CONTROLS FOR FINE PARTICLE EMISSIONS FROM INDUSTRIAL SOURCES IN CALIFORNIA

BY

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ABSTRACT

The objectives of this study are to evaluate the effectiveness and cost of control for existing and developing particle technologies that can be applied to the major industrial sources in California. Fine particles have been defined for this study as those particles having an aerodynamic diameter less than 3 μmA.

This report presents the design information for the fine particle control technologies in four major categories--scrubbers, electrostatic precipitators, fabric filters, and cyclone separators. Emission data and process information are given for fuel combustion, food and agriculture, metallurgical, mineral processing, surface coating, incineration, and wood milling. Capital and annualized operating costs for ten fine particle control devices--Venturi scrubber, Calvert Collision Scrubber, F/C scrubber, charged spray scrubber, SCAT scrubber, ESP, ESP with SoRI precharger, pulse charging ESP, fabric filter, and electrified filter--were estimated for several levels of fine particle collection efficiency.

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DISCLAIMER

The statements and conclusions in this report are those of the contractor and not necessarily those of the California Air Resources Board. The mention of commercial products, their source or their use in connection with material reported herein is not to be construed as either an actual or implied endorsement of such products.

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NOMENCLATURE

a	=	cyclone gas inlet height, cm
a	=	average acceleration of fabric during cleaning, m/s^2
A	=	$1.26 + 0.42 \exp[-1.08(d_p/2\lambda,]$
A_c	=	ESP collector plate area, m^2
A_c	=	particle collection area, cm^2
A_C	=	cleaned bag area/fraction
A_d	=	deposition area, cm^2
A_e	=	constant (eq. 4.5.1-2)
A_p	=	constant
A_s	=	cross sectional area of scrubber, m^2
A/C	=	air to cloth ratio in fabric filtration, $m^3/min/m^2$
b	=	cyclone gas inlet height, cm
b_m	=	ion mobility, $m^2/V\text{-}s$
B	=	cyclone dust outlet diameter, cm
B_e	=	constant (eq. 4.5.1-2)
B_s	=	correction factor for sneakage and reentrainment (eq. 5.6.3-2), dimensionless
B_v	=	$Q_L\ \rho_G/Q_G\ \rho_G\ C_{Do}$, dimensionless
c	=	concentration, g/m^3
C	=	cyclone geometry coefficient, dimensionless
C_{Do}	=	drag coefficient at Venturi throat entrance, dimensionless
C'	=	Cunningham slip correction factor, dimensionless
C_1	=	$4\ \varepsilon_{\smile}/e$
C_2	=	k/e
C_o	=	outlet concentration, g/m^3
CD/CP	=	charged drop and charged particle
CD/UP	=	charged drop and uncharged particle
d	=	diameter of cyclone at the vortex turning point, cm
d_c	=	packing diameter (nominal), cm
d_d	=	drop diameter, cm

NOMENCLATURE (continued)

d_h = diameter of sieve plate hole, cm

d_p = physical particle diameter, μm

d_{pa} = aerodynamic particle diameter, μmA = μm $(g/cm^3)^{1/2}$

d_{pa50} = aerodynamic diameter of particle collected with 50% efficiency, μmA

d_{pg} = geometric mean particle diameter, μmA

d_{ps} = specific area diameter of particle, μm

d_s = Sauter (surface) mean diameter, cm

d_{pc} = performance cut diameter, μmA

d_{RC} = required cut diameter, μmA

D = cyclone diameter, cm

D_e = cyclone gas exit diameter, cm

D_p = particle diffusivity, cm^2/s

e = electronic charge = 1.6×10^{-19} C

E = efficiency, fraction

E_{AV} = average electric field in ESP, V/m

E_o = uniform external electric field strength, V/cm

E_p = electric field at the collector plate, V/m

ESP = electrostatic precipitator

f = empirical factor

f_b = $150/N_{RE} + 1.75$ (eq. 6.6.2-4)

F = foam density, g/cm^3

F_A = adhesive force, N

F_G = correction factor for non-uniform gas flow (eq. 5.6.3-3)

F_S = separation force, N

F/C = flux force condensation scrubbing

g = acceleration force due to gravity, m/s^2 or cm/s^2

g_c = gravitational conversion factor = 9.8 $kg\text{-}m/N\text{-}s^2$

h = cyclone cylinder height, cm

h_p = enhancement factor equal to w_{kp}/w_k, dimensionless

h_{wp} = wire to plate spacing, cm

ΔH = cyclone pressure loss, number of inlet velocity heads

H = cyclone overall height, cm

HII = high intensity ionizer

j = current density, A/m^2

k = Boltzmann's constant = 1.38×10^{23} J/°K

k_1 = pressure loss coefficient for clean filter, 1/m

k_2 = average specific resistance of collected particle layer, m/kg

K = particle relative dielectric constant, dimensionless

K_c = Coulombic force parameter, dimensionless

K_{ex} = external electric field force parameter, dimensionless

K_{ic} = charged particle image force parameter, dimensionless

K_{icp} = electric dipole interaction parameter, dimensionless

K_{ip} = charged collector image force parameter, dimensionless

K_p = inertial impaction parameter, dimensionless

K_{po} = inertial impaction parameter at Venturi throat entrance, dimensionless

L = distance below the exit duct at which the vortex turns, cm

l_t = Venturi throat length, cm

m = exponent (eq. 5.7.2.3-1)

n = vortex exponent, see Figure 7.5.1-2

n_d = number of particle diameters

n_h = number of holes in sieve plate

n_p = number of charges on particle

n_t = number of time increments

N = free ion density, $1/m^3$

N_{Re} = Reynolds number, dimensionless

N_s = number of baffled sections in ESP

ND/CP = neutral drops and charged particle

ND/UP = neutral drop and uncharged particle

ΔP = pressure loss, N/m^2, or cm W.C.

NOMENCLATURE (continued)

Δp_j = dry plate pressure drop, cm W.C.
ΔP_o = pressure loss due to fabric filter, N/m^2 or cm W.C.
ΔP_p = pressure loss due to deposited particle layer, N/m^2, cm W.C.
Pt_d = penetration, fraction
$\overline{Pt}$ = overall penetration, fraction
q_d = drop charge, C
q_p = charge on particle, C
Q_G = gas volumetric flow rate, m^3/s
Q_L = liquid volumetric flow rate, m^3/s
r = radial distance from the vortex centerline, cm
r_d = radius of drop, cm
S = cyclone gas outlet duct length, cm
S_p = fraction of particles in ESP that are reentrained and that bypass the electrified region per section
SCA = specific collection area, $A_c/Q_G = m^2/m^3/s$
t = residence time for charging
t_g = penetration time, s
T = absolute temperature, ^0K
u_d = drop velocity, cm/s
u_{do} = drop velocity at Venturi throat entrance, cm/s
u_G = gas velocity relative to duct, cm/s
u_h = gas velocity through sieve plate hole, cm/s
u_o = undisturbed upstream velocity, cm/s
u_p = particle velocity, cm/s
u_{pD} = particle deposition velocity, cm/s
u_{po} = particle velocity at Venturi throat entrance, cm/s
u_r = drop velocity relative to gas, cm/s
u_s = filtering gas velocity (superficial) m/s
u_t = terminal settling velocity, cm/s
u^*_{dl} = $2[1-x^2 + (x^4-x^2)^{0.5}]$, (eq. 4.5.2-14)
U = applied voltage, V

NOMENCLATURE (continued)

v	=	mean thermal speed of ions, cm/s
v_g	=	gas velocity through cyclone inlet, cm/s
v_G	=	superficial gas velocity through bed, cm/s
v_t	=	tangential gas velocity, cm/s
W	=	collected dust loading on the filter, kg/m² or g/m²
W_R	=	residual dust loading on filters after cleaning, kg/m²
w	=	total weight of dust, g
w_p	=	migration velocity, cm/s
w_k	=	pulse charging migration velocity, cm/s
x	=	$3\ l_t\ C_{po} \rho_G / 16\ d_d \rho_L + 1$,(eq. 4.5.2-15)
X	=	estimated mass collected by last electrical section, mg/DSCM
Y_1	=	rapping emissions for a cold side ESP, mg/DSCM
Y_2	=	rapping emissions for a hot side ESP, mg/DSCM
z	=	bed depth, cm
Z	=	height or length of scrubber, cm

Greek

$\bar{\alpha}$	=	average specific resistance of collected particle layer, m/kg
β_o	=	pressure loss coefficient for clean filter, 1/m
ε	=	fraction void volume space
ε_a	=	apparent volumetric void fraction of particle layer
ε_b	=	bed porosity, fraction
ε_d	=	dielectric constant of drop, F/cm
ε_G	=	dielectric constant of gas, F/cm
ε_o	=	permitivity of free space = 8.854×10^{-12} F/m
ε_r	=	dielectric constant of particle, F/cm
η	=	collection efficiency, fraction
λ	=	mean free path of gas molecules, cm

NOMENCLATURE (continued)

μm	=	micrometer
μmA	=	$\mu m \sqrt{g/cm^3}$ = aerodynamic micrometer
μ_G	=	gas viscosity, poise
μ_L	=	liquid viscosity, poise
ρ_{H_2O}	=	density of water, g/cm^3
ρ_L	=	liquid density, g/cm^3
ρ_p	=	particle density, g/cm^3
σ	=	surface tension, dyne/cm
σ_g	=	geometric standard deviation of particle size
σ_G	=	normalized standard deviation of gas velocity diameter d_p, m/s

SECTION 1

SUMMARY AND CONCLUSIONS

The objectives of this study are to evaluate the effectiveness and cost of control for existing and developing fine particle control technologies that can be applied to the major industrial sources in California. Fine particles, defined for this study as those with an aerodynamic diameter less than 3 μmA, are a major air pollution problem. They reduce visibility, can be deposited in the lungs, and they are difficult to collect in conventional control devices.

This study consisted of two phases. In Phase 1 of this study information was acquired on fine particle control technologies and on the major sources of fine particle emissions in California. Phase 2 was a technical evaluation of the effectiveness and cost of control for various fine particle control devices applied to the major sources.

Sections 4 through 7 of this report present the design information for the fine particle control technologies in 4 major categories--wet scrubbers, electrostatic precipitators, fabric filters, and cyclone separators. Literature surveys and correspondence with individuals developing new fine particle control devices provided this information.

Sections 8 through 14 present the emission data and process information necessary for an evaluation of the fine particle control technology as applied to the largest source within the seven major source categories (fuel combustion, food and agriculture, metalurgical, mineral processing, surface coating, incineration, and wood milling). The information presented in these sections was obtained from the California Emissions Inventory System (EIS), the U. S. Environmental Protection Agency Fine Particle Emission Inventory System (FPEIS), and literature reviews.

Table 1-1 presents a summary of the emissions from the major sources of fine particle emissions in California, the types of control devices presently used on the different sources, and the fine particle control devices that were evaluated during Phase 2 of this study.

Particle collection systems can be designed to achieve almost any collection efficiency, at a cost which increases with efficiency. At present, there are no emission standards for fine particles considered separately. In order to explore the possibilities, CARB specified that the costs for 50, 75, and 90% collection of particles less than 3μmA were to be estimated. Of the ten fine particle control devices selected for evaluations, Venturi, ESP, flux-force/condensation, precharged ESP, and Calvert Collision Scrubber have proven mathematical models or empirical equations. Calculations with these devices were done only for the above three levels of efficiency, not to determine the maximum feasible collection efficiency of these devices on a source.

For the remaining five control devices (i.e. fabric filter, electrified filter, pulse charged ESP, charged spray scrubber, and the Spray Charging and Trapping (SCAT) scrubber), reliable design equations are not available. Calculations for conditions to achieve the three levels of efficiency cannot be done. Therefore, calculations were based on field test results and the reported efficiency shows what the control device could do under the same conditions as the field tests.

For a given efficiency, one calculates the dimensions and operating conditions of a control device on a source. Cost estimations were then made for a typical plant for this source. Capital cost, operating cost, and annualized operating cost were accounted for in the calculations.

Calculation results were reported in CARB data base format and are given in sections 8 through 14.

CONCLUSIONS

Control technologies are currently available, at reasonable costs, for removing the fine particle emissions from all of the sources considered in this study, to meet the criteria specified for removal of fine particles (90 percent). In addition, the information presented in this report is sufficient for technical personnel to estimate control costs and particle removal efficiencies needed for stationary sources to comply with emission standards that are expressed on a mass basis, including instances where required removal efficiencies may exceed 90 percent.

TABLE 1-1. MAJOR INDUSTRIAL SOURCES OF FINE PARTICLES IN CALIFORNIA

Process	Uncontrolled Emissions* (Tons/Yr)	Weight % < 3μmA	Control Technology Present	Control Technology Fine Particle
FUEL COMBUSTION				
Oil-Fired Boilers				V, ES, CS, E, EH, EP, B, EF
Residual Oil Field-Erected Boilers	6-80	70 - 95	E	
Residual Oil Package Boilers	0.2-2,125	45 - 70	P	
Crude Oil Package Boilers	38-77	30 - 70	S	
Distillate Oil Package Boilers	2	75 - 95	E	
Coal-Fired Boilers				V, ES, CS, E, EH, EP, B, EF
Field-Erected Boilers	4,400-879,000	40	P,C,E, S,B	

B = Baghouse (fabric filter)
C = Cyclone separator
CO = Confinement
CS = Calvert Collision Scrubber™
E = Electrostatic Precipitator (ESP)
EF = Electrostatically Augmented Filter
EH = ESP with SoRI precharger
EP = Pulse charging ESP
ES = Charged spray scrubber
F/C = Flux force/condensation scrubber
GB = Granular bed filter
P = Process modification
S = Scrubber
SCAT = Spray charging and trapping scrubber
V = Venturi scrubber

* Each source

TABLE 1-1. MAJOR INDUSTRIAL SOURCES OF FINE PARTICLES IN CALIFORNIA

Process	Uncontrolled Emissions (Tons/Yr)	Weight % < 3 µmA	Control Technology Present	Control Technology Fine Particle
FOOD AND AGRICULTURE				
Rice Drying	1,400	10 - 40	C	V, CS, B
Grain Drying	300	10 - 15	B	V, CS, B
Alfalfa Drying	600		C, S	
Primary Cooling		12		
Secondary Cooling				
Air Meal Separato		42		
Grain Grinding and Milling	310		C	B
Cotton Ginning	490			V, CS, B
Incliner Cleaner			C	
Unloading and Dryer			S	
Unloading Separator				
Mote Cleaner				
Lint Cleaner				
Battery Condenser		5	S	
METALLURGICAL				
Coke Ovens			P	V,F/C,ES SCAT,CS,E B,EF
Charging	140	<20		
Pushing-Clean	1,100	6		
Pushing-Green				
Primary Iron and Steel				V,F/C,ES,E CS,B,EF
Sintering Windbox	270	<5	S,E,B,C	
Blast Furnace Cast House	690	60	B	
Open Hearth Furnace with Oxygen Lancing	720	90	B,S,E	
Basic Oxygen Furnace				
Charging Clean Scrap		45	B,S,E	
Charging Oily Scrap		65		
Scarfing Machine	70			

TABLE 1-1. MAJOR INDUSTRIAL SOURCES OF FINE PARTICLES IN CALIFORNIA

Process	Uncontrolled Emissions (Tons/Yr)	Weight % < 3 μmA	Control Technology Present	Control Technology Fine Particle
METALLURGICAL				
Steel Foundry			B	V,F/C,ES,B CS,E,EF
Electric Arc Furnace				
No Oxygen Lancing	150	35		
with Oxygen Lancing				
Brass	110			V,F/C,ES,E CS,B,EF
Rotary Furnace		95	B	
Reverberatory Furnace				
Lead	100			V,F/C,ES,E CS,B,EF
Reverberatory Furnace		80	B	
Secondary Zinc	70			V,F/C,ES,E CS,B,E
Reverberatory Furnace		90	B	
MINERALS				
Cement				V,ES,CS,E EH,EP,B,EF
Dry Kiln	1,600	4	C,B,E	
Wet Kiln	520	4 - 30	C,B,E	
Dryer/Grinder	410		B	
Clinker Cooler	260	1.5-3	C,B	
Asphalt				V,ES,CS,E,B EH,EP,EF
Road Mix				
Agregate Dryer	1,800	1 - 8	C,S	
Lime Manufacture				V,ES,CS,E,B EH,EP,EF
Rotary Calcining Kiln	230	30-80	S	
Gypsum				V,ES,CS,E,B EH,EP,EF
Gypsum Calciner	140	50		

TABLE 1-1. MAJOR INDUSTRIAL SOURCES OF FINE PARTICLES IN CALIFORNIA

Process	Uncontrolled Emissions (Tons/Yr)	Weight % < 3 µmA	Control Technology Present	Control Technology Fine Particle
MINERALS				
Asbestos Milling				V, ES, CS, E, B EH, EP, EF
Glass Manufacture				V, F/C, ES, CS EH, EP, B, EF
Melting Furnace		>80		
Rock, Sand, and Gravel				V, ES, CS, E, B EH, EP, EF
Primary Crushing	5,100		CO, S, B	
Screening/Handling	780		CO	
Secondary Crushing	500		CO, S, B	
Aggregate/Sand Drying	470			
Fines Milling	110			
Abrasive Blasting	70		S, B, C	
SURFACE COATING	720	60-65	S	V, ES, CS
Auto Manufacturing				
Can Manufacturing				
Metal and Wood Manufacturing				
INCINERATION				
Municipal Incineration		30-40	E, S, B	V, F/C, ES, CS E, B, EF
Industrial Incineration				V, F/C, ES, CS E, B, EF
Wood Waste Boiler		96		
WOOD MILLING AND WORKING			C	V, ES, CS, E, B
Wood Sander		47		
Wood Saw		7		

SECTION 2

RECOMMENDATIONS

This study was limited to the use of existing knowledge of control technology, emission and source characteristics, and design methods. No experimental work was done to evaluate the accuracy of the information available in the literature, such as particle size distribution and concentration of emissions from a source. To accurately evaluate the effectiveness and cost of control for fine particles, the following are recommended.

1. Because of many adverse effects of fine particles, separate regulations on fine particle emissions may be appropriate. Evaluation of fine particle control technologies could be made more specific in terms of such regulations and therefore such evaluations should be performed.

2. Source sampling should be done to determine emission characteristics and control efficiency for the following operations:
   a. Food and agriculture processing
   b. Gypsum calcining
   c. Asbestos milling
   d. Industrial incineration
   e. Wood milling and working.

3. Pilot scale tests of developing technologies on actual sources are needed to provide more reliable performance information. The following systems need further evaluation:
   a. Charged particle/charged spray scrubber
   b. Electrostatically augmented filter
   c. Electrostatically augmented granular bed filter
   d. Electro-cyclone
   e. Pulse charging ESP and ESP with SoRI precharger (on sources other than coal-fired boilers).

SECTION 3

INTRODUCTION

3.1 BACKGROUND

The purpose of this study is to provide information on the degree of fine particle control feasible for stationary sources in California and estimate the costs for several devices of fine particle emission control. The cost estimates include capital and annual operating expenses. This information is intended as a reference for CARB staff and district personnel in considering the impact that an emission standard for fine particles would have on industry in California. Fine particles have been defined for this studies as those with an aerodynamic diameter less than 3 μmA.

The California Air Resources Board has sponsored previous studies to survey stationary industrial pollution sources and identify the pollutants and control devices used. A study done by Acurex Corporation (Minicucci et al. 1980) summarizes stationary air pollution sources in California and the control technologies used for these sources. The report for that study lists specific processes in eight industrial categories and the major air pollutants emitted from each process. Control methods are listed for each process as well as an estimate of the control efficiency of the device and cost information.

As part of that study, Acurex developed a data base and associated software to allow CARB to organize, access, and update the information. The information compiled by A.P.T. in the present study will be entered into this data base.

The CARB also contracted with KVB, Inc. to identify major sources of fine particles in The South Coast Air Basin (SCAB) and characterize the emissions from these sources. KVB (Taback et al., 1979) reported field test data for over twenty different sources. The information reported includes particle size distributions, chemical analysis of the particles, and characteristics of the gas stream, such as temperature and flow rate.

In the present study, the emissions from the major sources were characterized to determine the most applicable control devices and to estimate the fine particle control efficiency.

3.2 METHODOLOGY

This study was divided into three distinct tasks. The first task was to determine the stationary sources of fine particle emissions in California and characterize the emissions from these sources. The second task was to determine the control technolgies available for fine particles. The third task was to estimate the efficiency of the control devices on the sources and the costs associated with the control devices.

3.2.1 Identification and Characterization of Sources

Seven industrial categories were specified by the CARB for inclusion in this study:

1. Combustion of fuels
2. Food and agricultural operations
3. Metallurgical operations
4. Mineral operations
5. Solvent use
6. Incineration
7. Wood milling

The sources to be evaluated in each category were not specified, except for the fuel combustion category. In this case, the CARB specified that the following sources be evaluated:

1. Residual oil-fired utility boilers
2. Coal-fired utility boilers
3. Residual oil-fired industrial boilers
4. Distillate oil-fired industrial boilers
5. Crude oil-fired industrial boilers.

For the other six categories the sources of particle emissions were determined from Emission Inventory System (EIS) data supplied by the CARB. The EIS data are a compilation of data reported to the California Air Resources Board from all the Air Pollution Control Districts (APCDs) in the state. The EIS lists the companies which are major sources of air pollution in each APCD. Specific processes are listed under each company and the amount of pollutants emitted by that process are listed. The amount of particulate emissions are reported in tons per year. A list was compiled of specific industries and the operations within each industry which are the largest sources of particle emissions in the state.

Computer literature searches were performed to locate information on the sources of particle emissions. In particular, it was necessary to obtain particle size distributions to determine which sources emit fine particles. The following data bases were searched:

1. National Technical Information Services (NTIS)
2. Air Pollution Technical Information Center (APTIC)
3. Chemical Abstracts
4. Pollution Abstracts
5. Engineering Index

Useful reports from the lists of the searches were then obtained.

Contacts were made with people in various departments of the Environmental Protection Agency (EPA) to obtain information not yet published or which did not appear in the literature search. Officials of several APCDs were contacted as well as researchers at other companies.

Data from the Fine Particle Emission Inventory System (FPEIS) maintained by the EPA were used to characterize emissions from several sources. The FPEIS data are reported by organizations which have conducted source tests, generally under contract with the EPA. The FPEIS contains information on the source, the test conditions, particle size distributions, and mass concentrations.

For each of the sources identified as a major source of fine particles, a source description has been written. Information defining the gas flow and particle characteristics of each source is included in the descriptions.

3.2.2 Survey of Control Technology

Computer literature surveys for fine particle control technology were run on the same data bases listed in the previous section. An extensive amount of the control device literature was available in the A.P.T. library and additional information was obtained when necessary. Information about many developing control devices was obtained directly from the people involved in the research.

Discussion of the control devices has been divided into four sections: scrubbers, electrostatic precipitators, filters, and cyclones. Each section contains a discussion of both conventional devices and developing technology. The methods of calculating the particle collection efficiency of the devices and the cost data are also presented.

3.2.3 Technical Evaluation

3.2.3.1 Estimation of Efficiency

Table 3.2.3-1 shows a list of the devices which were evaluated for controlling stationary sources in California. They are described in Sections 4 through 7 of the report and those listed in Table 3.3.3-1 have the ability to control fine particles. Both conventional and advanced designs were included.

The method of estimating the collection efficiency is different for each device. In many cases, computer models are available and were used. In other cases, because theoretical models are not available or are not sufficiently accurate, efficiency was estimated from test data reported in the literature. The specific methods of technical evaluation for each device are described in sections 4.8, 5.7, 6.6, and 7.6. rThe purpose of the efficiency calculations is to determine the necessary operating conditions to achieve the required collection efficiency. Equipment size was estimated from operating conditions and the average gas flow rate from the source. The costs were then estimated from the design.

Particle collection systems can be designed to achieve almost any collection efficiency. The limiting factor is the cost of achieving that collection efficiency. At present, there are no emission standards for fine particles. Therefore costs were evaluated, whenever possible, for three levels of collection efficiency for particles less than 3 μmA in diameter: 50%, 75%, and 90%. For some developing technologies and devices there

TABLE 3.2.3-1. DEVICES EVALUATED FOR FINE PARTICLE CONTROL

1. Gas-Atomized Spray Scrubber
2. Flux-Force/Condensation Scrubber
3. Charged Dust/Grounded Spray Scrubber
4. Charged Dust/Charged Spray Scrubber
5. Spray, Charging and Trapping (SCAT) Scrubber
6. Calvert Scrubber
7. Electrostatic Precipitator (ESP)
8. ESP with High Intensity Ionizer
9. ESP with Pulse Energization
10. Conventional filter (Baghouse)
11. Electrostatically Augmented Filter
12. Granular Bed Filter

is not enough information available to design for all three efficiency levels, so efficiencies were calculated from the available information.

3.2.3.2 Cost Estimation

Cost estimation for electrostatic precipitators, baghouses, and Venturi scrubbers was calculated with the data reported by Viner and Ensor (1981) and Neveril (1978). Estimates for advanced designs were made from material and labor costs in fabricating the device. All costs are in fourth quarter 1981 U.S. dollars.

3.2.3.3 Format for Reporting Data

The information from this study is to be added to the data base developed by Minicucci et al. (1980). The format for reporting the cost and efficiency evaluations of this study conforms to this data base format. An example is shown in Figure 3.2-3.1. The efficiency for particles with $d_{pa} < 3$ μmA is reported in the remarks column and the overall efficiency is reported in the efficiency column.

