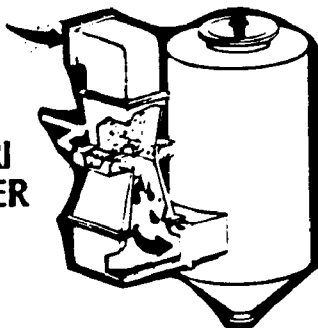
**WETTED
APPROACH
VENTURI**

cyclone
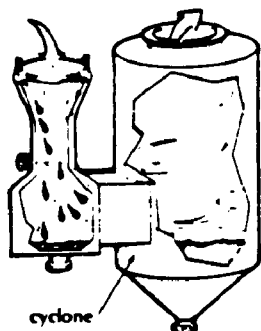
**ADJUSTABLE
THROAT
VENTURI**

VENTRI-ROD SCRUBBER

mist eliminator

**PLATE
TOWER**

TYPES OF PLATES

Sieve Tray   Impingement Tray

TYPES OF PLATES

Bubble Cap   Float Valve

clean gas
mist eliminator
scrubber liquor

PACKED TOWER
(countercurrent)

packing
feed gas
to drain

feed gas

PACKED TOWER
(cocurrent)

clean gas

PACKED TOWER
(cross flow)

feed gas   clean gas
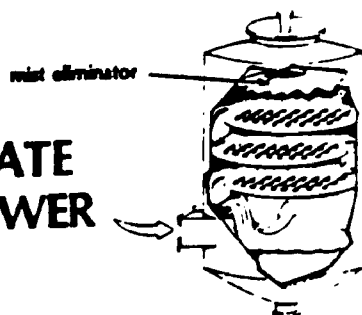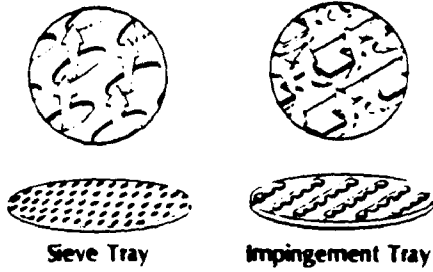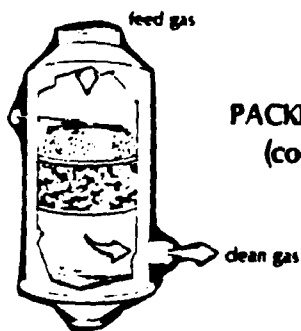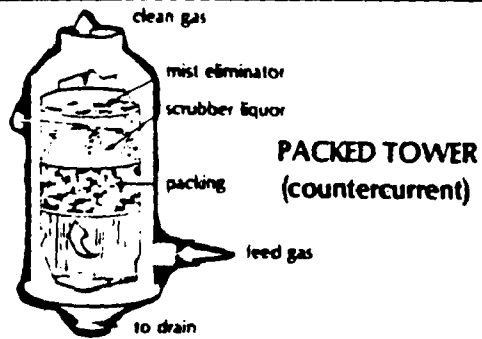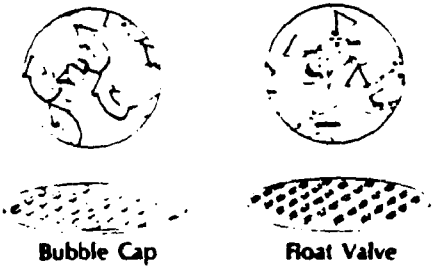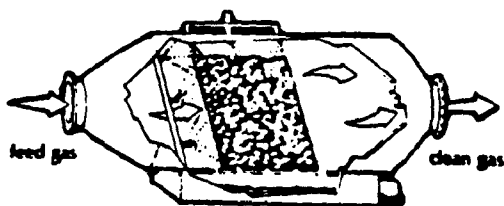
PACKED TOWER
(cross flow-3 beds)

feed gas   clean gas
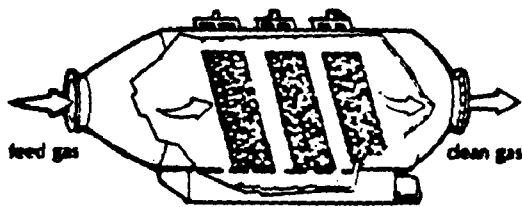
COMMON TOWER PACKING MATERIALS

Raschig Ring

Berl Saddle

Intalox Saddle

Pall Ring

Tellerette
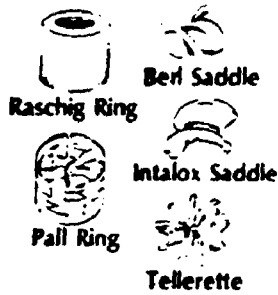
CONFIGURATION OF PACKING
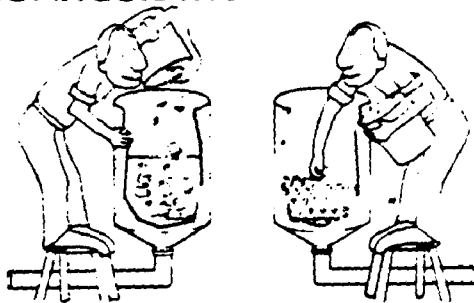
PLATE TOWER

- easier maintenance
- lower weight
- handles large temperature variations better

PACKED TOWER

- lower Δp
- better in corrosive atmospheres
- preferred for foamy liquids

FLOODED BED ABSORBER

FLUIDIZED ABSORBER

clean gas
mist eliminator
scrubber liquor
floating bed
feed gas
drain
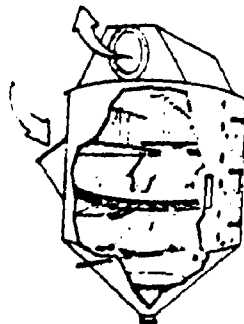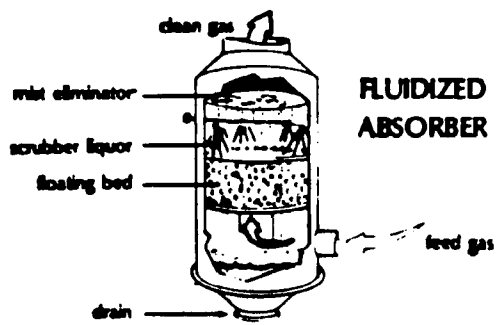
MIST ELIMINATOR

- prevents carryover of liquid droplets
- recovers scrubbing liquor
- performs additional scrubbing

MIST ELIMINATORS

Wire Mesh   "S" or Chevron Curve

REVIEW

- Characteristics of Contaminant Gas Streams
- Desirable Characteristics of an Absorbent
- Types of Absorbers
    - Spray   • Plate
    - Cyclonic   • Packed
    - Venturi   • Moving Bed

Chapter 8
Adsorption Principles

Lesson Goal

To familiarize you with the basic principles of adsorption for the control of gaseous emissions.

Lesson Objectives

Upon completion of this lesson, you should be able to:
1. Briefly define adsorption, adsorbate, and adsorbent.
2. List the three stages that occur during the mechanism of adsorption.
3. Describe the difference between physical attraction and chemical attraction between adsorbent and adsorbate.
4. Name the major force, van der Waals, used in physical adsorption, and describe the attraction of the gaseous molecules to the solid molecules.
5. List four types of materials used in adsorption and describe their features.
6. Name at least four factors that affect proper adsorption design.
7. Briefly define breakthrough, mass transfer zone, saturation, and retentivity.
8. Name two types of adsorption systems.
9. Describe the adsorption process throughput cycle and the regeneration of the adsorber bed.

References

1. APTI Course 415 Student Manual.
2. Bethea, R., *Air Pollution Control Technology*, 1978. NY., NY.: Van Nostrand Reinhold Co.
3. Cerny, S., and Smireh, M. 1970. *Active Carbon*. NY., NY.: Elsevier Publishing Corp.
4. Environmental Protection Agency (EPA). April 1973. *Packing Sorption Device System Study*, EPA-R2-73-202. Washington, DC.

ADSORPTION

ADSORPTION PHENOMENA

adsorbate

adsorbent — granules of charcoal

general bulk area

adsorbent

stagnant air area
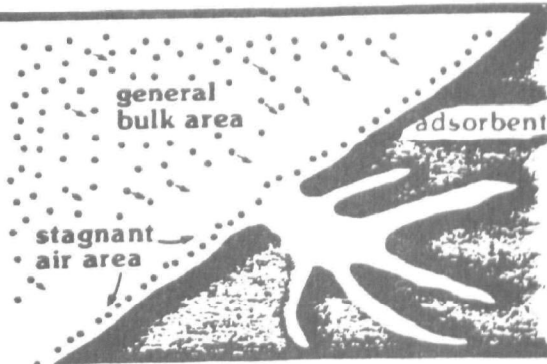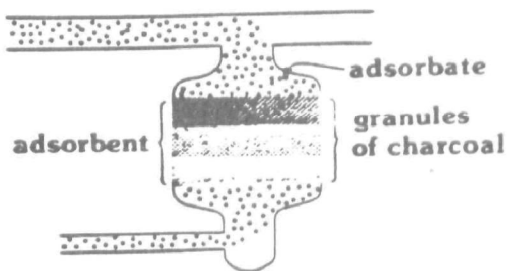
DIFFUSION INTO PORES
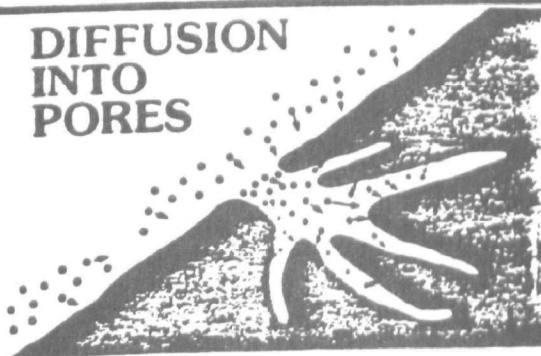
MONOLAYER BUILDUP
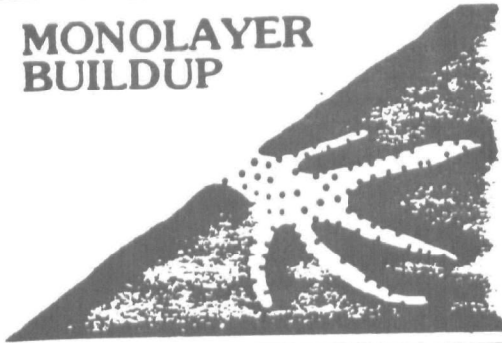
HEAT OF ADSORPTION

ADSORPTION THEORY

VAN DER WAAL FORCE

molecules in adsorbent wall

molecule of adsorbate

Monolayer

Condensation

Multilayer
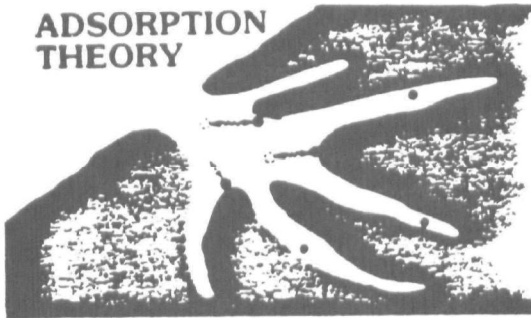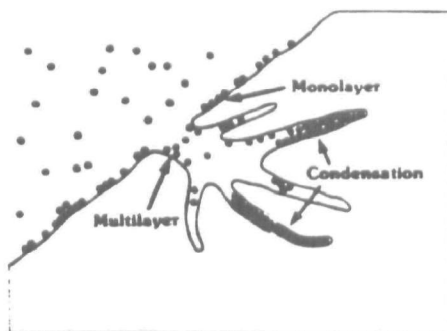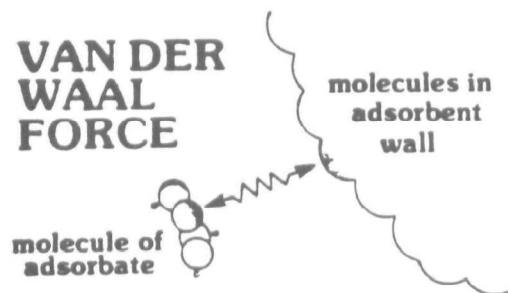
CHARACTERISTICS

Chemisorption	Physical Absorption
• releases high heat 80-120 calories/mole	• releases low energy 40 calories/mole
• forms a chemical compound	• dipolar interaction
• desorption is difficult	• desorption is easy
• impossible adsorbate recovery	• easy adsorbate recovery

TYPES OF ADSORBENT

Polar	Non-polar
• silica gel	• activated carbon
• activated oxides	
• molecular sieves	

RETENTIVITY

Retentivity vs Temperature

Retentivity vs Pressure

Retentivity vs Surface Area/Pore Size

Retentivity vs Molecular Weight of Solvent
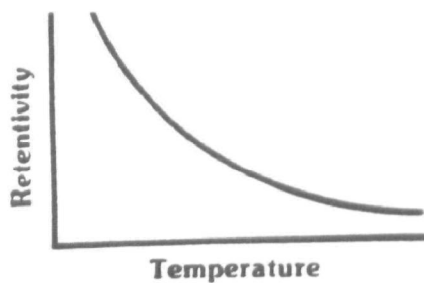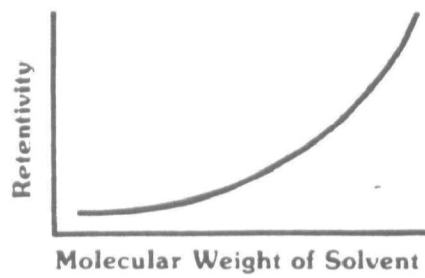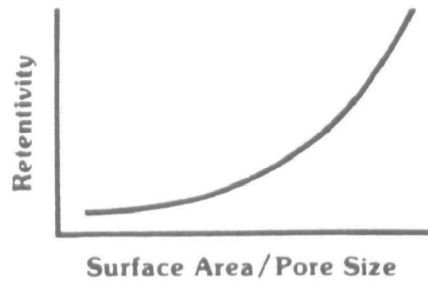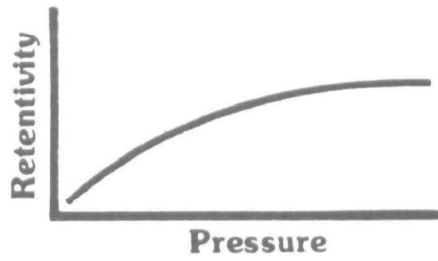
ADSORPTION SYSTEMS

- nonregenerative
- regenerative

2 BED ADSORPTION SYSTEM

vapor inlet

A   B

exhaust

2 BED ADSORPTION SYSTEM

vapor inlet

A   B

exhaust

REGENERATING BED A

vapor inlet

A   B

inlet steam →

exhaust
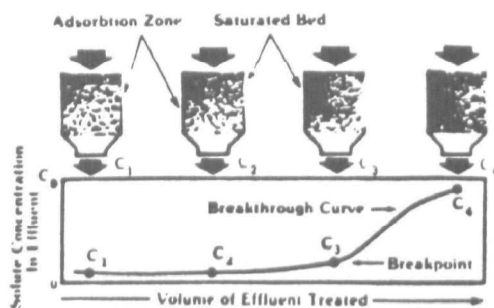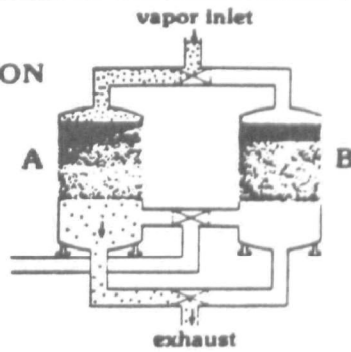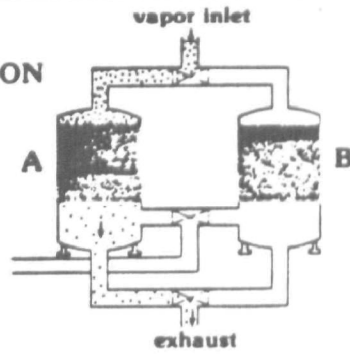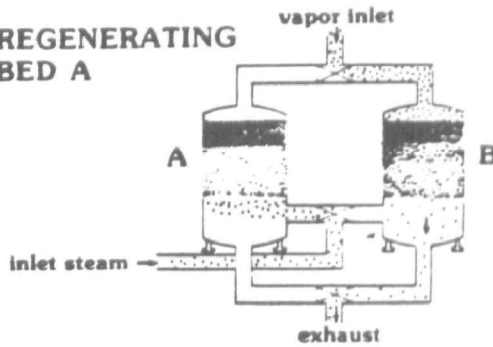
METHODS OF REGENERATION

- stripping
- thermal desorption
- vacuum desorption

Chapter 9
Adsorption Dynamics

Lesson Goal

To explain, in terms of adsorption principles, the dynamic adsorption system and the criteria for evaluating its effectiveness.

Lesson Objectives

Upon completion of this lesson, you should be able to:

1. Briefly define the following.
    a. Isotherm
    b. Isobar
    c. Isotere
2. Distinguish between saturation and working capacities of the adsorber bed.
3. Explain how the MTZ, depth of bed, and gas velocity are determined for adsorption systems.
4. List three factors affecting regeneration that should be considered when reviewing the design of an adsorption system.
    a. Time needed to regenerate
    b. Amount of stream required
    c. Drying and cooling systems provided

References

1. APTI Course 415 Student Manual.
2. Cheremisnoff, P. N., and Ellerbusch, F. 1978. *Carbon Adsorption Handbook*. Ann Arbor, MI. Ann Arbor Science Publishers, Inc.
3. Environmental Protection Agency (EPA). April 1973. *Packing Sorption Device System Study*. Washington, DC. EPA-R2-73-202.
4. Parmele, C. S., O'Connell, W. L., and Basdehis, H. S. Vapor Phase Adsorption Cuts Pollution, Recovers Solvent. *Chem. Engr.:* Dec. 31, 1979.
5. Stern, Arthur C. 1977. *Air Pollution* 3rd ed., volume IV NY., NY.: Academic Press, Inc.

