United States
Environmental Protection
Agency

Air Pollution Training Institute
MD 20
Environmental Research Center
Research Triangle Park NC 27711

EPA 450/2-80-067
April 1980

Air

EPA

APTI
Course 413
Control of Particulate Emissions

Student Workbook

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APTI Course 413 Control of Particulate Emissions

Student Workbook

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EPA Project Officer
R. E Townsend

United States Environmental Protection Agency
Office of Air, Noise, and Radiation
Office of Air Quality Planning and Standards
Research Triangle Park, NC 27711

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AIR POLLUTION TRAINING INSTITUTE
MANPOWER AND TECHNICAL INFORMATION BRANCH
CONTROL PROGRAMS DEVELOPMENT DIVISION
OFFICE OF AIR QUALITY PLANNING AND STANDARDS

The Air Pollution Training Institute (1) conducts training for personnel working on the development and improvement of state, and local governmental, and EPA air pollution control programs, as well as for personnel in industry and academic institutions; (2) provides consultation and other training assistance to governmental agencies, educational institutions, industrial organizations, and others engaged in air pollution training activities; and (3) promotes the development and improvement of air pollution training programs in educational institutions and state, regional, and local governmental air pollution control agencies. Much of the program is now conducted by an on-site contractor, Northrop Services, Inc

One of the principal mechanisms utilized to meet the Institute's goals is the intensive short term technical training course A full-time professional staff is responsible for the design, development, and presentation of these courses In addition the services of scientists, engineers, and specialists from other EPA programs governmental agencies, industries, and universities are used to augment and reinforce the Institute staff in the development and presentation of technical material

Individual course objectives and desired learning outcomes are delineated to meet specific program needs through training. Subject matter areas covered include air pollution source studies, atmospheric dispersion, and air quality management These courses are presented in the Institute's resident classrooms and laboratories and at various field locations

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1.1 Drag Coefficient and Settling Velocity

A spherical limestone particle is 400 μm in diameter, specific gravity = 2.67. Calculate the drag coefficient C_D and the settling velocity v_t in 70 °F air.

1.2 Settling Velocity and Drag Force

Particles 20 microns in diameter at 70 °F with a specific gravity of 1.8 flow in a duct. The density of H_2O is 62.4, the density of air is 0.075 $\frac{lb}{ft^3}$ and the viscosity of air is $1.23 \times 10^{-5} \frac{lb}{ft\text{-}sec.}$

(a) Calculate the settling velocity
(b) Calculate the Drag Force

2.1 Log-normal Distribution

Let's say you have collected some data on particle mass concentration with an optical particle counter or an Anderson Impactor. The following data was collected.

d_p range μm	concentration $\mu g/m^3$
0.1 – 0.2	10
0.2 – 0.5	13.2
0.5 – 2	20
2 – 5	13.2
5 – 10	10

How can you tell if these data represent a log normal distribution or some other distribution?

2.2 Log-normal Distribution, Geometric Mean and Standard Deviation

Given the following particle size data:

Size range d_p in μm	Mass concentration $\mu g/m^3$
<0.1	0.04
0.1 – 0.2	0.76
0.2 – 0.5	15.07
0.5 – 2.0	68.26
2.0 – 5.0	15.07
5.0 – 10.0	0.76
<10.0	0.04

Verify that this distribution is approximately log-normal, and find the geometric mean and the geometric standard deviation.

Hint: determine the percentage mass larger than d_p max in each size range.