INDUSTRY: PRIMARY METALS SECTION: 05.050.100

PROCESS	EMISSION SOURCE	PL	CONTROL TECHNOLOGY	COSTS, $ CAPITAL OPERATING ANNUALIZED	EFFY (%)	REL (%)	S	ENERGY USE	ENVIR IMPACT	REMARKS	REFS
STEEL	BASIC OXYGEN FURNACE -- HOT METAL TRANSFER (HOT METAL RELOADING)	PM	HOOD CANOPY HOOD (MOVABLE OR FIXED) VENTING TO A BAGHOUSE		50-70	LOW MED	2 3			EFFICIENCY DEPENDS ON HEIGHT ABOVE TORPEDO CAR OF HOT METAL LADLE MORE VENTILATION REQUIRED	116 198 120
STEEL	BASIC OXYGEN FURNACE -- HOT METAL TRANSFER (HOT METAL RELOADING)	PM	HOOD CLOSE FITTING LADLE HOOD (STATIONARY OR MOVABLE) VENTING TO A BAGHOUSE	500/TON OF METAL TRANSF NA NA		MED	2	250-400 CFM/ TON VOLUME FLOW RATE REQUIRED		COST INCLUDES HOOD ONLY	116 198 120
STEEL	BASIC OXYGEN FURNACE -- HOT METAL TRANSFER (HOT METAL RELOADING)	PM	HOOD PARTIAL BUILDING EVACUATION VENTING TO BAGHOUSE	5.9E6 WITH BAGHOUSE NA NA	70	MED	2	VENTILATION REQUIRED= 3600 ACFM/ TON OF METAL		COST FOR A COMPLETE SYSTEM TO CONTROL 2 BOF + TRANSFER STATION	116 198 120

Figure 3.2-3.1. Example of information from the Acurex data base (Minicucci, et al., 1980).

SECTION 3

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SECTION 4

WET SCRUBBING

4.1 INTRODUCTION

The Scrubber Handbook (Calvert et al., 1972) defined a wet scrubber as any device which uses a liquid in the separation of particulate or gaseous contaminants from a gas. The liquid may be used to contact the gas and particles directly, or may be used to clean solid surfaces on which the particles have been collected. In view of this very general definition, there are as many types of scrubbers as there are ways of contacting a liquid and a gas.

Scrubber manufacturers offer a wide array of products over a range of designs, sizes, advertised performance capabilities, and capital and operating costs. Choosing the optimum scrubber for a particular job requires an understanding of the fundamental principles underlying the various designs.

4.1.1 Collection Mechanisms

Particle collection in scrubbers is due to one or more of same phenomena which may be operative in other types of collection equipment. Deposition may be due to inertial impaction, interception, Brownian diffusion, turbulent diffusion, gravitational force, electrophoresis, diffusiophoresis, thermophoresis, photophoresis, and magnetophoresis.

1. Gravitational sedimentation. This mechanism is usually of little consequence for any particles small enough to require consideration of a scrubber.
2. Centrifugal deposition. Particles may be "spun out" of a gas stream by centrifugal force induced by a change in gas flow direction. Large-scale changes in flow direction, as would be encountered in a cyclone separator, are not very effective on particles smaller than about 5.0 microns diameter.
3. Inertial impaction and interception. When a gas stream flows around a small object, the inertia of the particles causes them to continue to move toward the object, and some of them will be collected.

Because inertial impaction is effective on particles as small as a few tenths micron diameter, it is usually the most important collection mechanism for fine particle collection in scrubbers. Since this mechanism is a function of the inertia of the particles, both their size and density are important in determining the ease with which they may be collected. All important particle properties may be lumped into one parameter, the aerodynamic diameter, defined as:

$$d_{pa} = d_p(\rho_p \; C')^{1/2} \qquad (4.1\text{-}1)$$

where d_{pa} = particle aerodynamic diameter, μmA

d_p = particle physical diameter, μm

C' = Cunningham slip correction factor, dimensionless

ρ_p = particle density, g/cm^3

Most methods for measuring particle size (such as the cascade impactor) measure the aerodynamic diameter. Since this is the most important parameter where inertial impaction is at work, one needs not know the actual physical diameter or particle density.

4. Brownian diffusion. When particles are small enough (i.e., less than about 0.1 micron diameter), they are buffeted around by gas molecules, and they begin to act like gas molecules. That is, they diffuse randomly through the gas because of their Brownian motion. In general, inertial impaction and Brownian diffusion are the two principal mechanisms operating in particulate scrubbers. As a consequence, there is generally a minimum point when collection efficiency is plotted against particle diameter. Above about 0.3 micron diameter, inertial impaction becomes important and efficiency rises with particle diameter. Below 0.3 micron diameter, diffusion begins to prevail and efficiency rises as particle diameter falls below that size.
5. Thermophoresis. If there is heat transfer between the gas and liquid, there will be a corresponding temperature gradient, and fine particles will be driven toward the cold region by differential molecular bombardment arising from the gradient. This effect will rarely be of much significance in a scrubber.
6. Diffusiophoresis. Mass transfer within the scrubber--as might be caused by condensation of water vapor from the gas onto a cold liquid surface--will exert a force upon particles that causes them to deposit on the surface. Diffusiophoretic deposition can be significant; the fraction of particles removed will roughly equal the fraction of the gas stream condensed out.
7. Electrostatic precipitation. If an electrostatic charge is induced on the particles, they can be precipitated from the gas stream by the influence of an electric field. This mechanism can be effective on all particle diameters and can provide high collection efficiency.
8. Particle growth. While it is not a collection mechanism in itself, the enlarging of particle mass by such means as having water condense in a film around it makes the particles more susceptible to collection by inertial impaction. This phenomenon, in combination with diffusiophoresis and thermophoresis, can take place in scrubbers where condensation occurs. The combination of mechanisms is referred to as "flux force/condensation" (F/C) scrubbing.

4.1.2 Cut Diameter

A very convenient parameter for describing the capability of a particle scrubber is the diameter of the particle that it will collect at 50% efficiency. This diameter is referred to as the cut diameter, generally given in aerodynamic units. Thus a scrubber with a cut diameter of 1.0 μmA would collect particles of 1 μmA diameter at 50% efficiency.

The reason cut diameter is so useful a parameter is that a plot of collection efficiency vs. particle diameter for collection by inertial impaction is fairly steep. Several important types of scrubbers have performance characteristics such that a particle whose aerodynamic diameter is half the cut diameter would be collected at about 10% efficiency, whereas a particle with an aerodynamic diameter twice the cut diameter would be collected at about 90% efficiency.

Because the cut is fairly sharp, one can use as a rough approximation the concept that the scrubber collects everything larger than the cut diameter and passes everything smaller.

4.2 TYPES OF SCRUBBERS

Scrubbers may be grouped into a number of categories: plate, massive packing, fibrous packing, preformed spray, gas-atomized spray, centrifugal, impingement-and-entrainment, mechanically aided, moving-bed, and various combinations (Calvert, 1977a). These will each be discussed briefly.

4.2.1 Plate Scrubbers

A plate scrubber consists of a vertical tower with one or more plates (trays) mounted transversely inside. Gas comes in at the bottom of the tower and must pass through perforations, valves, slots, or other openings in each plate before leaving through the top. Usually, liquid is introduced to the top plate, and flows successively across each plate as it moves downward to the liquid exit at the bottom. Gas passing through the openings in each plate mixes with the liquid flowing over it. Gas-liquid contacting causes the mass transfer or particle removal for which the scrubber was designed.

Figure 4.2.1-1 shows two common types of plates and a tower. Plate scrubbers are generally named for the type of plates they contain; for example, a tower containing sieve plates is called a sieve-plate tower.

In some designs, impingement baffles are placed a short distance above each perforation on a sieve plate, forming an impingement plate. The impingement baffles are below the level of liquid on the perforated plates, and for this reason are continuously washed clean of collected particles. The chief mechanism of particle collection is inertial impaction from gas jets impinging on the liquid or on solid members. Particle

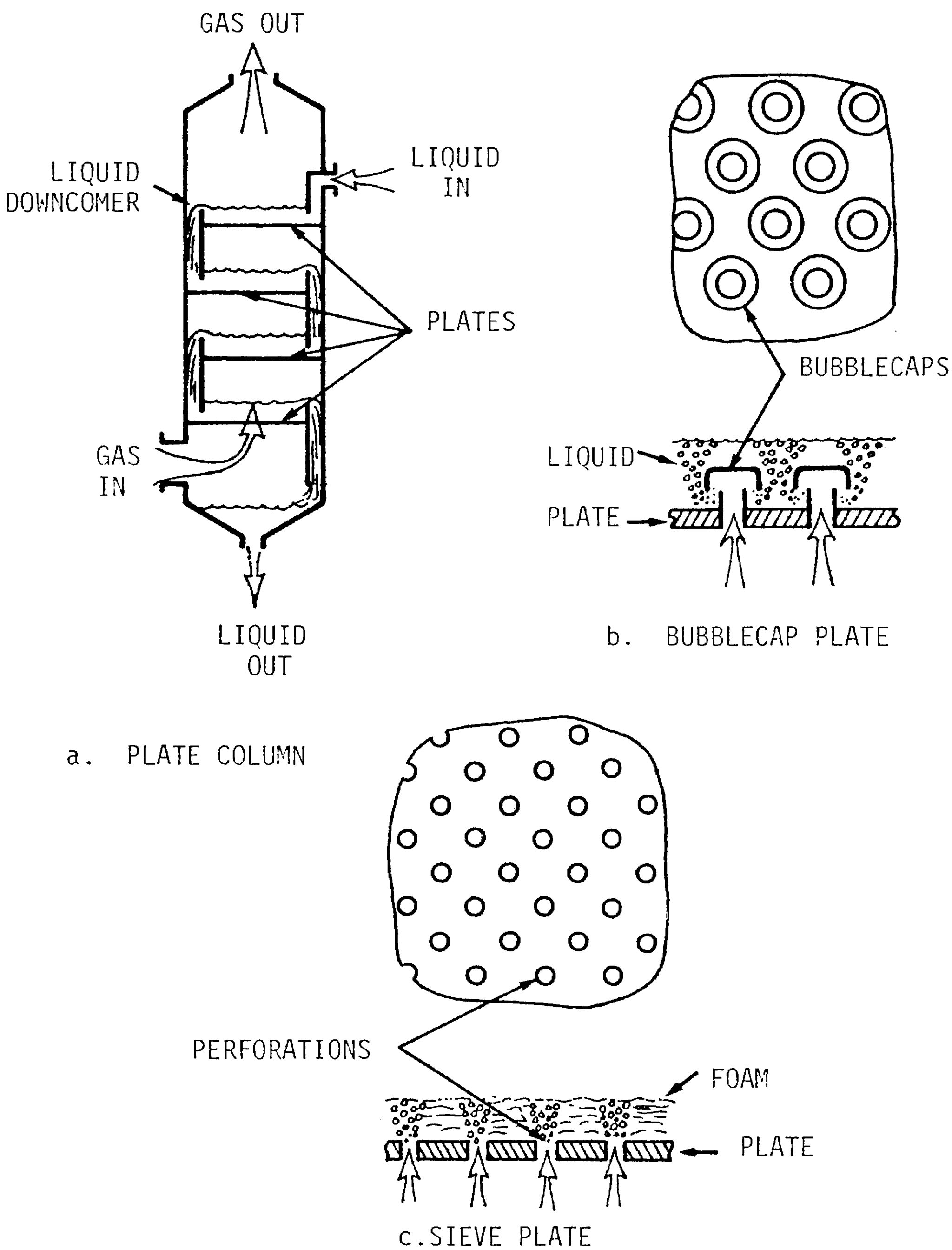


Figure 4.2.1-1. Plate arrangement in a scrubber tower, and two commonly used contacting devices.

collection may be aided by atomization of liquid flowing past openings in the irrigated perforated plate. Collection efficiency increases as the perforation diameter decreases and can enable a cut diameter of about 1.0 μmA for 0.32 cm (⅛ in.) diameter holes in a sieve plate.

Engineers are accustomed to the notion that plate columns become more efficient for mass transfer as the number of plates increases. This generally does not hold for particle collection whenever a range of particle diameters are present. A plate does not have the same efficiency for all particle sizes, but rather shows a sharp efficiency change around the cut diameter. Once particles larger than this size are removed from the gas, additional plates can do little good. This kind of behavior is characteristic of most types of scrubbers and should be kept in mind whenever one is tempted to try two scrubbers in series.

4.2.2 Massive Packing

Packed-bed or tower scrubbers are familiar as gas absorbers or fractionators and can also be used as particle scrubbers. They may be packed with a range of manufactured elements, such as various ring and saddle-shaped packings, or with commonly available materials like crushed rock. The gas-liquid contacting may be cocurrent, countercurrent, or crossflow. Mist collection in packed beds with subsequent drainage can be accomplished without additional liquid flow.

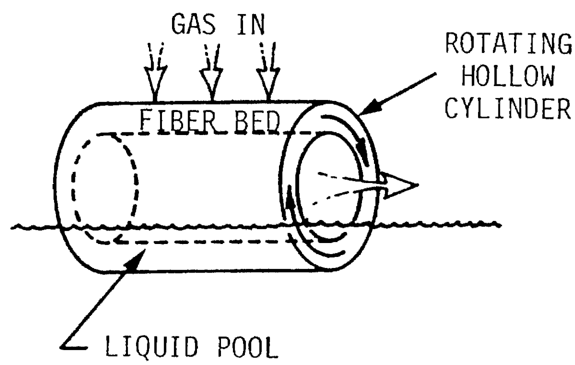
Collection in packing works mainly by centrifugal deposition due to curved gas-flow through the pore spaces, and by inertial impaction due to gas-jet impingement within the bed. The good mass-transfer characteristics of packings can also make for efficient collection of particles by diffusion if the particles are small enough.

Collection efficiency for particles in the inertial size range (larger than 0.3 μmA diameter) rises as packing size falls. A cut diameter around 1.5 μmA can be reached using columns packed with 1 in. Berl saddles or Raschig rings. Smaller packing gives higher efficiency: a 1.3 cm (0.5 in.) packing can achieve 0.7 μmA cut diameter at 9.2 m/s (30 ft/s) gas velocity. Packing shape does not appear to be very important so far as collection efficiency is concerned.

Packings are subject to plugging, but can be removed for cleaning. Temperature limitations are of special importance when plastics are used. Likewise, corrosion can have a severe effect on metallic packings.

4.2.3 Fibrous Packing

Beds of fiber can be employed in various configurations for the collection of particles (Figure 4.2.3-1). The fibers are made from materials such as plastic, spun glass, fiberglass and steel. Fibrous packing usually has a very large void fraction



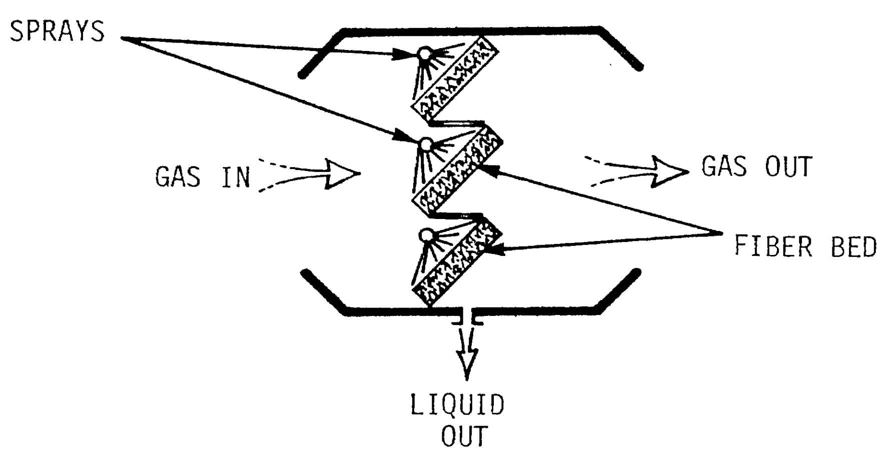


Figure 4.2.3-1. Two fiber-bed scrubber designs. Packing void fractions usually run 97-99%.

ranging around 97-99%. Fibers should be small in diameter for efficient operation, but strong enough to support collected particles or droplets without matting together. A liquid flow flushes away collected material from the fibers in cocurrent, countercurrent or crossflow arrangements similar to those for massive packings.

Collection is by inertial impaction accompanying the gas flow around the fibers. Efficiency rises as fiber diameter decreases and as the gas velocity increases. Diffusional collection can be important for very small particles, and the efficiency of this mechanism will improve as gas velocity diminishes through a given scrubber. Cut diameters can run as low as 1.0 or 2.0 μmA for knitted wire mesh with 0.028 cm (0.011 in.) diameter wire, and to around 0.5 μmA for very fine wires and/or higher gas velocities.

Fibrous beds are very susceptible to plugging and can be impractical where scaling persists and conditions favor deposition of suspended solids. Obviously, they will also be especially sensitive to chemical, mechanical and thermal attack.

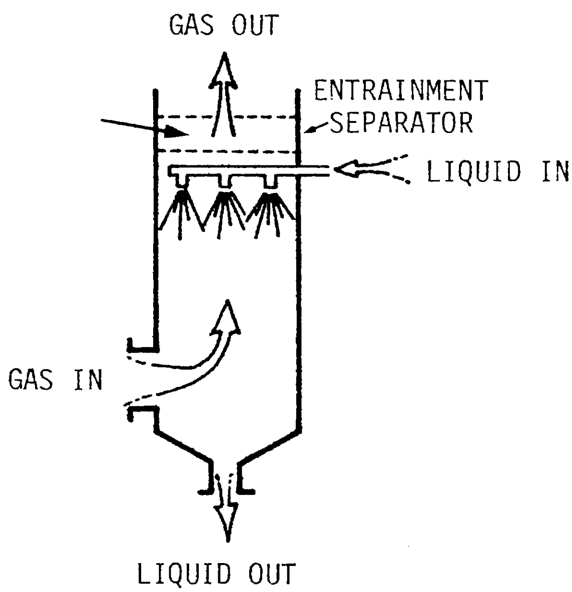
4.2.4 Preformed Spray

A preformed-spray scrubber collects particles or gases on liquid droplets that have been atomized by spray nozzles. The properties of the droplets are determined by the configuration of the nozzle, the liquid to be atomized and the pressure to the nozzle. Sprays leaving the nozzle are directed into a chamber that has been shaped so as to conduct the gas through the atomized drops. Horizontal and vertical gas flow paths have been used, as well as spray entry flowing cocurrent, countercurrent or crossflow to the gas (Figure 4.2.4-1). If the tower is vertical, the relative velocity between the droplets and the gas is ultimately the terminal settling velocity of the droplets.

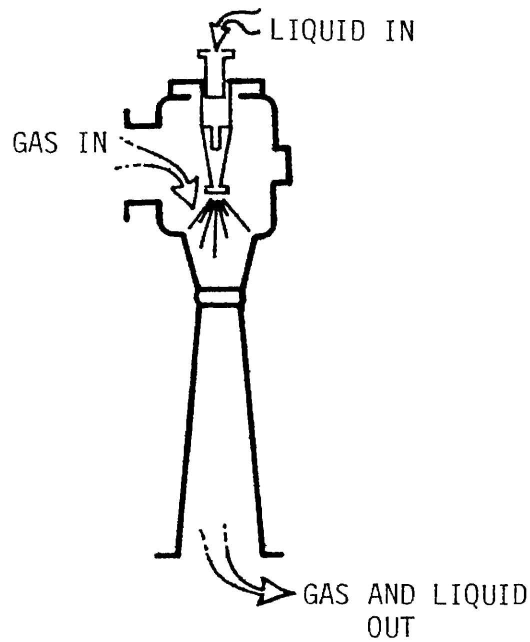
Ejector Venturis are preformed spray devices in which a high-pressure spray is used both to collect particles and move the gas. High relative velocity between the droplets and the gas aids particle separation. Preformed sprays have also been installed in Venturi scrubbers that use a fan to provide high gas-phase pressure drop.

Particle collection in these units results from inertial impaction on the droplets. Efficiency is a complex function of drop size, gas velocity, liquid-to-gas ratio, and drop trajectories. There is often an optimum drop diameter that varies with fluid flow parameters. For drops falling at their terminal settling velocity, the optimum drop diameter for fine particle collection is around 100 to 500 μm; for drops moving at high velocity within a meter of the spray nozzle, the optimum is smaller.

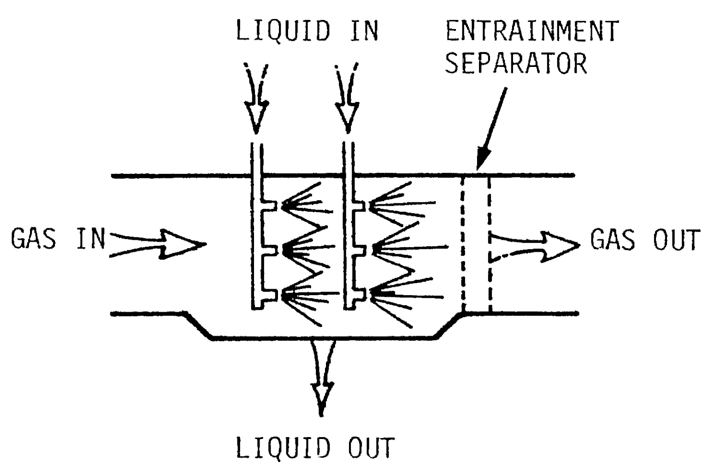
Spray scrubbers that take advantage of gravitational settling can achieve cut diameters around 2.0 μm at moderate liquid-to-gas ratios. High velocity sprays can reduce cut diameters



a. Countercurrent spray.



b. Ejector Venturi.



C. Cocurrent spray.

Figure 4.2.4-1. Preformed-spray scrubber recovers particles or gases on liquid droplets atomized by spray nozzles.

down to about 0.7 μmA. Efficiency improves with higher spray nozzle pressures and liquid-to-gas ratios.

Spray scrubbers are practically immune to plugging on the gas flow side but are subject to severe problems on the liquid side. The liquid-to-gas ratio required can be high, usually running 2-13 liters/m^3 (15-100 gal/Mcf) of gas treated, depending on efficiency.

The recirculating scrubber liquor can erode and corrode nozzles, pumps and piping. Nozzles can plug with pieces of scale or agglomerates of particles. By their nature, sprays generate a heavy loading of liquid entrainment, which must be collected. Gas-phase pressure drop is generally low or may even be positive, enhancing the flow of gas.

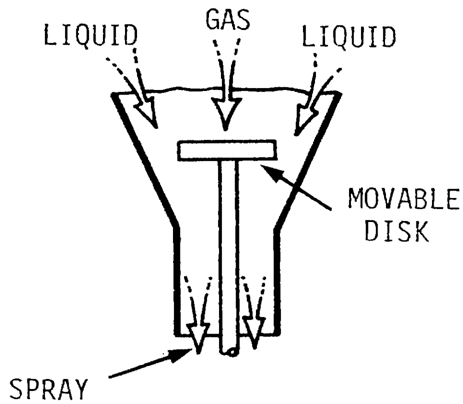
4.2.5 Gas-atomized Spray

Gas-atomized spray devices use a moving gas stream to first atomize liquid into drops, and then accelerate the drops. Typical of these devices are the Venturi scrubber and the various orifice-type scrubbers. High gas velocity of 60-120 m/s (200-400 ft/s) raise the relative velocity between the gas and the liquid drops, and promote particle collection. Many gas-atomized spray scrubbers incorporate the converging and diverging sections typical of the Venturi scrubber, but this modification does not appear to yield much benefit. Various geometries have been used successfully, as illustrated in Figure 4.2.5-1.

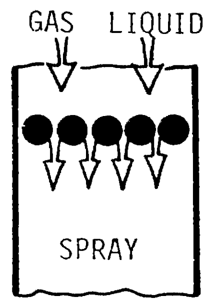
Liquid may be introduced in various places and in different ways without having much effect on collection efficiency. Usually, it is introduced at the entrance to the throat through several straight-pipe nozzles directed radially inward. Other gas-atomized-spray designs distribute a liquid film over the scrubber walls upstream from the throat.

Particle collection results from inertial impaction due to gas flowing around drops. Velocity is so high (and droplet residence time so short) that diffusional collection and deposition by other forces, such as electrostatic, are not very effective. Efficiency increases with throat velocity and with liquid-to-gas ratio. Because there must be enough liquid to effectively sweep the gas stream, it is good practice to use a high liquid-to-gas ratio rather than a high gas velocity to get a lower cut diameter. At least 1 liter/m^3 (7.5 gal/Mcf) should be specified. Cut diameters down to about 0.2 μmA have been achieved with Venturi scrubbers.

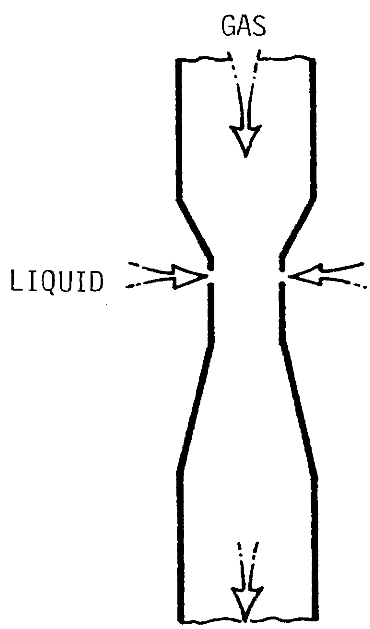
Gas-atomized scrubbers have about the simplest and smallest configurations of all scrubbers. While fairly difficult to plug up, they are susceptible to erosion because of their high throat velocity. They can be built with adjustable throat openings to permit variation of pressure drop and collection efficiency. Liquid-to-gas ratios ranging from 0.7 to 2.7 liters/m^3 (5 to 20 gal/Mcf) have been used. All of this liquid is entrained and must be removed from the gas. In general, the entrainment separator is much larger than the gas-atomized scrubber.



a. Annular orifice.



b. Rod bank.



c. Spray Venturi.

Figure 4.2.5-1. In gas-atomized units, high relative velocity between gas and droplets promotes collection.