ADSORPTION
DYNAMICS

ADSORBER OPERATION
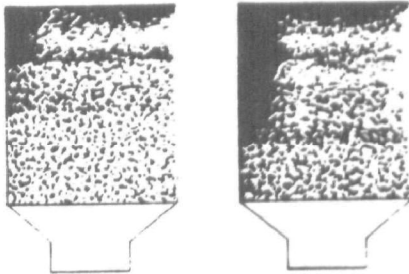
ADSORPTION
EQUILIBRIUM CONCEPTS

- Isotherm
- Isobar
- Isostere

ISOTHERM
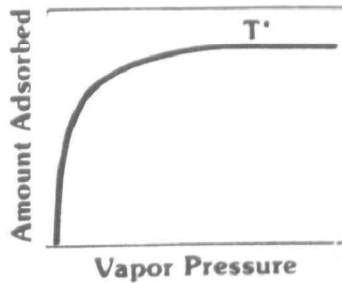
TYPICAL ADSORPTION
ISOTHERM
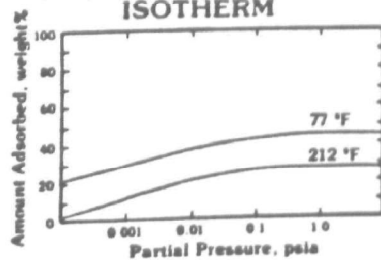
POLANYI EQUATION

$$\Delta F = {}^{-}RT \ln \frac{P_o}{P}$$

LANGMUIR (BET) EQUATION

$$\frac{P}{V(P_o - P)} = \frac{1}{V_m C} + \frac{C-1}{V_m C} \cdot \frac{P}{P_o}$$
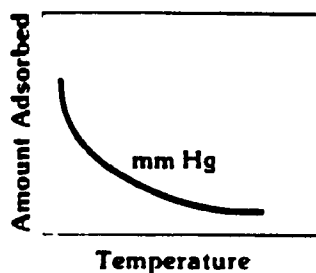
ISOBAR

ADSORPTION
ISOBAR FOR H_2S MOLECULAR SIEVE

ISOSTERE

ADSORPTION ISOSTERE OF H₂S ON MOLECULAR SIEVE

(graph: H₂S Pressure, mm Hg vs Reciprocal of Absolute Temperature, 10^{-3} · K; curves labeled 2%, 4%, 6%, 8%, 10%, 12%, 14%)
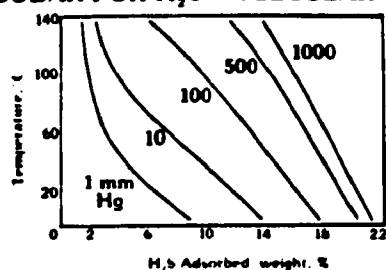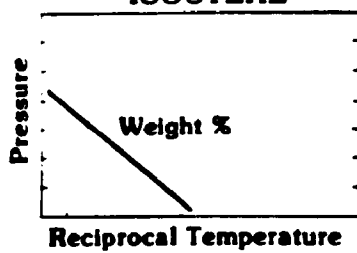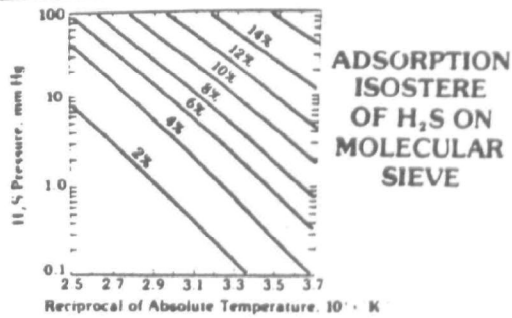
DYNAMIC ADSORBER OPERATION

- MTZ
- saturation and working capacity
- depth of bed
- gas velocity through bed
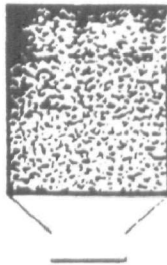
MASS TRANSFER ZONE

MTZ depends on:

- type of adsorbent
- particle size of adsorbent
- gas velocity
- temperature
- pressure
- efficiency

MASS TRANSFER ZONE

$$MTZ = \frac{1}{1-x} D_1 (1 - \frac{C_1}{C_s})$$

Where:

D_1 = bed depth
C_1 = breakthrough capacity of bed D_1
C_s = saturation capacity
X = degree of saturation in the MTZ

MASS TRANSFER ZONE

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

Where:

C = breakthrough capacity

D = bed depth

ADSORBER BED CAPACITY

Saturation Capacity   Breakthrough Capacity   Working Capacity

---
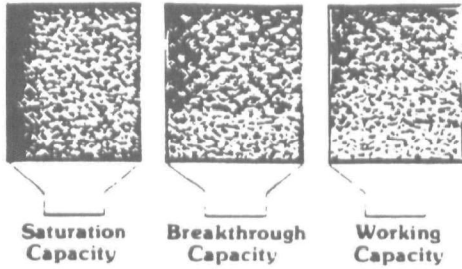
SATURATION AND WORKING CAPACITY

$$\text{Saturation Capacity} = \frac{\text{weight of adsorbate}}{\text{weight of adsorbent}}$$

$$\text{Working Capacity} = \frac{\text{weight of adsorbate} - \text{weight of heel}}{\text{weight of adsorbent}}$$

$$\text{Breakthrough Capacity} = \frac{.5\left(\begin{array}{c}\text{Saturation}\\\text{Capacity}\end{array}\right)\left(\begin{array}{c}\text{MTZ}\\\text{Length}\end{array}\right) + \left(\begin{array}{c}\text{Saturation}\\\text{Capacity}\end{array}\right)\left(\begin{array}{c}\text{Bed}\\\text{Depth}\end{array} - \begin{array}{c}\text{MTZ}\\\text{Length}\end{array}\right)}{\text{Bed Depth}}$$
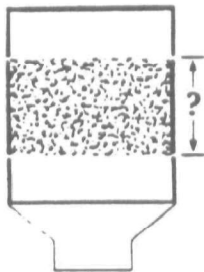
DEPTH OF ADSORBENT BED

EFFECT OF GAS VELOCITY ON MTZ

MTZ Length vs Gas Velocity, feet/minute

Pressure Drop per foot of bed vs Velocity, feet/minute (0 to 100)

6-16 mesh
4-10 mesh

GAS
VELOCITY
THROUGH
BED
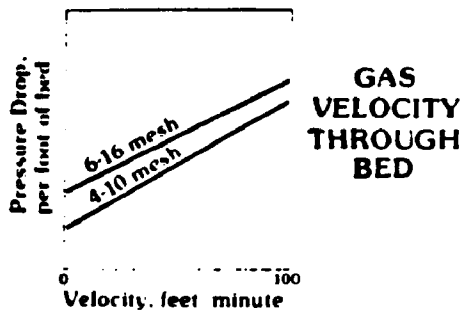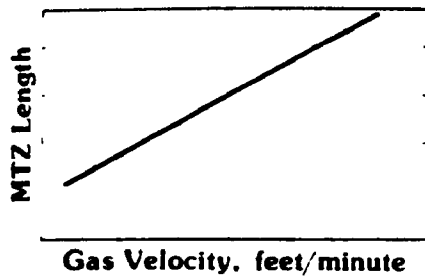
REGENERATION CONDITIONS

- types of regeneration .
- factors to be considered

Ways to Regenerate	Percent of Charge Dispelled
Thermal Desorption at 100 C	15
Vacuum Desorption at 20°C and 50 mm Hg	25
Gas Circulation at 130°C	45
Steam Stripping at 100°C	98

NOTE All for 40 minutes time period carbon loaded with 40% ether

FACTORS AFFECTING DESORPTION

- time available
- retentivity of adsorbent
- heat requirements of vessel and adsorbent
- direction of steam flow
- hysteresis

HYSTERESIS PHENOMENON

Plot with vertical axis "Amount Adsorbed" and horizontal axis "Adsorbate Pressure", showing Desorption and Adsorption curves forming a hysteresis loop.

STEAM REQUIREMENTS

Plot with vertical axis "Working Charge, weight %" (0 to 24) and horizontal axis "Pounds of Steam per Pound of Solvent" (0 to 6), showing curves for Acetone, Benzene, and Toluene.
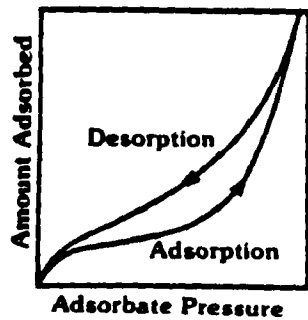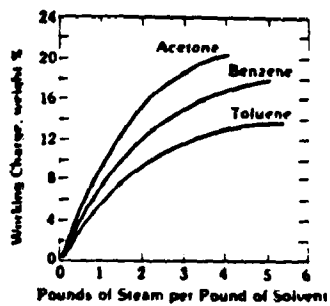
ADDITIONAL FACTORS

- drying and cooling of bed
- heat of adsorption
- fire hazards
- attrition

Chapter 10
Adsorption Control Equipment

Lesson Goal

To review factors affecting the adsorption process and to describe the operation of various types of adsorbers.

Lesson Objectives

Upon completion of this lesson, you should be able to:
1. List five factors which affect adsorber performance.
   a. Temperature
   b. Pressure
   c. Concentration
   d. Gas velocity
   e. Contaminants
2. Describe the operation of three types of adsorbers.
   a. Fixed (regenerable and nonregenerable)
   b. Rotary
   c. Fluidized
3. List three source categories to which adsorbers could be applied for gaseous emission control and list some typical installations related to each.
   a. Bulk terminals
   b. Solvent recovery
   c. Odor control

References

1. APTI Course 415 Student Manual.
2. Environmental Protection Agency (EPA). April 1973. *Packing Sorption Device System Study*. Washington, DC. EPA-R2-73-202.
3. Parmele, C. S., O'Connell, W. L., and Basdehis, H. S. Vapor Phase Adsorption Cuts Pollution, Recovers Solvent, *Chem. Engr.:* Dec. 31, 1979.
4. Technical Bulletin, "Carbon Adsorption/Emission Control" Vic Manufacturing, Minneapolis, MN.
5. Technical Bulletin, "Purasiv HR for Hydrocarbon Recovery", Union Carbide, NY., NY.

ADSORPTION CONTROL EQUIPMENT

FACTORS AFFECTING ADSORPTION

- Adsorbate – Gas Stream
  - Concentration
  - Temperature
  - Pressure
  - Velocity
  - Contaminants
- Adsorbent
  - Retentivity
  - Deactivation
  - Mechanical Stability

CONCENTRATION

TEMPERATURE

PRESSURE

VELOCITY

Length of MTZ vs Velocity, reaching 100 ft sec
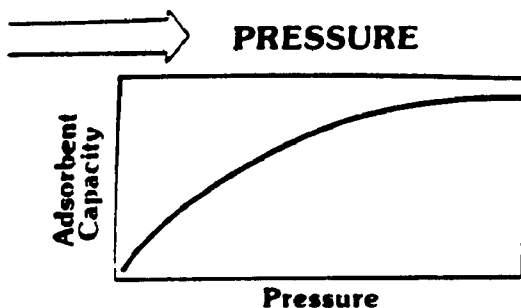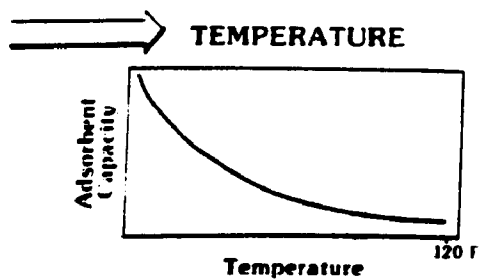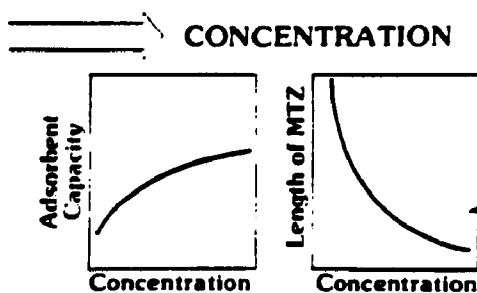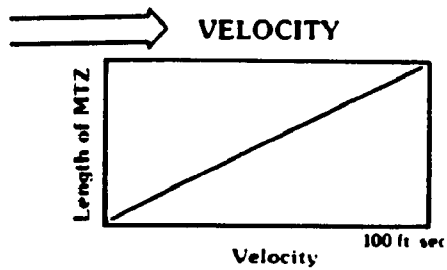
CONTAMINANTS

- particulate matter
- entrained liquid
- high humidity
- corrosive materials
- high boiling point hydrocarbons

RETENTIVITY

- high selectivity for contaminant
- easy regeneration

DEACTIVATION
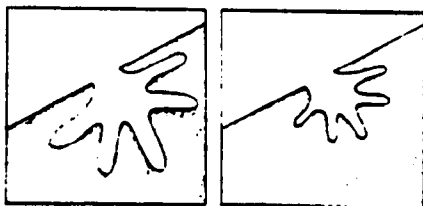
MECHANICAL STABILITY
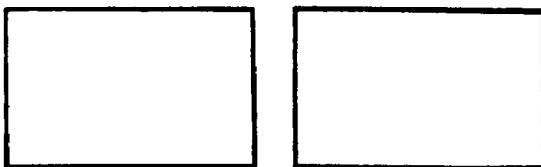
TYPES OF ADSORPTION SYSTEM

- Nonregenerable

- Regenerable

NONREGENERABLE
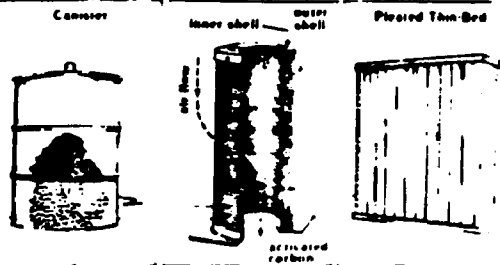
USES OF NONREGENERABLE ADSORBERS

- control of odor

- control of trace contaminants

ADVANTAGES	DISADVANTAGES
• low Δp • inexpensive	• unit replacement cost • no recovery credit

REGENERABLE ADSORBERS
Fixed Bed

REGENERABLE
Fixed Bed
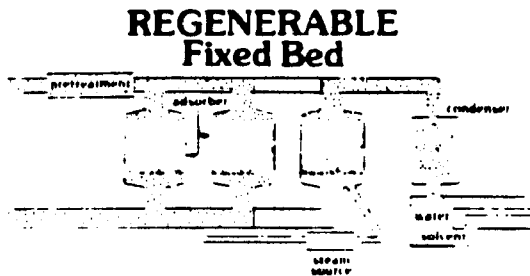
USES OF FIXED BED REGENERABLE ADSORBERS

- Solvent Recovery
- Gasoline Marketing
- Odor Control

ADVANTAGES
(over nonregenerable)

- reuse of carbon
- potential recovery value

DISADVANTAGE

- Idle carbon

Saturated

MTZ

Fresh

REGENERABLE
Fluidized Bed
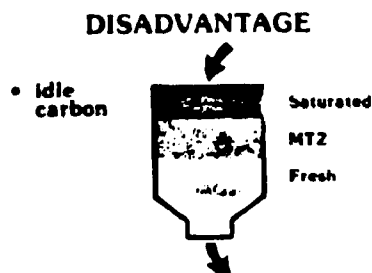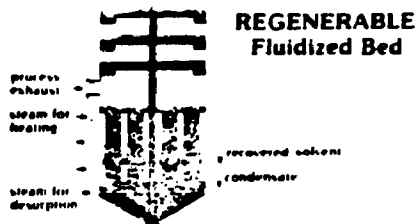
USES OF FLUIDIZED BED REGENERABLE ADSORBER

- Solvent Recovery
  - degreasing
  - printing
  - surface coating

ADVANTAGES	DISADVANTAGE
• increased efficiency of regeneration	• high attrition of carbon
• eliminates idle carbon	
• smaller than comparable fixed bed	
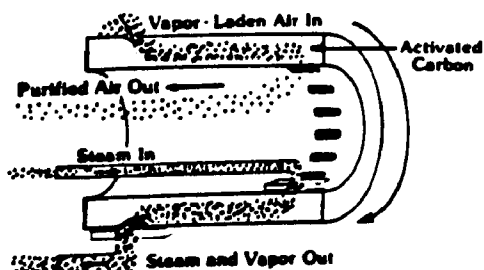
ROTARY BED

USES OF ROTARY BED
REGENERABLE ADSORBERS

- Odor Control
- Solvent Recovery

ADVANTAGES	DISADVANTAGE
• eliminates idle carbon • shorter than fixed bed	• wear on moving parts

TO ACHIEVE
HIGH EFFICIENCY

- allow for cooling/drying cycle
- be able to handle varying concentrations
- monitor the outlet concentration
- provide additional regeneration capabilities

Chapter 11
Condensation Principles and Applications

Lesson Goal

To familiarize you with the basic types of condensers used for control of gaseous air pollutants from industrial sources.

Lesson Objectives

Upon completion of this lesson, you should be able to:
1. List two types of condensers and briefly describe their operation.
2. Recognize some advantages/disadvantages of using either a surface or contact condenser.
3. Recall three applications of condensers for control of gaseous emissions.
4. Recall the steps in reviewing permits for construction and operation of condensers as air pollution control devices.

References

1. APTI Course 415 Student Manual.
2. Environmental Protection Agency (EPA). 1973. *Air Pollution Engineering Manual*. AP-40, 2nd ed. RTP, NC.
3. Perry, John H. 1950. *Chemical Engineering Handbook*. New York: McGraw-Hill Book Company Inc.
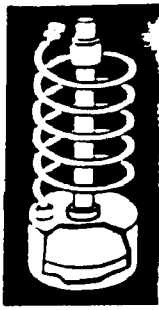
CONDENSATION PRINCIPLES AND APPLICATIONS

TYPES OF CONDENSERS
- Contact
- Surface
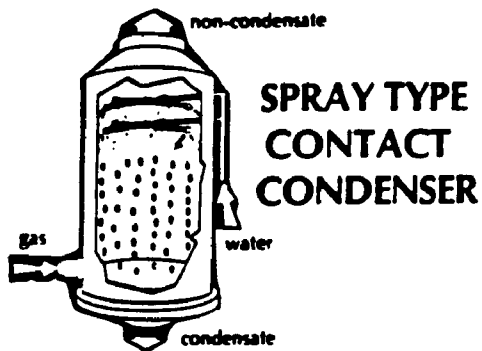
SPRAY TYPE CONTACT CONDENSER

SHELL-AND-TUBE CONDENSER
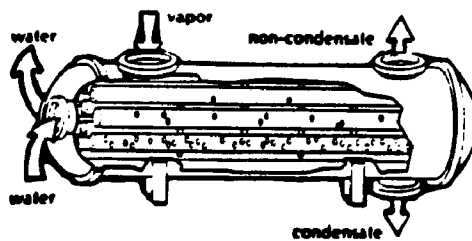
Surface Condensers	Contact Condensers
• less coolant required	• simpler
• less condensate produced	• less expensive
• product easily recovered	• less maintenance required
• no separation problem	• separation problem (coolant and pollutant)

USES OF CONDENSERS
IN A CONTROL SYSTEM

- Vapor Reduction
- Final Control Device
- Odor Control

TYPICAL APPLICATIONS
OF CONDENSERS

- Rendering Plants
- Degreasing Operations
- Petro-chemical Industry
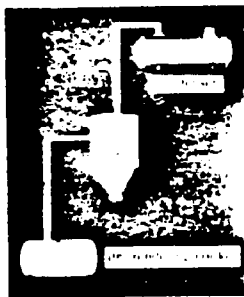
RENDERING PLANTS

- Odor Control
  - cookers
  - dryers
  - grease processing
  - raw materials

DEGREASING OPERATIONS
- Solvent Vapor Containment and Recovery
- Use condensation coils

PETRO-CHEMICAL INDUSTRY
- Vacuum Distillation of Petroleum
- Vapor Recovery in Bulk Terminals
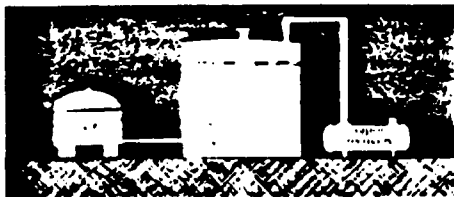
SIZING OF A CONTACT CONDENSER
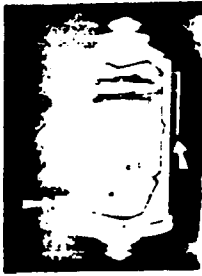
Calculate condensation rate:

- balance heat of vaporization

- balance condensate subcooling

SIZING OF A SURFACE CONDENSER
Calculate heat transfer

$$q = UA\Delta T_m$$
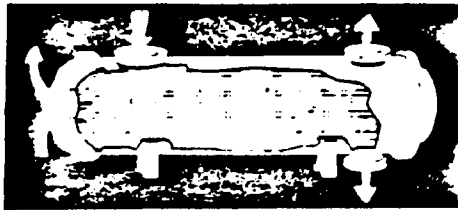
REVIEW OF A DESIGN PLAN

- Examine construction permit
- Review vendor literature
- Check process variables
- Confirm source compliance -
  - Calculate outlet emissions
  - Require source test

REVIEW

- Types of Condensers
  - Contact
  - Surface
- Advantages of Each Type
- Typical Applications
  - Rendering Plants
  - Degreasing Operations
  - Petro-chemical Industry
- Plan Review

Chapter 12
Reduction of SO₂ Emissions from Fossil-Fuel Burning Sources

Lesson Goal

To familiarize you with the characteristics and uses of flue gas desulfurization (FGD) systems.

Lesson Objectives

Upon completion of this lesson, you should be able to:
1. Recall the NSPS for sulfur oxide emissions from fossil-fuel-fired steam generators (FFFSG).
2. List three types of nonregenerable FGD processes and give a brief description of each.
3. List three types of regenerable FGD systems and give a brief description of each.
4. Describe the use of dry-scrubbing FGD systems with baghouses for SO_2 control.
5. List three processes or fuel modifications used to reduce SO_2 emissions.

References

1. Jones, D. G., Hargrove, O. W. *Lime/Limestone Scrubber Operation and Control.* Presented at the 72nd annual meeting of the Air Pollution Control Association. Cincinnati, OH. June 24-29, 1979. 79-23.6.
2. Hollett, Grant T., Jr. *Dry Removal of SO₂ Application to Industrial Coal Fired Boilers.* Presented at the 72nd annual meeting of the Air Pollution Control Association, Cincinnati, OH, June 24-29, 1979. 79-23.1.
3. Hatfield, Dennis L., Harris, James L., Steiner, Thomas P., Silk, Charles T. *Six Years' Operation and Maintenance Experience with a Wellman-Lord SO₂ Abatement System at a Sulfuric Acid Plant.* Presented at the 72nd annual meeting of the Air Pollution Control Association. Cincinnati, OH. June 24-29, 1979. 79-23.3.
4. Electric Power Research Institute (EPRI). 1980. *Comparible Economics of Advanced Regenerable Flue Gas Desulfurization Process.* EPRI CO-1381.
5. Environmental Protection Agency (EPA). 1979. *Definitive SO₂ Control Process Evaluations: Limestone, Double Alkali, and Citrate FGD.* EPA 600/7-79-177.