2.3 Particle Size Distribution

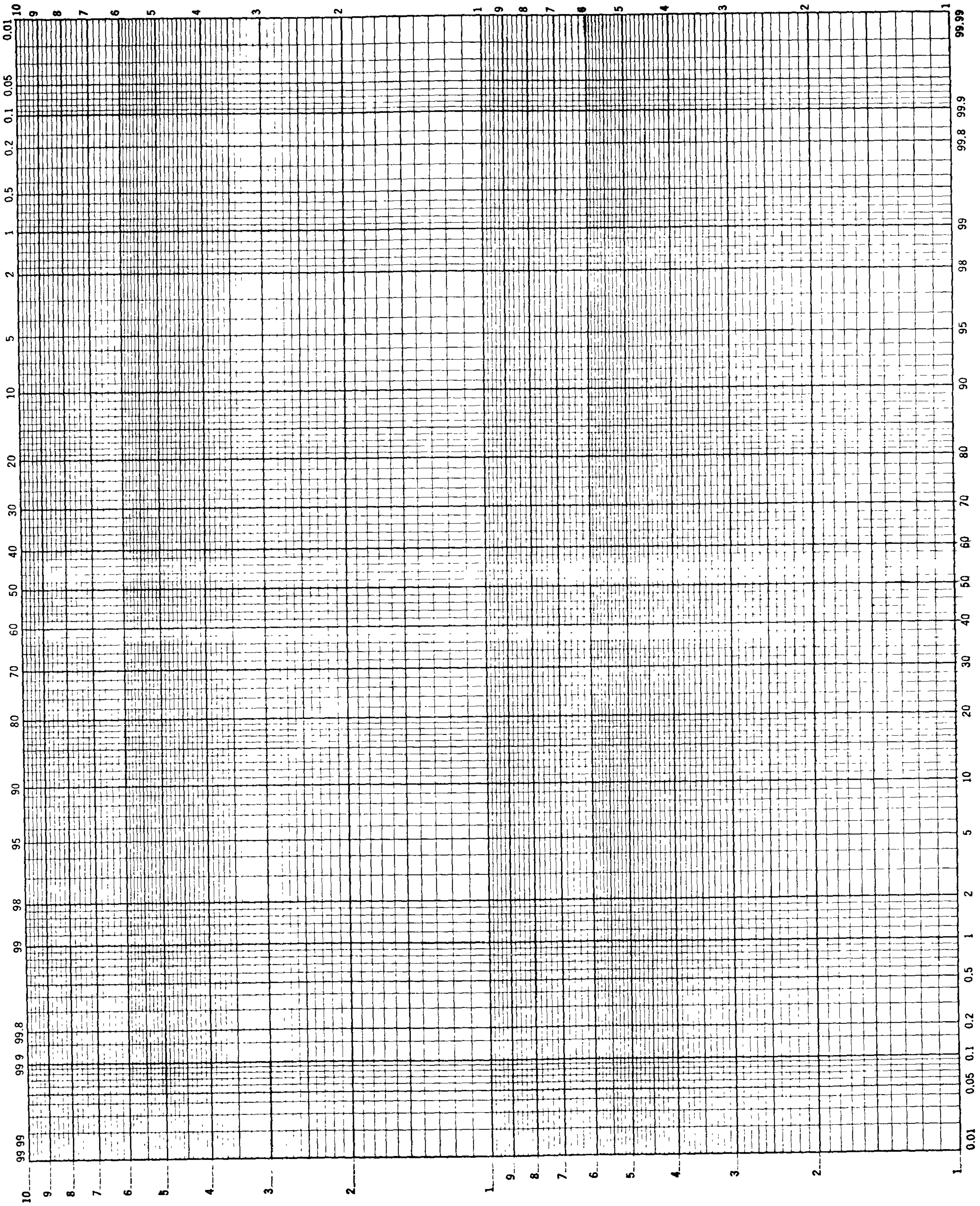
Given the following distributions obtained from size differentiating equipment:

Particle size d_p (microns)	Distribution A $\mu g/m^3$	Distribution B $\mu g/m^3$
<0.62	25.5	8.5
0.62 – 1.0	33.15	11.05
1.0 – 1.2	17.85	7.65
1.2 – 3.0	102.0	40.8
3.0 – 8.0	63.75	15.3
8.0 – 10.0	5.1	1.692
<10.0	7.65	0.008

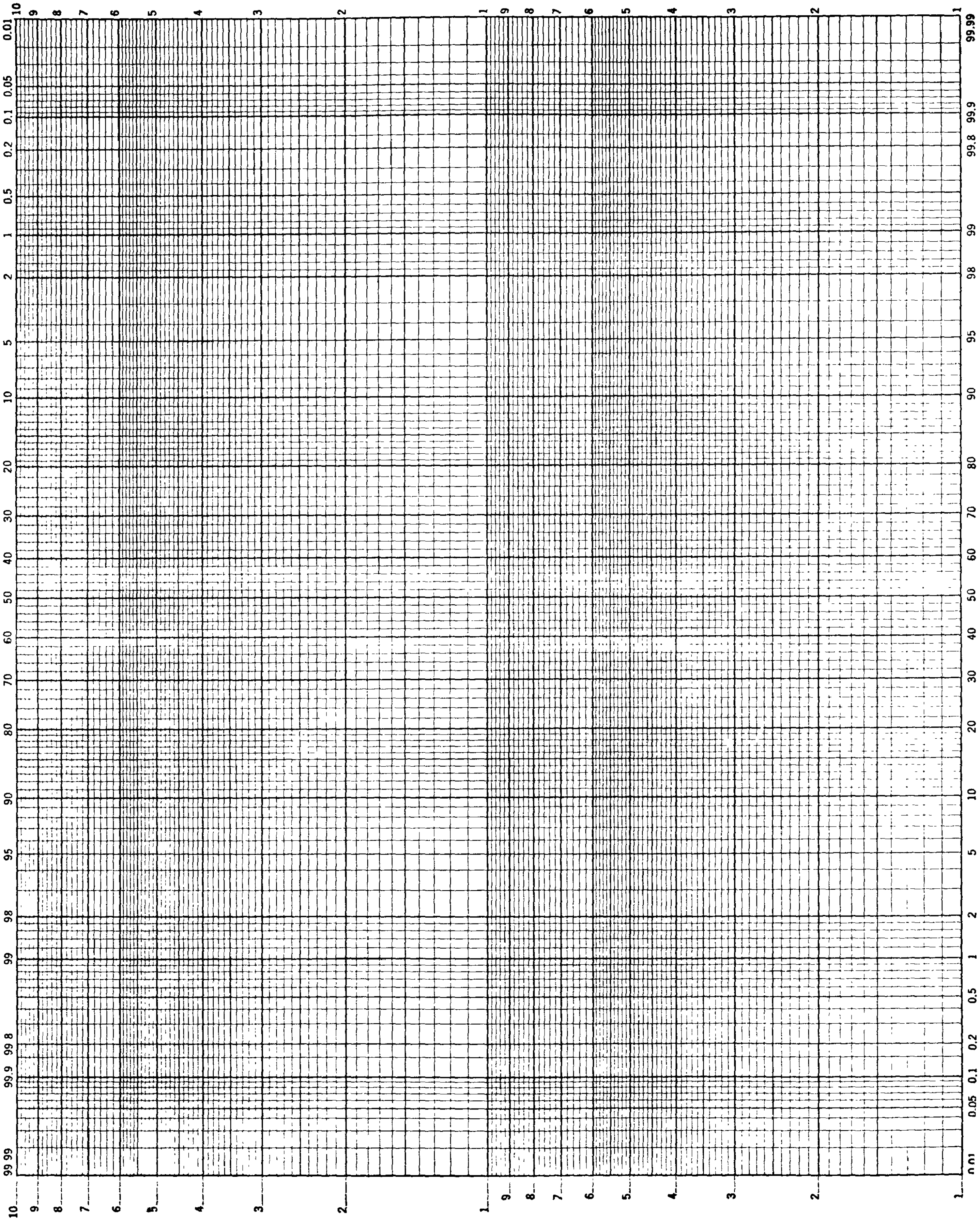
(a) Is either distribution A or distribution B log-normal