4.2.6 Centrifugal Scrubbers

Centrifugal scrubbers, usually cylindrical in shape, impart a spinning motion to the gas passing through them. The spin may come from tangential introduction of gases into the scrubber, or from direction of the gas stream against stationary swirl vanes. In a dry centrifugal collector (cyclone), the walls can be wetted down to hinder reentrainment of particles that collect there, and to wash off deposits. Often, sprays are directed through the rotating gas stream to catch particles by impaction on spray drops. Sprays can be directed outward from a central manifold, or inward from the collector wall. Spray connections directed inward from the wall are more easily serviced, since they can be made accessible from the outside of the scrubber.

A particle cut diameter of 4.0 to 5.0 μmA can be obtained with centrifugal scrubber in the absence of spray. As more spray is introduced or generated inside, the performance nears that of a preformed spray scrubber.

4.2.7 Impingement and Entrainment Scrubbers

Impingement and entrainment (self-induced spray) scrubbers feature a shell that retains liquid, so that gas introduced to the scrubber impinges on and skims over the liquid surface to reach a gas exit duct. This contact atomizes some of the liquid into droplets that are entrained by the gas and act as particle collection and mass transfer surfaces. The gas exit duct is usually designed so as to change the direction of the gas-liquid mixture flowing through it, reducing drop entrainment.

Particle collection is attributed to inertial impaction caused by the gas jet impinging on the liquid, and by the gas flowing around the atomized drops. Drop size and the liquid-to-gas flow ratio inside the scrubber depend upon scrubber geometry and gas flow rate, but are not controllable or measurable.

Generally, the performance of an impingement and entrainment scrubber seems to be comparable to a gas-atomized scrubber operating at the same gas-phase pressure drop. Cut diameter ranges from several microns for low-velocity impingement to around 0.5 μmA for high velocity impingement.

4.2.8 Mechanically Aided Scrubbers

Mechanically aided scrubbers incorporate a motor driven device between the inlet and the outlet of the scrubber body. Often, the motor-driven devices are fan blades, used to move air through the scrubber. Particles are collected by impaction upon the fan blades as the gas moves through the device. Usually, liquid is introduced at the hub of the rotating fan blades. Some liquid atomizes upon impact with the fan, and some runs over the blades, washing them of collected particles; the latter portion atomizes as it leaves the fan wheel. The liquid is recaptured by the fan housing, which drains into a sump.

Disintegrator scrubbers draw on a submerged, motor driven impeller to atomize liquid into small drops. The drops spin off the impeller across the gas stream, collecting particles on the way. Mechanically aided scrubbers are used almost exclusively for particle collection. Their mass transfer capabilities are generally low, due to relatively low amount of liquid available for contacting.

Particle collection mechanisms, in probable order of importance, are: inertial impaction on the atomized liquid, inertial impaction on the rotor elements, and centrifugal deposition on the housing. Cut diameters (aerodynamic) down to about 2.0 μmA have been achieved with devices having fine sprays and low-rpm fans and 1.0 μmA can be reached with a disintegrator type scrubber.

There seems to be no power advantage for mechanically aided units over other types. Disintegrators require more power than a gas-atomized scrubber with comparable efficiency. Further, high speed impaction of liquid and slurry on the scrubber parts promotes severe abrasion and corrosion conditions. Rotating parts are also subject to vibration-induced fatigue caused by solids deposition, or wear leading to unbalancing.

4.2.9 Moving-bed Scrubbers

Moving-bed scrubbers provide a zone of mobile packing--usually plastic or glass spheres--where gas and liquid can mix intimately. The vessel shell holds a support grid on which the movable packing is placed. Gas passes upward through the packing, while liquid is sprayed up from the bottom and/or down over the top of the moving bed, as shown in Figure 4.2.9-1. Gas velocities are sufficient to move the packing material around when the scrubber operates. This movement aids in making the bed turbulent and keeps the packing elements clean. When hollow or low density spheres are used, the bed fluidizes and bed depth extends to about double that of the quiescent bed.

Particle collection stems from inertial impaction on atomized liquid and on the packing elements. Cut diameters down to about 1.0 μmA are attained in the fluidized "ping pong ball" type of bed having three stages in the scrubber column (Yung et al., 1979). Performance of the less violently agitated "marble"-type bed resembles that of massive packing beds unless the gas velocity rises so high as to cause significant liquid atomization and entrainment from the bed.

Moving-bed scrubbers prove beneficial where good mass transfer characteristics are needed, as well as particle collection. The agitation cleans the packing and reduces problems with solids deposition. Ball wear can be severe, and the scrubber's hydrodynamic stability is limited by fluidization ranges and surging difficulties.

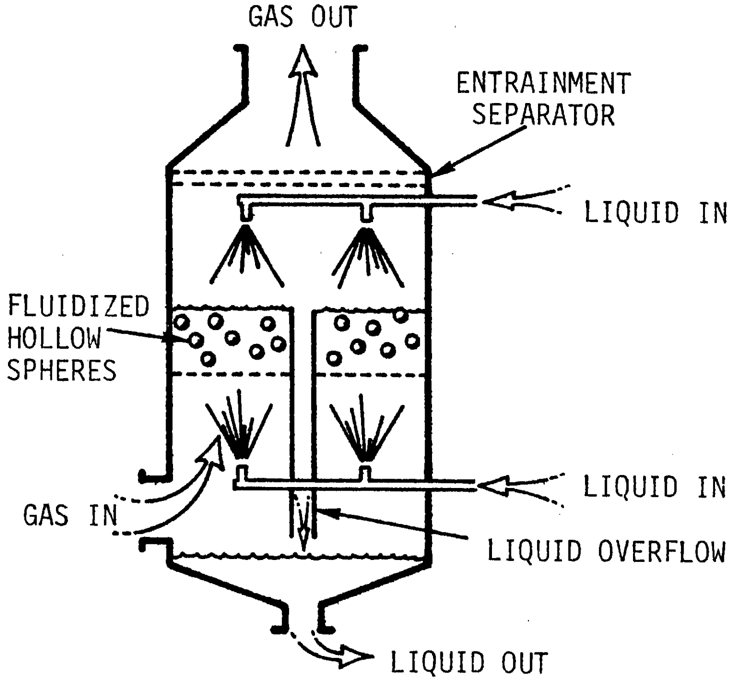


Figure 4.2.9-1. Mobile-bed unit. High gas velocity cleans packing elements and keeps bed turbulent.

4.2.10 F/C Scrubbing

Essentially an F/C scrubber is any wet scrubber which is designed to take advantage of water vapor condensation effects to enhance particle collection (Calvert and Parker, 1978). A simplified F/C scrubber system is illustrated schematically in Figure 4.2.10-1. Some of the water vapor condenses on the particles causing their mass and diameter to increase and thereby making them easier to collect. The rest of the condensing vapor sweeps particles with it as it moves toward the cold surface and condenses. To a lesser extent particle collection is also enhanced by thermal forces resulting from the temperature gradient between the gas and the cold surface. The diffusion and thermal forces are termed "flux" forces.

Water vapor condensation can enhance scrubber performance by increasing the mass of the particles, thereby bringing greater deposition forces to bear on them. Figure 4.2.10-2 (Calvert, 1977b) shows the effect of condensation on aerodynamic size. The straight line on the lob-probability plot of particle diameter vs. mass percent of particles under that size applies to the original size distribution, whereas the dashed line represents a particle size distribution accompanying condensation of water vapor. If a Venturi scrubber were used to obtain 85% collection efficiency, a pressure drop of about 190 cm W.C.(75 in.W.C.) would be required for the particle size distribution, however only about 75 cm W.C. (30 in. W.C.) would be needed if condensation and particle growth took place.

Two full-scale industrial F/C scrubber demonstration plants have now been built and operated (Calvert and Gandhi, 1977 and Chmielewski and Calvert, 1981). The results have been very impressive in terms of high collection efficiency for fine particles at relatively low pressure drop (and hence lower operating costs).

A cost comparison between F/C and conventional scrubbing is presented in Table 4.2.10-1 for a secondary metal recovery furnace. This installation which required both particle collection and acid gas absorption would have a 50% greater annualized cost if a conventional air pollution system were installed.

The lower annualized cost is the result of a lower pressure drop requirement for the scrubber. This substantially reduces the capital and power costs for the fan and motor. Similar annualized cost savings are possible for cleanup of other hot gas streams.

In general, F/C scrubbing is economically attractive when high removal efficiencies are required for fine particle emissions; and the flue gas enthalpy is higher than 100 kcal/kg or spent steam is available in the plant. These conditions are common for industrial combustion processes, which include several major stationary pollution sources in California. Table 4.2.10-2 lists some of the major industrial particulate pollutant sources

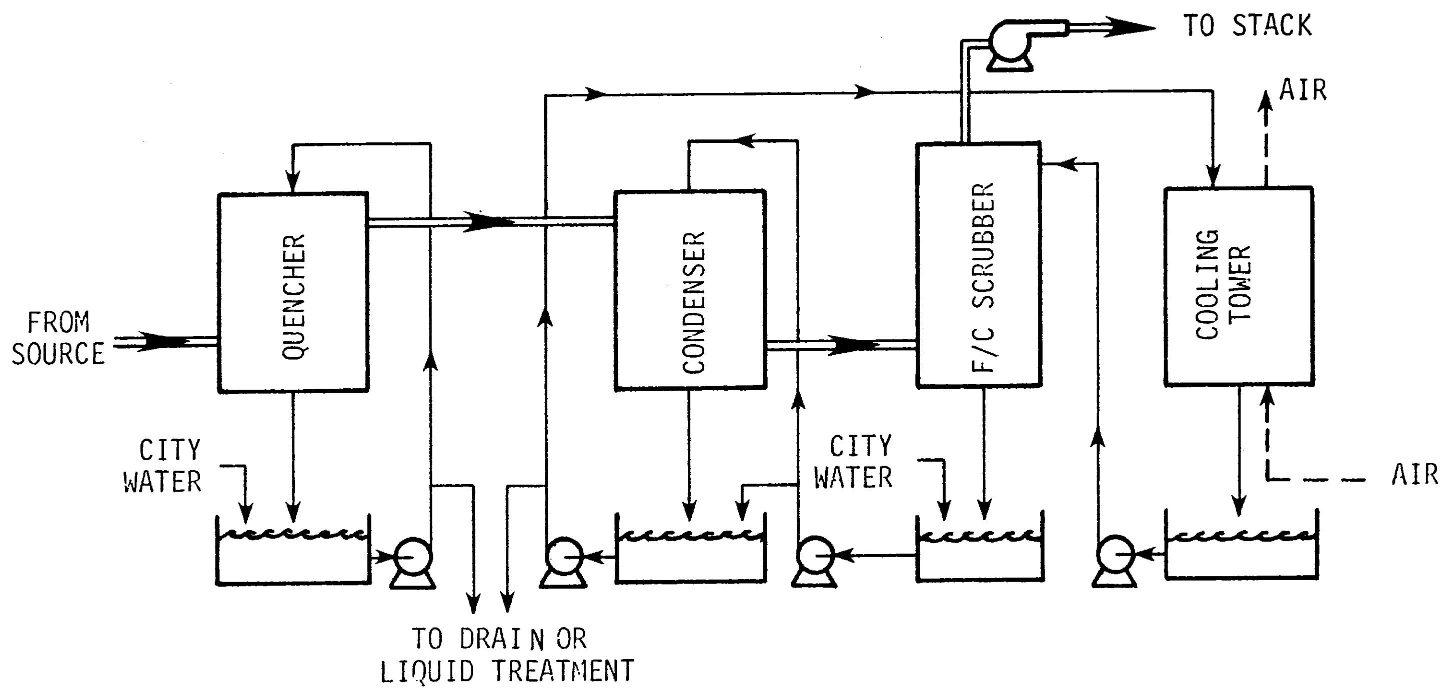


Figure 4.2.10-1. Generalized process design for F/C scrubber system.

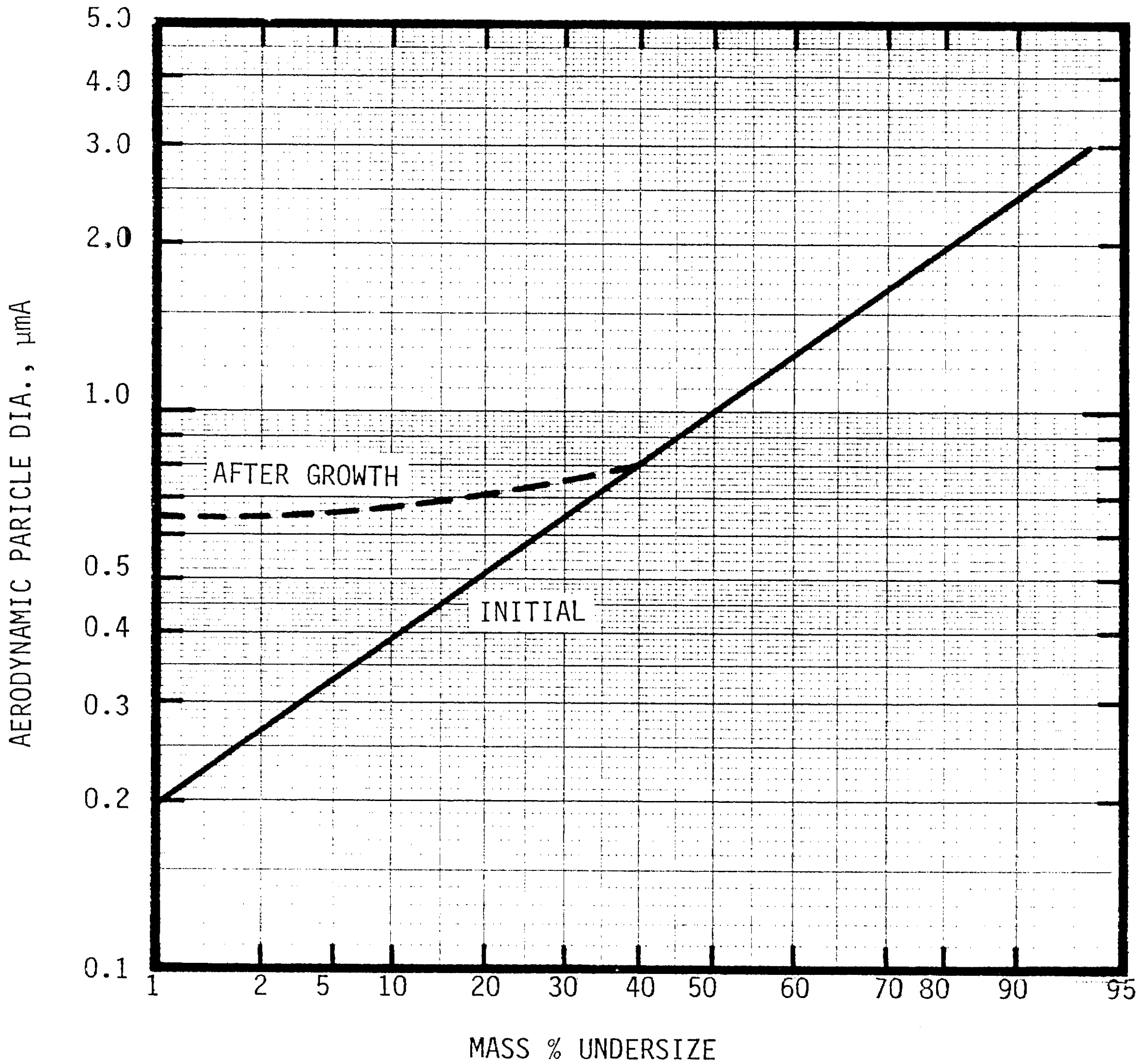


Figure 4.2.10-2. Particle growth resulting from water-vapor condensation reduces power demands.

TABLE 4.2.10-1. COST COMPARISON FOR A SECONDARY METAL RECOVERY FURNACE

Cost Item	Cost For F/C	Cost For Conventional
Scrubber	$ 1,700	$ 1,700
Cooling Tower	8,900	0
Condenser	4,040	4,040
Saturator	5,060	5,060
Blower & Motor*	3,790	14,450
Total Equipment	23,490	25,340
Total Capital Investment	$103,121	$111,242
Depreciation	$ 10,310	$ 11,125
Maintenance	6,185	6,675
Water	180	180
Raw Materials	1,650	1,650
Power*	2,370	11,530
	$ 20,695	$ 31,160

*Lower blower and motor and power costs for the F/C option results from a lower scrubber pressure drop requirement.

for which F/C scrubbing is attractive. It is clear that F/C scrubbing is a feasible and attractive particulate control method for several major industrial sources.

4.3 RECENT DEVELOPMENTS IN SCRUBBER TECHNOLOGY

For the past several years the EPA has conducted a program to develop and evaluate "novel devices" for fine particle scrubbing (Harmon and Sparks, 1978). The program has reached the point where there are not many more things to test, and in retrospect, very few new principles have been discovered. Though scrubber technology has been improved through the optimum combination of several fundamental collection mechanisms in several of the "novel devices".

More recently, EPA has focused on controlling fugitive particle emission sources, which represent a large fraction of the remaining uncontrolled sources. This work has lead to the development of additional new scrubber technology. The following sections cover the most promising control technologies using wet scrubbers.

4.3.1 Electrostatically Augmented Scrubbers

Electrostatically augmented scrubbers can be very efficient, depending on design and operating parameters. The variations available include: charged-dust/grounded-liquid scrubbers, charged-drop scrubbers, and charged-dust/charged-drop scrubbers.

Performance prediction methods are still in the elementary stages except for traditional electrostatic precipitator geometries. Some pilot plant data are available, however, electrostatic scrubbers have just started to receive industrial acceptance. Two of the operating problems which can be severe for certain designs are corrosion and voltage isolation. The following electrostatically augmented scrubbers have received the most attention.

4.3.1.1 Charged-Dust/Grounded-Liquid Scrubbers

4.3.1.1.1 Ionizing Wet Scrubber

The Ceilcote ionizing wet scrubber (IWS) consists of two sections: an ionizer or charger and a cross-flow scrubber (Ensor and Harmon, 1980). The ionizer consists of charging wires suspended between irrigated grounding plates. The scrubber contains irrigated packing as described in Section 4.2.2. The IWS is normally installed with two or more ionizing wet scrubber sections followed by a section of unirrigated packing for entrainment separation.

TABLE 4.2.10-2. MAJOR INDUSTRIAL PARTICULATE SOURCES FOR WHICH F/C SCRUBBING IS ATTRACTIVE

INDUSTRY	SOURCE
Iron & Steel	Sinter Plants Coke Manufacture Blast Furnaces Steel Furnaces Scarfing
Forest Products	Wigwam Burners Pulp Mills
Lime	Rotary Kilns Vertical Kilns
Primary Nonferrous Metals	
Aluminum	Calcining Reduction Cells
Copper	Roasting Reverberatory Furnaces Converters
Zinc	Roasting Sintering Distillation
Lead	Sintering Blast Furnaces Dross Reverberatory Furnaces
Asphalt	Paving Materials Roofing Materials
Ferroalloys	Blast Furnaces Electric Furnaces
Iron Foundry	Furnaces
Secondary Nonferrous Metals	
Copper	Material Preparation Smelting and Refining
Aluminum	Sweating Furnaces Refining Furnaces Chlorine Fluxing
Lead	Pot Furnaces Blast Furnaces Reverberatory Furnaces
Zinc	Sweating Furnaces Distillation Furnaces

4.3.1.1.2 Electrostatically Enhanced Venturi

The Scrub-E of Air Pollution Systems (APS) is basically an electrostatic charger (or ionizer) followed by a Venturi scrubber. Figure 4.3.1-1 shows a schematic diagram of the scrubber. An electrode is placed upstream of the Venturi to charge the inlet particles, which then enter the Venturi throat. The gas stream atomizes the water in the Venturi throat and the charged particles, according to APS, are then attracted and collected by the polarized water drops.

The charged particles are also collected on the walls of the ionizer section prior to the throat of the Venturi. A thin film of water is run down the inclined surfaces to keep the walls clear and prevent high voltage arcing. The water is separated from the gas stream in the downstream cyclone and is recycled or disposed.

A pilot scale Scrub-E was evaluated in the APS laboratory by lA.P.T. (Calvert et al., 1978) and a 566 Am^3/min (20,000 acfm) demonstration scrubber was installed on a magnesium recovery furnace (Kearns, 1979). The furnace produces submicron fume particles of MgO, $MgCl_2$ and $ZrCl_4$. The system was designed to demonstrate the effectiveness of the High Intensity Ionizer on a high pressure drop Venturi scrubber. The High Intensity Ionizer array operated stably at field strengths of 10-15 kV/cm and at velocities in excess of 18 m/s (60 fps). Unfortunately, the scrubber caught fire and was destroyed before obtaining any particle collection efficiency data.

4.3.1.2 Charged Drop Scrubbers

4.3.1.2.1 TRW Charged Droplet Scrubber

The TRW charged droplet scrubber (CDS) is a spray scrubber which uses charged water drops to collect uncharged particles in the presence of an external electric field (Lear, 1975, 1976). The imposed electric field is used both to form charged drops electrohydrodynamically and to move them through the scrubbing volume.

Figure 4.3.1-2 is a diagramatic sketch of the TRW/CDS showing its operating principle. The scrubbing liquor, generally fresh water, is raised from a ground potential to high voltage (about 40 kV) by flowing through a long electrical resistance path in the form of an insulating tubing. Electrical isolation must be achieved through the electrical resistance of the water.

The water is then introduced into a hollow electrode which contains a series of hollow, elongated spray tubes. Emerging at the tips of these spray tubes, the water sees a high electric field force. Drops are formed here by the joint action of electrical and surface tension forces in an electrohydrodynamic spraying process. The drops thus formed are highly charged, their surface field being near the local corona limit or Rayleigh stability limit. They move at high velocity through the scrub-

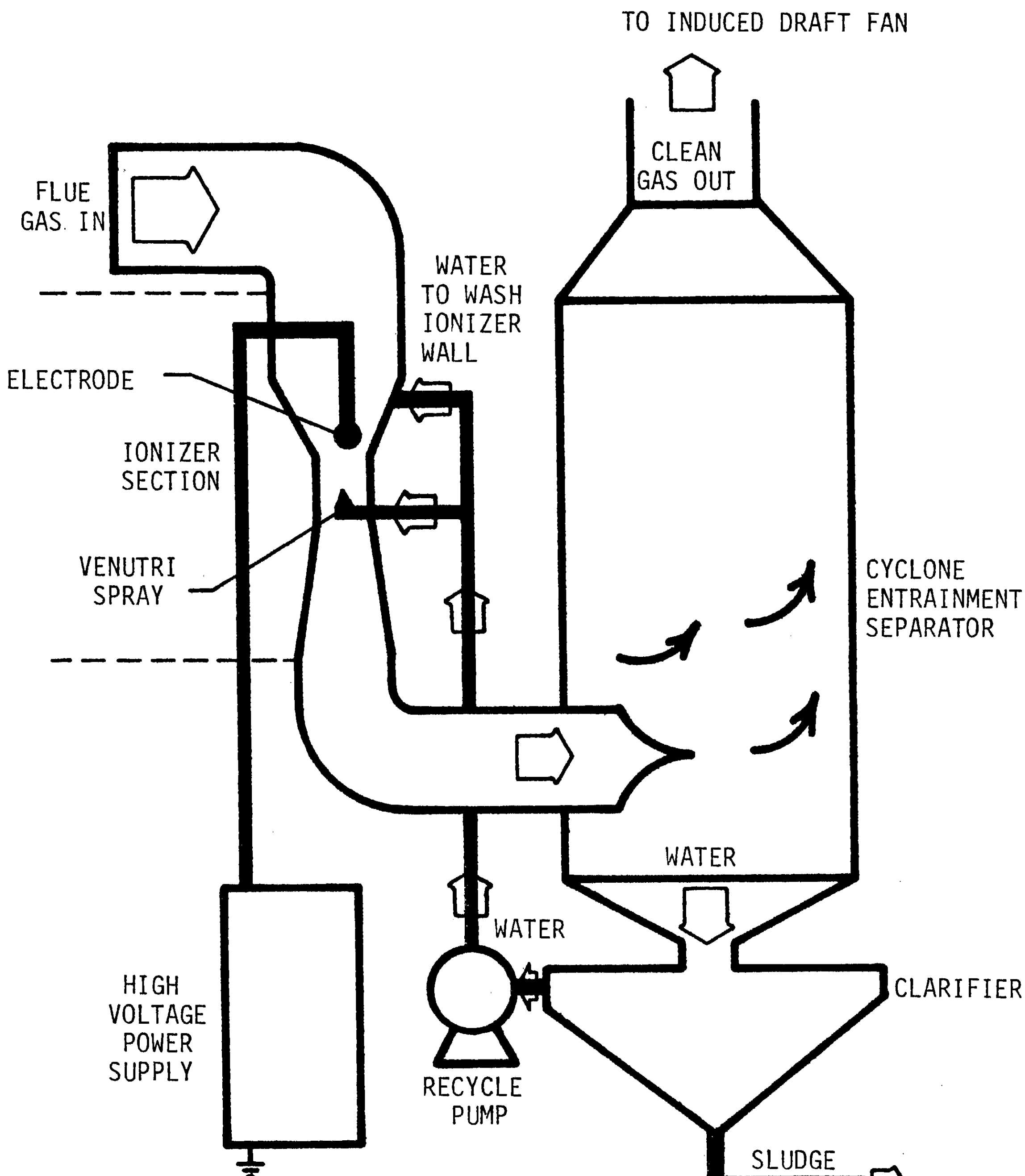


Figure 4.3.1-1. APS electrostatic scrubber.