REDUCTION OF SO₂ EMISSIONS
From Combustion Sources
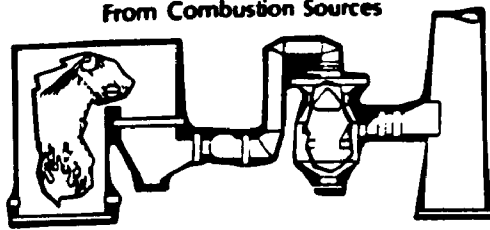
Flue Gas Desulfurization (FGD)

NSPS FOR SO₂

- FFFSG rated $>$ 250 x 10⁶ Btu/hr
  or 73 megawatts

New Sources after August 1971

- liquid gaseous fuel — 0.8 lb 10⁶ Btu
  or 340 ng/J
- solid fuel — 1.2 lb 10⁶ Btu
  or 520 ng/J

New Sources after September 1978

- liquid gaseous fuel — 0.8 lb 10⁶ Btu
  or 340 ng/J
  and 90% scrubbing

(If below 0.2 lb 10⁶ Btu, or 86 ng/J,
then no scrubbing required)

New Sources after September 1978
(continued)

- solid fuel — 1.2 lb 10⁶ Btu
  or 520 ng/J
  and 90% scrubbing

  — 0.6 lb/10⁶ Btu
  or 260 ng/J
  and 70% scrubbing

FGD SCRUBBING
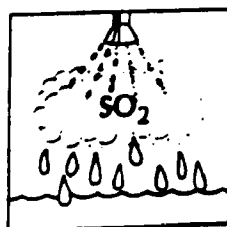
Wet   Dry

WET FGD SCRUBBING

| Nonregenerable | Regenerable |
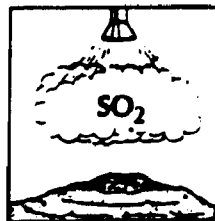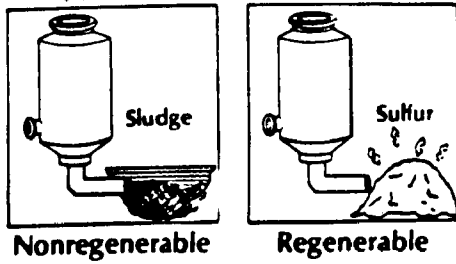
TYPICAL FGD SCRUBBER EQUIPMENT

- Spray Chambers
- Venturi Scrubbers
- Packed Towers
- Cross Flow Scrubbers
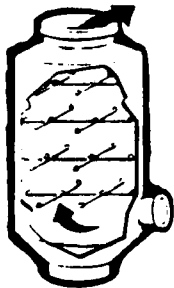
SIMPLE
SPRAY
CHAMBER

SPRAY
VENTURI
SCRUBBER

clean gas
mist eliminator
scrubber liquor
packing

PACKED
TOWER

feed gas
to drain
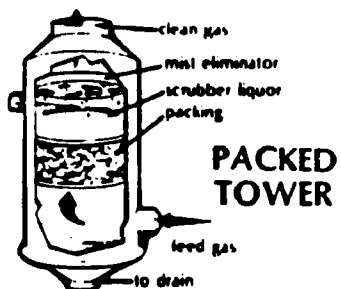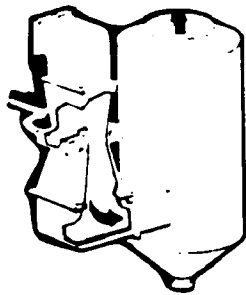
CROSS FLOW SCRUBBER
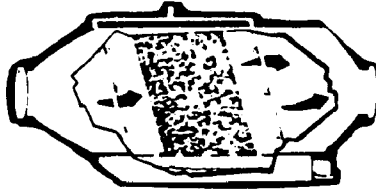
SO₂ REDUCTIONS

- Wet Scrubbing—at least 90%

- Dry Scrubbing—at least 75-85%

NONREGENERABLE PROCESSES

- Lime Scrubbing
- Limestone Scrubbing
- Double Alkali Scrubbing

SCRUBBER WASTE DISPOSAL

- Ponding
- Mine Disposal
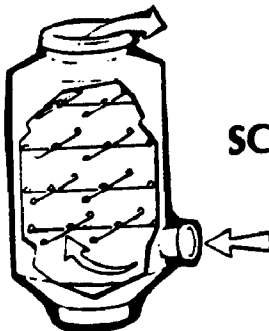
LIME SCRUBBING

LIME SCRUBBING PROCESS CHEMISTRY

$$SO_2 + Ca(OH)_2 \text{ (Slurry from CaO)} \rightarrow CaSO_3 / CaSO_4$$

LIME SCRUBBING

$Ca(OH)_2$ Spray $Ca(OH)_2$ Spray

SO_2

RELATIVE COSTS
(Nonregenerable Processes)

Dollars per kW
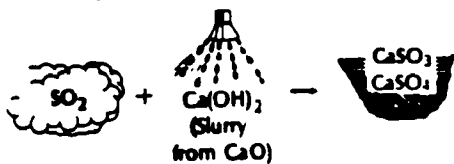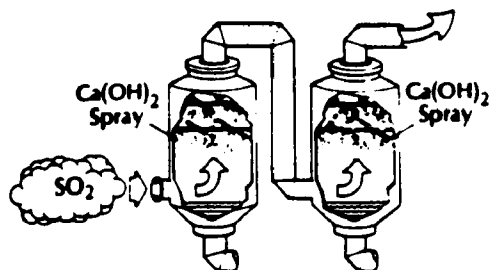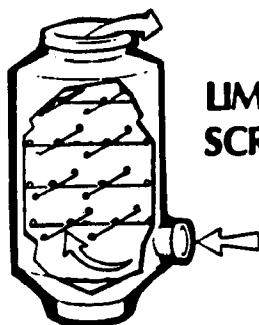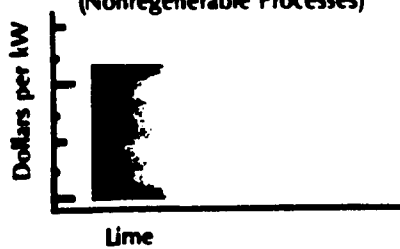
Lime

LIMESTONE SCRUBBING

LIMESTONE SCRUBBING
PROCESS CHEMISTRY

$$SO_2 + CaCO_3 \cdot H_2O \text{ (Slurry)} \rightarrow CaSO_3 / CaSO_4$$

LIMESTONE SCRUBBING

$CaCO_3$ Spray

SO_2

$CaCO_3$ Spray

RELATIVE COSTS
(Nonregenerable Processes)

Dollars per kW

Lime   Limestone
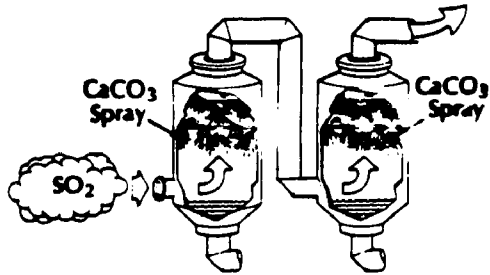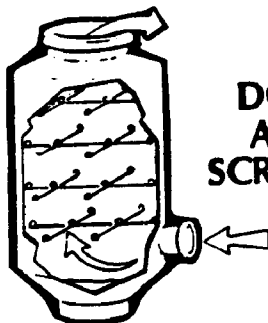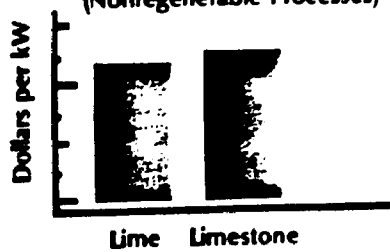
DOUBLE ALKALI SCRUBBING

DOUBLE ALKALI SCRUBBING
PROCESS CHEMISTRY
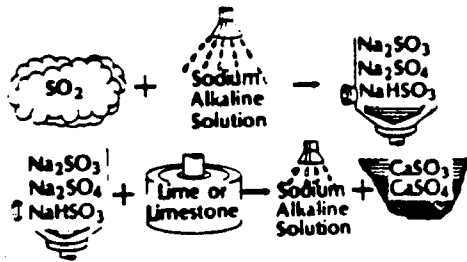
SO_2 + Sodium Alkaline Solution → Na_2SO_3 Na_2SO_4 $NaHSO_3$

Na_2SO_3 Na_2SO_4 $NaHSO_3$ + Lime or Limestone → Sodium Alkaline Solution + $CaSO_3$ $CaSO_4$

DOUBLE ALKALI SCRUBBING

Sodium Alkaline Solution

Regenerated Absorbent

SO_2

Lime or Limestone

RELATIVE COSTS
(Nonregenerable Processes)

Dollars per kW

Lime   Limestone   Double Alkali
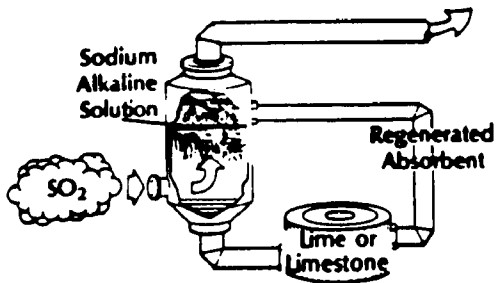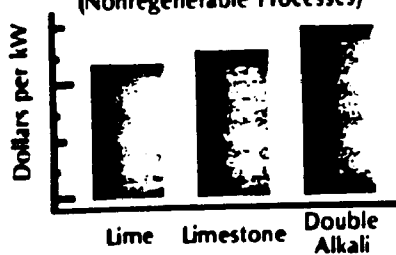
REGENERABLE PROCESSES

- Wellman-Lord/Allied Chemical
- Citrate
- Magnesium Oxide

TYPICAL REGENERATION PRODUCTS

- Sulfur
- Sulfuric Acid
- Gypsum Wallboard

WELLMAN-LORD / ALLIED CHEMICAL PROCESS
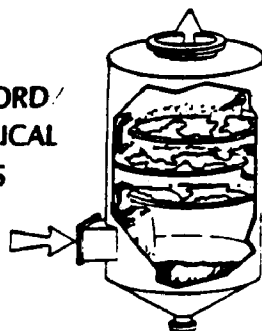
WELLMAN-LORD / ALLIED CHEMICAL PROCESS CHEMISTRY
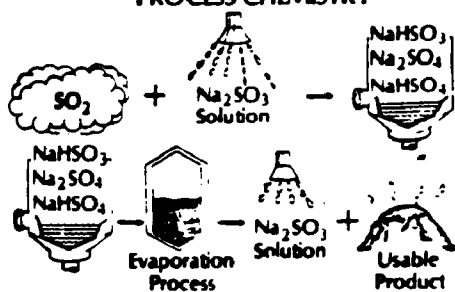
SO_2 + Na_2SO_3 Solution → $NaHSO_3$ Na_2SO_4 $NaHSO_4$

$NaHSO_3$ Na_2SO_4 $NaHSO_4$ → Evaporation Process → Na_2SO_3 Solution + Usable Product

WELLMAN-LORD / ALLIED CHEMICAL PROCESS

Particulate Matter Removed

Absorber   Regenerated Absorbent

Evaporator

RELATIVE COSTS
(Regenerable Processes)

Dollars per kW

Wellman-Lord
Allied Chemical
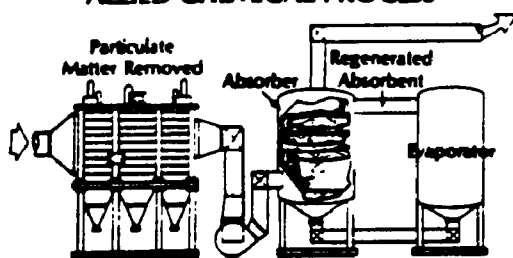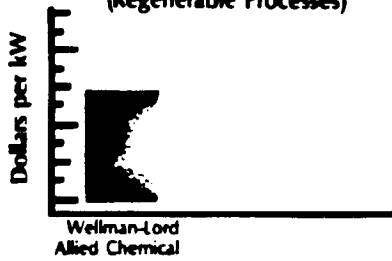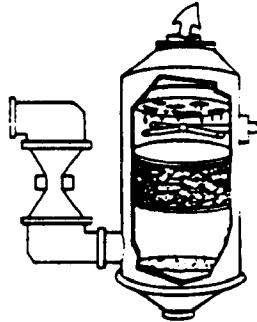
CITRATE
PROCESS

CITRATE PROCESS CHEMISTRY

SO_2 + Citrate Solution — H_2SO_3 Spent Citrate

H_2SO_3 Spent Citrate + H_2S — Citrate Solution + Reusable Sulfur

---

CITRATE PROCESS

Particulate Matter Removed

Absorber

Regenerated Absorbent

Reaction Tank

RELATIVE COSTS
(Regenerable Processes)

Dollars per kW

Wellman-Lord
Allied Chemical   Citrate
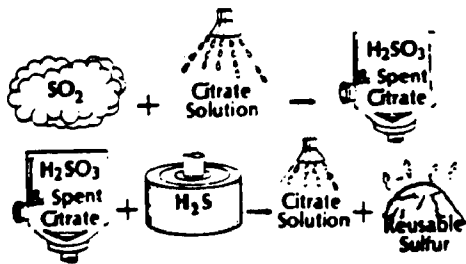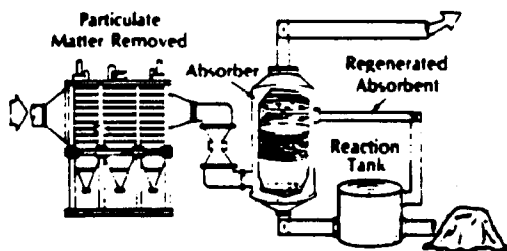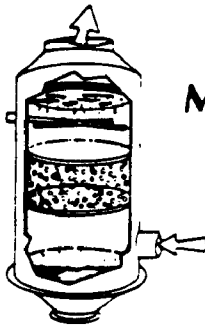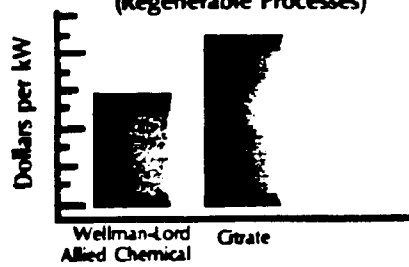
MAGNESIUM OXIDE PROCESS

MAGNESIUM OXIDE PROCESS CHEMISTRY

SO_2 + $Mg(OH)_2$ (Slurry from MgO) → $MgSO_4$ $MgSO_3$

$MgSO_4$ $MgSO_3$ → Calciner → MgO + Concentrated SO_2

MAGNESIUM OXIDE PROCESS

Particulate Matter Removed

Regenerated Absorbent

Calciner

Absorber

RELATIVE COSTS
(Regenerable Processes)

Dollars per kW

Wellman-Lord   Citrate   Magnesium
Allied Chemical   Oxide
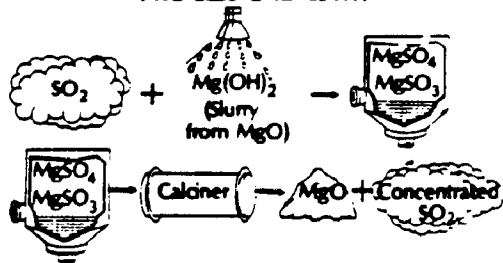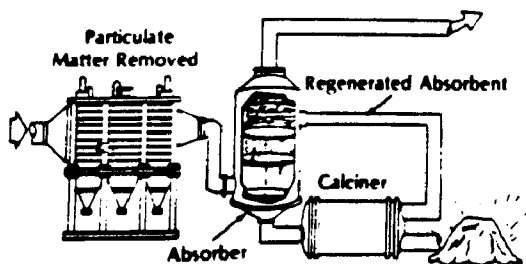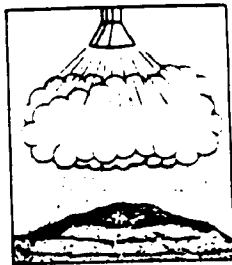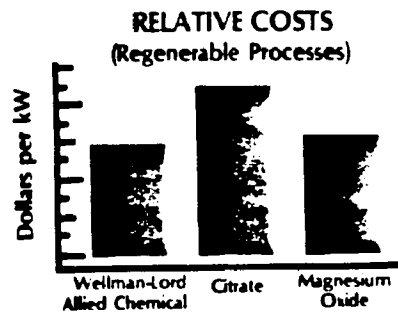
DRY FGD
SCRUBBING

TYPICAL DRY PROCESSES

- Spray Dryer with Baghouse /ESP

- Dry Injection

- Alkali and Coal Combustion

SPRAY DRYER WITH BAGHOUSE

Alkali Spray

SO_2
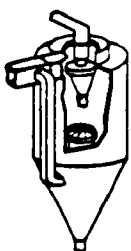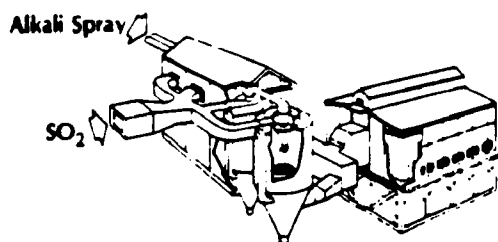
ALKALI SPRAYS

- **Sodium Bicarbonate**

- **Nahcolite**

- **Lime**

SO$_2$ REDUCTIONS

- Dry Scrubbing—75-85%
  (90% possible)

- Estimated Cost—$80-120 kW

TYPICAL DRY PROCESSES

- Spray Dryer with Baghouse/ESP

- Dry Injection

- Alkali and Coal Combustion

OTHER SO$_2$ REDUCTION TECHNIQUES

- Fuel Substitution
- Fuel Cleaning
- Coal Gasification
- Coal Liquification

Chapter 13
Control of Nitrogen Oxide Emissions from Fossil-Fuel Burning Sources

Lesson Goal

To introduce you to practices and equipment used to reduce nitrogen oxide emissions from combustion sources.

Lesson Objectives

Upon completion of this lesson, you should be able to:

1. List the NSPS for nitrogen oxide emissions from major combustion sources.
2. Briefly describe the various combustion modifications used for reducing nitrogen oxide emissions.
3. Briefly describe the operation of the Exxon Thermal DE-NO_x process for nitrogen oxide emission reduction.
4. Briefly describe the operation of the selective catalytic reduction (SCR) process for nitrogen oxide reduction using ammonia.
5. Briefly describe the operation of the UOP-Shell process for NO_x reduction.