(b) If so, what is the geometric mean and standard deviation.

(Use the sheet of log probability paper provided if necessary.)



0.01 0.05 0.1 0.2 0.5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99.8 99.9 99.99
99.99 99.9 99.8 99 98 95 90 80 70 60 50 40 30 20 10 5 2 1 0.5 0.2 0.1 0.05 0.01
10 9 8 7 6 5 4 3 2 1 9 8 7 6 5 4 3 2 1


0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99
10 9 8 7 6 5 4 3 2 1 9 8 7 6 5 4 3 2 1

3.1 Settling Chamber—Minimum Particle Size

A hydrochloric acid mist in air at 25 °C is to be collected in a gravity settler. The unit is 30 ft wide, 20 ft high, and 50 ft long. The actual volumetric flow rate of the "acidic" gas is 50 ft^3/sec. Calculate the smallest mist droplet (spherical in shape) that will be entirely collected by the settler. The specific gravity of the acid is equal to 1.6. Assume the acid concentration to be uniform through the inlet cross section of the unit.

Assume Stoke's Law applies and at 25 °C $\mu = 0.0185$ cp,

$$1 \text{ cp} = 6.72 \times 10^{-4} \frac{\text{lb}}{\text{ft-sec}}$$

3.2 Settling Chamber—Operating Efficiency

A gravity settler 5 meters wide, 10 meters long, and 2 meters high, is used to trap particles with diameters of 10 μm. The gas flow rate is 0.4 m^3/sec per second. Calculate the operating efficiency of a settling chamber for the data given below. Assume Stokes law regime and a Cunningham correction factor of 1.0.

$$\varrho_p = 1.10 \text{ gm/cm}$$

$$\varrho = 1.2 \times 10^{-3} \text{ gm/cm}$$

$$\mu = 1.8 \times 10^{-4} \ \frac{\text{gm}}{\text{cm}-\text{sec}}$$

4.1 Cyclone—Overall Collection Efficiency Using Lapple's Method

The particle size distribution of a dust from a cement kiln is provided below:

Particle size (microns)	% Wt
1	3
5	20
10	15
20	20
30	16
40	10
50	6
60	3
> 60	7

The following information is also known:

Gas Viscosity	0.02 centipoise (cp)
Particle Specific Gravity	2.9
Inlet Gas Velocity to Cyclone	50 ft/sec
Effective Number of Turns within Cyclone	5
Cyclone Diameter	10 ft
Cyclone Inlet Width	2.5 ft

(a) Determine the cut size particle diameter, i.e., diameter of particle collected at 50% efficiency, and estimate the overall collection efficiency using Lapple's Method.

(b) If the same cyclone is used, but the inlet gas velocity is increased to 60 ft/sec and the gas viscosity changes to 0.018 cp (all else remaining the same), find the new cut size particle diameter and determine the new overall collection efficiency using Lapple's Method.

4.2 Cyclone—Dimensions and Number of New Cyclones Required

A large-diameter conventional cyclone (no vanes) handles 5,000 acfm of a particulate-laden gas exhaust stream ($\varrho_G = 0.076$ lb/ft^3) from a certain metallurgical operation. The cyclone diameter if 4 ft. The remaining dimensions may be found from Figure 4.2.1 (in the manual). In an attempt to increase efficiency, a group of new cyclones is to be designed with the same geometrical proportions and pressure drop as the single cyclone. If the diameter of the small cyclone is to be 6 in., what will the dimensions of the new group be? How many will be needed to handle the original flow rate at the same pressure drop?