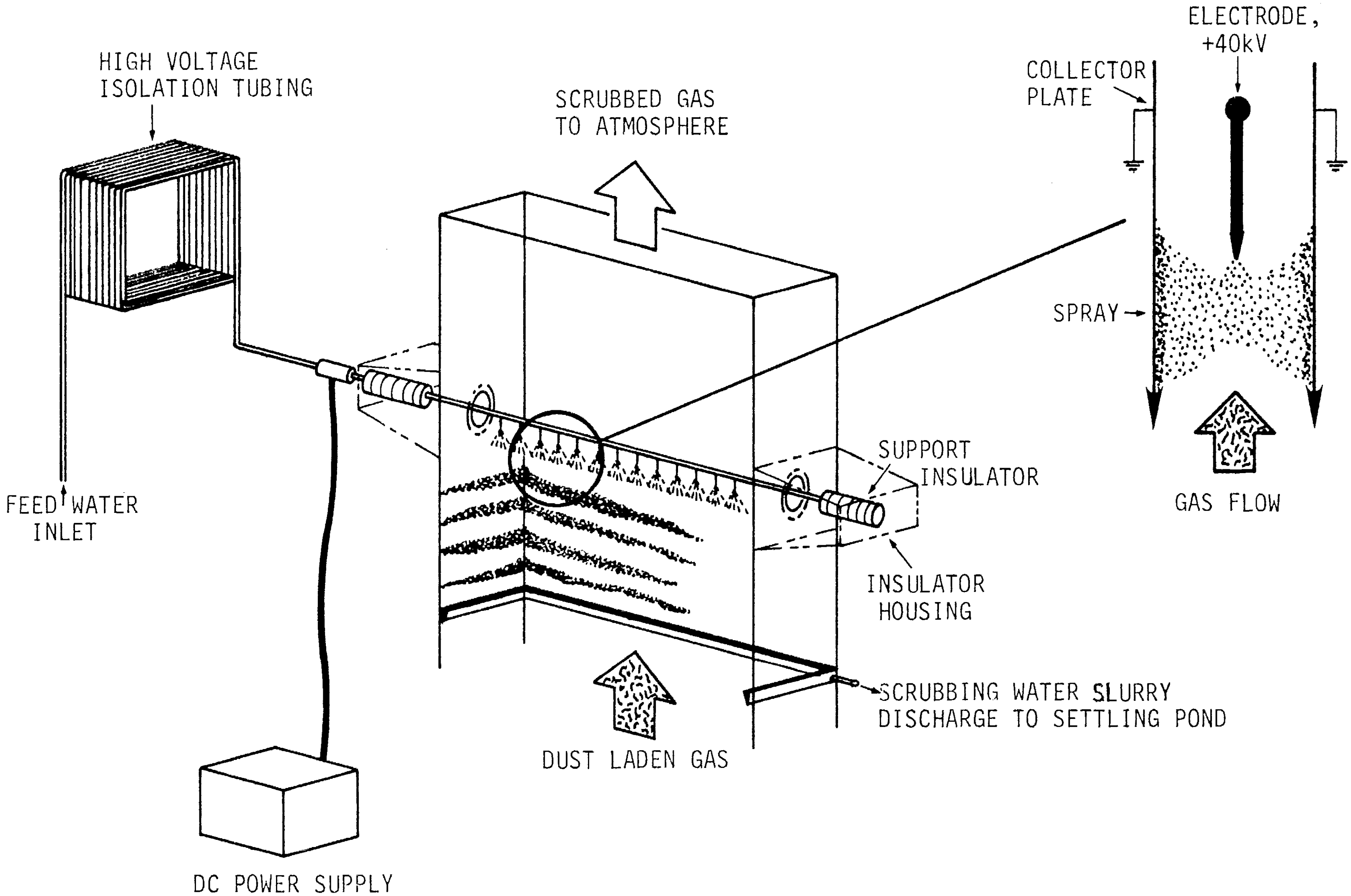


Figure 4.3.1-2. TRW systems charged droplet scrubber.

bing volume under the influence of the ambient electric field between the electrode and the collecting walls. Because of the high droplet velocities (around 30 m/sec) induced by the ambient electric field, there is a large relative motion between droplets and particules.

A pilot scrubber was installed in a steel plant to control the emission from a coke oven. This installation suffered from severe corrosion problems and has been the subject of a materials performance study (Bianchi and Rocales, 1979).

4.3.1.3 Charged-Dust/Charged-Spray Scrubbers

Charged-dust/charged-spray scrubbers offer the greatest potential of electrostatically augmented scrubbers for collection of submicron particles, because the electrostatic parameter is greatest for oppositely charged particles and spray drops.

4.3.1.3.1 Calvert Electrostatically Augmented Double Scrubber

Calvert Environmental Equipment Co. offers an electrostatically augmented option for their Double Scrubber shown in Figure 4.3.1-3. The Double Scrubber is a preformed spray scrubber whose unique compact design minimizes the amount of materials used for fabrication and the amount of space required for installation. A similar design, the Spray Charging and Trapping (SCAT) scrubber, has been developed by Air Pollution Technology, Inc. for fugitive particle emission control (Yung et al., 1981). The SCAT is described in Section 4.3.2.

The electrostatically augmented spray scrubber shown in Figure 4.3.1-4 uses charged water sprays for removing particles entrained in the gas stream. The particles entering the scrubber are charged negatively in a wire and plate corona charger. The drops are given a positive charge by induction. Induction charging of the drops can be accomplished by either holding the spray nozzles at ground potential or high voltage. A high voltage grid is placed in front of the spray nozzles when the nozzles are held at ground potential. Both induction charging methods have been shown to result in similar drop charge levels. The Double Scrubber uses the grounded nozzle system because it simplifies the electrical isolation.

Several stages of charged spray nozzles can be installed for additional collection of fine particles. The charged spray section is followed by a high efficiency entrainment separator.

4.3.1.3.2 University of Washington Electrostatic Spray Scrubber

The UW Electrostatic Scrubber uses electrostatically charged water droplets to collect oppositely charged particles (Pilat et al., 1974, 1975, 1976, 1977a, b, 1978a, b, c, d, 1979). A schematic illustration of the UW Electrostatic Scrubber system is shown in Figure 4.3.1-5.

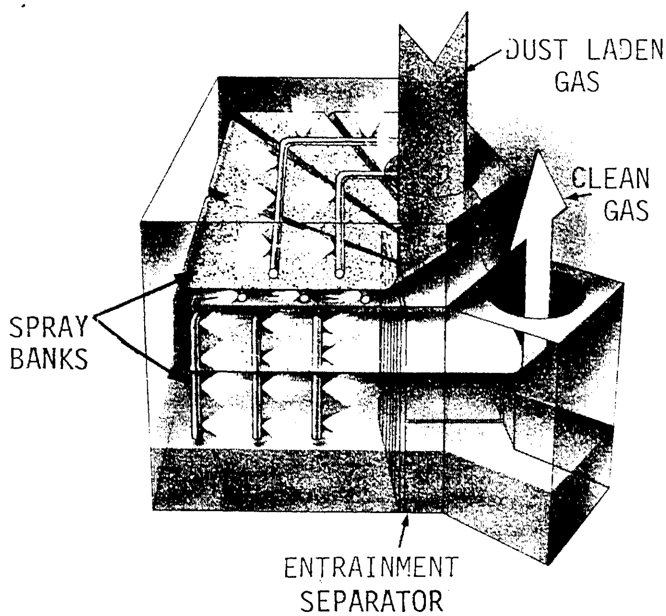


Figure 4.3.1-3. Calvert double scrubber.

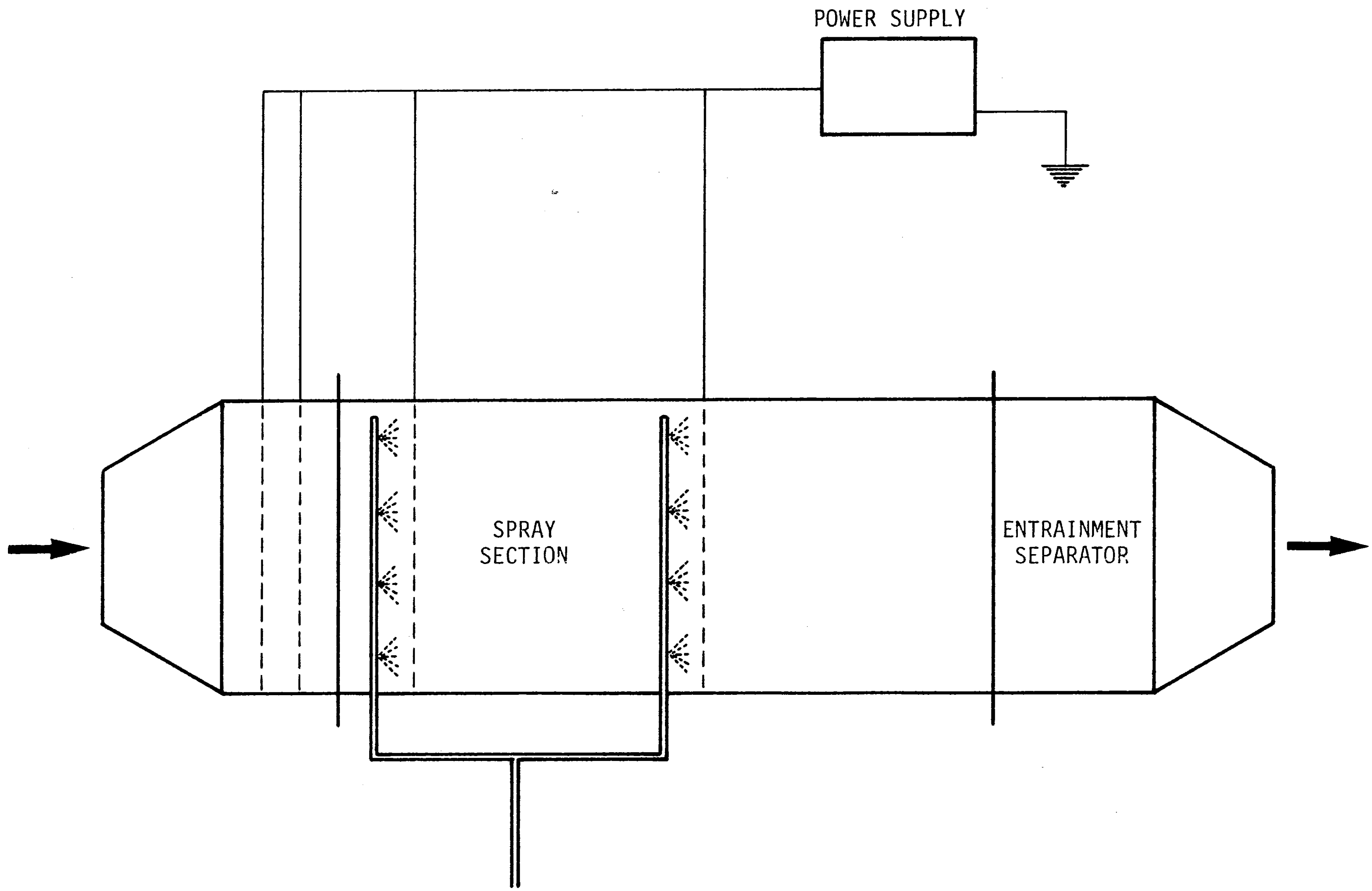


Figure 4.3.1-4. Schematic of Calvert electrostatically augmented scrubber.

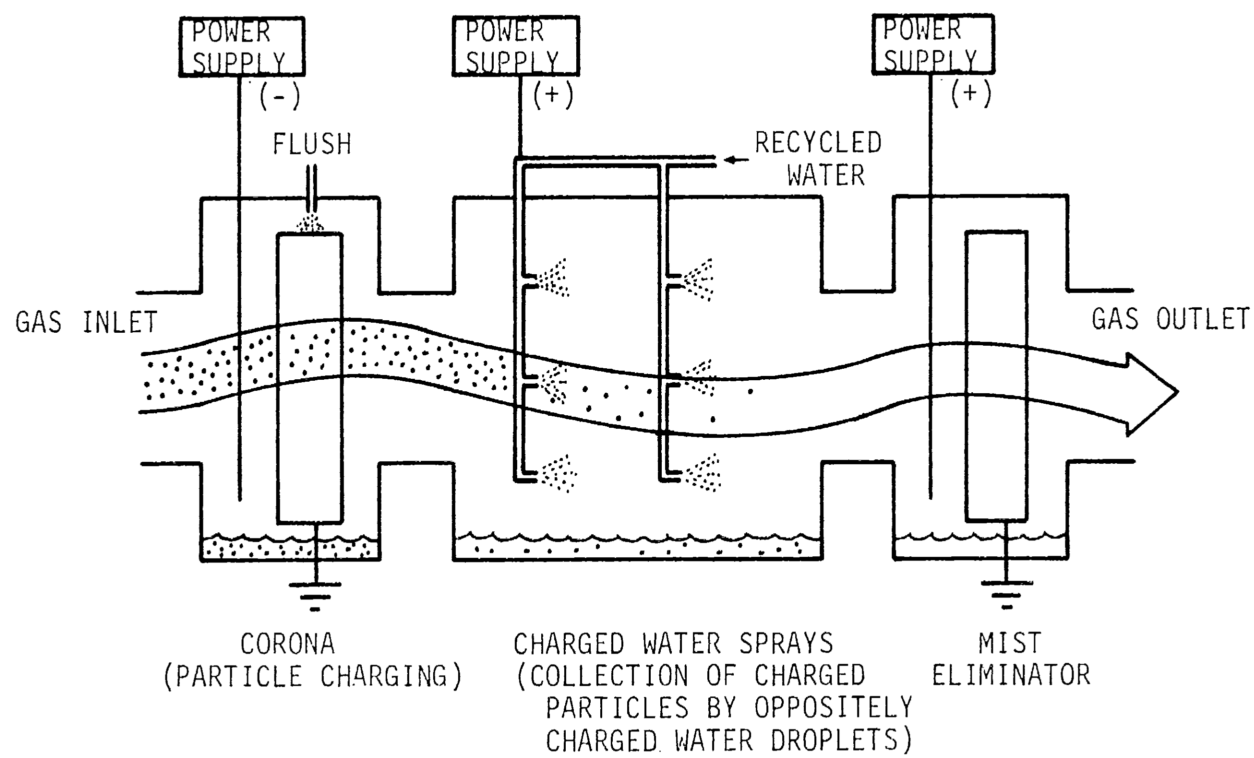


Figure 4.3.1-5. UW Electrostatic Scrubber.

The particles are electrostatically charged (negative polarity) in the corona section. From the corona section the gases and charged particles flow into a scrubber chamber into which electrostatically charged water drops (positive polarity) are sprayed. The water drops are induction charged by holding the spray nozzles at high voltage. This requires that the recycled scrubber water, pump and piping must be isolated from ground potential. The gases and some entrained water drops flow out of the spray chamber into a mist eliminator consisting of a positively charged corona section in which the positively charged water droplets are removed from the gaseous stream.

4.3.2 Spray, Charging and Trapping (SCAT) Scrubber for Fugitive Dust Control

The Spray, Charging and Trapping (SCAT) scrubber system is a unique fugitive emission control system developed by Air Pollution Technology, Inc. (Yung et al., 1981). It uses air curtains and push jets to contain, divert, and convey the fugitive emissions into a charged spray scrubber. It has many potential applications in the metallurgical and mineral industries including major sources such as coke ovens, blast furnaces, molding lines and stockpiles. Figure 4.3.2-1 shows an example of the SCAT system arrangement. The air curtain (and/or air jets) and the spray scrubber are arranged in a "push-pull" fashion with the fugitive particle emission source situated in between.

An air curtain involves the use of one or more high velocity air streams flowing as a sheet. The air sheets are produced by one or more air jets which issue from circular, or rectangular nozzles. The high velocity air streams will push and entrain the fugitive particles plus some additional air and will carry them away from the source. At some convenient distant downstream, charged water is sprayed concurrently into the gas stream to remove the entrained dust. After sufficient contacting distance to effect capture of the particles present in the gas, water spray drops are removed with a low pressure drop entrainment separator. Either a parallel plate or a zigzag baffle type entrainment separator may be used, depending on mist elimination and pressure drop requirements.

The water from the entrainment separator can be passed through a separation process, such as a filter, to remove the collected particles. The water may then be recycled and the particles may be disposed of in such a way as to prevent their redispersion. As an alternative, a blow-down stream of dirty liquid may be directed to a disposal system.

The SCAT system has the following features which suit it to fugitive process emission control:

1. Minimum use of solid boundaries enabling access to the source.
2. Air curtain and/or air push jets to contain, divert, and convey the fugitive partives. Minimum use of duct work or hooding.

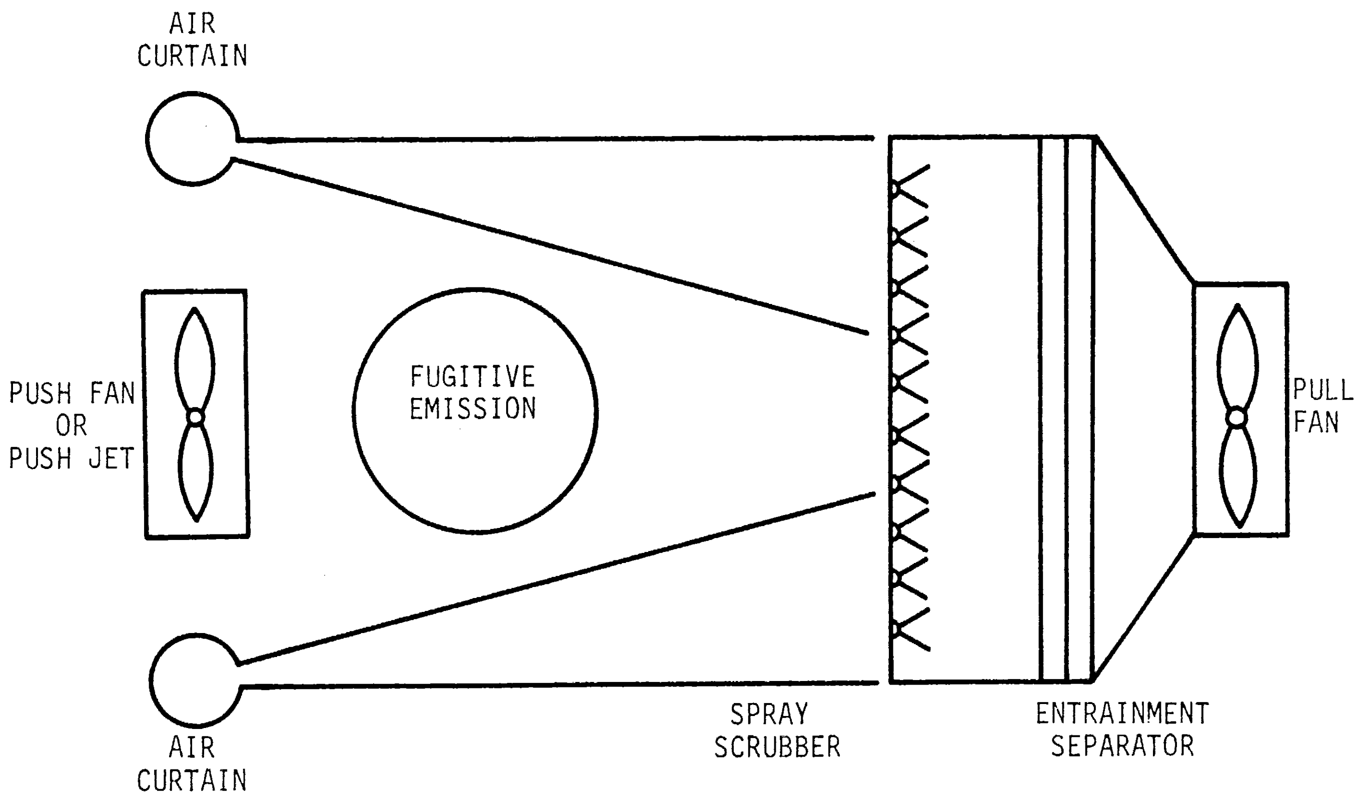


Figure 4.3.2-1. Example of SCAT system arrangement (top view).

3. Can deflect crosswind.
4. Can contain hot buoyant plume.
5. Unobstrusive.
6. Portable.
7. Traps particles and removes rather than depositing them at the source site.

4.3.3 Calvert Collision Scrubber

The Calvert Collision scrubber is a patented device sold by the Calvert Environmental Equipment Company. It uses the capability of a conventional Venturi scrubber throat and then takes another major step in collecting particles and absorbing gas. First the gas flows through a pair of primary scrubber throats into which water is injected and which give the same performance as a Venturi scrubber operating at the same "u_G" and "Q_L/Q_G".

After the Venturi throats have done all they can (because the relative velocity is depleted) the two streams are directed at each other so they collide head-on, as shown in Figure 4.3.3-1. Now the relative velocity between drops and the opposing gas stream increase to about twice the maximum value it had in the throat. The relative large drops formed in the throats are no longer stable so they undergo a secondary atomization and shatter into much smaller drops.

Particle collection efficiency increases abruptly as the gas flows thation and shatter
into much smaller drops.

Particle collection efficiency increases abruptly as the gas flows through the collision zone and contacts very small drops at very high relative velocity. Gas absorption is also enhanced by the large amount of newly created liquid surface (which causes a large liquid phase mass transfer coefficient) and the high relative velocity (which causes a large gas coefficient). After flowing through the second throat and a diffuser section, the clean gas goes into an entrainmenrt separator prior to discharge.

4.3.4 Lone Star Steel Hydrosonic Scrubber

Lone Star Steel Hydro-Sonic air cleaners are powered by either: (1) an I.D. or F.D. fan drive, (2) a compressible fluid ejector drive, or (3) combinations of both (Ewan and Master 1980; Mitchel, 1980). The pumping energy consumption ranges from 0.23 $kW/Am^3/min$ to 4.6 $kW/Am^3/min$ of off-gas, depending on the pumping and cleaning requirements of the process.

The "Steam-Hydro" as shown in Figure 4.3.4-1 uses a steam ejector to pull the process gas through the cleaner. Water is sprayed around the steam jet, resulting in violent shattering of the water and ejection of high-velocity drops through the polluted gas. The system can also be operated with a compressed air ejector with no loss in performance.

The "Fan Coalescer" shown in Figure 4.3.4-2 is subsonic

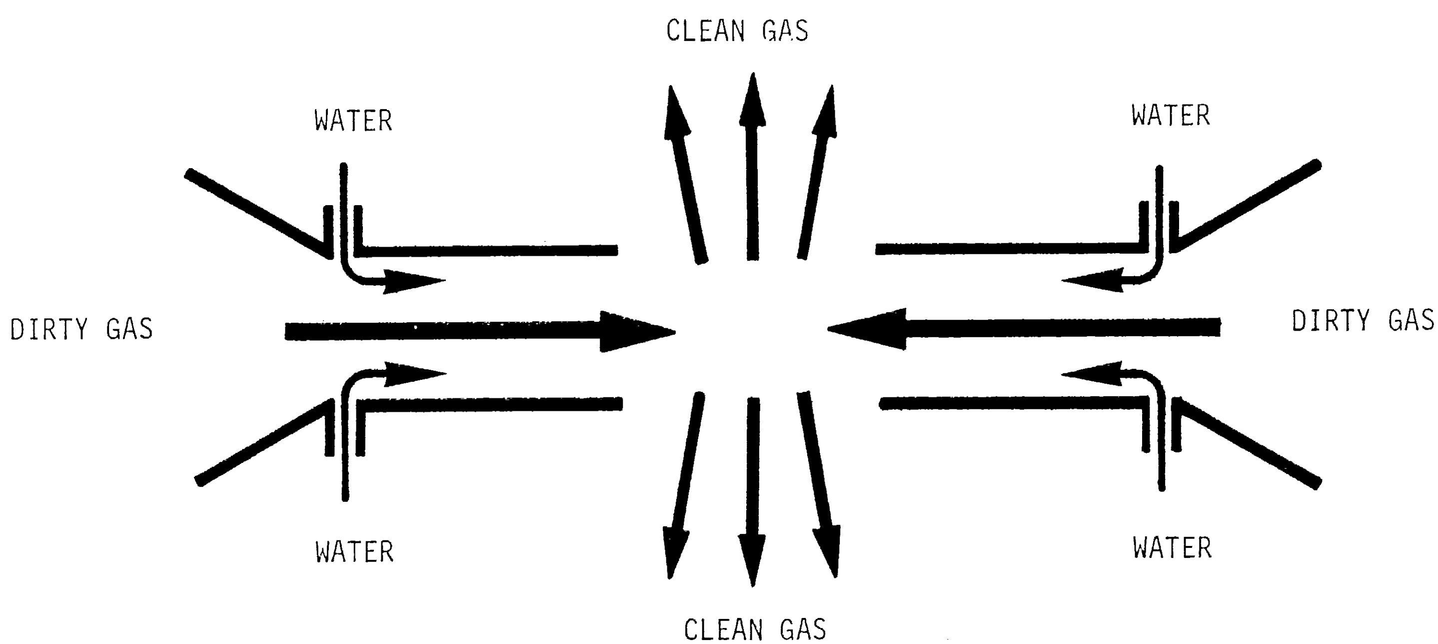


Figure 4.3.3-1. Calvert Collision Scrubber

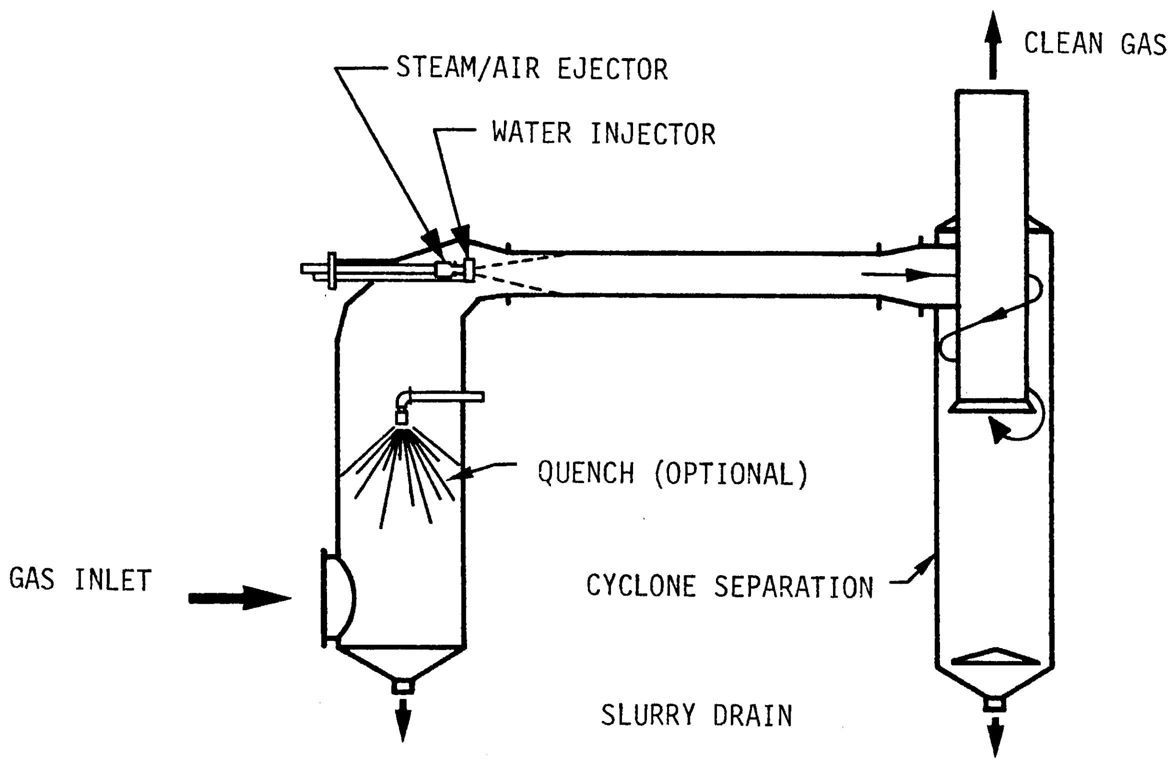


Figure 4.3.4-1. Hydro-sonic steam-hydro scrubber with ejector drive.