References

1. Environmental Protection Agency (EPA). 1977. *Proceedings of the Second Stationary Source Combustion Symposium*, volume II. Utility and Large Industrial Boiler. EPA-600/7-77-073b.
2. Electric Power Research Institute (EPRI). 1979. *Proceedings: Second NO_x Control Technology Seminar*. EPRI/FP 1109-SR.
3. Mobley, J. David. *Assessment of NO_x Flue Gas Treatment Technology*. Paper presented at Symposium on Stationary Combustion NO_x Control, USEPA and EPRI, October 6-9, 1980, Denver, CO.
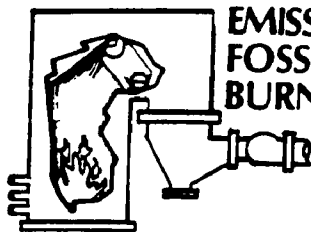
CONTROL OF NO$_x$ EMISSIONS FROM FOSSIL FUEL BURNING SOURCES

METHODS OF REDUCTION
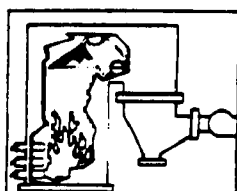
Combustion Modifications
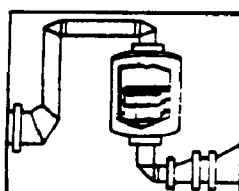
Flue Gas Treatment

NSPS FOR NO$_x$

- FFFSG rated > 250 × 10^6 Btu hr

  New Sources after August 1971

  - gaseous fuel   0.2 lb 10^6 Btu

  - liquid fuel   0.3 lb 10^6 Btu

  - solid fuel   0.7 lb 10^6 Btu
    (except lignite)

NSPS FOR NO$_x$

- FFFSG rated at 73 megawatts

  New Sources after August 1971

  - gaseous fuel   86 ng J

  - liquid fuel   130 ng J

  - solid fuel   300 ng J
    (except lignite)

- FFFSG rated > 250 × 10^6 Btu hr

  New Sources after September 1978

  - gaseous fuel   0.2 lb 10^6 Btu

  - liquid fuel   0.3 lb 10^6 Btu

  - subbituminous coal   0.5 lb 10^6 Btu

  - bituminous anthracite
    coal, lignite   0.6 lb 10^6 Btu

  - lignite in slag top
    furnace   0.8 lb 10^6 Btu

- FFFSG rated at 73 megawatts
  New Sources after September 1978
  - gaseous fuel   86 ng J
  - liquid fuel   130 ng J
  - subbituminous coal   210 ng J
  - bituminous anthracite
    coal, lignite   260 ng J
  - lignite in slag top
    furnace   340 ng J

COMBUSTION MODIFICATIONS

- Low Excess Air

- Staged Combustion

- Flue Gas Recirculation

- Low NO_x Burners

LOW EXCESS AIR

STAGED COMBUSTION

air rich

fuel rich
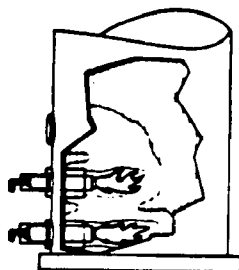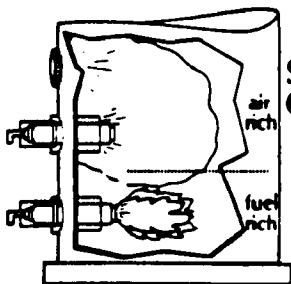
STAGED COMBUSTION TECHNIQUES

- Overfire Air Ports

- Burners Out Of Service

- Air/Fuel Mixing

FLUE GAS RECIRCULATION

LOW NO$_x$ BURNER

fuel and
primary air
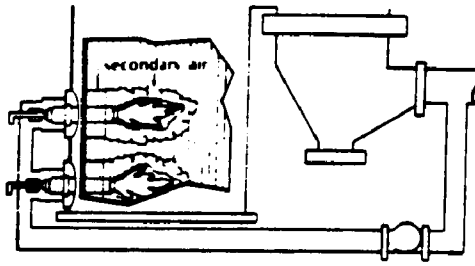
secondary air
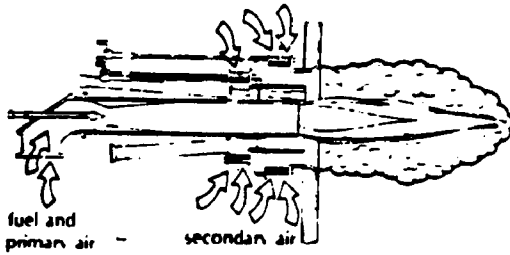
FLUE GAS TREATMENT

* Exxon Thermal De-NO$_x$

* Selective Catalytic Reduction (SCR)

* UOP Shell Process

* Wet NO$_x$/SO$_x$ Process

ammonia injection

EXXON THERMAL DE-NO$_x$
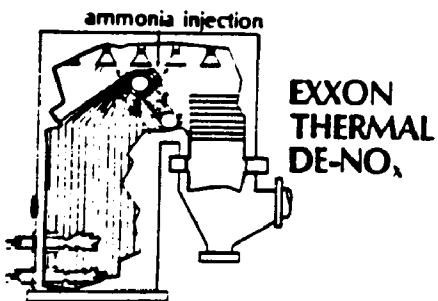
**THERMAL DE-NO$_x$
PROCESS CHEMISTRY**

$$4NH_3 + 4NO + O_2 \rightarrow 4N_2 + 6H_2O$$
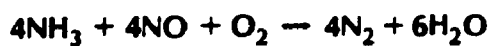
* Required Flue Gas Temperature — 950 °C
  (If hydrogen injected — 700 °C)

AMMONIA INJECTION SPRAY INTO BOILER

ammonia

steam

air

SELECTIVE CATALYTIC REDUCTION (SCR)

300 - 400 °C

ammonia injection

SCR PROCESS CHEMISTRY

$$4NH_3 + 4NO + O_2 \xrightarrow{Catalyst} 4N_2 + 6H_2O$$

$$4NH_3 + 2NO_2 + O_2 \xrightarrow{Catalyst} 3N_2 + 6H_2O$$

Metal Honeycomb

Parallel Plate

Tubular

Ceramic Honeycomb
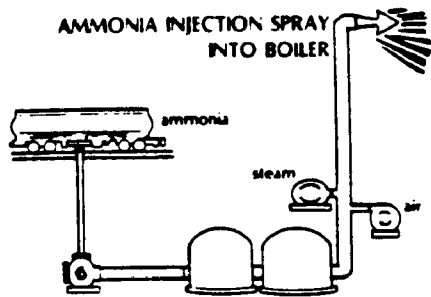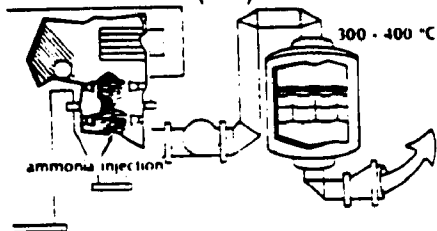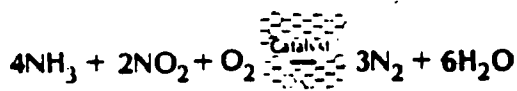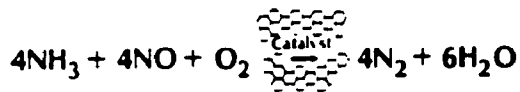
SHAPES OF PARALLEL FLOW CATALYSTS

UNIT CELL OF A PARALLEL FLOW CATALYST

13-5
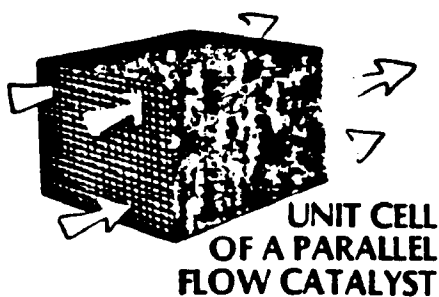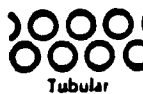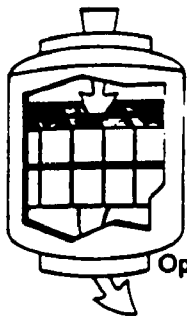
**TYPICAL
PARALLEL FLOW
CATALYTIC REACTOR**

Optimum Flue Gas Temperature
300 – 400 °C

REACTORS
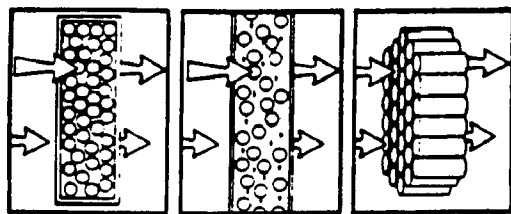
Fixed Bed   Moving Bed   Parallel Flow

UOP SHELL PROCESS

ammonia injection

350 - 450 °C
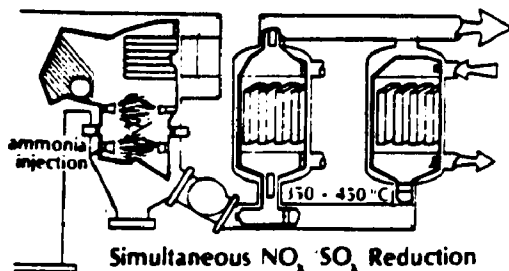
Simultaneous NO_x SO_x Reduction

N_2/H_2O

NO_x SO_x REDUCTION

$$CuO + \tfrac{1}{2}O_2 + SO_2 \longrightarrow CuSO_4$$

$$4NO + 4NH_3 + O_2 \xrightarrow{CuSO_4} 4N_2 + 6H_2O$$

SO_2/NO_x

H_2

CATALYST REGENERATION

$$CuSO_4 + 2H_2 \longrightarrow Cu + SO_2 + 2H_2O$$

$$Cu + \tfrac{1}{2}O_2 \longrightarrow CuO$$

SO_2/H_2O

13-6
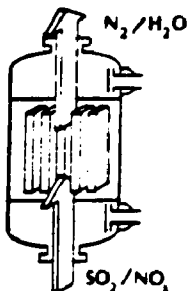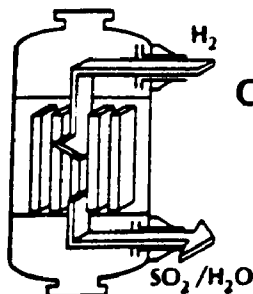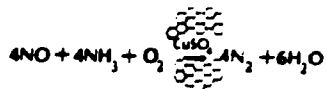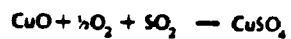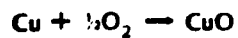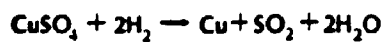
Relative Reduction and Cost
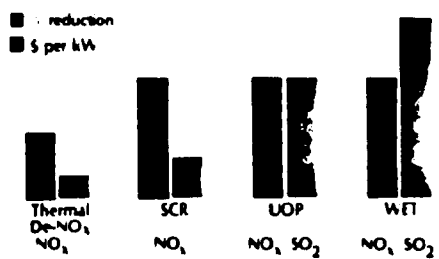
Chapter 14
Exhaust Systems

Lesson Goal

To provide a review of the basic functions of the components of an exhaust system.

Lesson Objective

Upon completion of this lesson, you should be able to:
1. Identify and locate the various parts of an exhaust system: hood, duct, fan, and air pollution control equipment.
2. Define system efficiency as a function of the components of the exhaust system.
3. Describe two types of hoods.
4. List at least three types of pressure losses that occur in a duct.
5. List two types of fans and briefly describe the characteristics of each.
6. Define and relate to each other the following terms pertaining to fans.
   a. Air horsepower (AHP)
   b. Brake horsepower (BHP)
   c. Mechanical efficiency (E_M)
7. Recognize the "Fan Laws" that are used for comparing similar fans.

References

1. APTI Course 415 Student Manual.
2. Environmental Protection Agency (EPA). 1973. *Air Pollution Engineering Manual*. AP-40. 2nd ed. RTP, NC.
3. Baumerster, T. *Fans*. 1st ed. New York, NY.: McGraw-Hill Book Co.

EXHAUST SYSTEMS
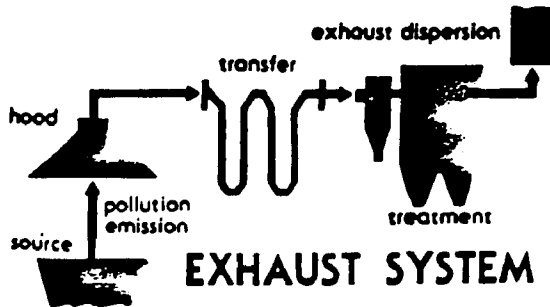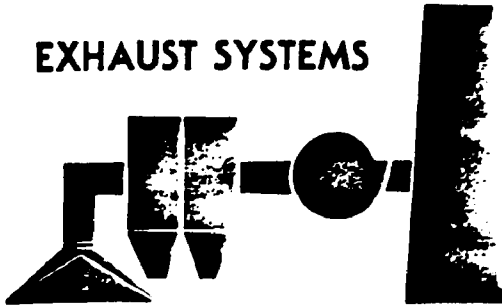
EXHAUST SYSTEM

SYSTEM EFFICIENCY

$$E_{ES} = E_H \times E_D \times E_{APCE}$$

HOOD DESIGNS
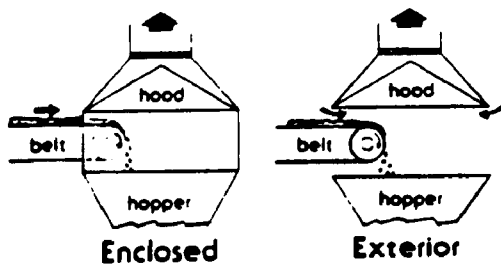
Enclosed   Exterior

DESIRABLE HOOD CHARACTERISITICS

* enclose process or source if possible

* locate exterior hood in path of exhaust

* with exterior hood, minimize interference from cross drafts

PRESSURE
MEASUREMENTS IN DUCT

air flow

Total Pressure − Static Pressure = Velocity Pressure
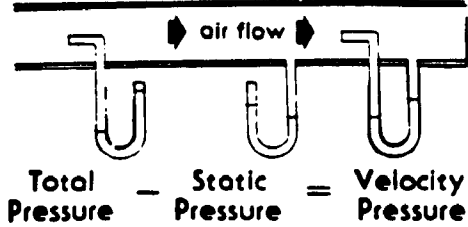
PRESSURE LOSSES

- Inertia (velocity pressure)
- orifice
- straight run
- elbow and branch entry
- contraction and expansion

DESIRABLE DUCT
CHARACTERISTICS

- minimize changes in flow direction
- smooth duct surface
- avoid abrupt expansions

AXIAL-FLOW FAN

CENTRIFUGAL FAN
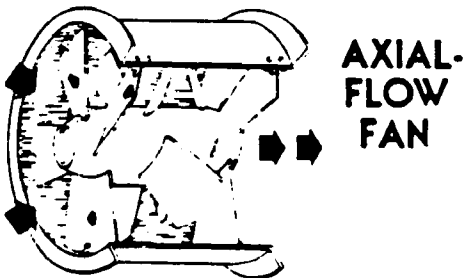
PRESSURE BLOWER FAN
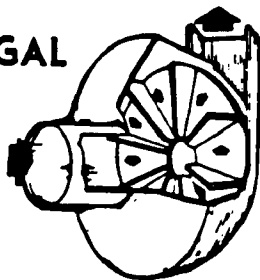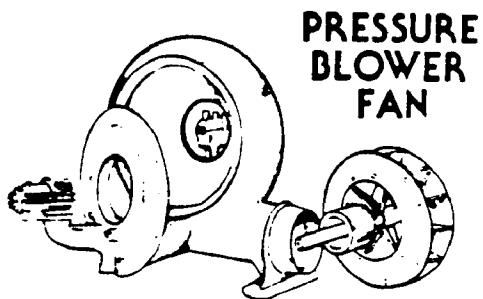
AIR HORSEPOWER

$$AHP = \frac{Q(cfm) \times P_T(in.\ water)}{6356}$$

BRAKE HORSEPOWER

$$BHP = \frac{Q(cfm) \times P_T(in.\ water)}{6356 \times fan\ mech.\ eff.}$$

FORCED DRAFT FAN (Dirty)

INDUCED DRAFT FAN (Clean)
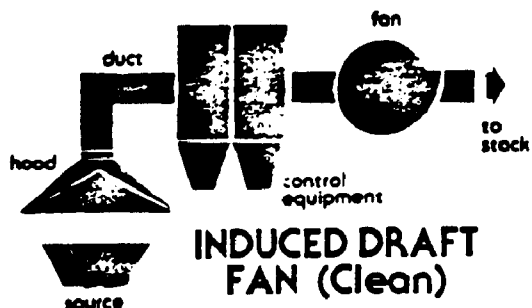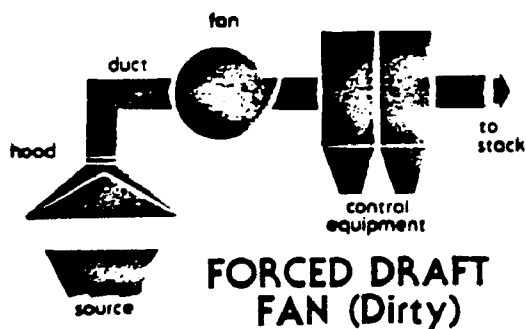
FAN CHARACTERISTIC CURVES

Total Pressure

Horsepower

Mechanical Efficiency

Static Pressure

Pressure

Volume Flow

SYSTEM CURVE

Pressure

Volume Flow
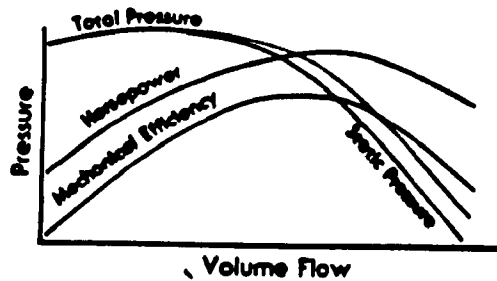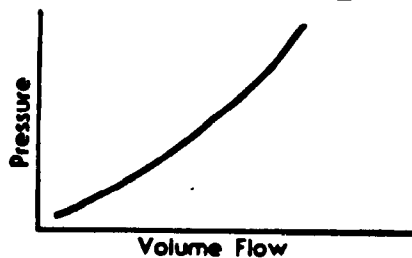
FAN CURVE VERSUS SYSTEM CURVE

Pressure

Fan Performance Curve

System Curve

Volume Flow
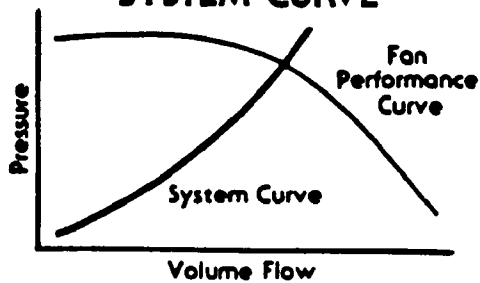
VARIABLES AFFECTING FAN OPERATION

Air Volume (Q) and Horsepower ($\mathscr{P}$)

- fan size (d)
- fan speed (N)
- gas density (ρ)
- system resistance (h_f)

FAN LAWS

- are descriptions of the relationships among the variables

- used to determine what will happen (in terms of fan performance) if a given variable is changed

EXAMPLE PROBLEM

A fan is exhausting 12,000 cfm of air at 600°F (density = .0375 lb/ft³). Fan speed is 630 rpm and 13 horsepower is required. What would be the required horsepower if air at 70°F (density = .075 lb/ft³) is pulled through the system?

SOLUTION

Using Fan Law 4c:

$$\frac{\mathscr{S}_2}{\mathscr{S}_1} = \frac{\varrho_2}{\varrho_1}$$

We get:

$$\mathscr{S}_2 = \mathscr{S}_1\left(\frac{\varrho_2}{\varrho_1}\right) = 13 \text{ hp}\left(\frac{0.075 \text{ lb/ft}^3}{0.0375 \text{ lb/ft}^3}\right)$$

$$\mathscr{S}_2 = 26 \text{ hp}$$

hood
▼
duct
▼
control
equipment
▼
fan
▼
stack

EXHAUST
SYSTEMS
REVIEW

Part 2
Problem Sets

Problem Set 1
Review of Basics

Problem 1-1. Orsat Analysis

Problem Statement

From an Orsat analysis of a boiler's exhaust gas we get the following percentages of components in the flue gas:

$$N_2 = 79\%$$
$$O_2 = 9\%$$
$$CO_2 = 10\%$$
$$CO = 2\%$$

(NOTE: Orsat gives % on a *dry* basis.)

Question

What is the molecular weight of this stack gas?

Problem 1-2. Partial Pressure of Gases

Problem Statement

An air stream of 15,000 scfm contains 1% by volume water vapor and 1000 ppm H_2S.

Questions

1. What is the partial pressure of the water vapor and H_2S?
2. If Henry's Law constant is 483 atm/mole fraction for H_2S dissolved in water, what is the maximum mole fraction of H_2S that can be dissolved in solution?

Problem 1-3. Properties of a Gas

Problem Statement

Carbon dioxide gas (molecular weight = 44) flows through a duct that is three meters in diameter. Assume the following to be true:

$P_b = 1$ atm

$p_v = 0.1$ atm, vacuum

$T = 150\ °F$

$R = \dfrac{(0.082\ \text{atm})(\text{liters})}{(\text{g-mol})(K)}$

kinematic viscosity $= 1.1 \times 10^{-5}\ m^2/s$

velocity $= \dfrac{0.5\ m}{s}$

Question

What are the values of the following?
  a. density, ϱ
  b. absolute viscosity, μ
  c. Reynolds Number, Re

Problem Set 2
Combustion

Problem 2-1. Combustion of Gases

Problem Statement

Consider a gaseous fuel composed of:

$$N_2 = 5\%$$
$$CH_4 = 81\%$$
$$C_2H_6 = 10\%$$
$$C_3H_8 = 4\%$$
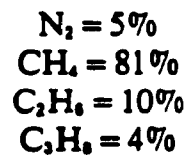
by volume.

Questions

1. What is the volume of air required for complete combustion of 1 acfm of the above fuel with 100% theoretical air?
2. What is the volume of the product of combustion of the fuel?