4.3 Cyclone—Overall Collection Efficiency

(a) The size, mass, and cyclone collection efficiency data for a gas containing limestone dust are given below.

Particle diameter, μm	Wt %	Collection efficiency, %
0–5	2	4
5–10	8	6
10–20	13	20
20–30	26	32
30–50	12	78
50–75	11	89
75–100	9	95
100–200	8	98
200–	11	99+

Calculate the overall collection efficiency of the unit.

(b) If the inlet dust loading in the previous problem is 2.2 grains/ft^3 and the quantity of gas processed is 150,000 acfm, calculate the mass of limestone collected daily.

4.4 **Cyclone Collection Efficiency**

Determine loss and collection efficiency for a cyclone from the following information.

(1) collection efficiency curve—figure 1
(2) size-efficiency curve—figure 2
(3) size distribution by weight

Particle size Micron	% by Wt Less than
10	.1
15	1.0
26	10.0
40	32.0
67	70.0
100	90.0
>100	100.0

(4) weight of inlet loading—50 lb/hr.

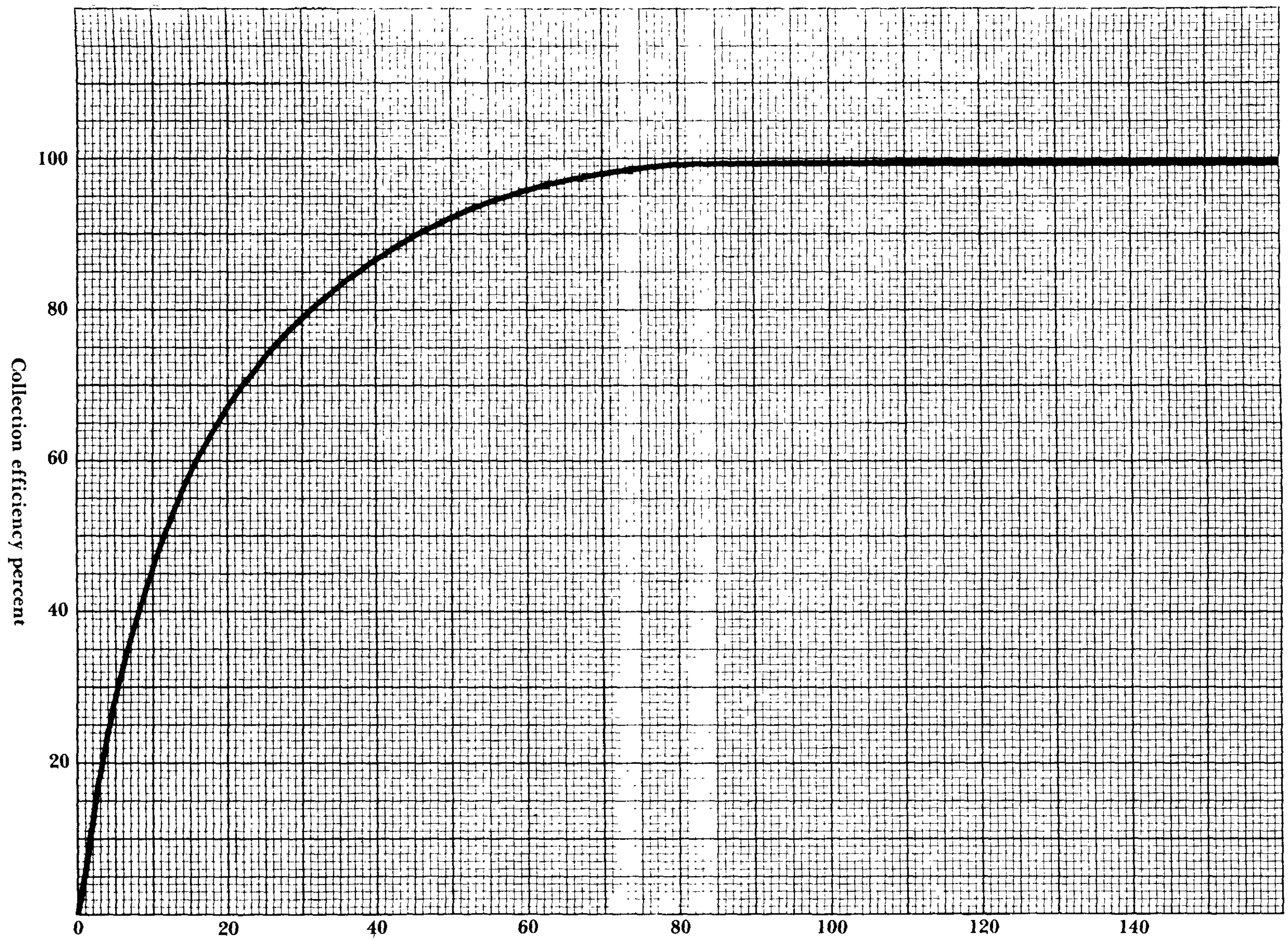
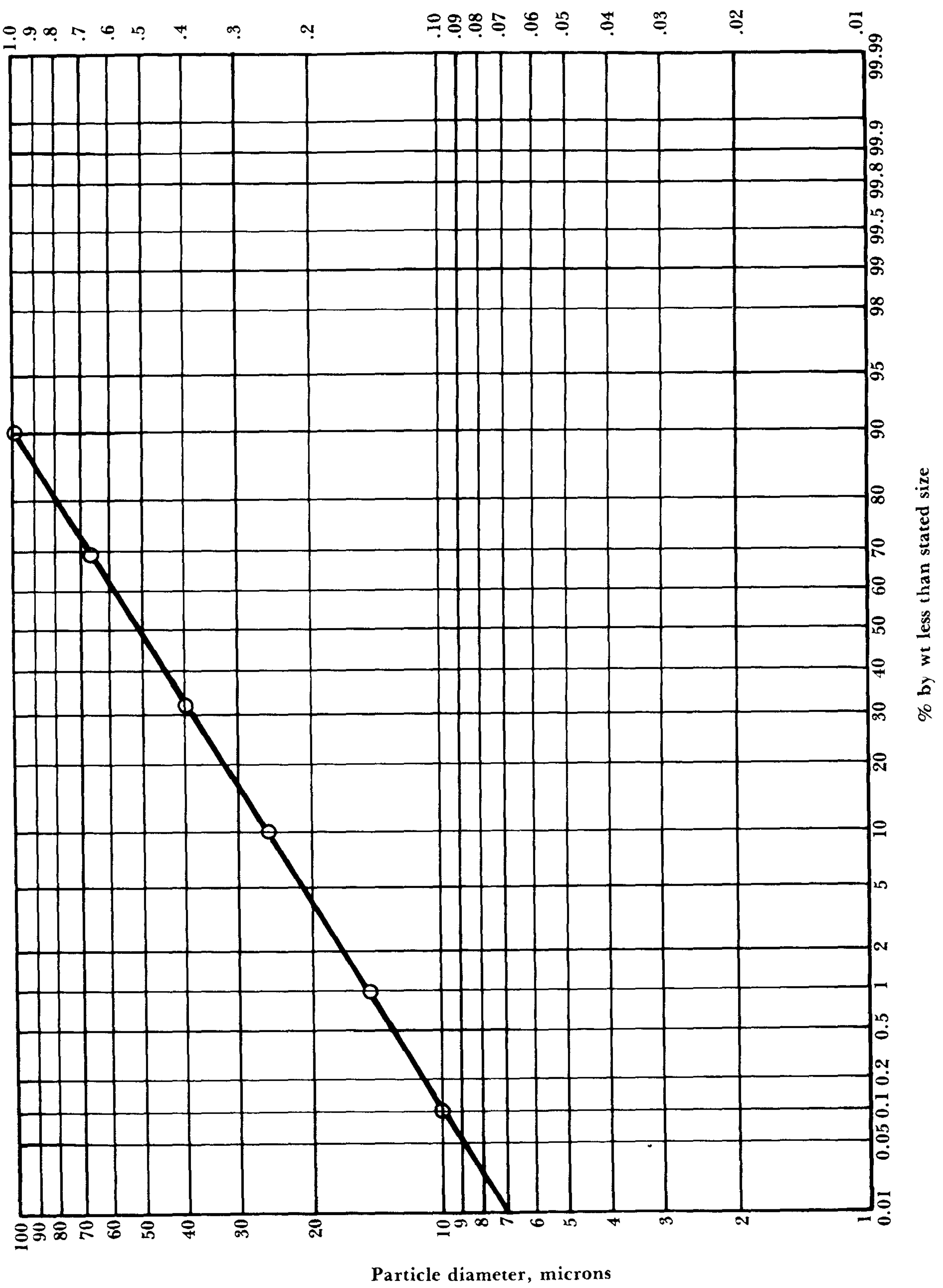