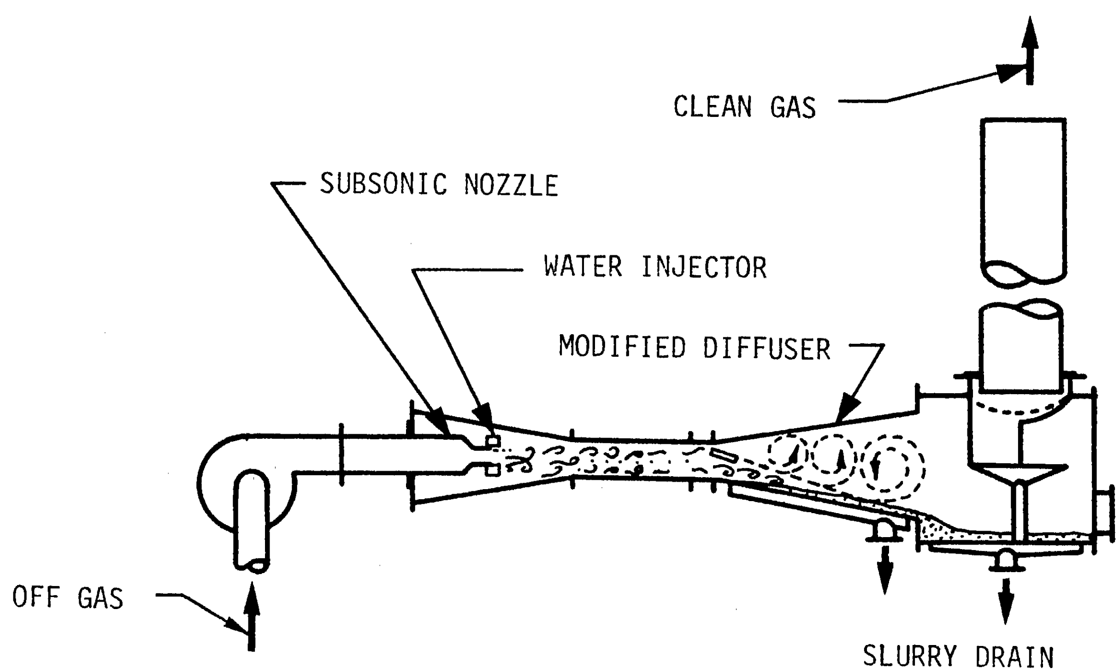


Figure 4.3.4-2. Hydro-sonic fan coalescer.

free-jet design which uses a fan to pump the gas through a nozzle where it flows out in a diverging cone as shown. The inner cone retains its velocity and serves as the energy source for atomizaion and pollutant capture. The contacting is reported to take place in the turbulent mixing zone, although some water may penetrate into the core.

4.4 ENTRAINMENT SEPARATION

Mist eliminators or entrainment separators are required to prevent undesirable emissions of liquid drops from the scrubber (Calvert, 1977b).

An unfortunate consequence of thorough and vigorous liquid-gas contacting in the scrubber is that some liquid is atomized and carried out of the scrubber by the gas that has been cleaned. The liquid entrainment, or mist as it is commonly referred to, will generally contain both suspended and dissolved solids.

In many cases, excessive entrainment imposes a limitation upon scrubber capacity. That is, while the scrubber itself might be capable of handling a larger gas flow rate, the rate at which entrainment becomes excessive will dictate a limit on capacity.

4.4.1 Separation Principles

Drops entrained from the scrubber contacting zone may be separated from the gas by the same mechanisms described earlier for particles. Since drops are usually larger than particles, dominant collection mechanisms are gravitional sedimentation, centrifugal deposition, and inertial impaction.

4.4.2 Equipment Types

Apparatus used for entrainment separation can be grouped into categories according to the mechanism of operation:

1. Gravitation sedimentation. Within the scrubber and its outlet ducting, sedimentation is always active and important. However, discrete entrainment separators using sedimentation rarely follow a scrubber.
2. Centrifugal deposition. Cyclone separators of various designs are commonplace. Radial baffles and other types of guide vanes can be installed to induce a rotary motion of the gas stream within the scrubber shell. Zigzag-baffles, chevrons, corrugated sheets and similar devices force one or more abrupt changes in the gas flow direction. Drops deposit on the baffles, and the collected liquid film either runs down the baffles (if the major axis is vertical) or drips off as large drops (if the axis is horizontal). A directional change in the gas duct can likewise cause considerable deposition of large drops.
3. Inertial impaction. Beds of massive packing--such as saddles, rings and other elements--are used in either

vertical or horizontal gas-flow configurations. Fibrous packings can also be used in beds comparable to massive-packed systems. Knitted-wire mesh, screens, and glass fiber have been used for this purpose. Other impaction devices employ banks of round tubes, stream-lined struts, and other shapes in vertical and horizontal orientations. Trays (perforated, valve, impingement and others) have been used for special purposes. Because these are scrubbing devices, they generate entrainment; their use after another type of scrubber may be redundant and should be carefully assessed.

4.4.3 Primary Efficiency

Primary collection is defined as fractional collection of the drops present in the original entrainment by various mechanisms and is reported in terms of mass fraction as an efficiency. Primary efficiency includes only the collection of drops present in the original entrainment. The reentrainment of these collected drops or the subsequent collection of these reentrained drops does not affect the primary collection efficiency even though it affects the net entrainment collection efficiency.

Methods for predicting primary collection efficiency for various types of separators were reported by Calvert et al. (1974, 1975, 1977c, 1979). A concise representation of the primary efficiencies of several types of separators can be shown using the same cut/power relationship used for characterizing particle collection efficiencies in the scrubber itself. This relationship is given by a plot of the drop diameter collected at 50% efficiency (i.e., the cut diameter) against the gas-phase pressure drop, or power input for the separator (Figure 4.4.3-1).

Plots shown in Figure 4.4.3-1 are based on design equations and experimental correlations. Curves are given for baffles at two angles of attack to the flow direction, tube banks with two different spacings between tubes within a row, packing of one particular size, and knitted mesh with a certain wire diameter.

4.4.4 Reentrainment

The overall collection efficiency of an entrainment separator is equal to the mass ratio of net liquid collected in the entrainment separator to the liquid present in the inlet. It can also be expressed as the the difference between the primary collection and reentrainment. Reentrainment is the drops generated and entered the gas in the entrainment separator.

Reentrainment from an entrainment separator may take place by any one or more of the the following mechanisms:

1. Shattering of liquid drops upon impaction.
2. Creeping of liquid along the solid surface and movement into the gas exit in the entrainment separator.
3. Rupture of bubbles at the gas-liquid interface and subsequent drop formation.

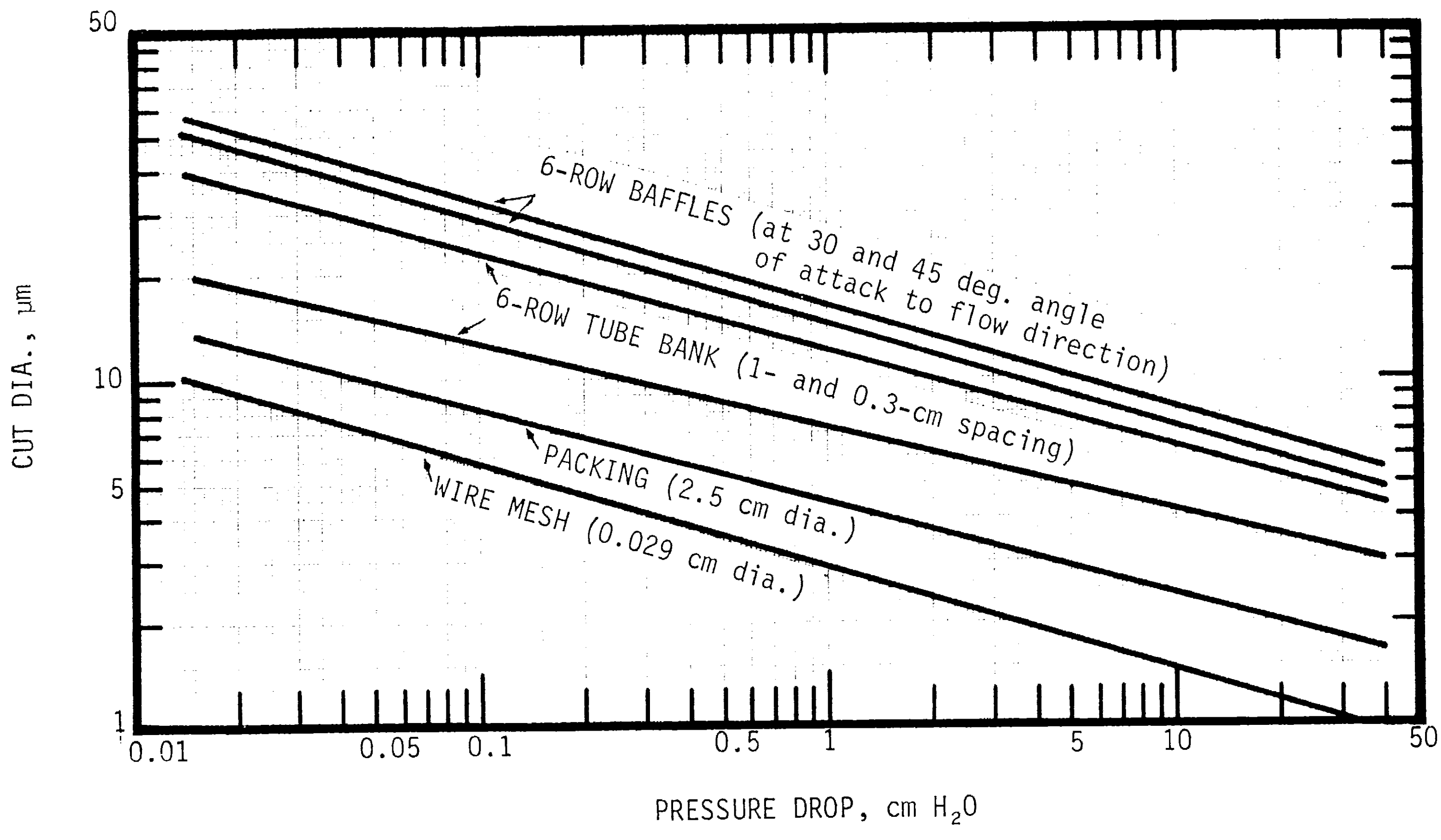


Figure 4.4.3-1. Cut/power plot for entrainment separators.

4. Transition from separated flow to entrained flow caused by high gas velocity.

The first three mechanisms of reentrainment depend upon the design of entrainment separators. The last mechanism represents the upper limit of the operation of entrainment separators.

The rate of reentrainment depends on separator geometry, gas velocity, liquid flow rate, and separator orientation. Increasing the gas or liquid flow rate will incrase the rate of reentrainment. Liquid drainage is best when gas flow is horizontal and collection surface are near-vertical; also, with this configuration, reentrainment occurs at higher flow rates than for horizontal elements.

Some approximate values of gas velocity (based on an empty cross-section) at the onset of entrainment are given here to illustrate the range possible for well-designed equipment at moderate liquid loadings (Calvert et al., 1975):

Separator	Gas Velocity m/s
Zigzag with upward gas flow and horizontal baffles	3.7-4.6
Zigzag with horizontal gas flow and vertical baffles	4.6-6.1
Cyclone (inlet gas velocity)	30-40
Knitted mesh with vertical gas flow	3.0-4.6
Knitted mesh with horizontal gas flow	4.6-7.0
Tube bank with vertical gas flow	3.7-4.9
Tube bank with horizontal gas flow	5.5-7.0

4.4.5 Solids Deposition

Industrial experience with entrainment separator fouling and plugging, and experimentation on suspended solids deposition, have yielded quantitative guidelines for design. Vertical collection surfaces stay cleaner than horizontal ones, due to better liquid drainage. Intermittent washing with sprays is beneficial, but the details of the washing system and procedure depend on the specific case. Precipitation scaling must be controlled through the system's chemistry.

4.5 SCRUBBER PERFORMANCE PREDICTIONS

The basic approach for predicting scrubber collection efficiency is to consider the collection efficiency of individual unit mechanisms, such as collection by single drops, and derive a relationship for the overall collection efficiency based on the unit mechanisms (Yung and Calvert, 1978). A unit mechanism is the basic particle collection element which accounts for the scrubber particle collection. For example, in a Venturi scrubber, particle collection is achieved by contacting the particles with the atomized liquid drops. Thus, collection by drops is a unit mechanism. Other unit mechanisms for particle collection include collection by cylinders, sheets, bubbles, and jet impingement.

For each unit mechanism, the particles are separated from the gas by one or more of the following particle collection mechanisms: gravitational sedimentation, centrifugal deposition, inertial impaction, interception, Brownian diffusion, thermophoresis, diffusiophoresis, and electrostatic precipitation. Particle collection also may be enhanced by increasing the particle size through agglomeration, condensation, or other particle growth mechanisms.

The general design equation which describes particle collection by any control device in which the gas and dust are well mixed is:

$$-\frac{dc}{c} = \frac{u_r}{Q_G} \eta \, dA_c \qquad (4.5\text{-}1)$$

where
A_c = particle collection area, cm^2
c = particle concentration, g/cm^3
Q_G = volumetric gas flow rate, cm^3/s
u_r = relative velocity between gas and collector, cm/s
η = overall collection efficiency of a unit mechanism, dimensionless

Relationships between particle collection performance and design parameters may be predicted from equation 4.5-1 with the appropriate "η" for the unit mechanisms involved, or measured by experiment, or both. A specific performance relationship between collection efficiency and particle size (often called a "grade-efficiency curve") can be integrated over the particle size distribution to yield the overall collection efficiency. Alternatively, a generalized and somewhat idealized method, which is described below, can be used for rapid prediction of scrubber performance.

4.5.1 Cut Diameter Method

The "cut diameter" method for scrubber performance prediction (Calvert et al., 1972) is based on the idea that the most significant single parameter to define both the difficulty of separating particles from gas and the performance of a scrubber is the particle diameter for which collection efficiency is 50%. This diameter is referred to as the cut diameter.

When a range of sizes is involved, the overall collection efficiency of a control device will depend on the amount of each size present and on the efficiency of collection for that size. In mathematical expression, the overall (integrated) penetration, $\overline{Pt}$, of any device on a dust of any type of size distribution is:

$$\overline{Pt} = \int_0^w \frac{Pt_d}{w}\, dw \qquad (4.5.1\text{-}1)$$

where $\overline{Pt}$ = overall penetration, fraction

Pt_d = penetration for particles with diameter "d_{pa}", fraction

w = total dust loading, g

The right-hand side of the above equation is the integral of the product of each weight fraction of dust times the penetration of that fraction.

Penetration for many types of inertial collection equipment can be expressed as:

$$Pt_d = \exp(-A_e d_{pa}{}^{B_e}) = 1-E \qquad (4.5.1\text{-}2)$$

where A_e = constant

B_e = constant

E = efficiency, fraction

In some cases, one is concerned with particles larger than 1 micron diameter or where the particle size distribution is log-normal in terms of physical rather than aerodynamic diameter, it may be convenient to use the simplifying assumption that penetration is related to physical diameter by:

$$Pt_d = \exp(-A_p d_p{}^{B_e}) \qquad (4.5.1\text{-}3)$$

where A_p = constant

Packed towers, centrifugal scrubbers, and sieve plate columns follow the first relationship. For the packed tower and sieve plate column, "B_e" has a value of 2. For centrifugal scrubbers, "B_e" is about 0.67. Venturi scrubbers also follow the above relationship and "B_e" is approximately equal to 2 when the throat impaction parameter is between 1 and 10.

Calvert (1974) solved equations 4.5.1-1 and 4.5.1-2 for a variety of log-normal size distributions and presented the results in graphical forms in Figures 4.5.1-1 and 4.5.1-2. Figure

4.5.1-1 is a plot of "$\overline{Pt}$" vs "$(d_{pc}/d_{pg})^{B_e}$" with "$B_e \ln(\sigma_g)$" as a parameter. Figure 4.5.1-2 is presented as a plot of "$\overline{Pt}$" vs. "(d_{pc}/d_{pg})" with "σ_g" as the parameter when $B_e = 2$.

To illustrate the use of these graphs, assume the scrubber cut diameter determined from the cut/power plot (see Section 4.5.6) is 0.63 μmA and the particles from an emission source have a size distribution of $d_{pg} = 10$ μmA and $\sigma_g = 3.0$. Then, $d_{pc}/d_{pg} = 0.063$. From Figure 4.5.1-2, the overall penetration corresponding to $d_{pc}/d_{pg} = 0.063$ and $\sigma_g = 3.0$ is 0.01. Since penetration is 100% minus the percent efficiency, the overall collection efficiency of the control device is 99%.

4.5.2 Scrubber Performance for Inertial Collection

The efficiency estimated by the cut diameter method is only an approximation because the inlet particle size distribution might not follow the log-normal distribution closely and equation 4.5.1-2 is correct only for packed beds and similar devices and is an approximation for others. To accurately predict the scrubber overall collection efficiency, one should perform the integration in equation 4.5.1-1 with the actual size distribution and the grade penetration for the scrubber. In the following sections, design equations for predicting the grade penetration will be presented for several scrubber types.

Along with particle collection efficiency, the scrubber power requirement is also an important consideration in designing the optimum pollution control system. The power requirment for particle scrubbing is mainly a function of the gas pressure drop. Preformed sprays and mechanically aided scrubbers have significant power inputs to pumps and other devices. Equations for predicting the gas phase pressure drop for various types of scrubber are also presented in the following sections.

4.5.2.1 Plate Columns

Particle separation in sieve (perforated) and impingement plates can be defined mathematically by starting from the basic mechanisms of particle collection in bubbles, on drops, and jet impaction.

Experimental data on the collection of hydrophilic particles by water on sieve plates (Taheri and Calvert, 1968) are correlated by:

$$Pt_d = \exp(-40\ FK_p) \qquad (4.5.2\text{-}1)$$

$$K_p = u_h d_{pa}^2 / 9 \mu_G d_h \qquad (4.5.2\text{-}2)$$

where K_p = inertial impaction parameter, dimensionless

F = foam density, g/cm³

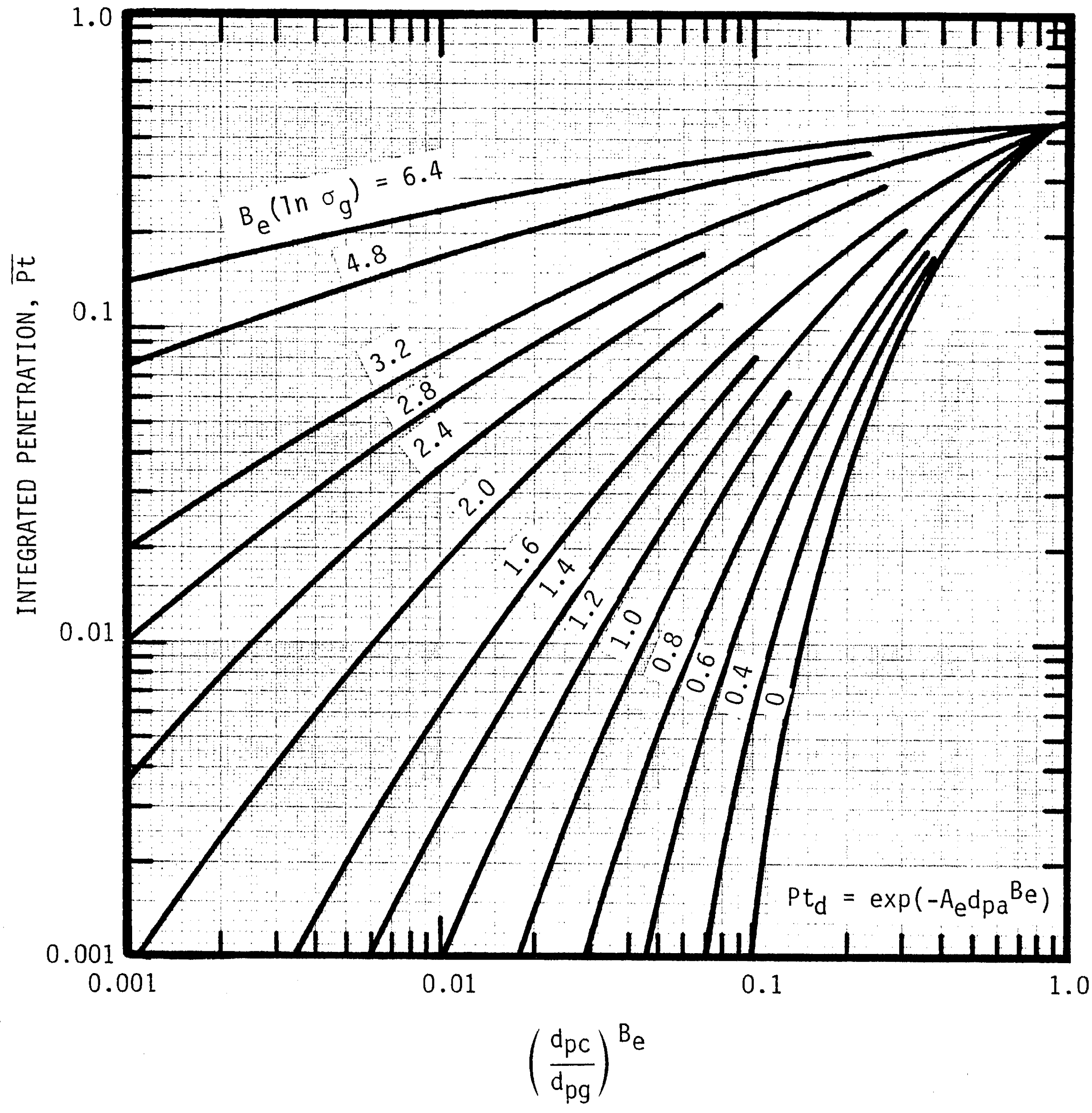


Figure 4.5.1-1. Integral (overall) penetration as a function of cut diameter, particle parameters, and collector characteristics.