Problem 2-2. Fuel Required
to Incinerate Waste Gases

Problem Statement

We have an exhaust air stream from a meat smokehouse that contains obnoxious odors and fumes. The exhaust is 5000 acfm at 90°F and we want to incinerate the fume at 1200°F.

Question

How much natural gas will be required if the gross heating value of the fuel is 1059 Btu/scf? NOTE: Use Figures 2-4 and 2-6 on pages 16-8 and 16-10, respectively.

Solution to Problem 2-2

Note: base all calculations on 1 hour.	**A.** Must first find mass flow rate of air $\dot{m}$ = (volume flow rate) × (density) $\dot{m} = \left(5000\ \frac{acf}{min}\right)\left(\frac{lb\ mole}{359\ scf}\right)\left(\frac{492}{460+90}\right)\left(\frac{29\ lb}{lb\ mole}\right)\left(\frac{60\ min}{hr}\right)$ $\dot{m} = 21{,}678\ lb/hr$
Note: ΔH values are obtained from Figure 2-4 on page 16-8.	**B.** Heat required $q = \dot{m}\,\Delta H$ H at 1200°F = 288.5 Btu/lb H at 90 °F is obtained by interpolating H at 90 °F $= \left(\frac{9.6}{100\text{-}60}\right)30 = 7.2$ Btu/lb $q = (21{,}678\ lb/hr)\left(288.5\ \frac{Btu}{lb} - 7.2\ \frac{Btu}{lb}\right)$ $q = 6.098 \times 10^6$ Btu/hr
Note: can calculate q another way by using an average specific heat value.	**C.** $q = \dot{m}\Delta H = \dot{m}\bar{C}_p\Delta T$ $\bar{C}_p = 0.26\ \frac{Btu}{lb°F}$ average for air over the temp. range $q = (21{,}678\ lb/hr)\left(0.26\ \frac{Btu}{lb°F}\right)(1200\text{-}90)$ $q = 6.256 \times 10^6\ \frac{Btu}{hr}$ (more of an estimate)
	D. Heat available from Figure 2-6 on page 16-10, H_A for natural gas with a H_G of 1059 Btu/cf at 1200°F is 690 Btu/cf
Use heat from B.	**E.** Amount of natural gas needed $\left(6.098 \times 10^6\ \frac{Btu}{hr}\right)\left(\frac{scf}{690\ Btu}\right) = 8{,}837\ \frac{scf}{hr}$

Problem 2-3. Design of Afterburner with Heat Recovery

Problem Statement

A two-bed heat recovery unit removes odors and fumes from a 10,000 acfm air stream. The exhaust air enters at 200°F and is heated to 950°F in the preheater before being combusted at 1400°F. The exit air leaves at 500°F.
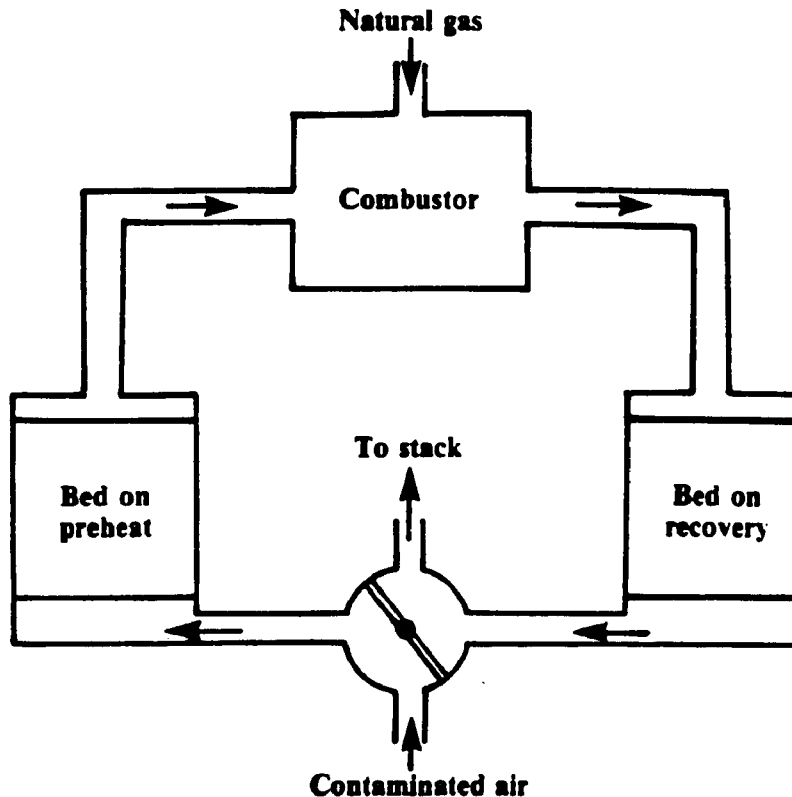
Figure 2-1. Two-bed heat recovery incinerator.

Assume the following:

- $\overline{C}_p$ = mean heat capacity of air = .26 Btu/lb°F
- H_A = available heat of fuel = 950 Btu/scf
- velocity through combustion chamber = 20 ft/sec
- products of combustion = $\dfrac{11.5 \text{ ft}^3 \text{ of combustion products}}{\text{ft}^3 \text{ of fuel}}$
- there are no heat losses
- all calculations are to be based on a reference temperature of 60°F
- there is a minimum residence time of .3 sec

Questions

1. How much fuel is required?
2. What are the diameter and length of the combustion chamber?
3. What are the fuel savings by using heat recovery based on 5000 hrs/yr operation at $1/1000 scf of gas?

Problem 2-4. Plan Review
of a Direct-Flame Afterburner

Problem Statement

Plans have been submitted to your air pollution control agency for a permit to construct a direct-flame afterburner serving a lithographer. As an engineer with the agency, it is up to you to determine if the afterburner meets the following equipment design standards required by your agency.

90% removal by:

a. afterburner temperature 1300-1500°F

b. residence time 0.3-0.5 seconds

c. velocity through afterburner 20-40 fps

The applicant has provided you with the following information needed to evaluate the system:
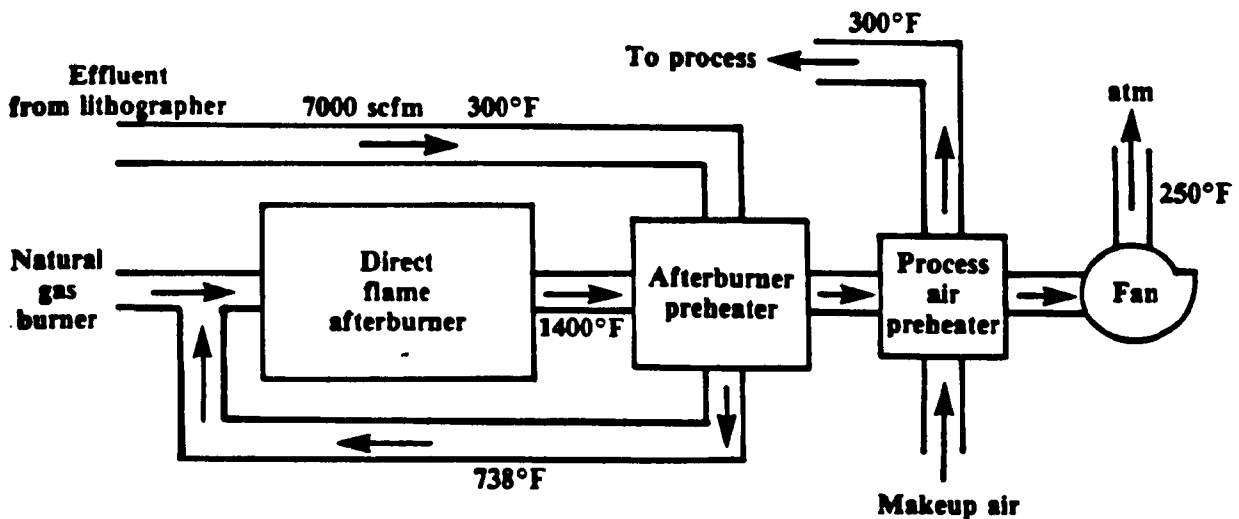
Figure 2-2. Afterburner with heat recovery system.

Assume the following:

- afterburner dimensions are 4.2 ft dia × 14 ft long

- gross heating value of natural gas = 1059 $\dfrac{Btu}{ft^3}$

- hydrocarbon in effluent air to afterburner = 30 lbs/hr (assume hydrocarbons same as toluene)

- heat loss from afterburner = 10%

- molecular weight of toluene = 92

- LEL of toluene = 1.2%

- refer to Figures 2-3, 2-5, and 2-6 on pages 16-7, 16-9, and 16-10, respectively

- for natural gas assume 11.5 ft³ of the flue products per ft³ of gas burned and 10.3 ft³ of theoretical air required per ft³ of gas burned

16-5

Questions

1. Is the concentration of toluene in effluent less than the required 25% of the LEL?
2. How much fuel is required?
   - use C_p values from Figure 2-5 on page 16-9
   - use Figure 2-3 on page 16-7 for the heating value of toluene
   - use Figure 2-6 on page 16-10 to compute the available heat of natural gas
3. Based on volumetric flow of the flue gases is the chamber size adequate?
   - use Figure 2-3 for the products of combustion and theoretical air required for burning of the toluene

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						For 100% Total Air Lb per Lb of Combustible					
							Btu per Cu Ft		Btu per Lb		Required for Combustion			Flue Products			Required for Combustion			Flue Products		
							Gross (High)	Net (Low)	Gross (High)	Net (Low)	O_2	N_2	Air	CO_2	H_2O	N_2	O_2	N_2	Air	CO_2	H_2O	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
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_2H_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	12.39
9.	Propane	C_3H_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	1.68	12.07
10.	n-Butane	C_4H_{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_4H_{10}	58.118	0.1582	6.321	2.0665	3363	3105	21,257	19,679	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_5H_{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_5H_{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_5H_{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_6H_{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_2H_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	14.81	3.14	1.29	11.39
17.	Propylene	C_3H_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_4H_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_4H_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_5H_{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_6H_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_7H_8	92.132	0.2431	4.113	3.1760	4484	4284	18,440	17,670	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_6H_{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_2H_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_3OH	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_2H_6OH	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
29.	Sulfur*	S	32.06	—	—	—	—	—	3,983	3,983	1.0	3.76	4.76	SO_2 1.0	—	3.76	1.00	3.29	4.29	SO_2 2.00	—	3.29
30.	Hydrogen sulfide	H_2S	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_2O	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*, courtesy of American Gas Association. All gas volumes corrected to 60°F and 30 in. Hg dry.

Figure 2-3. Combustion constants.

Temp °F	Relative heat content (H) in Btu per pound (at atmospheric pressure)								
	O_2	N_2	Air	CO	CO_2	SO_2	H_2	CH_4	H_2O
60	0	0	0	0	0	0	0	0	0
100	8.8	9.9	9.6	10.0	8.0	5.9	137	21.0	...
200	30.9	34.8	33.6	34.9	29.3	21.4	484	76.1	...
300	53.3	59.9	57.7	59.9	52.0	37.5	832	136.4	1165
400	76.2	85.0	81.8	85.0	75.3	54.4	1182	202.1	1212
500	99.4	110.3	106.0	110.6	99.8	71.8	1532	272.6	1259
600	123.1	136.1	130.2	136.3	125.1	89.8	1882	347.8	1307
700	147.2	161.7	154.5	162.4	149.6	108.2	2233	427.4	1355
800	171.7	187.7	178.9	188.7	177.8	127.0	2584	511.2	1404
900	196.6	213.9	203.4	215.6	205.6	146.1	2935	599.2	1454
1000	221.7	240.7	235.0	242.7	233.6	165.5	3291	691.1	1505
1200	272.5	294.7	288.5	297.8	290.9	205.1	4007	886.2	1609
1400	324.3	350.8	343.0	354.3	349.7	245.4	4729	1094.1	1717
1600	377.3	407.3	398.0	407.5	416.3	286.4	5460	1313.0	1829
1800	430.7	465.0	455.0	465.3	470.9	327.8	6198	1542.6	...
2000	484.0	523.8	513.0	523.8	532.8	369.1	6952	...	...
2200	539.3	583.2	570.7	583.3	596.1	411.1	7717	...	...
2400	594.4	642.3	628.5	643.0	659.2	452.7	8490	...	...
2600	649.0	702.8	687.3	703.2	723.2	495.2	9272	...	...
2800	702.8	763.1	746.6	771.3	787.4	557.5	10060	...	...
3000	758.6	824.1	806.3	832.6	852.0	580.0	10870	...	...
3200	816.4	885.8	866.0	894.0	916.7	622.5	11680	...	...
3400	873.4	947.6	925.9	956.0	981.6	665.0	12510	...	...
3600	931.0	1010.3	986.1	1018.3	1047.3	707.5	13330	...	...

Figure 2-4. Heat contents of various gases.

Source: North American Combustion Handbook, North American Manufacturing Co., Cleveland, OH, 1st ed. (1952).

t = °F C_p = Btu/(lb mole)(F°)

t	N_2	O_2	H_2O	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

Figure 2-5. Mean molal heat capacities of gases above 0°F*.

*Williams, E. T. and Johnson, R. C. 1958. *Stoichiometry for Chemical Engineers* New York: McGraw-Hill Book Company. p. 321.
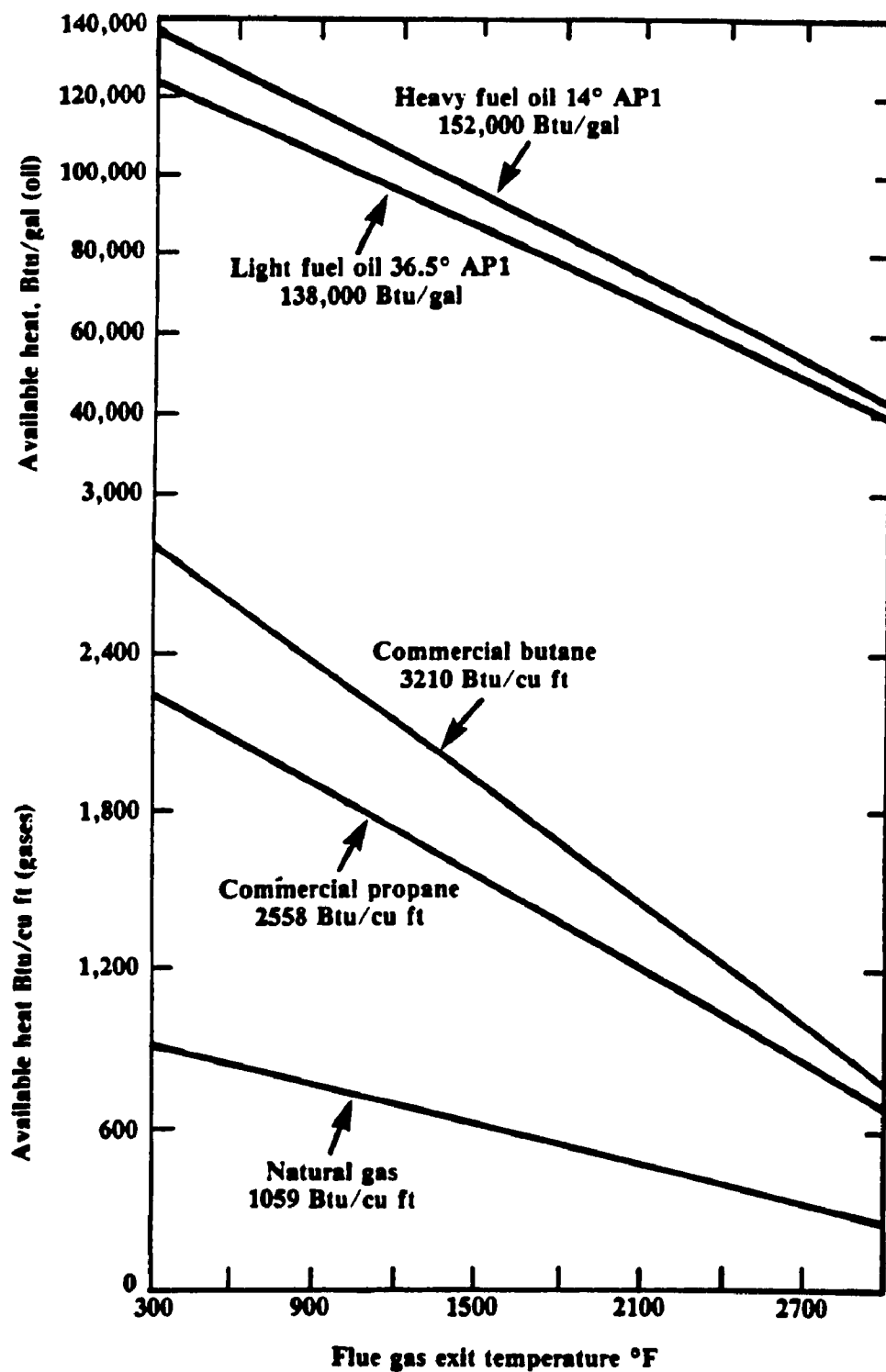
Figure 2-6. Available heats for some typical fuels (referred to 60°F).

Source: North American Manufacturing. 1978. "North American Combustion Handbook" 2nd edition. Cleveland, Ohio.

Problem Set 3
Absorption

Problem 3-1. Equilibrium Diagram

Problem Statement

The following data are from McCabe, W. L., and Smith, J. C., 1956, "Unit Operations of Chemical Engineering." McGraw Hill Book Co., NY., NY. Page 496.

Weight of SO_2 per 100 weights of H_2O	Partial pressure of SO_2, mm Hg
0.5	45
1.0	87
1.5	137
2.0	182
2.5	225
3.0	273
3.5	340
4.0	376

The data are given at 30°C and 1 atm.

Questions

1. Plot the equilibrium curve for this SO_2-air-water system on the following graph paper.
2. Does Henry's Law apply?

Problem 3-2. Packed Tower for H₂S Removal

Problem Statement

The Blackgold Refinery has submitted plans for an H_2S scrubber. Hydrogen sulfide is to be removed from a waste air discharge by scrubbing with a triethanolamine-water solution in a packed tower at atmospheric pressure. Specifications indicate that the gas flow rate is 10,000 acfm at 70°F and contains 15,000 ppm H_2S. The inlet liquid is to be solute free. They must reduce the H_2S to 500 ppm (250 on SO_2 basis).

The pilot plant data indicate that Henry's Law applies (m = 2.0) and the $H_{OG} = 1.94$ ft.

The company proposes to install a 5-ft diameter, 10-ft high packed tower.

Questions

1. What is the minimum L/G (gal/1000 cfm) that you would approve?
2. If they operate at 80.65 lb moles of scrubbing liquid per minute, is their tower adequate?

Problem 3-3. SO$_x$ Absorption by Water

Problem Statement

An exhaust stream of 3000 acfm is known to contain 3% SO$_x$ by volume. The plans must reduce the SO$_x$ content by 90% and plans to do this by scrubbing with water.

Assume the following:

- Henry's Law constant = 42.7 mole fraction SO$_2$ in gas/mole fraction SO$_2$ in liq (from Problem 3-1)
- $\varrho_\ell = 62.4$ lb/ft^3
- $\varrho_s = 0.0732$ lb/ft^3
- packing is 2-inch Intalox saddle
- refer to Figures 3-1 and 3-4 on pages 17-15 and 17-18, respectively
- temperature 30°C

Questions

1. Draw the material balance.
2. What is the liquid requirement in gal/min at 1.5 times the minimum L/G ratio?
3. What is the column diameter at 75% of flooding?
4. Determine the number of transfer units.
5. Based on an H$_{OG}$ of 2.72 ft, what is the total height of the tower?