Figure 1. Particle size, microns size-efficiency curve for medium-efficiency high throughput cyclone



1.0 .9 .8 .7 .6 .5 .4 .3 .2 .10 .09 .08 .07 .06 .05 .04 .03 .02 .01
100 90 80 70 60 50 40 30 20 10 9 8 7 6 5 4 3 2 1
0.01 0.05 0.1 0.2 0.5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99.5 99.8 99.9 99.99
Particle diameter, microns
% by wt less than stated size

Figure 2.

5.1 ESP Problem

An electrostatic precipitator consists of two parallel 10 ft high by 16 ft wide plates with corona wires positioned half way between the plates. Find the effective migration velocity at a flow rate of 35 acfs if the required collection efficiency is 95%.

5.2 ESP Problem

A horizontal-flow-single-stage electrostatic precipitator is used to remove particulates from a dry process gas stream of a Portland cement manufacturing plant. The precipitator consists of multiple ducts formed by collecting plates 14 ft wide by 16 ft high and placed 9 inches apart. The rate of flow through each duct is estimated to be 2400 acfm and the content of dust is 5 grains/ft^3. Assume $w = 0.19$ ft/sec.

(a) Calculate the collection efficiency.

(b) Calculate the amount of dust collected by a duct each day.

5.3 **ESP Problem**

An electrostatic precipitator has three ducts with plates 12 ft wide and 12 ft high. The plates are 8 inches apart.