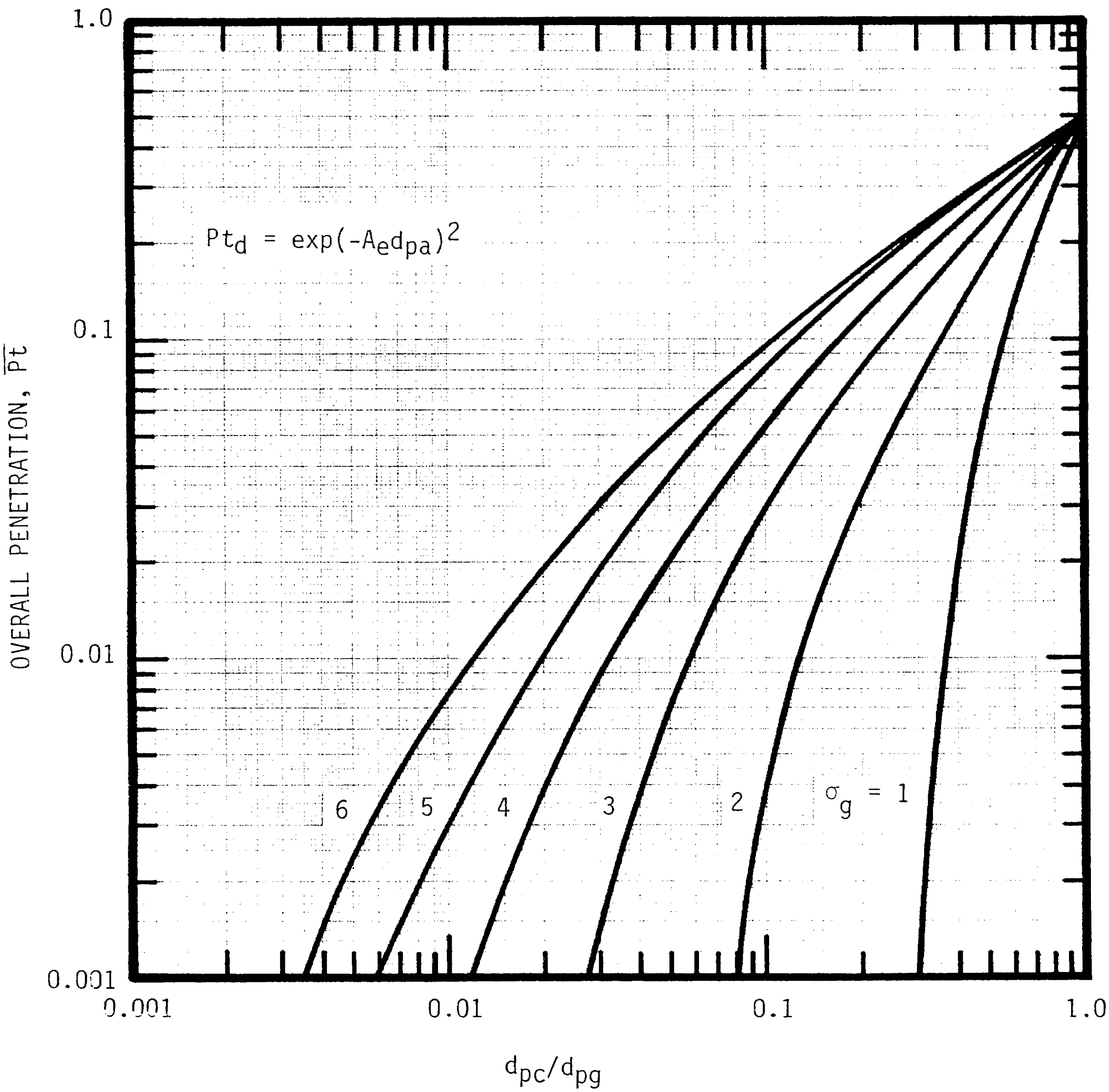


Figure 4.5.1-2. Overall penetration as a function of a cut diameter and particle parameters for common scrubber characteristics.

u_h = gas velocity through sieve plate hole, cm/s
μ_G = gas viscosity, g/cm-s
d_h = diameter of sieve plate hole, cm

By setting Pt_d = 0.5 in Equation 4.5.2-1, the following relationship for cut diameter in a sieve plate is obtained:

$$d_{pc} = 0.4(\mu_G d_h / u_h F)^{\frac{1}{2}} \qquad (4.5.2\text{-}3)$$

Pressure drop in a sieve plate column under usual operating conditions runs about 2.5 to 10 cm W.C. per plate. Section 5.2.2, Perry's Handbook (1963) gives the necessary equations and correlations to calculate the pressure drop in a sieve plate column.

For impingement plates there are no reliable experimental data available so the efficiency is predicted based on the impingement of round jets on plane surfaces. The cut diameter is given by:

$$d_{pc} = \left(\frac{1.37 \mu_G \, n_h \, d_h^3}{Q_G} \right)^{\frac{1}{2}} \qquad (4.5.2\text{-}4)$$

where d_{pc} = aerodynamic diameter of particle collected with 50% efficiency, μmA
n_h = number of holes
Q_G = gas volumetric flow rate, m³/s

The total pressure drop per plate can be divided into three main components: dry plate pressure drop, wet plate pressure drop, and frictional losses in the scrubber. The wet plate pressure drop can be estimated from liquid depth above the plate. Frictional losses must be evaluated from experimental work.

The dry plate pressure drop, which is mainly due to jet exit, can be approximated by the following equation.

$$\Delta p_j = 588 \; (d_h^2 \; / \; d_{pc}^2)^2 \qquad (4.5.2\text{-}5)$$

where Δp_j = dry plate pressure drop, cm W.C.

4.5.2.2 Packings

Particle collection in packed columns (Jackson and Calvert, 1966) can be described in terms of gas flow through curved passages, and performance for a variety of packing shapes, such as saddles, rings, and spheres, can be correlated simply by the packing diameter, as shown in Equation 4.5.2-6:

$$Pt_d = \exp(-7.0 \; ZK_p/\varepsilon d_c) \qquad (4.5.2\text{-}6)$$

where Z = height of packing, cm

K_p = inertial impaction parameter, dimensionless

ε = void volume, fraction

d_c = nominal packing diameter, cm

where "K_p" is defined as in Equation 4.5.2-2, but with gas velocity equal to the superficial velocity through the total bed area, v_G, and collector dimension, d_c, taken as the packing diameter. Aerodynamic cut diameter is given by:

$$d_{pc} = \left(\frac{\varepsilon \; d_c{}^2 \; \mu_G}{v_G Z} \right)^{\frac{1}{2}} \qquad (4.5.2\text{-}7)$$

where v_G = superficial gas velocity through bed, cm/s

The pressure drop in a packed column can be predicted from Eckert's (1961) generalized correlation or from methods by Sherwood and Pigford (1952), Treybal (1980), Noeman(1961), and Morton et al. (1964).

The pressure drop in a packed column as usually operated is small. The pressure drop at flooding is in the range 12 to 35 cm W.C. per meter of packing height (1.5 to 4 in. W.C./ft) for most packings, with 15 cm W.C./m (2 in. W.C./ft) being an average value for crude estimation purposes.

A substantial amount of pressure drop data is available in packing manufacturers' literature. These data can be useful if the operating conditions of the scrubber are exactly identical to a situation for which there are data.

4.5.2.3 Preformed Spray

4.5.2.3.1 Vertical Countercurrent Flow--Inertial Impaction

Starting from a material balance over a small section of the tower, one gets after integration,

$$Pt_d = \exp\left(- \frac{3 \; Q_L \; u_t \; Z\eta}{4 \; Q_G \; r_d \; (u_t - u_G)} \right) = \exp\left(- \; 0.25 \left(\frac{A_d \; u_t \; \eta}{Q_G} \right) \right) \qquad (4.5.2\text{-}8)$$

where $A_d = [3 \; Q_L \; Z/r_d \; (u_t - u_G)]$ = total surface area of all drops in the scrubber, assuming no liquid reaches the scrubber wall

Q_L = liquid volumetric flow rate, m^3/s

u_G = gas velocity relative to the duct, cm/s

u_t = drop terminal settling velocity, cm/s

η = collection efficiency of a single drop, fraction

r_d = drop radius, cm

Single drop collection efficiency is obtained from Figure 4.5.2-1. Target efficiency is greatly influenced by the drop Reynolds number and is calculated from an interpolation between the target efficiencies for viscous and potential flows around the drop. Actually, only a small fraction of the drops remain in suspension, and as little as 20% of "Q_L" may be effective, depending on scrubber size.

The pressure drop through a spray scrubber is very low. Mehta and Sharma (1970) found pressure drops of 1 to 2 cm W.C./m of column height (0.4 to 0.8 in.W.C./ft of column) for gas velocities of 500 to 1,600 m/hr (0.5 to 1.5 ft/s), with the liquid flow rate having negligible effect for L = 20,000 to 80,000 kg/hr-m² (4,100 to 16,000 lb/hr-ft²).

For vertical countercurrent flow, the gas pressure drop has to be sufficient to support the weight of liquid holdup, overcome frictional loss against the walls, and absorb any excess momentum imparted to the drops by spray nozzles. If the latter two components are neglected, the pressure drop for countercurrent scrubbing is given by:

$$\Delta p = \frac{Q_L \rho_L Z}{(u_t - u_G) A} \qquad (4.5.2\text{-}9)$$

where Δp = pressure drop, cm W.C.

u_t = drop terminal velocity, cm/s

u_G = upward gas velocity, cm/s

A = tower cross-sectional area, cm²

Z = column height, cm

ρ_L = liquid density, g/cm³

4.5.2.3.2 Cross Flow--Inertial Impaction

In the cross-flow case, the water is sprayed at the top of the spray chamber while the gas flows horizontally. For collection by inertial impaction in a spray chamber, equation 4.5.2-10 predicts the penetration:

$$Pt_d = \exp -\left(\frac{3\, Q_L\, Z\, \eta}{4\, Q_G\, r_d}\right) = \exp\left(-\ 0.25\ \frac{A_d\, u_r\, \eta}{Q_G}\right) \qquad (4.5.2\text{-}10)$$

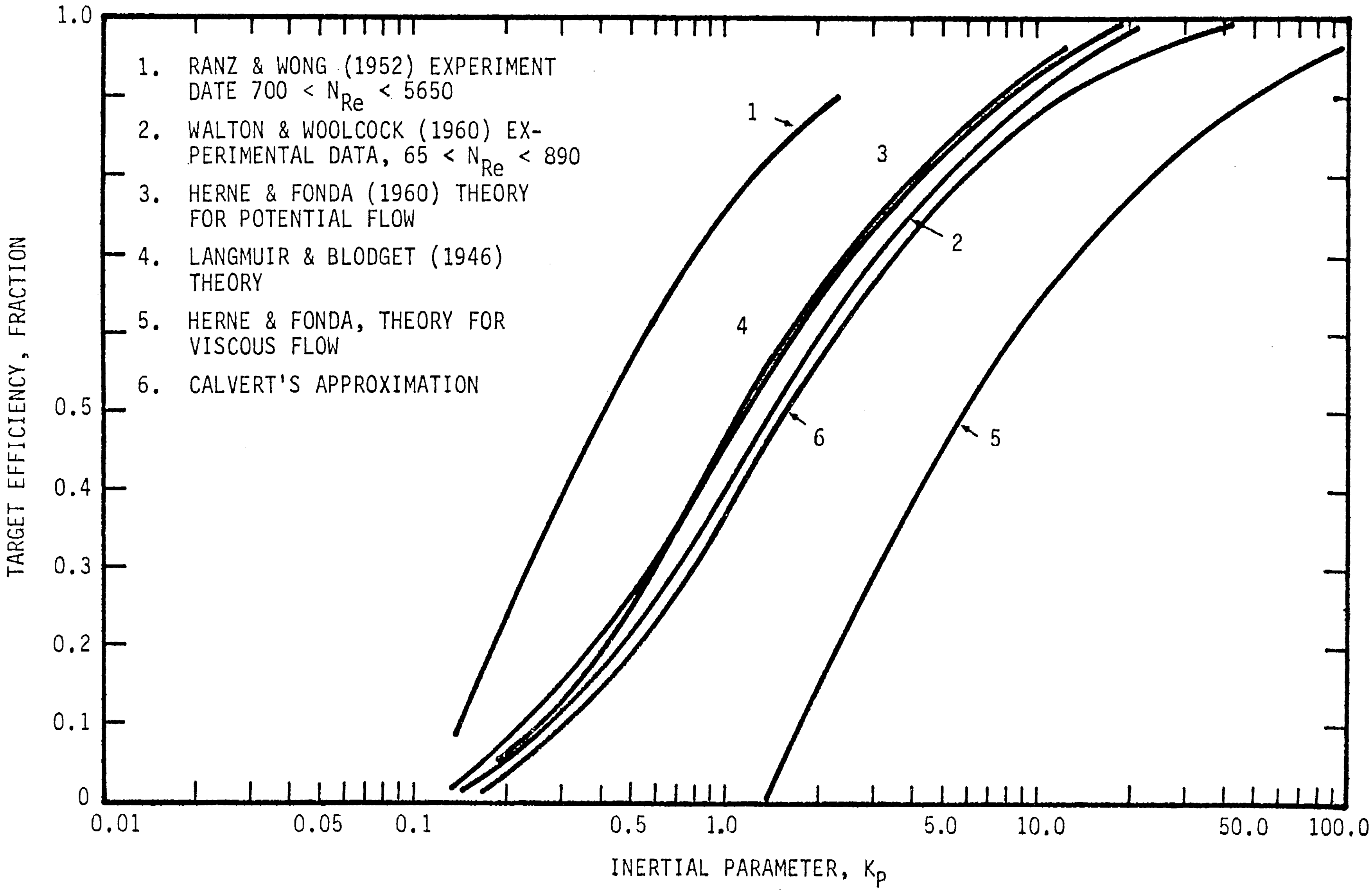


Figure 4.5.2-1. Target efficiency results of various investigators.

where u_r = drop velocity relative to gas, cm/s

For crosscurrent and cocurrent flow, Calvert (1968) estimated the pressure drop on the basis of the change in momentum of the liquid when accelerated from zero velocity to the gas velocity.

$$\Delta p = 1.0x10^{-3} \frac{Q_L}{Q_G} u_G^2 \qquad (4.5.2\text{-}11)$$

4.5.2.4 Venturi Scrubbers

Particle collection by liquid drops is the predominant occurrence in the Venturi scrubber. Inertial collection, interception, diffusion, electrostatic collection, and gravitational collection are several of the mechanisms causing collection by drops. All investigators have concluded that inertial impaction is the principal mechanism of particle collection in a Venturi scrubber for particles larger than 0.5 μm diameter. For particles smaller than 0.1 μm diameter, diffusional collection prevails.

By performing a material balance for the dust over a differential scrubber volume with the assumption of constant liquid holdup, Calvert (1968, 1970) obtained a differential equation for the prediction of Venturi scrubber performance:

$$-\frac{dc}{c} = \frac{1.5|u_p - u_d|}{u_d d_d} \frac{Q_L}{Q_G} \eta \, dz \qquad (4.5.2\text{-}12)$$

where u_p = velocity of particle, cm/s

u_d = velocity of drop, cm/s

Other investigators, such as Ekman and Johnstone (1951), Morishima et al.(1972), Boll (1973), and Behie and Beeckmans (1973) have presented the same equation in slightly different forms to describe the particle collection in a Venturi scrubber.

In a Venturi scrubber, particle collection occurs mainly in the throat section. Yung et al. (1978) solved equation 4.5.2-12 for the Venturi throat section and obtained the following equation for particle collection.

$$\ln Pt_d = \frac{B_V}{K_{po}(1 - u^*_{dl}) + 0.7}$$

$$\times \left[4K_{po}(1 - u^*_{dl})^{1.5} + 4.2(1-u^*_{dl})^{0.5} - 5.02\, K_{po}^{0.5} \right.$$

$$\left. \times \left(1 - u^*_{dl} + \frac{0.7}{K_{po}}\right) \tan^{-1}\left(\frac{(1 - u^*_{dl})K_{po}}{0.7}\right)^{0.5} \right] - \frac{B_V}{K_{po} + 0.7}$$

$$\times \left[4K_{po} + 4.2 - 5.02\, K_{po}^{0.5} \left(1 + \frac{0.7}{K_{po}}\right) \tan^{-1}\left(\frac{K_{po}}{0.7}\right)^{0.5} \right] \quad (4.5.2\text{-}13)$$

where B_V = $Q_L\, \rho_L / Q_G\, \rho_G\, C_{Do}$

K_{po} = inertial impaction parameter evaluated at throat entrance, dimensionless

C_{Do} = drag coefficient at throat entrance, dimensionless

u^*_{dl} = drop velocity at throat exit, dimensionless

$$K_{po} = \frac{C'\, \rho_p\, d_d^2 (u_{po} - u_{do})}{9 \mu_G\, d_d} \quad (4.5.2\text{-}14)$$

where u_{po} = particle velocity at throat entrance, cm/s

u_{do} = drop velocity at throat entrance, cm/s

The particle velocity is assumed equal to the gas velocity. Drag coefficient at the throat entrance "C_{Do}" is determined from the "standard curve" using a Reynolds number calculated on the basis of the relative velocity applying at the throat entrance. Drop velocity at the throat exit is calculated from the following equation:

$$u^*_{dl} = 2[1-x^2 + (x^4 - x^2)^{0.5}] \quad (4.5.2\text{-}15)$$

$$x = \frac{3 l_t\, C_{Do} \rho_G}{16\, d_d \rho_L} + 1 \quad (4.5.2\text{-}16)$$

where l_t = Venturi throat length, cm

Particles are collected only by atomized liquid drops. The drop diameter is the Sauter mean diameter predicted by the empirical correlation of Nukiyama and Tanasawa (1936):

$$d_d = \frac{0.0585}{u_G}\left(\frac{\sigma}{\varrho_L}\right)^{0.5} + 1{,}884\left[\frac{\mu_L}{(\sigma\varrho_L)^{0.5}}\right]^{0.5}\left(\frac{Q_L}{Q_G}\right)^{1.5}$$

(4.5.2-17)

where d_d = Sauter mean drop diameter, cm

σ = surface tension, dyne/cm

Although in actuality a distribution of drop sizes will exist, the use of a single representative size similifies calculations and gives reasonable results.

The pressure drop for gas flowing through a Venturi scrubber is due to the frictional loss along the wall of the scrubber and the acceleration of liquid drops. Frictional loss depends largely upon the geometry of the scrubber. Acceleration loss, which is frequently predominant in the Venturi scrubber pressure drop, is fairly insensitive to scrubber geometry and in most cases can be predicted theoretically.

Currently, there are several correlations available, both theoretical and experimental, for the prediction of pressure drop in a Venturi scrubber. Equations proposed by Yoshida et al. (1960, 1965), Calvert (1968), Tohata et al. (1964), Bol (1973), and Behie and Beeckmans (1973) are theoretical correlations. All equations were derived from the equations of motion and momentum balance.

Yung et al. (1977) have modified Calvert's equation which neglects the pressure loss due to wall friction and pressure recovery by the gas in the divergent section. This simplification is acceptable since wall friction is compensated to some extent by the pressure recovery. For this case, the pressure loss in a Venturi scrubber is equal to the momentum expended to accelerate the liquid in the Venturi throat and is given by:

$$\Delta P = -\frac{2\varrho_L u_G^2}{g_c}\,\frac{Q_L}{Q_G}\,[1 - x^2 + (x^4 - x^2)^{\frac{1}{2}}] \qquad (4.5.2\text{-}18)$$

4.5.3 Scrubber Performance for Other Collection Mechanisms

Scrubber performance for other collection mechanisms can be predicted from the following general relationship which describes particle deposition in any control device in which turbulent mixing eliminates any concentration gradient normal to the flow outside the boundary layer and in which the deposition velocity is constant:

$$Pt_d = \exp-(u_{pD}\, A_d/Q_G) \qquad (4.5.3\text{-}1)$$

where u_{pD} = particle deposition velocity, cm/s

A_d = deposition area, cm^2

The particle deposition velocity is the net particle deposition velocity caused by the collection mechanism(s). The deposition velocity for any collection mechanism depends on the force balance between the driving force (deposition force) and the resistance force of the gas. Table 4.5.3-1 is a list of theoretical equations predicting the deposition velocity for each collection mechanism. The scrubber collection efficiency can be calculated from equation 4.5.3-1 coupled with the appropriate deposition velocity and the total deposition area of the scrubber.

4.5.4 Electrostatically Augmented Scrubbers

The scrubber performance for an electrostatically augmented scrubber can also be predicted from equation 4.5-1 if "η" is known.

Particle collection in an electrostatically augmented scrubber may be due to impaction and (Yung et al., 1981):

1. The Coulombic force between a charged particle and a charged collector.
2. The electrical image force between a charged particle and a neutral collector.
3. The electrical image force between a neutral particle and a charged collector.
4. The force on a charged particle in the presence of a neutral collector by a uniform external electric field directed parallel to the flow field.
5. The electric dipole interaction force between a neutral particle and a neutral collector, both polarized by a uniform external electric field directed parallel to the flow field.

For the collection of particles by drops, the dimensionless electrical force parameters for the above five conditions are:

$$K_c = \frac{Q_d\ Q_p\ C'}{3\ \pi^2\ k_G\ \mu_G\ u_o\ d_d^2\ d_p} \qquad (4.5.4\text{-}1)$$

$$K_{ic} = \left(\frac{k_d - k_G}{k_p + 2\ k_G}\right)\left(\frac{Q_p^2\ C'}{3\ \pi^2\ \varrho_o\ \mu_G\ u_o\ d_d^3\ d_p}\right) \qquad (4.5.4\text{-}2)$$

$$K_{ip} = \left(\frac{k_d - k_G}{k_p + 2\ k_G}\right)\left(\frac{2\ Q_d^2\ d_p^2\ C'}{3\ \pi^2\ k_G d_d^5\ \mu_G\ u_o}\right) \qquad (4.5.4\text{-}3)$$

TABLE 4.5.3-1. PARTICLE DEPOSITION VELOCITY

Collection Phenomena	Particle Deposition Velocity
Gravitational Sedimentation	$u_{PD} = \frac{1}{18} \frac{C' d_p^2 (\rho_p - \rho_G) g}{\mu_G}$
Centrifugal Deposition	$u_{PD} = \frac{1}{18} \frac{C' d_p^2 (\rho_p - \rho_G) u_t^2}{\mu_G R}$
Brownian Diffusion	$u_{PD} = 1.13 \left(\frac{D_p}{\theta}\right)^{0.5}$
Thermophoresis	$u_{PD} = - \frac{3 C' \mu_G}{2 \rho_G T} \left(\frac{k_G}{2 k_G + k_p}\right) \nabla T$
Diffusiophoresis	$u_{PD} = - \frac{M_V^{0.5}}{p_V M_V^{0.5} + p_G M_G^{0.5}} \frac{P D_{VG}}{p_G} \nabla p_V$
Electrical Migration	$u_{PD} = \frac{\varepsilon}{\varepsilon + 2} \frac{C' \varepsilon_o E_c E_p d_p}{4 \pi \xi_G}$
Magnetic Precipitation	$u_{PD} = \frac{C' \mu_o H q_p \mu_G}{3 \pi \mu_G d_p}$

$$K_{ex} = \frac{Q_p E_o C'}{3 \pi \mu_g u_o d_p} \qquad (4.5.4\text{-}4)$$

$$K_{icp} = \left(\frac{k_p - k_G}{k_p + 2 k_G}\right)\left(\frac{k_d - k_G}{k_d + 2 k_G}\right)\left(\frac{k_G d_p^2 E_o^2 C'}{d_d \mu_G u_o}\right) \qquad (4.5.4\text{-}5)$$

where K_c = Coulombic force parameter, dimensionless

K_{ic} = charged particle image force parameter, dimensionless

K_{ip} = charged collector image force parameter, dimensionless

K_{ex} = external electric field force parameter, dimensionless

K_{icp} = electric dipole interaction force parameter, dimensionless

Q_d = drop collector charge, C

Q_p = particle charge, C

C' = Cunningham slip correction factor, dimensionless

d_d = drop diamaeter, cm

d_p = particle diameter, cm

u_o = undisturbed upstream velocity, cm/s

E_o = uniform external electric field strength, V/cm

μ_G = gas viscosity, g/cm-s

k_d = dielectric constant of the drop, F/cm

k_p = dielectric constant of the particle, F/cm

k_G = dielectric constant of the gas, F/cm

The single drop collection efficiency, in the presence of electrostatic force, can be predicted by performing a force balance and solving the resulting equation. Kraemer and Johnstone (1955) numerically solved the equation of motion and obtained approximate collection efficiencies for potential flow and Stokes flow around a spherical collector in the absence of particle inertia. For the collection of a charged aerosol by a charged collector, considering only the Coulombic force, the collection efficiency is:

$$\eta = -4K_c \qquad (4.5.4\text{-}6)$$

For the collection of uncharged aerosol particles by a charged spherical collector considering only the induced charge on the particles, the collection efficiency is:

$$\eta = \left(\frac{15}{8} \pi K_{ip} \right)^{0.4} \qquad (4.5.4\text{-}7)$$

Nielson (1974) and Nielsen and Hill (1976a) numerically solved the equation of motion for the collection of inertialess particles on spheres with electrical force. Their result for collection efficiency under the influence of Coulombic force is the same for potential flow and viscous flow and is identical to that reported by Kraemer and Johnstone (1955). The collection efficiency for external electric field force is:

$$\eta = \left(1 + 2 \frac{k_d - k_o}{k_d + 2k_o} \right) \frac{K_{ex}}{1 + K_{ex}} \qquad (4.5.4\text{-}8)$$

The flow field does affect the collection efficiencies for the image force cases. Their results are plotted in Figure 4.5.4-1.

George and Peohlein (1974) and Nielsen and Hill (1976b) numerically calculated the target efficiencies for the collection of fine particles by a single spherical collector under the combined influence of particle inertia and electrostatic forces. The results of Nielsen and Hill for the collection of charged particles by charged collectors are presented in Figure 4.5.4-2.

4.5.5 Flux Force/Condensation

When a hot and saturated gas is in contact with cold water or a cold solid surface, condensation of water vapor occurs. Part of the vapor will be condensed on the particles which serve as condensation nuclei. Thus, the particles will have grown in mass due to the layer of water they carry and will be more susceptible to collection by inertial impaction. While condensation occurs, there will be diffusiophoretic and thermophoretic deposition on the cold surfaces as well as some inertial impaction. The particle growth by condensation in combination with diffusiophoresis and thermophoresis is referred to as "flux force/condensation" (F/C) scrubbing.

A typical F/C scrubbing system is shown in Figure 4.5.5-1. The gas leaving the source is hot and has a water vapor content which depends on the source process. The first step is to saturate the gas by quenching it with water. This will cause no condensation if the particles are insoluble, but will if they are soluble. There will be a diffusiophoretic force directed away from the liquid surface.