Solution to Problem 3-3

Part 1—Material Balance

NOTE: Y = mole fraction for the gas. Since we are starting with pure water and no recycle $X_2 = 0$	$L = ?$ $X_2 = 0$ $\longrightarrow$ $Y_2 = .003$ (box) $Y_1 = .03$ $X_1 = ?$ Exhaust gas flow rate = 3000 acfm
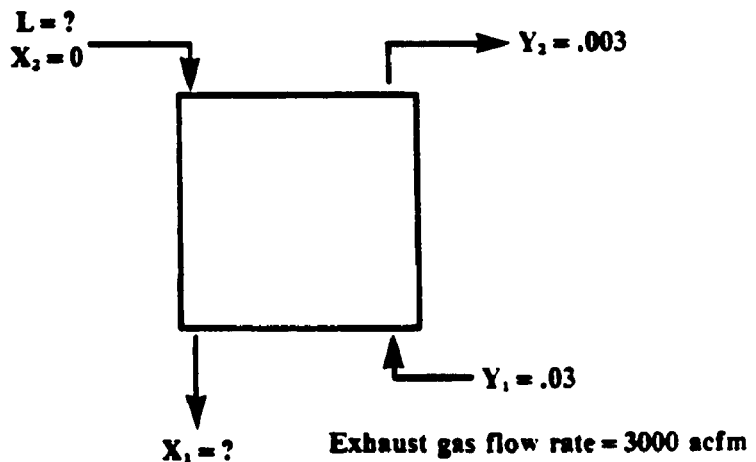
Part 2—Determining Liquid Requirement

	We can compute L_m minimum two ways
	  1. graphically by plotting the inlet and outlet concentrations on an equilibrium diagram from Problem 3-1, or
	  2. by using Henry's Law and the equation for a straight operating line as follows:

NOTE: that we are only concerned with the *very dilute* end of our equilibrium diagram from from Problem 3-1	A. Using Henry's Law $Y = HX$ we know at bottom of tower Y_1 and X_1 are in equilibrium $= 42.7 \dfrac{\text{mole fraction } SO_2 \text{ in gas}}{\text{mole fraction } SO_2 \text{ in liq}}$ (from example) $Y_1 = X_1 H$ $X_1 = Y_1/H$ $X_1 = (.03)/42.7 = .000703 \dfrac{\text{moles of } SO_2}{\text{mole } H_2O}$

	B. Minimum L_m/G_m ratio—now we want to compute the slope of this line, this will give us the minimum L_m/G_m $$Y_1 - Y_2 = L_m/G_m(X_1 - X_2)$$ $$L_m/G_m = \frac{Y_1 - Y_2}{X_1 - X_2} \quad \frac{.03-.003}{.000703-0}$$ $$L_m/G_m = 38.4 \frac{\text{lb mole water}}{\text{lb mole air}}$$

	C. Operating L_m/G_m ratio—absorbers are operated at some liquid rate above the minimum—since at the min. we hit the equilibrium line and absorption *stops*.
	
	Typical situation would be at 1.5 times minimum.
	
	Therefore,
	
	    (L_m/G_m) operating = 1.5 (L_m/G_m) minimum.
	    (L_m/G_m) op = (1.5)(38.4) = 57.6

NOTE: $\dfrac{398\ cf}{\text{lb mole}}$ is a conversion factor corrected for temp.	D. Operating liquid requirement our gas flow into absorber is: $$G_m = \left(\frac{3000\ cf}{\min}\right)\left(\frac{\text{lb mole}}{398\ cf}\right) = 7.54 \frac{\text{lb mole air}}{\min}$$ our liquid required is: $$(L_m/G_m)\text{ operating} = 57.6 \frac{\text{lb mole } H_2O}{\text{lb mole air}}$$ $$L_m = \left(57.6 \frac{\text{lb mole } H_2O}{\text{lb mole air}}\right)\left(7.54 \frac{\text{lb mole air}}{\min}\right)$$ $L_m - 434.3$ lb moles H_2O/min in gallons per minute that is: $$\text{gal/min} = 434.3 \frac{\text{lb mole}}{\min}\left(\frac{18\ lb}{\text{lb mole}}\right)\left(\frac{gal}{8.34\ lb}\right)$$ gal/min = 937.34 liquid requirement = 937.34 gal/min.

Part 3—Column Diameter Determination

NOTE: density from Perry's Handbook	A. Given information:
	$L_m = 434.3 \; \dfrac{\text{lb mole } H_2O}{\text{min}}$ $\quad \varrho_\ell = 62.4 \; \text{lb/ft}^3$
	$G_m = 7.54 \; \dfrac{\text{lb mole air}}{\text{min}}$ $\quad \varrho_g = .0732 \; \text{lb/ft}^3$

B. Convert lb moles to lb

$$G = 7.54 \; \frac{\text{lb mole air}}{\text{min}} \left(\frac{29 \text{ lb}}{\text{lb mole}}\right) = 218.7 \text{ lb/min}$$

$$L = 434.3 \; \frac{\text{lb mole } H_2O}{\text{min}} \left(\frac{18 \text{ lb}}{\text{lb mole}}\right) = 7817.4 \text{ lb/min}$$

C. Compute the abscissa $(L/G)\left(\dfrac{\varrho_g}{\varrho_\ell}\right)^{0.5}$

$$(L/G)\left(\frac{\varrho_g}{\varrho_\ell}\right)^{0.5} = \frac{(7817.4)}{(218.7)}\left(\frac{.0732}{62.4}\right)^{0.5} = 1.225$$

D. Use Figure 3-4 from the 415 Student Workbook and read the ordinate from the flood line

ϵ (ordinate) – .019

E. Gas flow rate at flooding conditions from graph

$$\frac{G'^2 F\phi\mu^{0.2}}{\varrho_g\varrho_\ell g_c} = \text{ordinate} = \epsilon$$

for water $\phi = 1.0$ and $\mu = .8$ centipoise
if we use 2 inch ceramic Intalox saddles
F = 40, from Fig 3-1 415 Student Workbook

$$\frac{G'^2(40)(1.0)(.8)^{0.2}}{(.0732)(62.4)(32.2)} = .019$$

$G' = .27 \text{ lb/ft}^2 \text{ sec}$

F. Gas flow at operating conditions
assume we operate at 75% of flooding conditions
G operating $= (f)(G'_{flooding})$

$$G \text{ operating} = (.75)(.27) = .20 \; \frac{\text{lb}}{\text{ft}^2 \text{ sec}}$$

	G. Cross sectional area of column $$A = \frac{\text{mass flow rate (lbs/sec)}}{\text{operating flow rate lbs/sec ft}^2}$$ $$A = \frac{(218.7 \text{ lbs/min}) \left(\frac{\text{min}}{60 \text{ sec}}\right)}{.20 \text{ lb/sec ft}^2}$$ $A = 18.23 \text{ ft}^2$
	H. Column diameter $$d_t = \left(\frac{4A}{\pi}\right)^{\frac{1}{2}}$$ $d_t = 1.13 \ A^{\frac{1}{2}}$ $d_t = 1.13 \ (18.23 \text{ ft}^2)^{\frac{1}{2}} = 4.8 \text{ ft}$ $\therefore$ need a 5-ft diameter tower **Column diameter = 5 ft**

Part 4—Number of Transfer Units

	A. From previous sections $X_2 = 0 \qquad m = 42.7 \ \dfrac{\text{mole fraction } SO_2 \text{ in air}}{\text{mole fraction } SO_2 \text{ in liq}}$ $Y_1 = .03 \qquad L_m - 434.4 \text{ lb mole } H_2O/\text{min}$ $Y_2 = .003 \qquad G_m = 7.54 \text{ lb mole air/min}$
NOTE: can use Colburn diagram to get same solution	**B. Computing N_{OG}** $$N_{OG} = \ell n \ \frac{\left[\left(\dfrac{Y_1 - mX_2}{Y_2 - mX_2}\right)\left(1 - \dfrac{mG_m}{L_m}\right) + \dfrac{mG_m}{L_m}\right]}{1 - \dfrac{mG_m}{L_m}}$$ $$\frac{mG_m}{L_m} = \frac{(42.7)(7.54)}{434.4} = .741$$ $$N_{OG} = \ln \frac{\left[\dfrac{.03 - 0}{.003 - 0}(1 - .741) + .741\right]}{1 - .741}$$ $N_{OG} = 4.65$

C. Total height of packed section
given $H_{OG} = 2.72$ ft from pilot studies of
air-SO_2-water system
$Z = N_{OG} \times H_{OG} = (4.65)(2.72)$
$Z = 12.65$ ft of packing

D. Graphic solution:
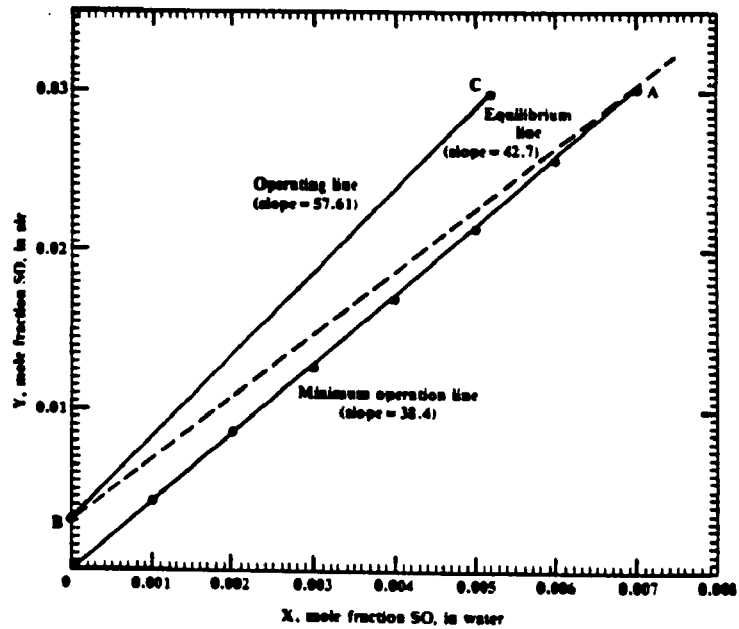
Problem 3-4. SO$_x$ Absorption by Dilute Alkaline Solution

Problem Statement

Assume the conditions from Problem 3-3 (i.e., a 3000 acfm air stream containing 3% SO$_x$), but this time reduce the sulfur content by 90% by absorbing with a dilute sodium hydroxide solution. (NOTE: This is a very rapid reaction.)

Questions

NOTE: Use any additional information supplied or derived from Problem 3-3.
1. What would be the number of transfer units needed to accomplish this?
2. From pilot plant studies we know the new operating L/G ratio is 5.0 gal/1000 cf. What diameter tower is needed if the company operates at 75% of flooding?

Problem 3-5. Permit Review of Ammonia Absorber

Problem Statement

Pollution Unlimited, Inc. has submitted plans for a packed ammonia scrubber on a 1575 cfm air stream containing 2% by volume NH_3. The emission regulation is 0.1% by volume NH_3. Their permit supplies the following information:

- Tower diameter is 3.57 ft
- Packing height is 8 ft
- Operating temp is 75°F
- Operating pressure is 1.0 atm
- Gas flow rate is 1575 cfm
- Ammonia free liquid flow rate is 1000 lb/m ft²
- Packing is 1½" Raschig rings
- Air density is 0.0743 lb/ft³

From Perry's Chemical Engineering Handbook, you've obtained:

- Figure 3-2 on page 17-16
- Henry's Law Constant, $H = 0.972$ (slope of equilibrium line, m)

Question

What is your determination—are liquid rate and tower height sufficient to meet the regulation?

Problem 3-6. Spray Tower

Problem Statement

A steel pickling operation emits HCl fumes (hydrochloric acid) of 300 ppm average with peak values of 400 ppm 15% of the time. The air flow is a constant 10,000 cfm at 75°F and 1 atm pressure. Regulations limit emissions to no more than 50 ppm HCl at any time. Only sketchy information was submitted with the scrubber permit application. The plans show a 14-foot tall, 9-foot diameter counter-current water spray tower.

Assume the following:

- Gas velocity through the tower is not to exceed 3 ft/sec.
- For HCl, Henry's Law does not apply because HCl is very soluble.
- 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 to the back mixing of liquids and gases. The final spray, if placed in the inlet duct, adds no height and has an N_{OG} of .5.
- The spray sections of a tower are normally spaced at three foot intervals.

Questions

Is the spray unit satisfactory? You will need to determine:
1. actual velocity through tower
2. N_{OG} needed
3. number of spray sections to meet N_{OG}
4. height of required tower
5. whether or not the spray unit is satisfactory

Packing	Size	Weight lb/ft^3	Surface area, a (ft^2/ft^3 packing volume)	Percent void fraction	Packing factor (F)
Raschig rings (ceramic and porcelain)	½	52	114	65	580
	1	44	58	70	155
	1½	42	36	72	95
	2	38	28	75	65
	3	34	19	77	37
Raschig rings (steel)	½ × 1/32	77	128	84	300
	1 × 1/32	40	63	92	115
	2 × 1/16	38	31	92	57
Berl saddles (ceramic and porcelain)	¼	55	274	63	900
	½	54	155	64	240
	1	48	79	68	110
	2	38	32	75	45
Intralox saddles (ceramic)	¼	54	300	75	725
	½	45	190	78	200
	1	44	78	77	98
	2	42	36	79	40
Pall rings (plastic)	5/8	7	104	87	97
	1	5.5	63	90	52
	2	4.5	31	92	25

Figure 3-1. Packing data.
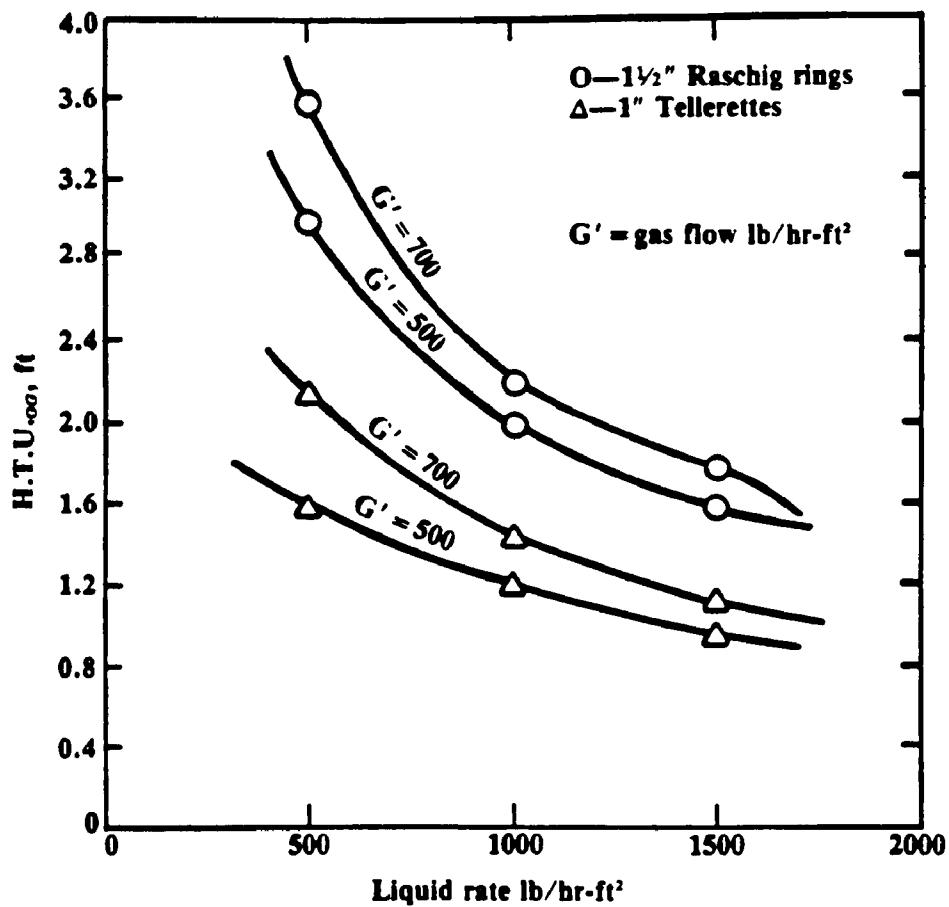
Figure 3-2. Ammonia-water absorption system.

Source: Perry, J. H. 1973. Chemical Engineers Handbook, 5th ed. NY., NY. McGraw Hill.

Figure 3-3. Colburn chart.
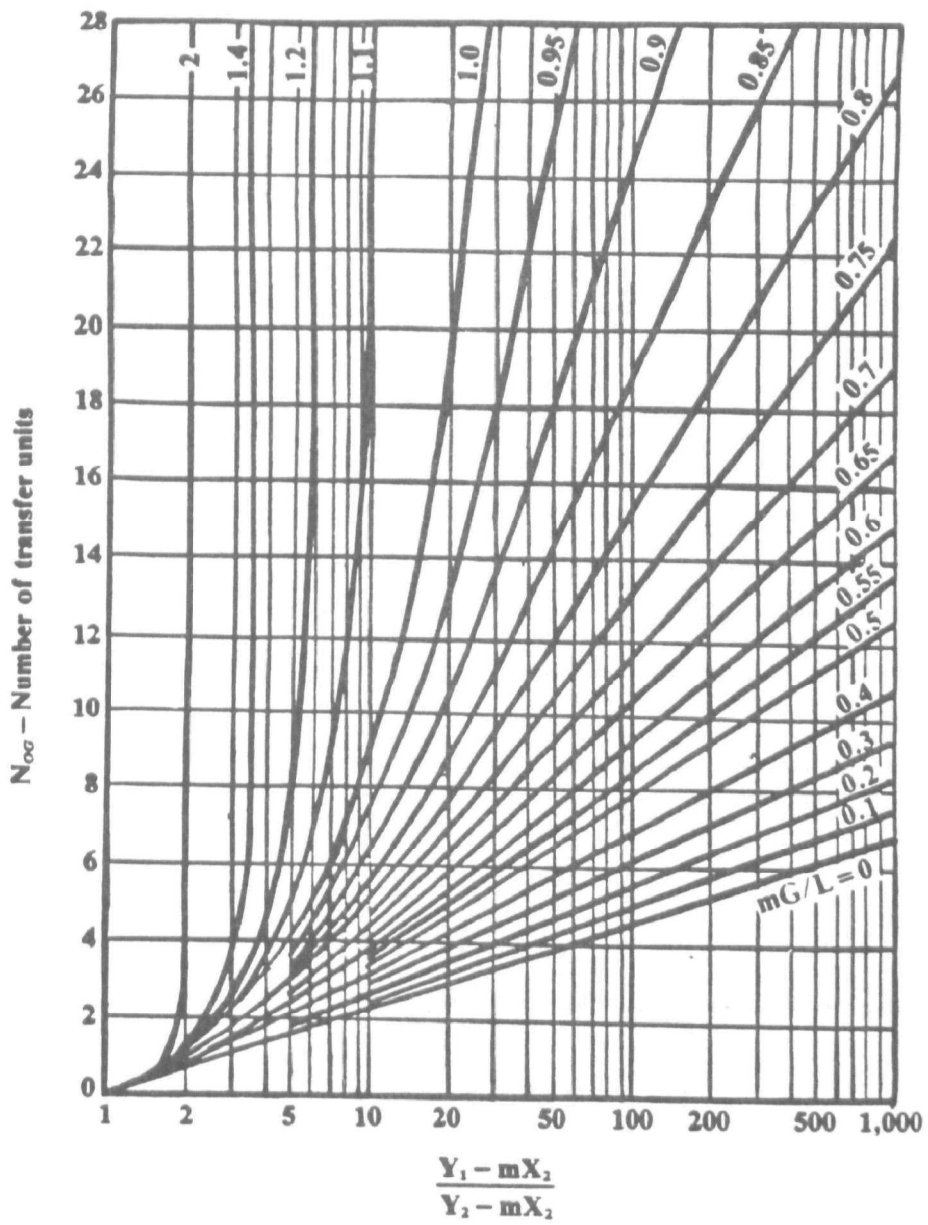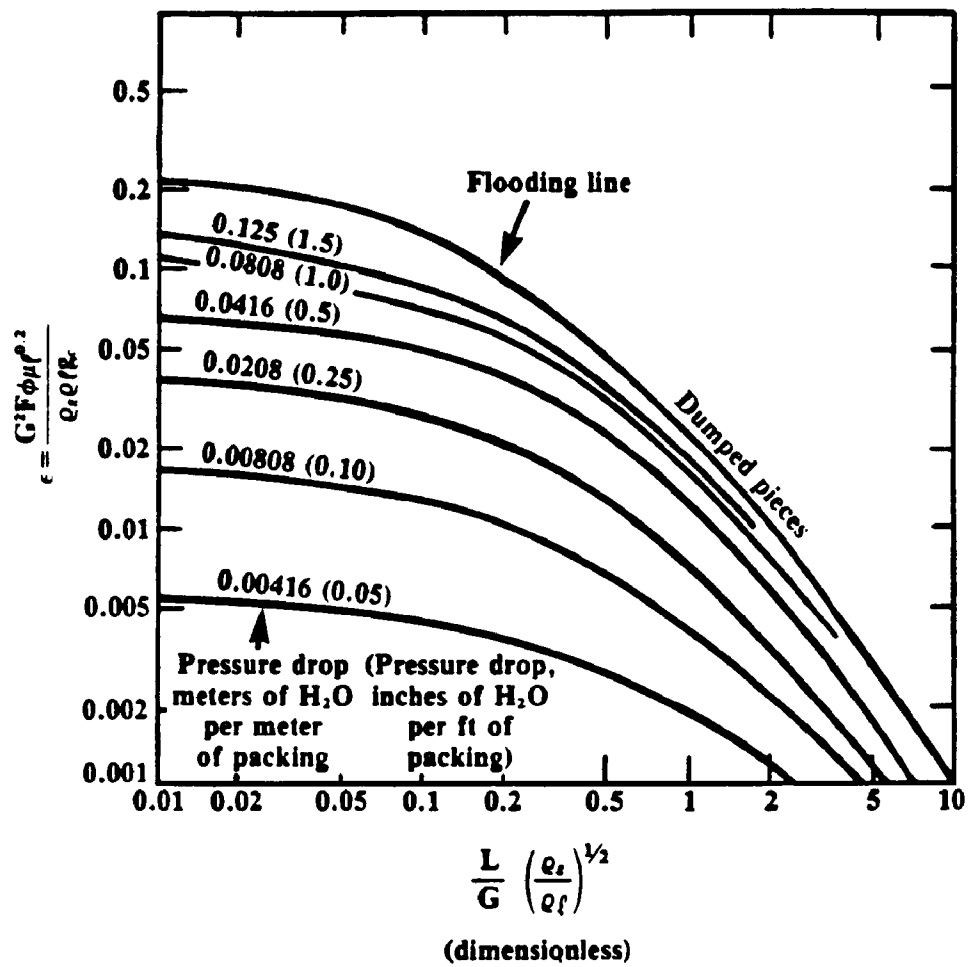
Figure 3-4. Generalized flooding and pressure drop correlation.