(a) Assuming a uniform distribution of particles and a drift velocity of 0.4 ft/sec, calculate the collection efficiency at a rate of flow of 4,000 acfm at 20 °C and 1 atm.

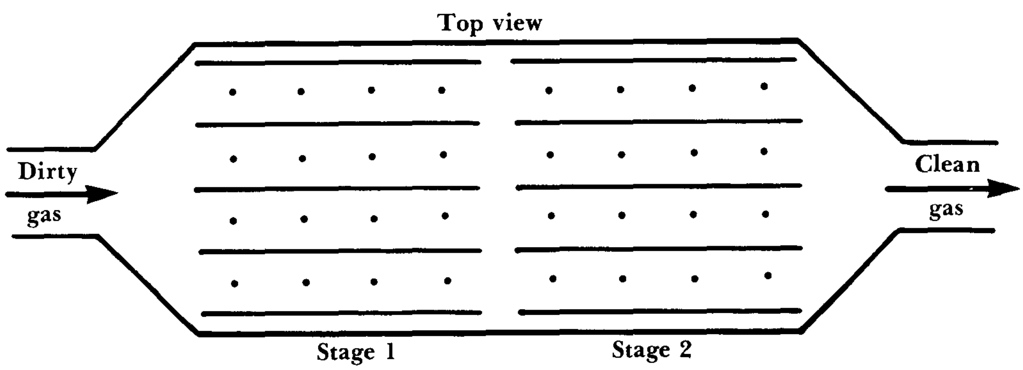
(b) Calculate the efficiency if one duct were fed 50% of the gas and the others 25% each.

5.4 ESP Problem

A precipitator consists of two Stages each with five plates in a series (see figure below). The corona wires between any two plates are independently controlled so that the remainder of the unit can be operated in the event of a wire failure.

The following operating conditions exist:

Gas Flow Rate	10,000 acfm
Plate Dimensions	10 ft × 15 ft
Drift Velocity	19.0 ft/min Section 1
	16.3 ft/min Section 2



(a) Determine the normal operating efficiency.

(b) During operation, a wire breaks in Stage 1. As a result, all of the wires in that row are shorted and ineffective, but the others function normally. Calculate the collection efficiency under these conditions.

(c) Similarly, a wire breaks in Stage 2 after Stage 1 is repaired. What is the overall collection efficiency of the unit under these conditions?

6.1 Fabric Filters—Number of Bag Calculation

Small scale tests showed that filtration of an air stream containing one grain of particulates per cubic foot of air gave a maximum pressure drop of 5 inches of water at a flow rate of 3 ft^3/min per square foot of filtering surface.

(a) Calculate the horsepower required for a fan for a flow rate of 6,000 ft^3/min. through the baghouse.

(b) Calculate the number of 0.5 ft diameter by 10 ft filtering bags required for the system.

Assume an over-all fan-motor efficiency of 63%.

$$hp = \frac{[\text{flow rate cfm}] \times [\Delta p \text{ ins. } H_2O][1.575 \times 10^{-4}]}{\text{efficiency (fan)}} \text{(Chemical Engr. Handbook)}$$

6.2 **Fabric Filters—Number of Bags and Pressure Drop**

A plywood mill plans to install a fabric filter as an air cleaning device.

(a) How many bags, each 8 inches in diameter and 12 ft long, must be used to treat the exhaust gas which has a particulate loading of 2 grains/ft^3 and the exhaust fan is rated at 7,000 ft^3/min?

(b) If the pressure drop is given by the formula

$$\Delta p = \Delta p_{\text{clean fabric}} + \Delta p_{\text{dust cake}}$$

Estimate the pressure drop after four hours of operation if the resistance coefficients of the filter and dust cake are, respectively, $k_1 = 0.8$ inches water/ft min. and $k_2 = 3$ inches water/(lb/dust/ft^2 cloth area) (ft/min, filtering velocity). Assume velocity is 2 ft/min.

6.3 Fabric Filters—Number of Bags and Cleaning Frequency

A plant emits 50,000 acfm of gas with a dust loading of 5 grains ft^3. The dust is collected by a fabric filter at 98% efficiency when the average filtration velocity is **10 ft/min**. The pressure drop is given by

$$\Delta p = 0.2v + 5c_i v^2 t$$

where:

Δp is the pressure drop in inches of water,
v is the filtration velocity in ft/min,
c_i is the dust concentration in lb/ft^3 of gas,
t is the time in minutes since bags were cleaned.

(a) How many cylindrical bags, 1 ft in diameter and 15 ft high will be needed?

(b) The system is designed to begin cleaning when the pressure drop reaches 8 inches of water. How frequently should the bags be cleaned?

