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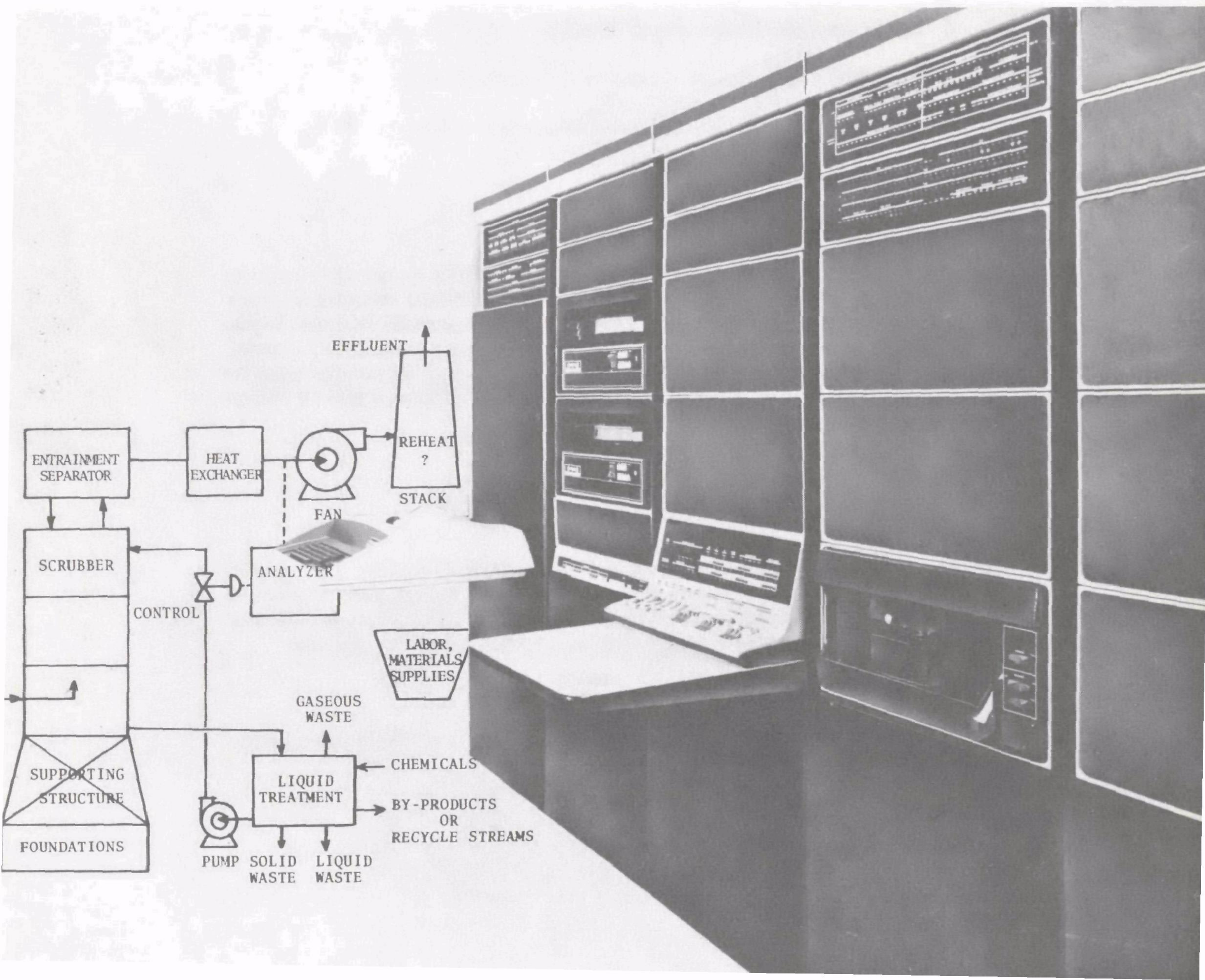
Particulate Control Highlights: Performance and Design Model for Scrubbers



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Particulate Control Highlights: Performance and Design Model for Scrubbers

by

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ABSTRACT

When EPA initiated the Wet Scrubber Systems Study in 1970 the state-of-the-art was largely empirical. Each application was considered to be a special case which could only be dealt with on the basis of long and specific experience. Engineering design was based on a primitive, cut-and-try approach and often resulted in an expensive overdesign to cover the wide range of uncertainty. There was also very little scrubber performance information available.