Problem Set 4

Adsorption

Problem 4-1. Adsorption Working Capacity

Problem Statement

Assume the following data:
- 10,000 cfm air stream at 77°F
- atmospheric pressure
- 2000 ppm toluene
- 3000 ppm carbon tetrachloride
- 95% removal objective
- isotherms—Figures 4-1 and 4-4 on pages 18-8 and 18-9 respectively
- MW carbon tetrachloride = 154
- MW toluene = 92

Questions

1. How many pounds per hour of organics must be removed?
2. Assuming stream regeneration at 212°F, what is the working capacity?
3. Using vacuum regeneration, what is the working capacity?

NOTE: For rough estimates of working capacity, we can use the difference between the saturation capacity (read from the isotherm) at adsorbing partial pressure and the saturation capacity at regenerating partial pressure.

Problem 4-2. Sizing an Adsorber

Problem Statement

Assume the information given in Problem 4-1 and the following data:
- Bulk density of carbon = 30 lb/ft³
- 90 fpm velocity through bed
- 16 hr/day operation
- steam regeneration at 212°F
- depth of bed cannot exceed 4 feet
- need 3031 lbs of carbon to remove 939 lbs of solvent per hour

Questions

1. What is the appropriate cycle time (based on bed depth limitation)?
2. What is the volume of carbon needed?
3. What is the bed diameter?
4. What is the bed depth?

Problem 4-3. Benzene Adsorber Plan Review

Problem Statement

A solvent recovery system was designed to recover benzene from an air stream. The company has plans to increase production, which would result in a 75% increase in benzene that must be controlled. You are given the following data on the present system:

Existing System—Carbon I

- Carbon density is 23 lbs/ft^3
- Carbon size is 4×6 mesh
- Gas velocity is 100 fpm
- Bed area is 120 ft^2
- Bed depth is 24 inches
- Concentration of benzene is 1316 ppm
- Temperature is 26°C
- Carbon charge is 5200 lbs
- Working capacity is 36 lbs benzene/100 lbs carbon
- Residual capacity is 2.2%
- Cycle time is 10 hrs adsorbing, 2 hrs steaming and drying
- Vapor pressure of benzene at 26°C is 100 mm Hg
- MTZ is 2 inches
- MW is 78.11

Refer to Figure 4-2 on page 18-8, Adsorption isotherm for benzene (use the line for Carbon I).

Questions

1. What is the new saturation capacity?
2. What is the new breakthrough capacity?
3. What is the new working capacity?
4. What is the cycle time?
5. Can the present system handle the increased benzene load?

Problem 4-4. Adsorption Plan Review—Gasoline Marketing

Problem Statement

A bulk terminal that transfers gasoline to service stations has submitted plans to install a carbon adsorption unit to control emissions from the filling of their tank trucks. You are given the following information:

- Average daily throughput is 120,000 gal/day of gasoline
- Maximum pumping rate is 2000 gal/min
- Air flow to adsorber is 350 cfm
- Diameter of adsorber is 4 ft
- Height of carbon is 3 ft
- 2 beds, regeneration cycle time of ½ hour for each bed
- Emission factor is 5 lbs/1000 gal loaded
- Emission limit is .67 lbs/1000 gal loaded
- MW of gasoline is 68 lb/lb mole
- Ideal gas constant, $R = .732 \dfrac{\text{atm ft}^3}{\text{lb mole }^\circ R}$
- T is 70°F
- Carbon density is 30 lb/ft³
- Vacuum regeneration

Refer to Figure 4-3 on page 18-9, Adsorption isotherm for gasoline vapors

NOTE: Rules of Thumb
1. Velocity through adsorber should be between 20-100 fpm
2. Working charge of carbon may be estimated by doubling the amount of carbon at saturation capacity. (Remember, the saturation capacity is the ideal amount of solvent the carbon can hold and is read from the adsorption isotherm.)

Questions

1. What is the velocity through the adsorber?
2. How much carbon is required?
3. What is the bed depth?
4. Will the unit be in compliance?

Problem 4-5. Rotogravure Printing Adsorber

Problem Statement

A printing company must reduce the amount of toluene they emit from their Rotograve printing operation. The company comes in with some preliminary information on installing a carbon adsorption system. You are given the following information:

- Air flow is 20,000 cfm
- They operate at 25% of LEL for toluene in the exit air
- LEL for toluene is 1.2%
- Toluene MW is 92.1 lb/lb mole
- Carbon density is 30 lb/ft^3
- Working charge is 30% of saturation capacity
- Regeneration is just under 1 hour
- Temperature is 77°F
- Maximum velocity through adsorber is 100 fpm

Refer to Figure 4-4 on page 18-9, Adsorption isotherm for toluene.

Questions

Determine the minimum size of adsorber that you would approve:
1. Diameter of the adsorber: _____
2. Square feet of carbon face area: _____
3. Depth of bed: _____

Solution to Problem 4-5

(NOTE: all amounts are based on 1 hour because desorption takes only 1 hour)

NOTE: can point out again that saturation capacity is ideal amount.	**A. amount of carbon needed** 1st calculate amount of toluene emitted per hour (20,000 cfm)(25%)(1.2%) = 60 cfm of toluene $$\left(60 \frac{scf}{min}\right) \times \left(\frac{lb\ mole}{359\ scf}\right)\left(\frac{492°R}{537°R}\right) \times \left(\frac{92.1\ lb}{lb\ mole}\right) \times \left(\frac{60\ min}{hr}\right)$$ = 846 lb/hr in order to compute saturation capacity from Figure 4-4 on page 18-9, we need partial pressure of toluene $$p = \left(\frac{60\ cfm}{20,000\ scfm}\right)(14.7\ psia) = 0.044\ psia$$ saturation capacity = 38% from Figure 4-4 working capacity is 30% of saturation $$w.c. = (38\%)(30\%) = 11.4\%\ \text{or}\ \frac{11.4\ lb\ toluene}{100\ lb\ carbon}$$ amount of carbon needed for 1 hour cycle $$\left(\frac{846\ lb\ toluene}{hr}\right)\left(\frac{100\ lb\ carbon}{11.4\ lb\ toluene}\right)(1\ hr)$$ = 7,421 lbs carbon/hr **Amount of carbon = 7,421 lb**
	B. volume occupied by the carbon $$(7,421\ lbs\ carbon)\left(\frac{ft^3}{30\ lb}\right) = 247\ ft^3$$
	C. cross-sectional area of bed $$20,000 \left(\frac{scf}{m}\right) \left(\frac{m}{100\ ft}\right) = 200\ ft^2$$ based on 100 fpm limiting NOTE: this requirement could be met by a horizontal flow bed 10 ft wide and 20 ft long.

D. depth of carbon bed

$$D = \frac{\text{volume of carbon}}{\text{cross sectional area}} = \frac{247 \text{ ft}^3}{200 \text{ ft}^2} = 1.24 \text{ ft}$$

Depth of carbon bed = 1.24 ft

Note that these calculations are based on minimum acceptable design conditions using only two beds. In practical situation may opt for three bed systems each handling only 10,000 cfm. This will decrease the diameter (cost) of each individual unit and allow for more carbon length to ensure against breakthrough.
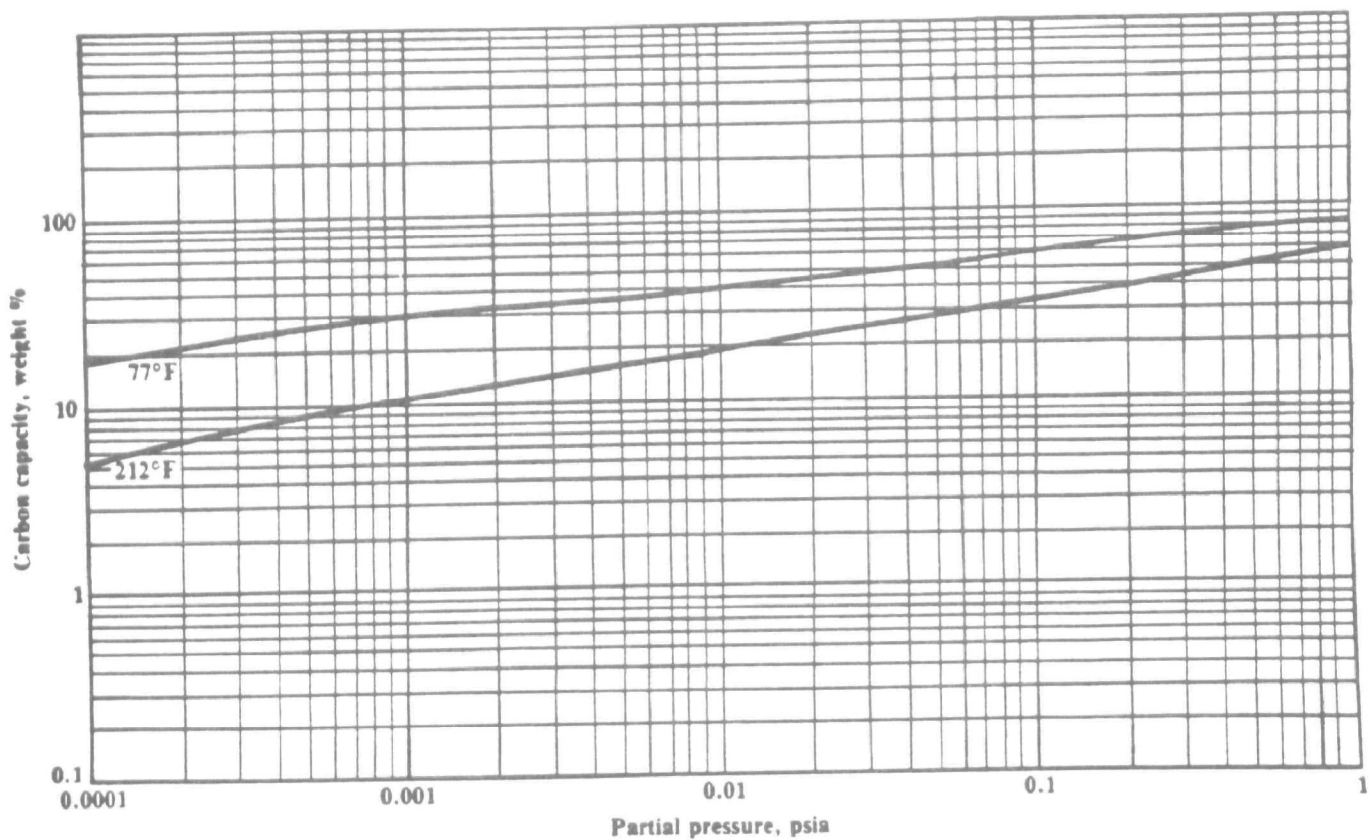
Figure 4-1. Adsorption isotherm for carbon tetrachloride.
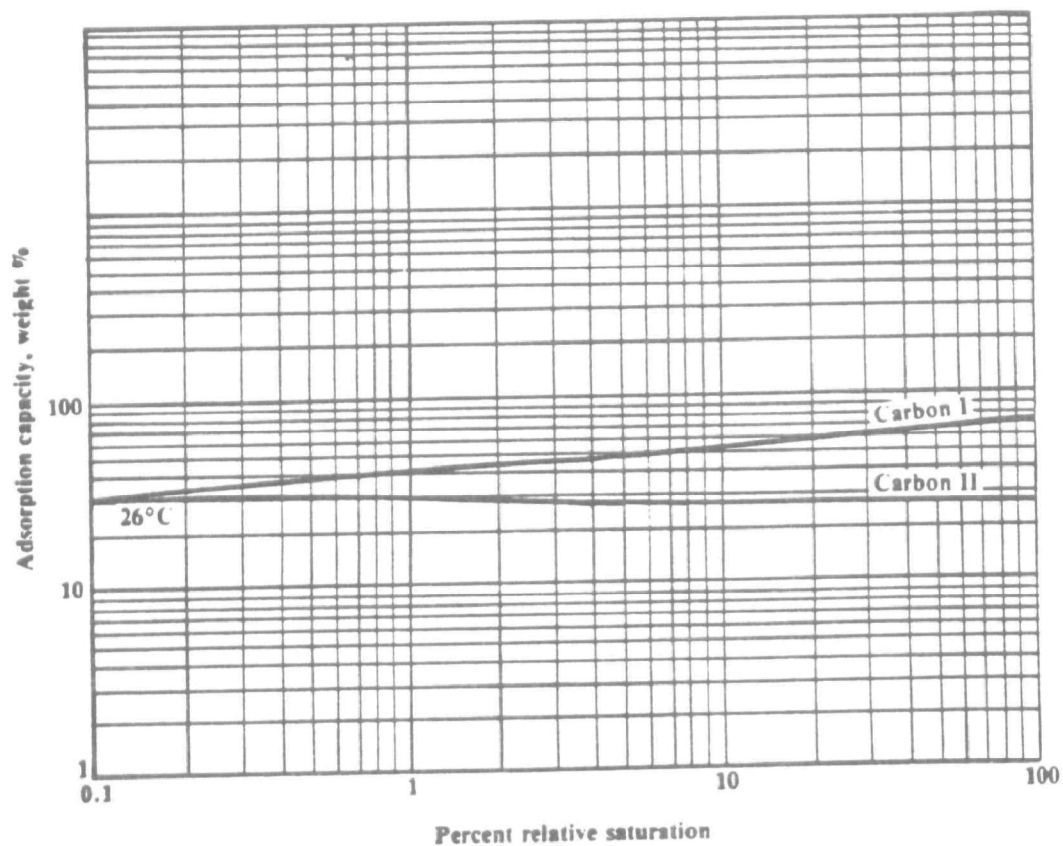
Figure 4-2. Adsorption isotherm for benzene.
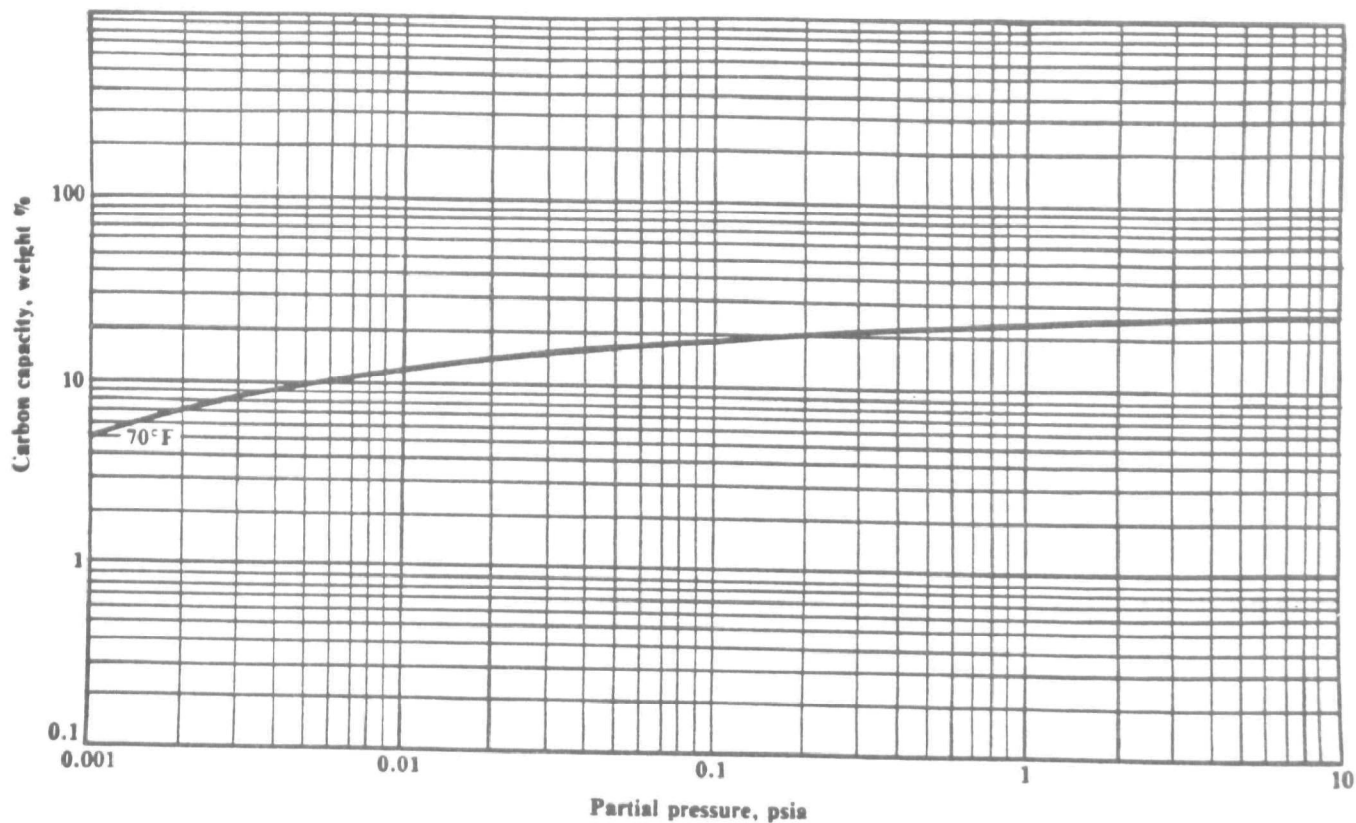
Figure 4-3. Adsorption isotherm for gasoline vapors.
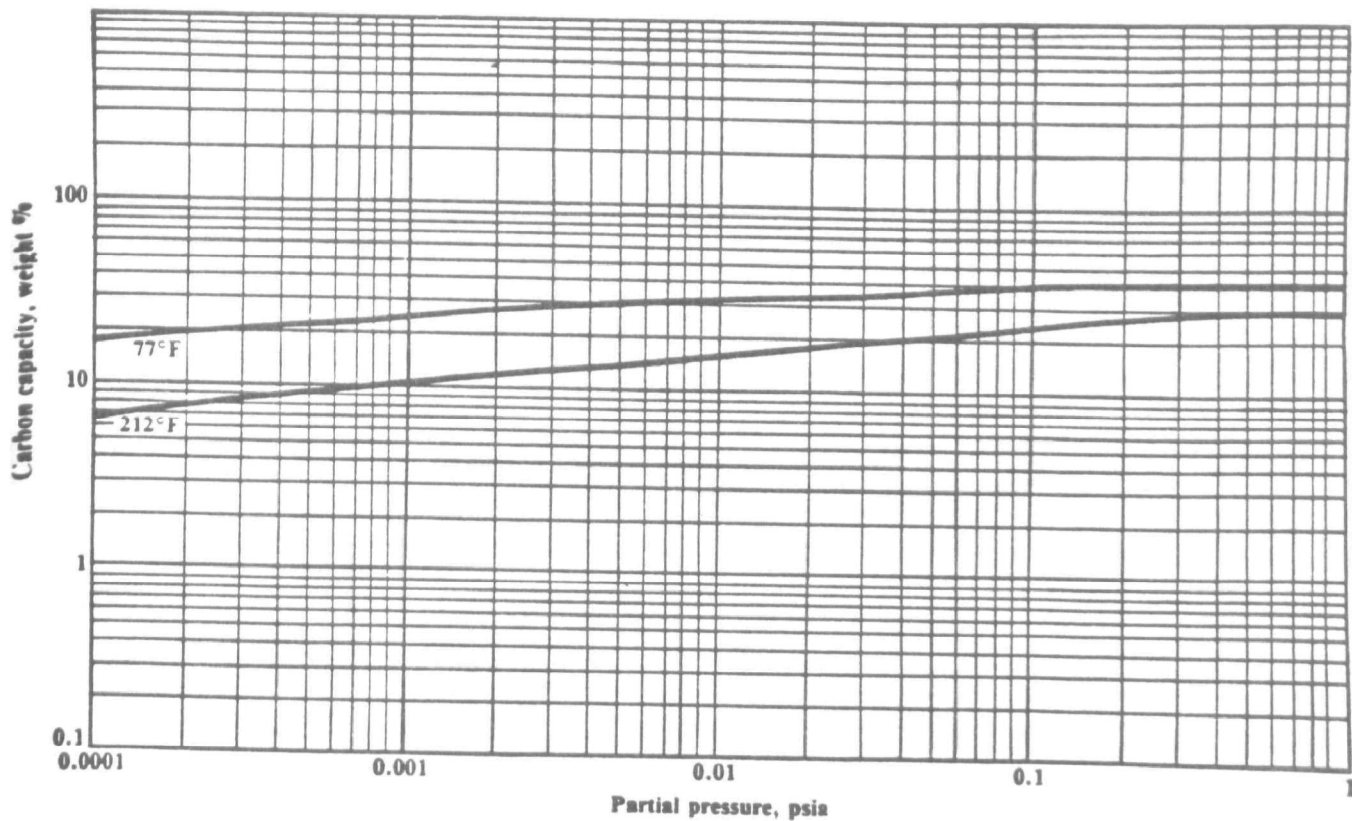
Figure 4-4. Adsorption isotherm for toluene.