6.4 **Fabric Filters—Design of Filter Bag**

It is proposed to install a pulse-jet fabric filter system to clean a 10,000 scfm air stream at 250°F, containing 4 grains/ft^3 of pollutant. For a 99% efficiency, the average air-to-cloth ratio is 2.5 cfm ft^2 cloth. The following information, given by filter bag manufacturers, is available at the beginning of the selection process:

Filter bag	A	B	C	D
Tensile strength	Excellent	Above average	Fair	Excellent
Recommended maximum operation temperature, °F	260	275	260	220
Resistance factor	0.9	1.0	0.5	0.9
Relative cost per bag	2.6	3.8	1.0	2.0
Standard size	8" × 16'	10" × 16'	1" × 16'	1' × 20'

(a) Determine the filtering area required for this operation.

(b) Based on the required area and the above information, select the most suitable filter bag and calculate the number of them that should be used. The proposal of a pulsed jet device using strong forces to clean the bags necessitates the selection of a fabric with at least above average tensile strength.

7.1 **Contact Power Theory Application**

A vendor proposed to use a spray tower on a lime kiln operation to reduce the discharge of solids to the atmosphere. The inlet loading of the gas stream from the kiln is 5.0 grains/ft^3 and is to be reduced to 0.05 in order to meet state regulations. The vendor's design calls for a water pressure drop of 80 psi and a pressure drop across the tower of 5.0 in. H_2O. The gas flow rate is 10,000 acfm, and a water rate of 50 gal/min is proposed. Assume the contact power theory to apply.

(1) Will the spray tower meet regulations?

(2) What total pressure loss is required to meet regulations?

(3) Propose a set of operating conditions that will meet the standard. The maximum gas and water pressure drop across the unit are 15 in. H_2O and 100 psi, respectively.

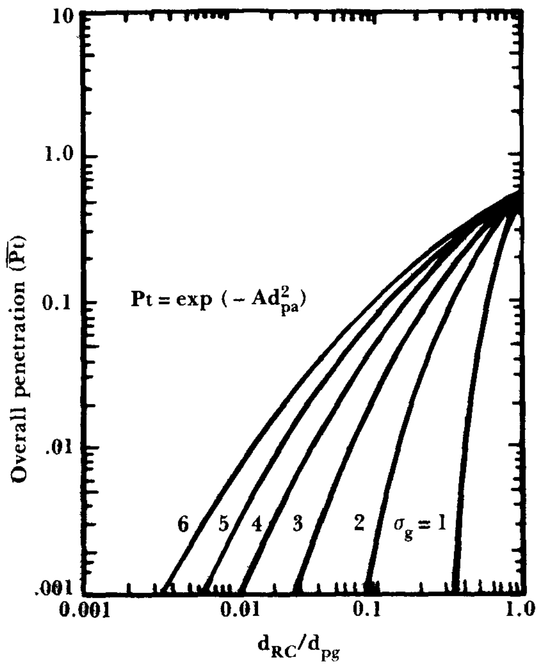
(4) What conclusions can be drawn concerning the use of a spray tower for this application.