Condensation is required in order to have diffusiophoretic

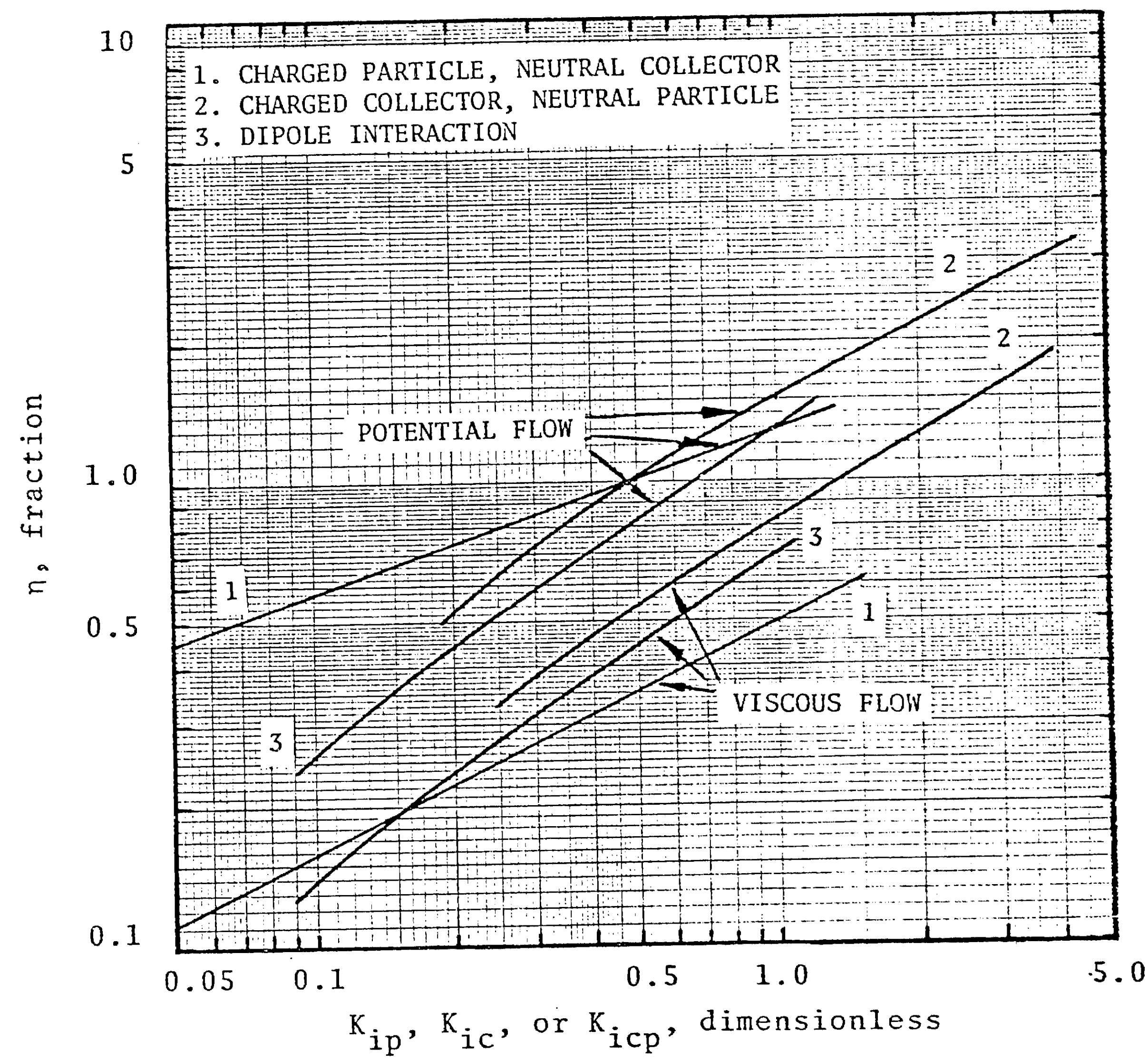


Figure 4.5.4-1. Single collector collection efficiencies for inertialess particles.

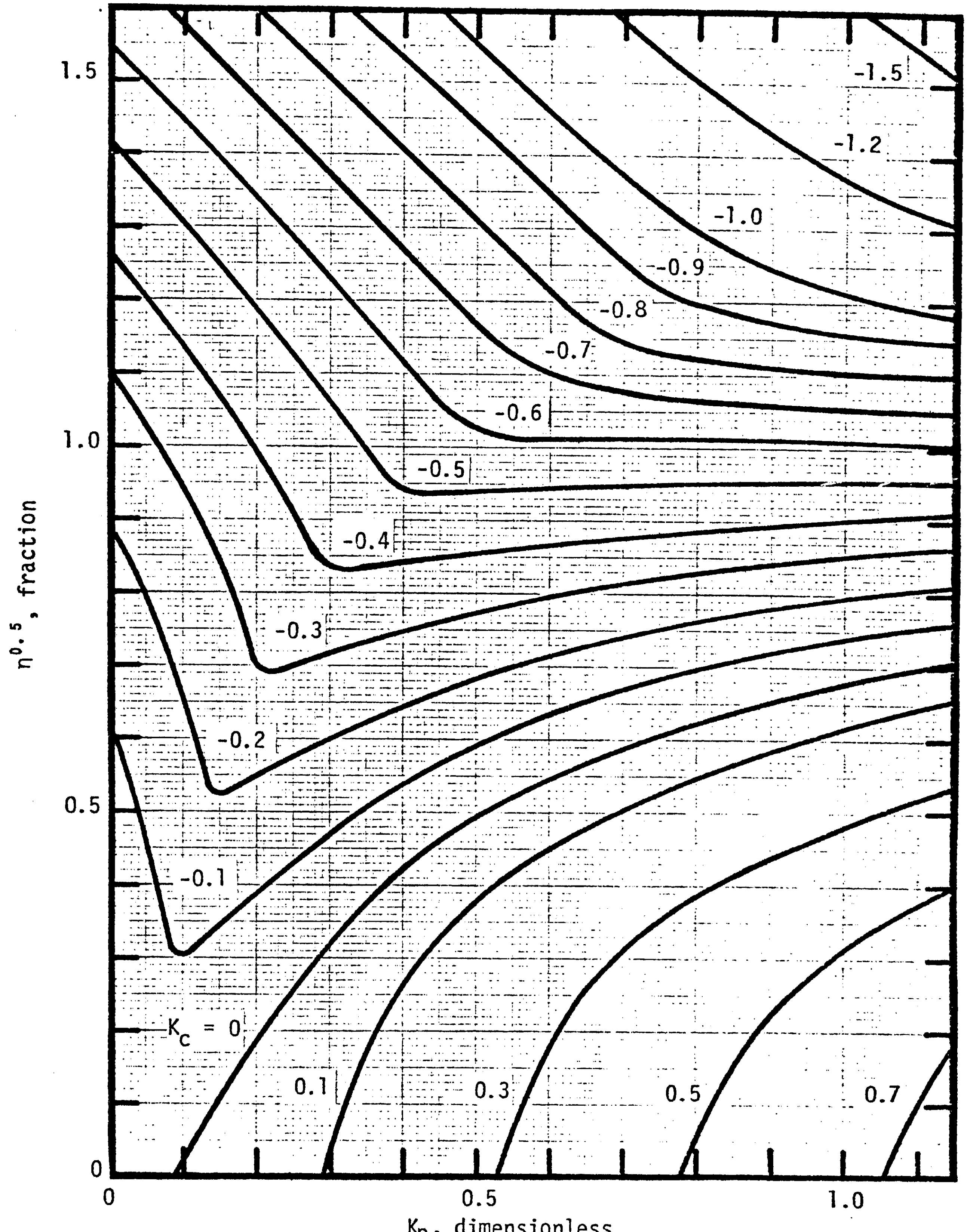


Figure 4.5.4-2 Single drop collection efficiency versus inertial impaction parameter with Coulombic force parameter as parameter.

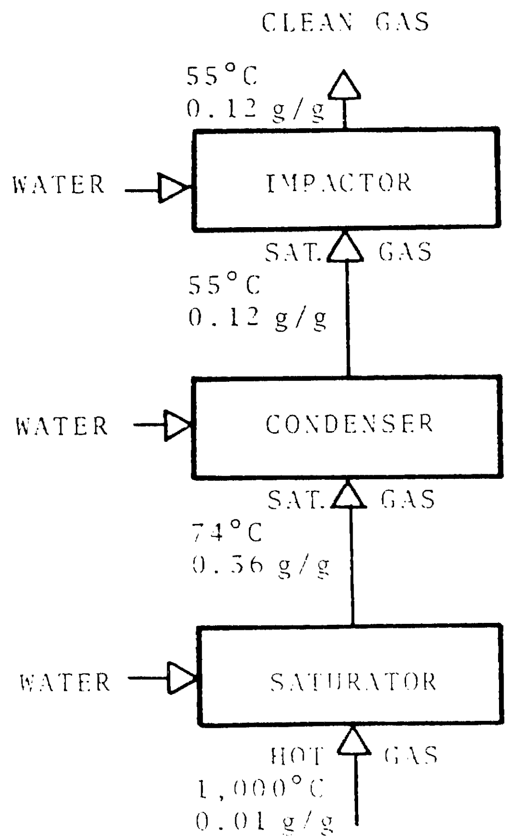


Figure 4.5.5-1. Generalized F/C scrubber system.

deposition, any growth on insoluble particles, and extensive growth on soluble particles. Contacting with cold water or a cold surface is employed to cause condensation.

Subsequent scrubbing of the gas will result in more particle collection by inertial impaction. This will be more efficient than impaction before particle growth because of the greater inertia of the particles. There may be additional condensation, depending on water and gas temperatures, and its effects can be accounted for as discussed above.

One can apply this general outline of F/C scrubbing to a variety of scrubber types. The condenser may be a separate unit or can be part of the scrubber.

Several phenomena are simultaneously involved in a F/C scrubber and the mathematical model is complex and cumbersome. Calvert and Gandhi (1977), through a series of studies, concluded that the flux force effects and condensation effect can be treated separately. Based on this conclusion, they developed a simplified performance prediction and design method. Their method is summarized in the following paragraphs.

4.5.5.1 Diffusiophoretic Deposition

Particle deposition by diffusiophoresis was described by the following equation (Calvert et al. 1973, 1975, 1976):

$$u_{pD} = \frac{(M_1)^{0.5}\, D_G}{\left(y\,(M_1)^{0.5} + (1-y)\,(M_2)\right)\,(1-y)}\;\frac{dy}{dr} \qquad (4.5.5\text{-}1)$$

or,

$$u_{pD} = C_1\, D_G \left(\frac{1}{1-y}\right) \frac{dy}{dr} \qquad (4.5.5\text{-}2)$$

where D_G = diffusivity of water vapor in carrier gas, cm^2/s

M_1 = molecular weight of water, g/mol

M_2 = molecular weight of nontransferring gas, g/mol

y = mole fraction water vapor, dimensionless

r = distance in the direction of diffusion, cm

u_{pD} = diffusiophoretic deposition velocity, cm/s

The molecular weight and composition function represented by "C_1" described the effect of molecular weight gradient on the deposition velocity corresponding to the net motion of the gas due to diffusion (the "sweep velocity"). For water mole fraction in air ranging from 0.1 to 0.5, "C_1" varies from 0.8 to 0.88. Calvert and Gandhi (1977) used a rough average of 0.85 for "C_1"

for computing "u_{pD}" and consequent particle collection efficiency by integrating over the period of condensation.

Whitmore (1976) concludes that the fraction of particles removed from the gas by diffusiophoresis is equal to either the mass fraction or the mole fraction condensing, depending on what theory is used for deposition velocity. In other words, it is not necessary to follow the detailed course of the condensation process, computing instantaneous values of deposition velocity, and integrating over the entire time to compute the fraction of particles collected. One can simply observe that if some fraction of the gas is transferred to the liquid phase it will carry along its load of suspended particles.

4.5.5.2 Particle Growth

Particle growth is dependent on how well the particles can compete with the cold surface for the condensing water. There are several transport processes at work simultaneously in the condenser section of an F/C scrubber:

1. Heat transfer
   a. from the gas to the cold surface
   b. from the particles to the gas
2. Mass transfer
   a. from the gas to the cold surface
   b. from the gas to the particles

A mathematical model which accounted for these transport processes in addition to particle deposition has been described in EPA reports by Calvert et al. (1973, 1975, 1976). Calvert and Gandhi (1977) solved the equations through a finite difference method for sieve plates under various situations to predict the fraction of the total condensate which goes to the particles (this fraction defined as "f_p"). It was found that "f_p" depends heavily on "n_p," the particle number concentration, and liquid phase heat transfer coefficient. It decreases significantly with "n_p" below about 10^6 particles/cm^3 and does not change much for particle number concentration greater than 10^7/cm^3.

"f_p" varies between 0.1 and 0.4. Calvert and Gandhi (1977) used an average of 0.25 for the sieve plate scrubbers.

4.5.6 Cut/Power Relationship

Mathematical models for scrubber performance and the cut diameter approach developed by Calvert et al. (1972) led to the concept that performance cut diameter could be related to gas-phase pressure drop, or power input to the scrubber. Subsequent performance tests on a variety of scrubbers in industrial installations, combined with mathematical modeling, has led to the refinement of the cut/power relationship shown in Figure 4.5.6-1. The curves give the cut diameter as a function gas-phase pressure drop (cm W.C.) for a number of typical installations--sieve-plate column, packed column, gas-atomized spray

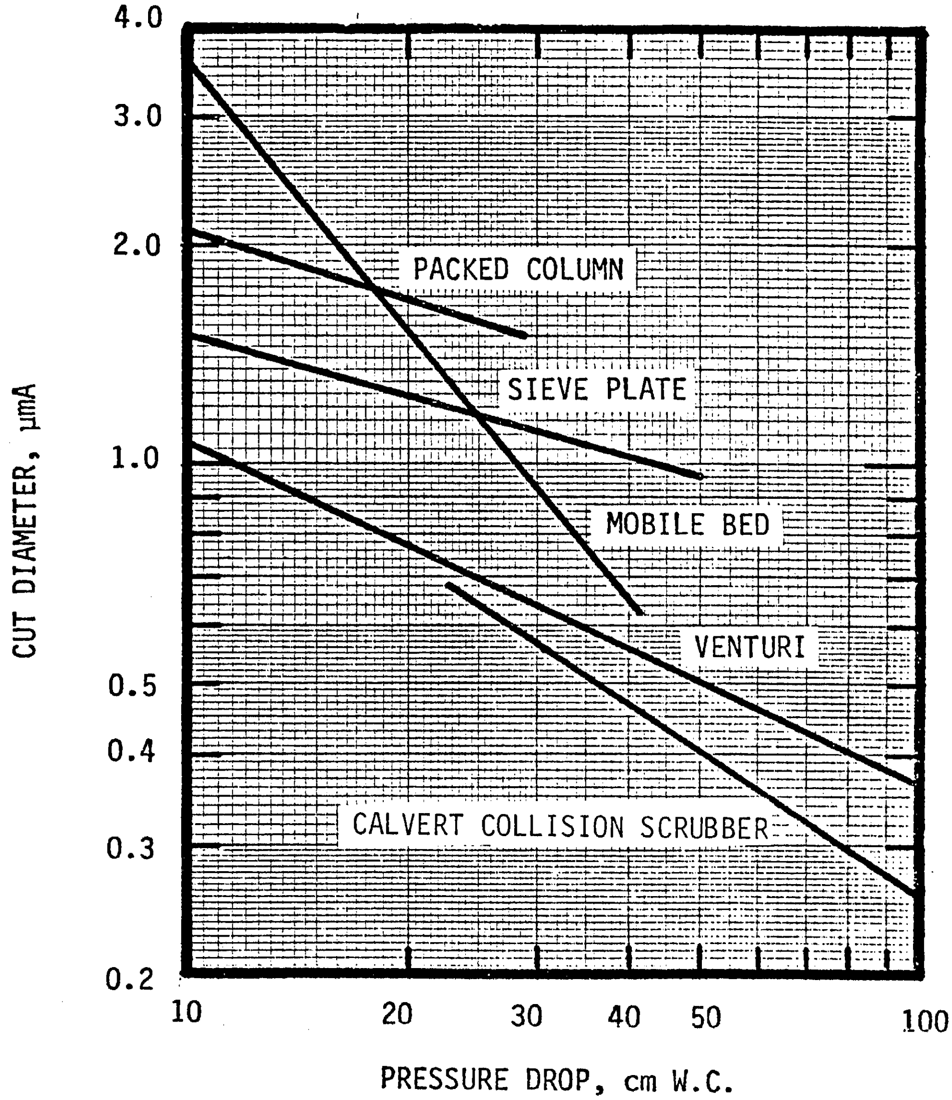


Figure 4.5.6-1. Cut/power plot.

(Venturi and Calvert Collision Scrubbers) and the mobile fluidized bed scrubbers.

The A.P.T. cut/power relationship has been devised and tested on the basis of all of the published data available to the authors. It appears to be an accurate and reliable criterion for scrubber selection and performance prediction.

The cut/power plot gives a measure of what the scrubber can do for a given pressure drop. It can be used to predict the scrubber performance if the scrubber operating pressure drop is known. For example, a Venturi scrubber with a pressure drop of 33 cm W.C. is installed on a source which has a mass emission of 2.3 g/Nm^3 (1 gr/scf). From Figure 4.5.6-1, the performance cut diameter of the Venturi scrubber is 0.63 μmA. Suppose the particle size distribution has d_{pg} = 10 μmA and σ_g = 3, then the overall penetration is 0.01 (from Figure 4.5.1-2) and the controlled mass emission will be 0.023 g/Nm^3 (0.01 gr/scf).

4.6 SCRUBBER DESIGN

4.6.1 Design Equation Approach

Air pollution control regulation generally specify a maximum mass rate of emissions and often set a concentration limit as well. By knowing the particle concentration and mass rate at the scrubber inlet, one can specify the minimum collection efficiency or the maximum allowable penetration through the scrubber being designed or selected.

When a range of particle sizes is involved, as generally is the case, the overall particle concentration will depend on the size distribution and on the penetration for each size. The overall penetration of any device collecting a dust with any size distribution can be calculated from equation 4.5.1-1.

In designing a scrubber, the maximum allowable penetration and size distribution in the process stream must be known. The only variable in equation 4.5.1-1 is "Pt_d" which is a function of scrubber geometry and scrubber operating conditions. One must first choose the scrubber geometry and operating conditions, then evaluate "Pt_d" by means of the design equations presented in the last section and integrate equation 4.5.1-1 to obtain the overall penetration. If the calculated overall penetration is greater than the allowable maximum, new scrubber geometry and operating conditions are chosen and the calculations are repeated.

These trial and error procedures are continued until one arrives at a scrubber design which gives an overall penetration smaller than or equal to the maximum allowable "Pt". Generally, more than one scrubber geometry and set of operating conditions give satisfactory performance. The final selection will be based on cost, experience, and other factors.

Choosing a scrubber is simpler than designing one. The scrubber manufacturer's proposed geometry and operating condition may be used to calculate "Pt_d". Then, the overall penetration may be calculated from equation 4.5.1-1 to check whether it is acceptable.

4.6.2 Cut Diameter Method

When precision is not required, the cut diameter method provides quick designs. From the maximum allowable scrubber penetration and the particle size distribution, one specifies the required cut diameter from Figure 4.5.1-2. The required cut diameter defines what the scrubber needs to do. It is the particle diameter at which the collection efficiency (or penetration) must be 50% in order that the necessary overall efficiency for the entire particle size distribution be attained.

Once the required cut diameter is specified, one can design a scrubber such that its performance cut diameter is smaller or equal to the required cut diameter. For example, suppose the size distribution has d_{pg} = 10 μmA and σ = 3.0 and 99% collection efficiency is needed. The penetration is 100% minus the percent collection efficiency, or 1%, which corresponds to $\overline{Pt}$ = 0.01 in fraction units.

The diameter ratio corresponding to $\overline{Pt}$ = 0.01 and σ_g = 3.0 is d_{RC}/d_{pg} = 0.063 (from Figure 4.5.1-2). Since d_{pg} = 10.0 μmA, d_{RC} = 0.63 μmA. This means that a scrubber with a cut diameter of 0.63 μmA or less to achieve 99% collection of the particles in question.

It can be seen from Figure 4.5.6-1 that the only "unaided" scrubbers capable of giving a 0.63 μmA cut diameter are the gas-atomized spray types (Venturi and the Calvert Collision Scrubber). The separation would require a gas-phase pressure drop of about 33 cm W.C. for the Venturi scrubber whereas the Calvert Collision scrubber would only require 20 cm W.C.

Other types of scrubbers would achieve the required performance if augmented by F/C effects or by electrostatic charging. Each system would have to be examined to determine whether it would be economically attractive.

4.7 ECONOMICS

Costs are the ultimate criterion of the optimum system in gas scrubbing, as in any industrial operation. One must decide whether one type of equipment is better than another when both are capable of the desired performance; whether to use less expensive equipment and more power; whether to use more expensive materials or to have higher maintenance costs; or whether to use a higher stack and less efficient collection equipment. The rationalization of these various trade-offs requires the use of a single method of evaluation: total cost.

Cost estimation methods range from quick and dirty predesign approximations to elaborate compilations of firm bids on completely design systems. Even the latter will only give results with a probable error of between 7% over and 15% under actual capital costs. Other elements such as labor and maintenance will be more inaccurate. Nevertheless, a decision based on approximate costs is better than one based on no cost considerations.

The situation is eased considerably because the comparison of cost estimates generated in the same way is likely to be more accurate than their absolute magnitudes and because sometimes the most doubtful items may contribute only a small fraction of the total cost.

4.8 METHODS FOR TECHNICAL EVALUATION

4.8.1 Devices for Further Evaluation

Based on the survey of existing and developing technologies, the following devices, which are appropriate for control of particles with diameters less than 3μmA, have been selected:

1) Venturi scrubber
2) Electrostatically augmented spray scrubber
3) Flux force condensation scrubber
4) SCAT scrubber (for fugitive particles)
5) Calvert Collision scrubber

The specific method which is used to estimate the efficiency and the costs for the control devices listed above is explained in the following sections.

4.8.2 Methods for Predicting Collection Efficiency

4.8.2.1 Venturi Scrubber

Predictions for Venturi scrubber efficiency and pressure loss are determined from equation (4.5.2-13) and (4.5.2-18), respectively. The particle penetration as a function of particle diameter is calculated for specified operating conditions. Using particle size distributions for the specific sources, the penetration is integrated to obtain an overall penetration for particles less than 3 μmA in diameter for each source.

4.8.2.2 Electrostatically Augmented Spray Scrubber

The theoretical model for particle collection in electrostatically augmented spray scrubbers is not well developed. Therefore, the particle collection efficiency for charged particle/grounded drop scrubbers and charged particle/charged drop scrubbers is calcualted based on experimental results reported by Yung et al. (1981). Figures 4.8.2-1 and 4.8.2-2 show experimental efficiency curves for electrostatically augmented spray scrubbers. The dashed lines show where the curves have been extrapolated beyond the experimental data. The curves are for one spray bank with a liquid to gas ratio (Q_L/Q_G) of 4 x 10^{-4} m^3/m^3 (3 gal/1,000 acfm). On each figure a second curve is shown which is the efficiency of the scrubber, neglecting the particle collection in the particle charger.

Efficiency as a function of particle diameter is estimated for scrubbers having one or more spray banks. For example, the penetration for a 1.0 μmA diameter particle through a charged particle/charged spray scrubber with 3 spray banks is estimated

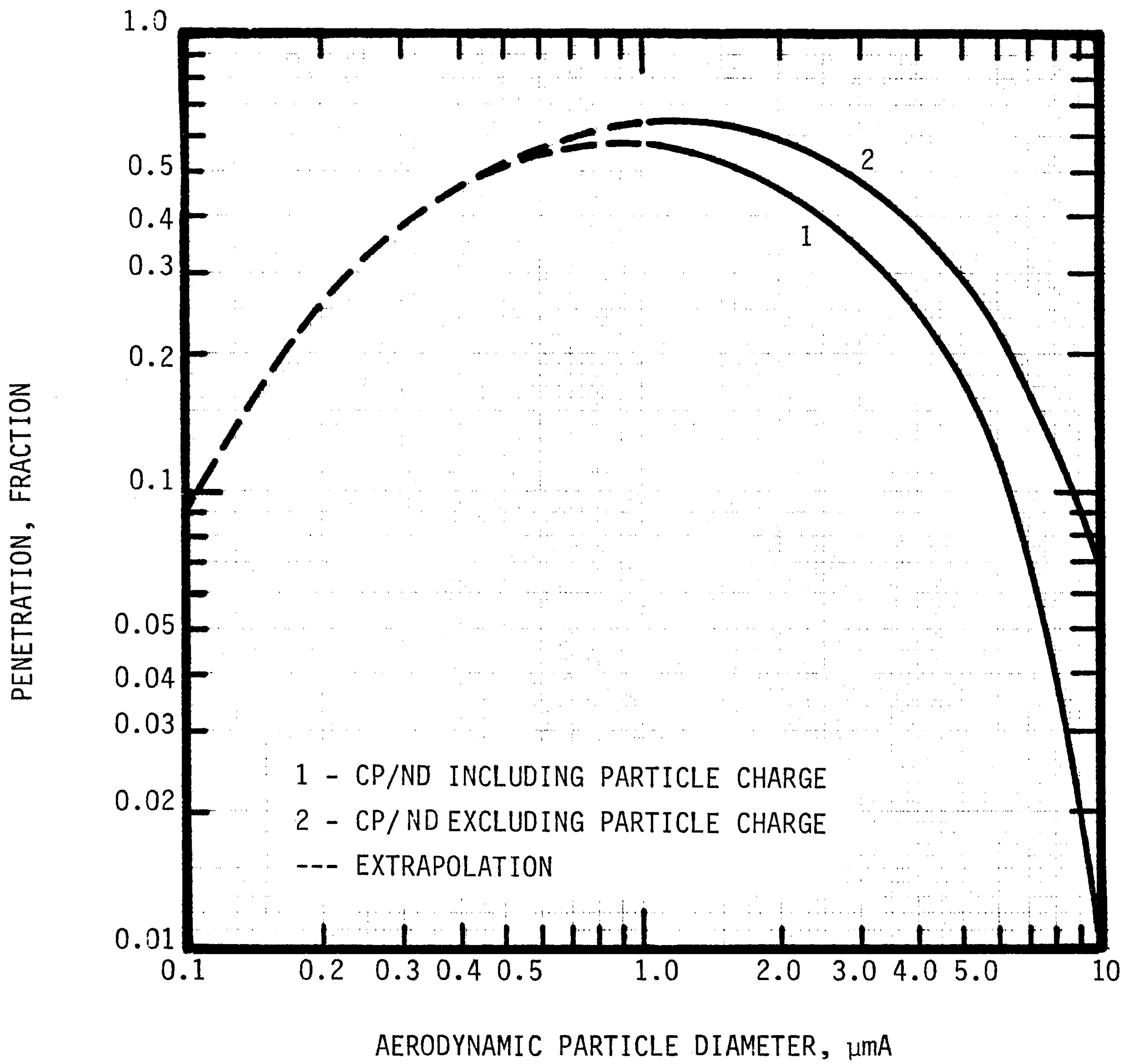


Figure 4.8.2-1. Spray scrubber penetration, charged particle/neutral drop (Yung et al., 1981).