Problem Set 5
Condensation

Problem 5-1. Contact Condenser

Problem Statement

In an oil refinery, a stream of light hydrocarbons is to be condensed by a direct contact condenser as shown in Figure 5-1. The light hydrocarbon stream is essentially benzene. From Perry's Chemical Engineering Handbook you found that for benzene: the boiling point is 175°F, the latent heat of vaporization (H_v) is 160 Btu/lb, and the specific heat (C_p) is 0.45 Btu/lb°F. Water is used as the coolant at 60°F and $C_p = 1.0$.

Questions

1. For a benzene mass flow rate ($\dot{m}$) of 10,000 lbs/hr, how much coolant (W) is required if condensate temperature (T_c) can be no higher than 100°F.
2. How much benzene is lost in the water if the solubility of benzene at 100°F is 0.05 lb/100 lb of water.
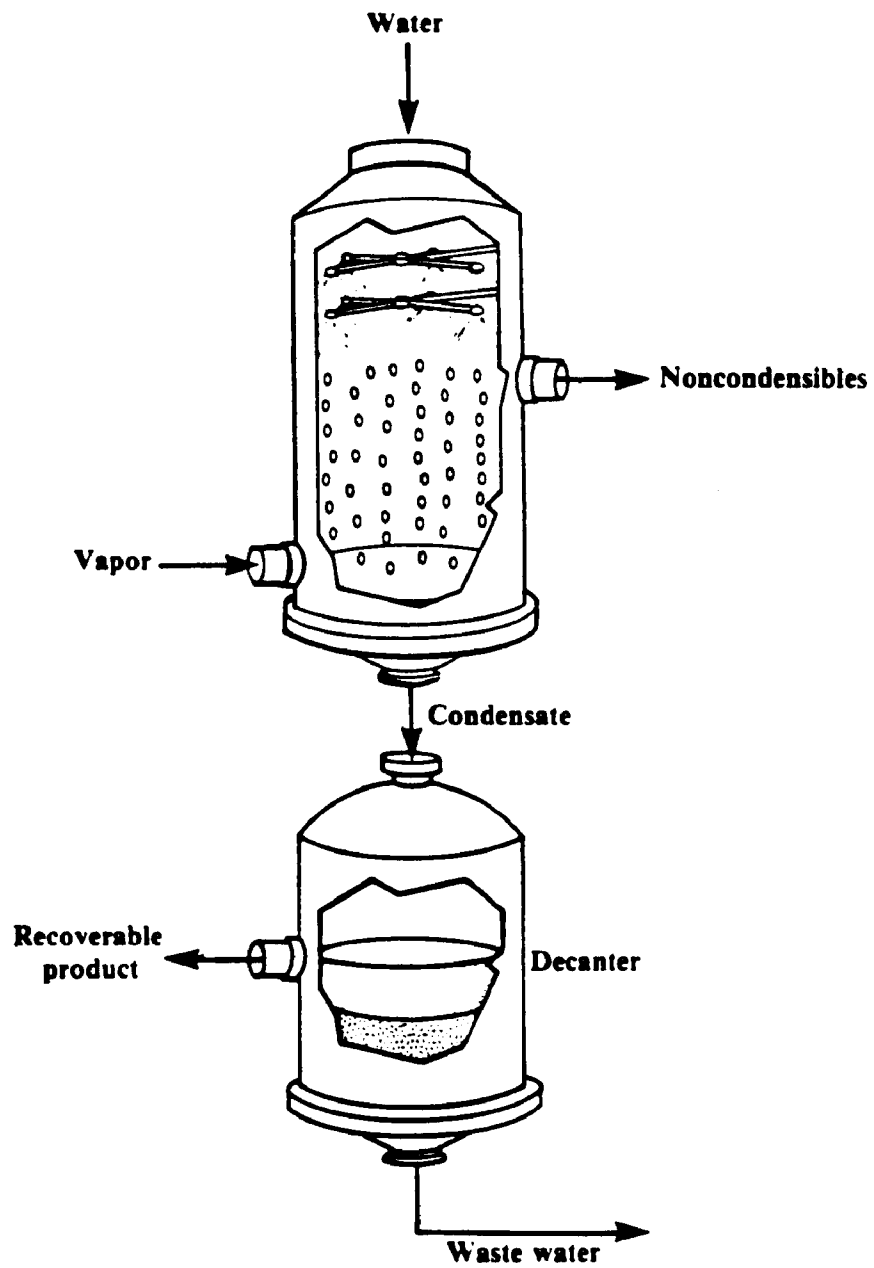
Figure 5-1. Contact condenser.

Solution to Problem 5-1

	A. To calculate amount of water must set up a heat balance
	$$IN = OUT$$
	$$\begin{array}{c}\text{heat required} \\ \text{to condense} \\ \text{vapors}\end{array} + \begin{array}{c}\text{heat required} \\ \text{to cool vapors} \\ \text{to outlet} \\ \text{temperature}\end{array} = \begin{array}{c}\text{heat supplied} \\ \text{by water}\end{array}$$
	$$\dot{m} \times H_V + \dot{m} \times C_p \times (T_{IN} - T_c) = WC_p(T_e - T_{IN})$$
	$$\frac{10,000 \text{ lb}}{hr} \times \frac{160 \text{ Btu}}{lb} + \frac{10,000 \text{ lb}}{hr} \times \frac{.45 \text{ Btu}}{lb \ ^\circ F}$$
Note: there are 8.34 lb/gal H_2O	$$\times (175 - 100^\circ F) = W \times 1.0 \frac{Btu}{lb \ ^\circ F} (100 - 60)$$
	$$160 \times 10^4 \text{ Btu/hr} + 33.8 \times 10^4 \frac{Btu}{hr} = W \times \frac{40 \text{ Btu}}{lb}$$
	$$W = 48,450 \text{ lb/hr} = 97 \text{ gal/min}$$
	Amount of coolant required = 97 gal/min
	B. Benzene lost in water
	$$\frac{benzene}{lost} = \frac{.05 \text{ lb benzene}}{100 \text{ lb water}} \times \frac{48,450 \text{ lb water}}{hr} = 24 \text{ lb/hr}$$
	Benzene lost in cooling water = 24 lb/hr

Problem 5-2. Surface Condenser

Problem Statement

The surface condenser shown below is used to condense the hydrocarbon vapors for the same conditions as in Problem 5-1.
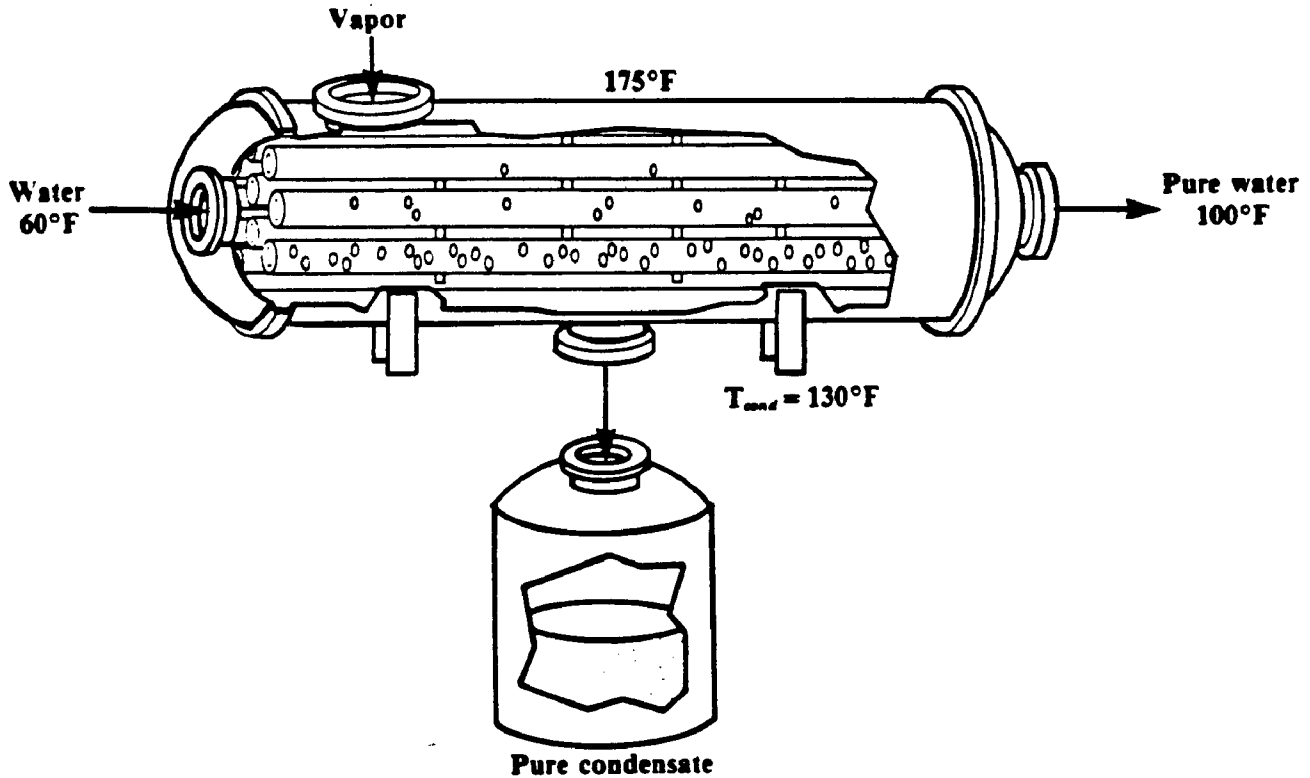
Figure 5-2. Surface condenser.

The overall heat transfer coefficient (U) from Perry's Chemical Engineering Handbook is $\underline{110 \ Btu/hr/ft^3}$.
$$\degree F$$

Question

What is the surface area of the tubes required for the surface condenser?

Solution to Problem 5-2

To calculate surface area of tubes, use equation

$$q = UA\Delta T_m$$

A. Must first calculate the mean temperature change
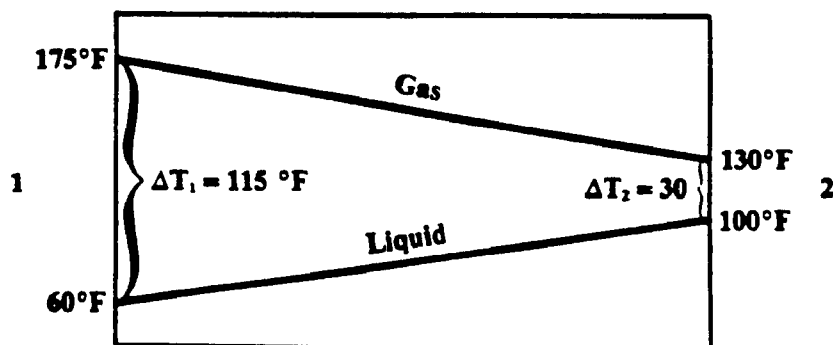
$$\Delta T_m = \frac{(T_{G1} - T_{L1}) - (T_{G2} - T_{L2})}{\ln\left[\left(\dfrac{T_{G1} - T_{L1}}{T_{G2} - T_{L2}}\right)\right]}$$

$$\Delta T_m = \frac{(175 - 60) - (130 - 100)}{\ln\left(\dfrac{175 - 60}{130 - 100}\right)}$$

$$\Delta T_m = \frac{(115) - (30)}{\ln\dfrac{115}{30}} = 62.2 \text{ F}°$$

B. The heat required is

q = heat required to + heat required to
     condense vapors   subcool

$$q = \dot{m}H_v + \dot{m}C_p(T_{G1} - T_{G2})$$

$$q = \left(10{,}000 \ \frac{lb}{hr}\right)\left(\frac{160 \ Btu}{hr}\right) + 10{,}000 \ \frac{lb}{hr}$$

$$\times \ \frac{.45 \ Btu}{lb \ °F} \ (175°F - 130°F)$$

$$q = 160 \times 10^4 \ Btu/hr + 20.25 \times 10^4 \ Btu/hr$$

$$q = 180.25 \times 10^4 \ Btu/hr$$

C. Surface area

$$A = \frac{q}{U \Delta T_m}$$

$$A = \frac{180.25 \times 10^4 \text{ Btu/hr}}{\left(\dfrac{110 \text{ Btu/hr/ft}^2}{F^\circ}\right)(62.2 \text{ F}^\circ)} = 263 \text{ ft}^2$$

Surface area of the condenser tubes = 263 ft²

Appendix A
Common SI units

Quantity (1)	Some common units	Symbol	Equivalent	Symbol
length	kilometer meter centimeter millimeter micrometer	km m cm mm μm		
area	square kilometer square hectometer square meter square centimeter square millimeter	km² hm² m² cm² mm²	hectare (2)	ha
volume	cubic meter cubic decimeter cubic centimeter	m³ dm³ cm³	liter (3) milliliter (3)	L mL
speed or velocity	meter per second kilometer per hour (4)	m/s km/h		
acceleration	meter per second squared	m/s²		
rotational frequency	revolution per second revolution per minute (4)	r/s r/min		
mass (5)	megagram kilogram gram milligram	Mg kg g mg	metric ton	t
density	kilogram per cubic meter	kg/m³	gram per liter	g/L
force	kilonewton newton	kN N		
movement of force (6)	newton meter	N•m		
pressure (or vacuum)	kilopascal	kPa		
stress	megapascal	MPa		
viscosity (dynamic)	millipascal second (7)	mPa•s		
viscosity (kinematic)	square millimeter per second (8)	mm²/s		
energy, work, or quantity of heat	joule (9) kilowatt hour (10)	J kW•h	kilowatthour	kWh
power, or heat flow rate	kilowatt watt	kW W		
temperature, or temperature interval	kelvin degree Celsius (11)	K °C		

NOTES

(1) Any measurable property (such as length, area, temperature) is called a *quantity*. Listed in same sequence as ISO 1000 and ISO 31, except plane angle.

(2) For land or water area only.

(3) To be used only for fluids (both gases and liquids), and for dry ingredients in recipes, or for volumetric capacities. Do not use any prefix with liter except *milli*.

(4) The symbols for minute, hour, and day are min, h, and d, respectively.

(5) Commonly called *weight*.

(6) Torque or bending movement.

(7) 1 mPa•s = 1 cP (centipoise, which is obsolete).

(8) 1 mm²/s = 1 cSt (centistokes, which is obsolete).

(9) The unit-multiples kilojoule (kJ) and megajoule (MJ) are also commonly used.

(10) To be abandoned eventually. 1 kW•h = 3.6 MJ.

(11) The degree mark ° is always used in °C to avoid confusion with coulomb (C), but never with K for kelvin.

Source: The American National Metric Council, *Metric Editorial Guide*, 3rd ed., January 1978.

20-1

Appendix B
Conversion Factors

Length
1 inch = 2.54 cm
1 m = 3.048 ft
1 ft = .305 m

Mass
1 lb = 453.6 g
1 lb = 7000 grains
1 kg = 2.2 lb

Pressure
1 atm = .101, 325 Pa
= 760 mm Hg (0°C)
= 14.7 psia

Force
1 N = 1 kg m/s^2
1 N = 0.225 lb,

Energy
1 cal = 4.184 J
1 J = 9.48 × 10^{-4} Btu
1 Btu = 252.2 cal

Kinematic viscosity
1 m^2/S = 10^4 stokes
1 m^2/S = 3.875 10^4 ft^2/hr

Power
1 W = 1 J/S
1 W = 3.414 Btu/hr
1 W = 1.341 × 10^{-3} hp
1 hp = 33,479 Btu/hr

Area
1 m^2 = 10.764 ft^2
1 cm^2 = .155 in^2
1 m^2 = 1.196 yd^2

Volume
1 m^3 = 35.31 ft^3
1 cm^3 = 0.061 in^3
1 m^3 = 264 gal (US)
1 ft^3 = 28.317 L
1 m^3 = 10^3 L
1 barrel (oil) = 42 gal
1 ft^3 = 7.48 gal

Density
1 kg/m^3 = .0624 lb/ft^3

Dynamic viscosity
1 Pa s(Nm/s) = 1000 centipoise
1 cp = .000672 lb/ft s

Volume flow
1 m^3/s = 35.3 ft^3/s
1 m^3/min = 35.3 ft^3/min
1 scfm = 1.7 m^3/h
1 gpm = 0.227 m^3/h

Velocity
1 m/s = 3.28 ft/s
1 m/s = 196.85 ft/min
1 mi/hr = 0.447 m/s

Geometry
area of circle = πr^2
circumference of circle = 2 πr
surface area of sphere = 4 πr^2
volume of sphere = 4/3 πr^3

Appendix C
Constants and Useful Information

Gas constants

$R = 0.0821$ atm liter/g mol K

$= 83.14 \times 10^6$ g cm³/s² g mol K

$= 8.314$ Nm/g mol K

$= 0.7302$ atm ft³/lb mol °R

1.987 g cal/g mol K or Btu/lb mol °R

Acceleration of gravity

$g = 32.17$ ft/s² $= 980.7$ cm/s²

Newton's conversion constant

$gc = 32.17$ (lb mass)(ft)/(lb force)(s²)

1 lb mol $= 359$ ft³ of ideal gas at STP (32°F and 14.7 psia)

1 g mol $= 22.4$ L of ideal gas at STP (0°C and 760 mm Hg)

$\overline{C}_p$ for water ≈ 1 Btu/lb°R ≈ 1 cal/g °C (at 20°C and 1 atm)

$\overline{C}_p$ for air $\approx .26$ Btu/lb°R $\approx .26$ cal/g °C

viscosity of water $(\mu) = 1$ cp $= 0.01$ g/cms (at 20°C and 1 atm)

density of air $= 1.29$ kg/m³ $= 7.49 \times 10^{-2}$ lb/ft³ (at 20°C and 1 atm)

density of water $= 1$ g/cm³ $= 62.4$ lb/ft³ (at 4°C and 1 atm)

1 cubic foot of air weighs 34.11 g

conversion from ppm to g/m³ at STP (273.15 K and 1 atm)

$$\frac{g}{dscm} = \frac{ppm \times MW\left(\frac{g}{g\,mol}\right)}{22.414\frac{liters}{g\,mol} \times 10^{-3}\frac{m^3}{10^3 L}\left(\frac{293.15\ K}{273.15\ K}\right)} \times \frac{1}{1\times 10^6\ ppm}$$

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16. ABSTRACT

This Workbook is designed for student use in APTI Course 415, "Control of Gaseous Emissions." Its chapters correspond to each of the 14 lessons and 5 problem sets in the course. Each chapter contains lesson goals and objectives, references, and printed versions of selected course slides.

The Workbook is intended for use in conjunction with the Instructor's Guide (EPA 450/2-81-004) and Student Manual (EPA 450/2-81-005) for APTI Course 415.

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