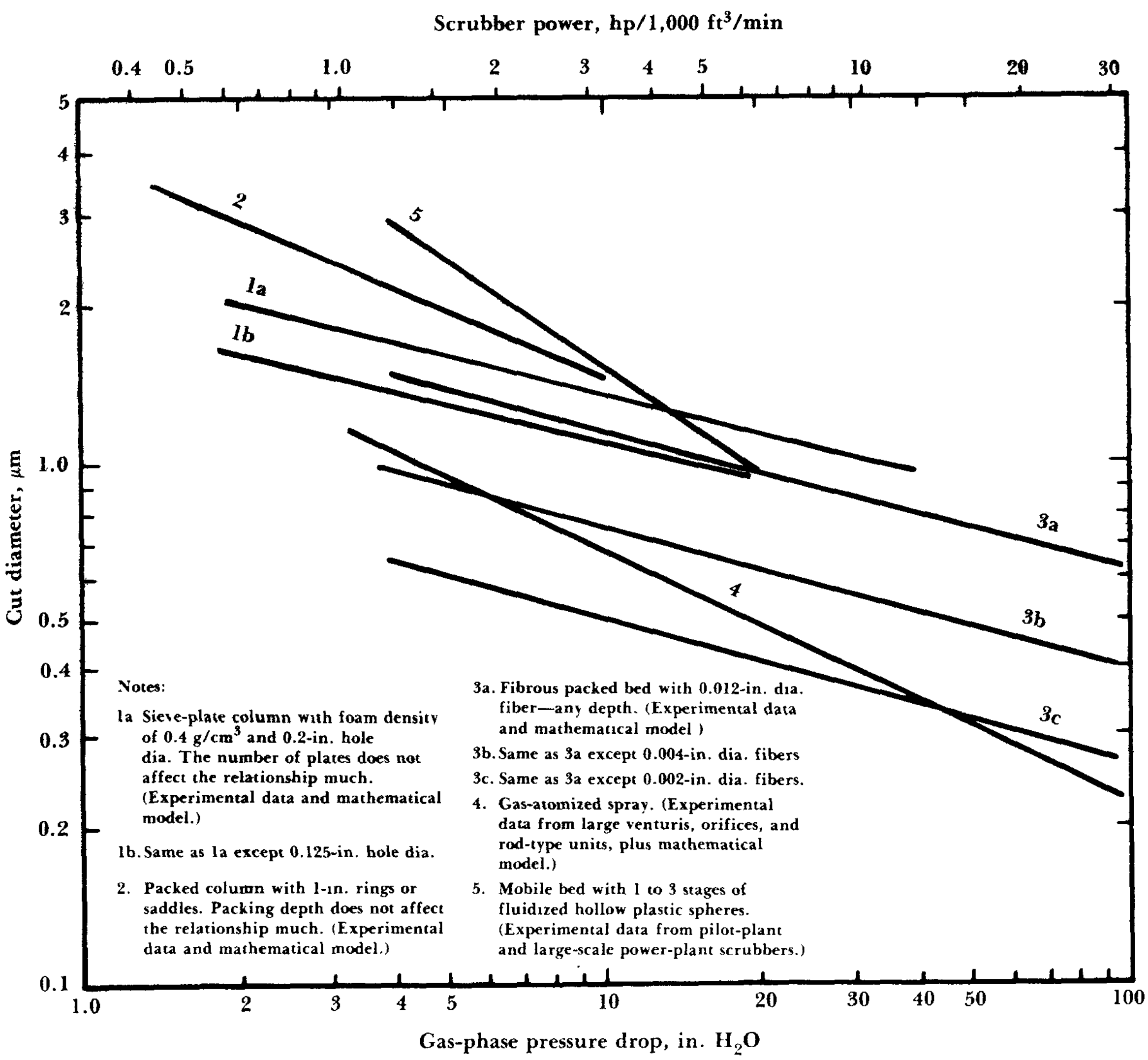
7.2 Contact Power Theory Application

The installation of a venturi scrubber is proposed to reduce the discharge of particulates from an open-hearth steel furnace operation. Preliminary design information suggests a water and gas pressure drop across the scrubber of 5.0 psi and 36 in. H_2O, respectively. A liquid-to-gas ratio of 6.0 gal/min/1,000 acfm is usually employed in this application. Estimate the collection efficiency of the proposed venturi scrubber. Assume contact power theory to apply.

7.3 **Cut Power Rule**

What would be the pressure drop required on a venturi scrubber to achieve an overall collection efficiency of 99.3% for particulate matter having a mass-median aerodynamic diameter of 5μm with particle size deviation, σ_g, of 2.0 μm?


Overall penetration (Pt)
$Pt = \exp(-Ad_{pa}^2)$
6
5
4
3
2
$\sigma_g = 1$
d_{RC}/d_{pg}


Scrubber power, hp/1,000 ft³/min
Cut diameter, µm
Gas-phase pressure drop, in. H₂O
2
5
1a
1b
3a
3b
3c
4
Notes:
1a Sieve-plate column with foam density of 0.4 g/cm³ and 0.2-in. hole dia. The number of plates does not affect the relationship much. (Experimental data and mathematical model.)
1b. Same as 1a except 0.125-in. hole dia.
2. Packed column with 1-in. rings or saddles. Packing depth does not affect the relationship much. (Experimental data and mathematical model.)
3a. Fibrous packed bed with 0.012-in. dia. fiber—any depth. (Experimental data and mathematical model.)
3b. Same as 3a except 0.004-in. dia. fibers
3c. Same as 3a except 0.002-in. dia. fibers.
4. Gas-atomized spray. (Experimental data from large venturis, orifices, and rod-type units, plus mathematical model.)
5. Mobile bed with 1 to 3 stages of fluidized hollow plastic spheres. (Experimental data from pilot-plant and large-scale power-plant scrubbers.)

7.4 **Equation for Venturi Scrubbers**

A fly ash laden gas stream is to be cleaned by a venturi scrubber using a liquid-to-gas ratio of 8.5 gal/1000 ft^3. The efficiency can be calculated from

$$\eta_i = 1 - \exp\left(-k \frac{Q_L}{Q_G} \sqrt{\Psi_i}\right)$$

Where η_i is the fractional efficiency of collection of particles of size d_{pi}. The fly ash has a particle density of 0.7 gm/cm^3, and $k = 200$ ft^3/gal.

Use a throat velocity of 272 ft/sec, a liquid-to-gas ratio of 8.5 gal/1000 ft^3, and a gas viscosity of 1.5×10^{-5} lb/ft sec. The particle size distribution is:

d_{pi} (microns)	% by Weight
< 0.10	0.01
0.1 – 0.5	0.21
0.6 – 1.0	0.78
1.1 – 5.0	13.0
6.0 – 10.0	16.0
11.0 – 15.0	12.0
16.0 – 20.0	8.0
> 20.0	50.0

Make use of the Nukiyama and Tanasawasa relationship.

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16. ABSTRACT

This workbook contains problems for the Air Pollution Training Institute's Course 413, "Control of Particulate Emissions". The problems cover calculation of collection efficiencies, pressure drop values, and particle size distributions for such emission control devices as settling chambers, cyclones, electrostatic precipitators, baghouses, and wet collectors. The workbook, when used with the Student Manual, EPA 450/2-80-066, during the lecture sessions, is part of comprehensive training in particulate control.

The course also has an Instructor's Guide, EPA 450/2-80-068, which should be used in conducting the course.

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