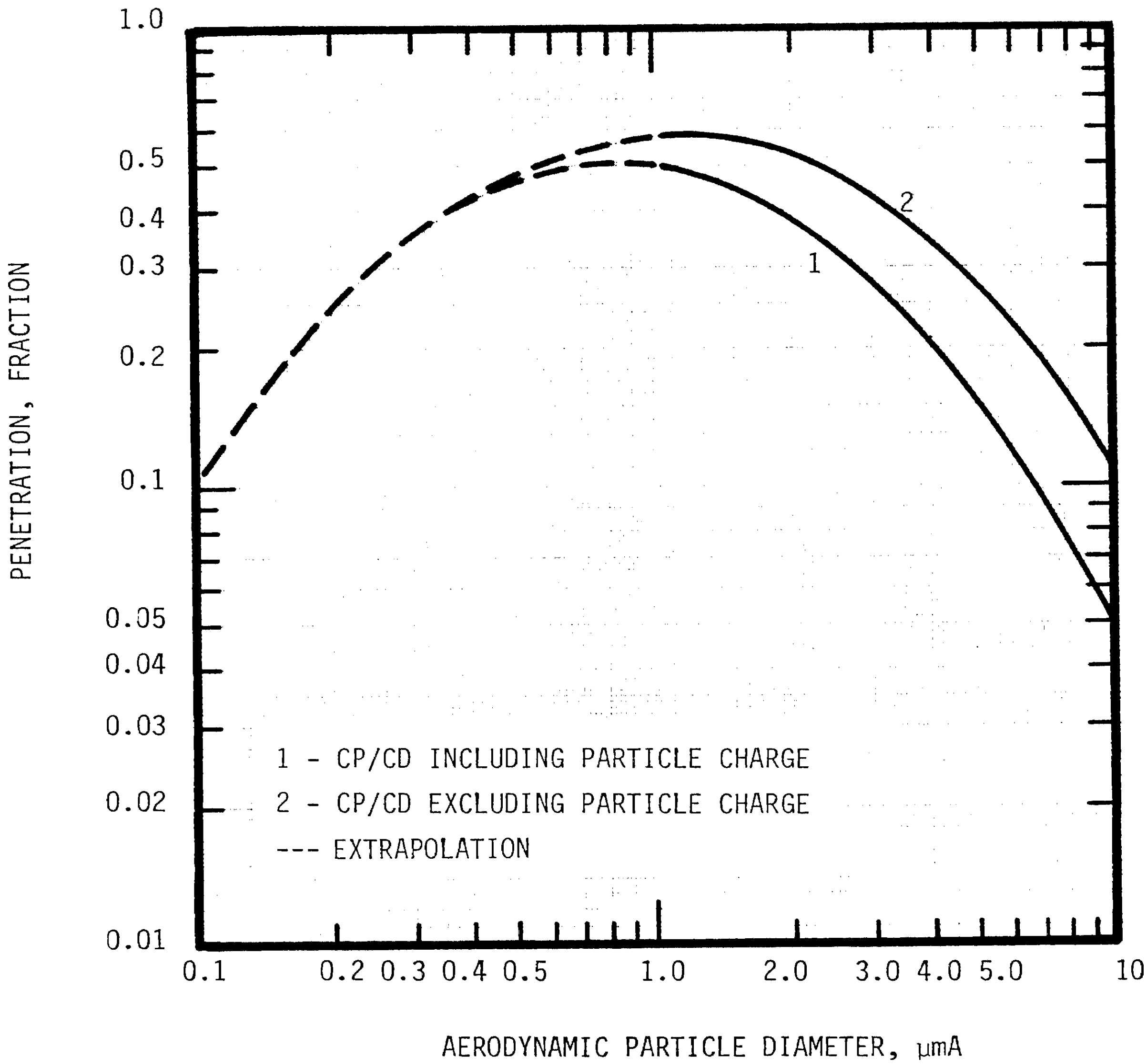


Figure 4.8.2-2. Spray scrubber penetration, charged particle/ charged drop (Yung et al., 1981).

as follows:

1) The penetration through the first spray section is read from line 1 on Figure 4.8.2-2, which includes collection by the particle charger.
2) Spray sections two and three will have the same penetration, read from line 2, which excludes the particle charger.
3) The fractional penetration of a particle with $d_{pa} = 1.0$ μmA can be estimated by multiplying the penetrations through the individual spray sections.

$$Pt_d = (Pt_d)_1 \times (Pt_d)_2 \times (Pt_d)_3 \qquad (4.8.2\text{-}1)$$

$$= (0.5)(0.8)(0.8) = 0.32$$

Once this has been done for a number of particle diameters, the overall penetrations are determined by integrating over the size distributions of each of the sources. In this manner, the overall penetration and the overall penetration for $d_{pa} < 3$ μmA can be estimated.

4.8.2.3 Calvert Collision Scrubber

Calculations for the Calvert Collision Scrubber are based on empirical correlations of experimental data. Figure 4.8.2-3 shows a plot of "d_{pc}" versus "Pt_d" for the Calvert Collision Scrubber. The dashed line in Figure 4.8.2-3 is a conservative correlation of the experimental data for practical values of liquid/gas flow rate ratio and pressure drop. This figure and the cut/power relationship shown in Figure 4.5.6-1 are sufficient for predicting the performance of a Calvert Collision Scrubber on any source. The procedure is:

1. Select a pressure drop and determine the cut diameter from Figure 4.5.6-1.
2. Construct a grade penetration curve from the plot in Figure 4.8.2-3.
3. Plot "Pt_d" versus percent smaller than "d_p" (from particle size distribution curve).
4. Integrate the area under the curve of step (3). The result is the overall penetration.
5. To calculate the integrated penetration for particles smaller than 3 μmA diameter, the area under the curve of step (3) from 0 to the percent undersize for $d_{pa} = 3$ μmA is obtained numerically. The integrated penetration for particles smaller than 3 μmA diameter is equal to this area divided by the area obtained in step (4).
6. Steps (1) to (5) are repeated for other pressure drops.

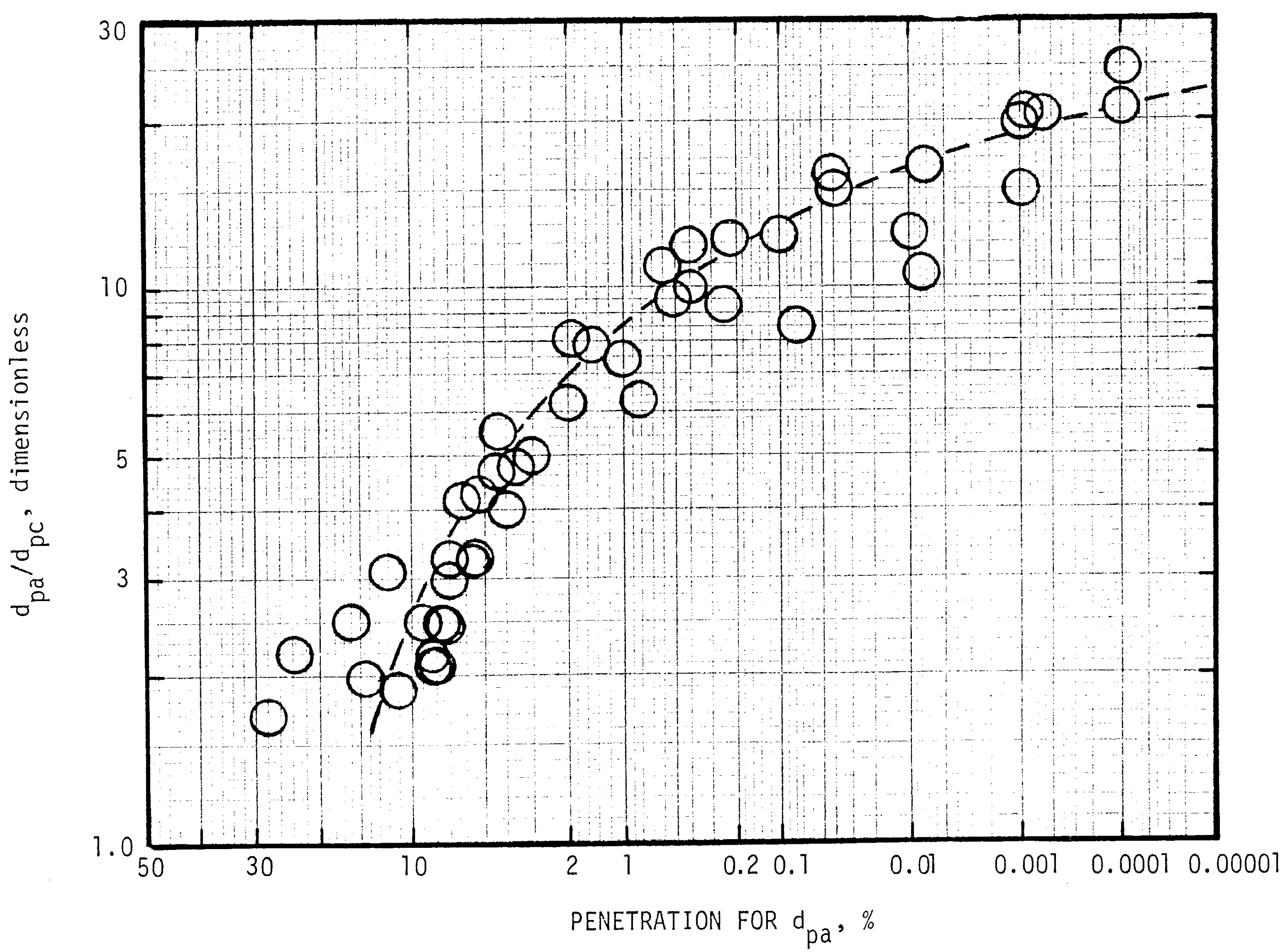


Figure 4.8.2-3. Normalized particle penetration for Calvert Collision Scrubber.

4.8.2.4 Flux Force/Condensation

The procedure for predicting the collection efficiency of a F/C scrubber system depends on whether the condensation and particle growth occurred within the scrubber or before the scrubber. The sequence of steps to be followed for before the scrubber is outlined in the following:

1. Determine the initial particle size distribution at the condenser inlet.
2. Calculate the condensation ratio corresponding to the condenser operating conditions.
3. Calculate the penetration due to diffusiophoresis according to the following equation. Collection by other mechanisms may be neglected.

$$Pt_{dd} = 1 - 0.85\, f_v = 1 - \frac{0.85q'}{H_2 + \frac{18}{29}} \qquad (4.8.2\text{-}2)$$

where Pt_{dd} = penetration due to diffusiophoresis, fraction

f_v = volume fraction of gas condensing, fraction

q' = condensation ratio, g/g

H_1 = original humidity ratio, g/g

4. Calculate the grown particle size distribution at the condenser outlet, assuming that an equal amount of vapor condensed on each particle.
5. Compute the grade penetration for the scrubber and calculate the overall penetration for the grown particle size distribution leaving the condenser.
6. Calculate the total overall fractional penetration for the F/C scrubber system. Overall penetration is equal to the product of steps 3 and 5.

4.8.3 Cost Data

4.8.3.1 Venturi Scrubber

The cost of the scrubber is based on the volumetric flow rate, operating pressure drop, and materials of construction. Neveril et al. (1979) gave the following price equation for Venturi scrubbers with gas flow rate up to 5,663 Am^3/min (200,000 acfm).

$$p_p = 10{,}498 + 1{,}275\, Q_G - 5.63\, Q_G^2 \qquad (4.8.3\text{-}1)$$

where P_p = purchase price of Venturi scrubber, \$

Q_G = volumetric gas flow rate, Am^3/s

The price is in December 1981, U.S. Dollars and it includes the Venturi, cyclone entrainment separator, elbow (between Venturi and cyclone), pumps, and controls. Prices are for 0.32 cm (1/8") thick carbon steel scrubbers. Additional cost factors are provided in the following for different metal thickness, fiberglass or rubber liners, manual or automatic Venturi throat, and stainless steel construction.

Item	Price Adjustment Factor
1. Other metal thickness	From Figures 4.8.3-1 & 4.8.3-2
2. 316 stainless steel	x 3.20
3. 304 stainless steel	x 2.30
4. 0.48 cm (3/16") rubber liner	\$74.43/m² (\$6.92/ft²)
5. Manual variable throat	\$5,100
6. Automatic variable throat	\$9,400
7. Fiberglass lined	Add 15% of price for 0.32 cm (1/8") carbon steel scrubber to total price.

The internal surface area of the scrubber system (for lining) can be estimated from the following equation:

$$A = 0.0492\ Q_G \qquad (4.8.3\text{-}2)$$

where A = internal surface area, m^2

Q_G = gas flow rate, Am^3/min

4.8.3-2 F/C Scrubber

The equipment in a F/C scrubber system could include:

a) Gas humidifier or saturator
b) Condenser
c) Scrubber
d) Cooling tower
e) Auxiliary equipment such as fan and pump

In this study, the scrubber is assumed to be a Venturi scrubber and its cost can be estimated from data presented in the last section. Cost data for fan and pump are presented in Appendix "A."

The saturator, in most cases, is a spray chamber. The cost of the spray chamber is estimated from the following equation due to Neveril (1978).

$$P_p = 12.24\ Q_G + 63{,}400 \qquad (4.8.3\text{-}3)$$

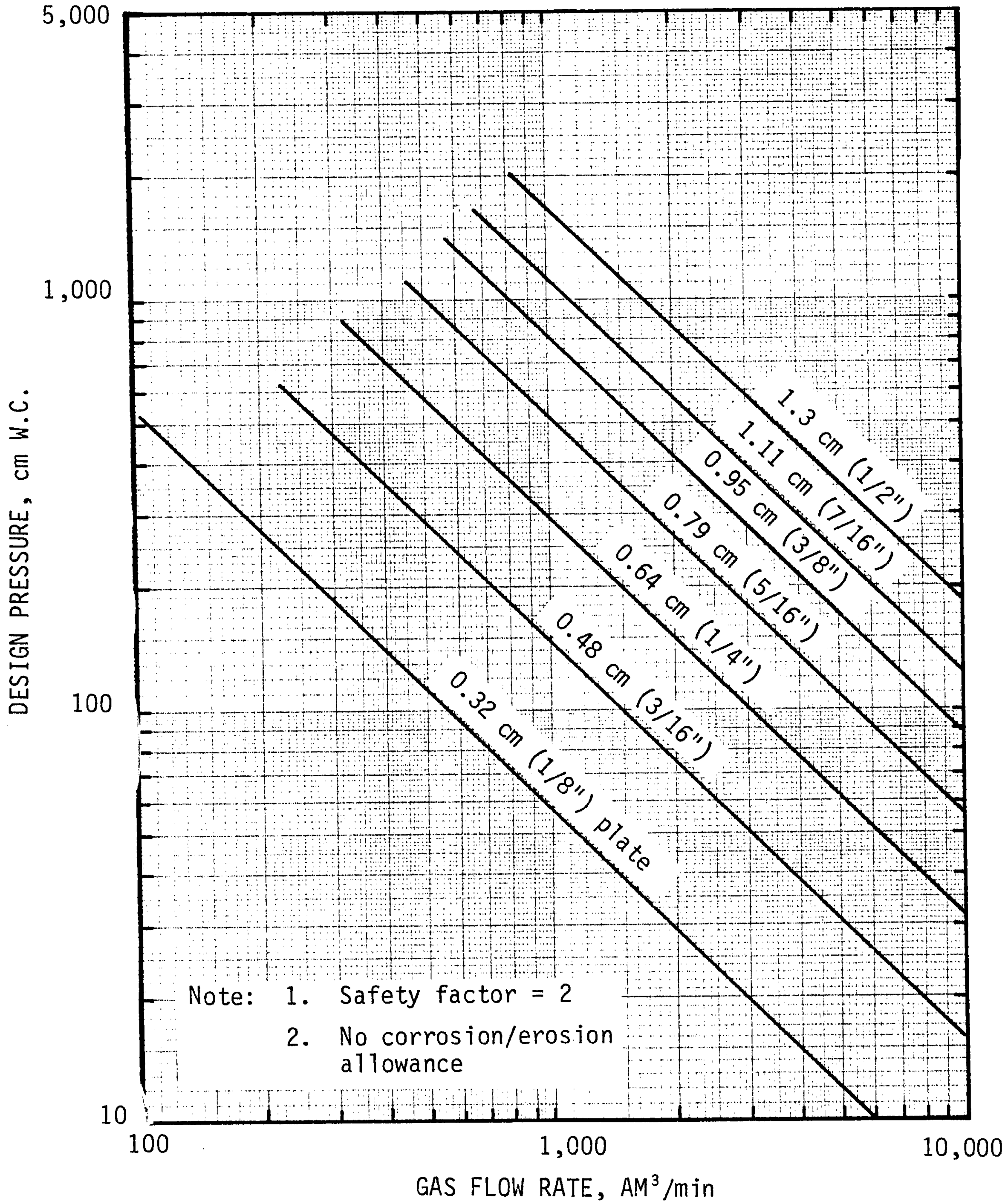


Figure 4.8.3-1. Required metal thickness

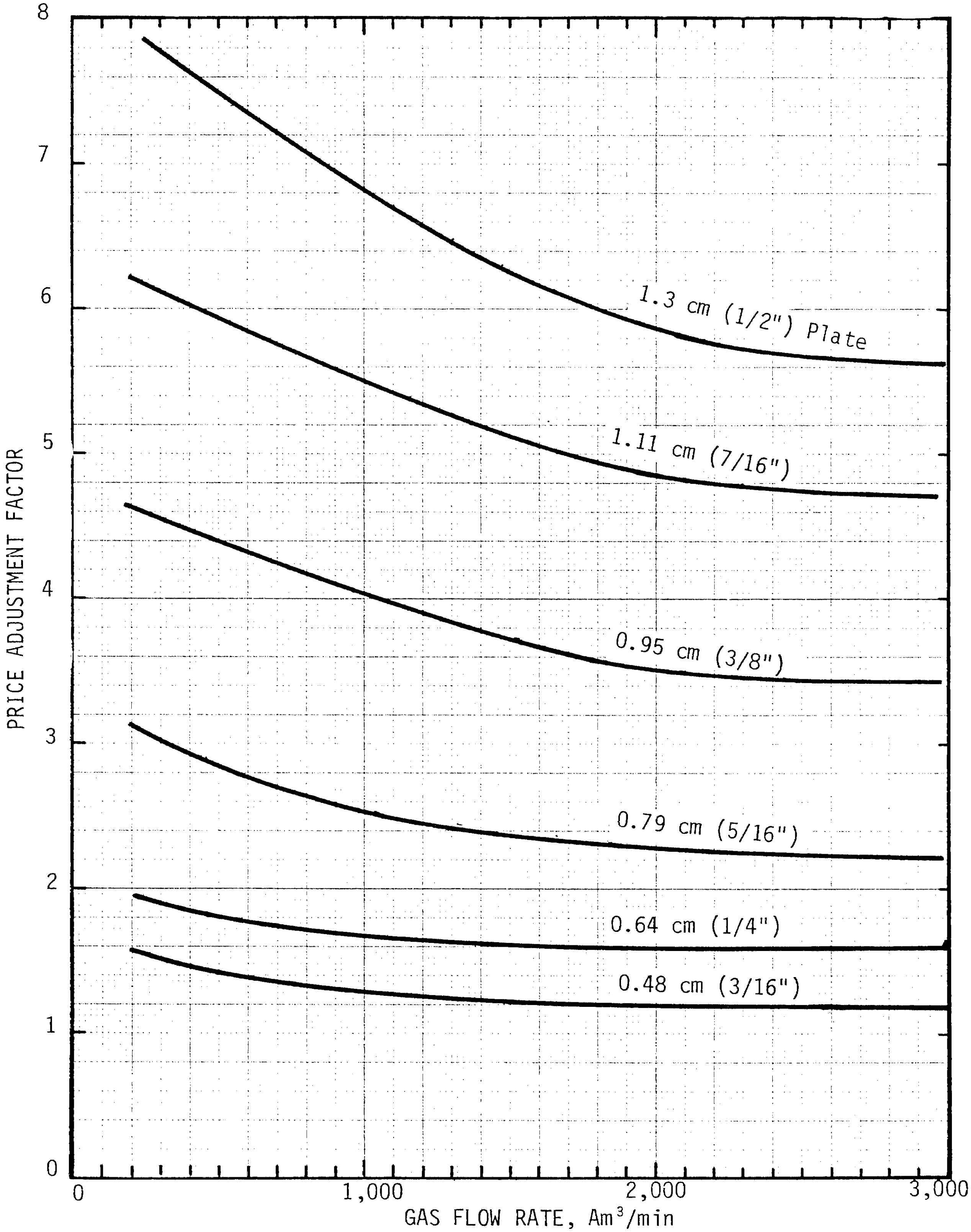


Figure 4.8.3-2. Price adjustment factor

where p_p = purchase price of saturator, \$

Q_G = gas flow rate, Am^3/min

The saturator cost includes vessel of carbon steel construction and support rings, platform, ladder, gratings, spray system, and control.

The quencher could be a spray tower or packed beds. It is usually fabricated from corrosion resistant materials, or is refractory lined, and can be either horizontally or vertically oriented. Costs for quenchers is estimated from the following equation (Neveril, 1978).

$$p_p = 11.46\ Q_G + 11.800 \qquad (4.8.3\text{-}4)$$

where p_p = Quencher price, \$

Q_G = gas flow rate, Am^3/min

The cost includes the vessel of carbon steel construction, inspection holes, supports, and internal water supply system. It does not include pumps, piping, and refractory.

To maximize the effects of condensation and particle growth, the water to the quencher should be as cold as possible. Therefore, if the water is recycled, the water to the quencher should be first passed through a cooling tower.

The cost of a cooling tower depends on cooling capacity. For capacities less than 1,000 tons (1 ton = 3,024 kcal/hr, (12,000 btu/hr) of useful refrigeration effect, or 3,780 kcal/hr (15,000 btu/hr) of heat rejected), installed cooling tower cost is (Neveril, 1978):

$$p_p = 1{,}530 + 138\ Q_t \qquad (4.8.3\text{-}5)$$

where p_p = installed cost of cooling tower, \$

Q_t = capacity of the cooling tower, ton

For capacities over 1,000 tons, cost is estimated from equations and adjustment factors presented in Table 4.8.3-1.

The cooling tower price includes the cooling tower, fan, pumps, motors, and installation. It does not include the price of the basin. The installed basin cost is about \$1,110/m^2 of basin area. The basin area is estimated as follows:

$$\text{Basin area } (m^2) = 6.2 \times 10^{-4}\ p_p \qquad (4.8.3\text{-}6)$$

where p_p = cooling tower price, \$

4.8.3-3 Calvert Collision Scrubber and Electrostatically Augmented Spray Scrubber

The price for the Calvert Collision Scrubber and electrostatically augmented spray scrubber is estimated from material and labor costs in fabricating the scrubber.

TABLE 4.8.3-1. PRICES FOR INSTALLED COOLING TOWER

Price Equations

Wet bulb temperature = 27.7°c (82°F)
Approach = 5.6°c (10°F)
Q_L = inlet water flow rate, Am^3/min

Range		Equation
33°C	60°F	\$ = 50,900 + 65,450 Q_L
28°C	50°F	\$ = 50,900 + 61,330 Q_L
22°C	40°F	\$ = 50,900 + 56,360 Q_L
17°C	30°F	\$ = 50,900 + 48,940 Q_L
14°C	25°F	\$ = 50,900 + 44,120 Q_L
11°C	20°F	\$ = 50,900 + 38,470 Q_L
8°C	15°F	\$ = 50,900 + 32,390 Q_L
6°C	10°F	\$ = 50,900 + 24,720 Q_L

Adjustment Factors

For Wet-Bulb Temperature

Wet-Bulb Temp	Factor
20°C (68°F)	1.54
21.1°C (70°F)	1.46
22.2°C (72°F)	1.38
23.3°C (74°F)	1.30
24.4°C (76°F)	1.22
25.6°C (78°F)	1.15
26.7°C (80°F)	1.07
27.7°C (82°F)	1.00

For Approach

Approach	Factor
3.3°C	1.60
4.4°C	1.20
5.6°C	1.00
6.7°C	0.85
8.9°C	0.65
11.1°C	0.50
13.3°C	0.40

SECTION 4

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