In the Wet Scrubber Systems Study all available information concerning wet scrubber theory and practice was reviewed and evaluated. The best available engineering design methods were evaluated and where necessary new or revised methods were developed to provide as sound a basis as possible for predicting performance. The result of this study was the publication in 1972 of the "Scrubber Handbook."

This capsule report summarizes the best available design models for wet scrubbers. Details of the models are reported in the Scrubber Handbook and other EPA publications listed in the bibliography.

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LIST OF ABBREVATIONS AND SYMBOLS

A = cyclone inlet area, m^2
A = dimensionless constant in equation (6)
A_c = cross-sectional area of the collector normal to gas flow direction, m^2
A_D = deposition area, m^2
A_p = projected area of baffles, m^2
A_t = cross-sectional area of duct, m^2
B = dimensionless constant in equation (6)
C = cyclone geometry parameter, dimensionless
C = particle concentration, g/m^3
C' = Cunningham slip correction factor, dimensionless
C_D = drag coefficient, dimensionless
C_i = particle concentration at the scrubber inlet, g/m^3
C_o = particle concentration at the scrubber outlet, g/m^3
D_d = cyclone diameter, m
D_p = particle diffusivity, m^2/s
D_{VG} = molecular diffusivity, m^2/s
d_c = collector diameter, m
d_d = drop diameter, m
d_e = cyclone exit diameter, m
d_f = fiber diameter, m
d_n = sieve plate perforation diameter, m
d_p = particle diameter, m or μm
d_{pa} = aerodynamic particle diameter, μmA
d_{pg} = mass median diameter, m or μmA
d_{RC} = required cut diameter, μmA
E = collection efficiency, fraction
E_c = charging electric field strength, v/m
E_p = effective precipitating electric field strength, v/m
F = foam density, dimensionless
f = empirical constant = 0.5
f_D = drag coefficient, dimensionless
f_h = fraction of hole area, fraction
$f(d_p)$ = frequency distribution of particles
g = acceleration of gravity, m/s^2
H = magnetic field strength, A/m
h = distance of drops traveled, m
K_p = inertial impaction parameter, dimensionless
K_{pt} = inertial parameter at the throat, dimensionless
k_G = gas thermal conductivity, J/m-s-°K
k_p = particle thermal conductivity, J/m-s-°K
ℓ = thickness of fibrous packing, m
M_G = molecular weight of gas, g/g-mol
M_v = molecular weight of vapor, g/g-mol
N_{Pe} = Peclet number, dimensionless
N_{Re} = Reynolds number, dimensionless
P = absolute pressure, Pa
$\overline{Pt}$ = overall particle penetration
Pt_d = penetration for particles with diameter d_p, fraction
R = radius, m
Q_G = gas volumetric flow rate, m^3/s
Q_L = liquid volumetric flow rate, m^3/s
q_c = collector charge, C
q_p = particle charge, C
p_G = gas partial pressure, Pa
T = gas temperature, °K
u_G = gas velocity passing the collector, m/s
u_G = gas velocity, m/s
u_{Gt} = gas velocity at the throat, m/s
u_h = gas velocity through perforation, m/s
u_{pD} = particle deposition velocity, m/s
u_t = terminal settling velocity, m/s
W = mass of particles, g
w_ℓ - weir length, m
A = depth of packing, m

Greek

α = fiber fraction, fraction
ε = dielectric constant, dimensionless
ε = porosity, fraction
ε_o = permitivity constant (8.854×10^{-12} coulomb^2/nt-m^2)
η = overall collection efficiency of a unit mechanism, dimensionless
cylinder = single cylinder collection efficiency, fraction
η_D = particle collection due to diffusion, fraction
η_{drop} = single drop collection efficiency, fraction
η_E = particle collection due to electric precipitation, fraction
η_G = particle collection due to gravity, fraction
η_I = particle collection efficiency due to impaction, fraction
η_{pot} = potential flow drop collection efficiency, fraction
η_{vis} = viscous flow drop collection efficiency, fraction
σ = angle of attack, degree
σ = penetration time, s
σ_g = geometric standard deviation, dimensionless
μ_G = gas absolute viscosity, kg/m-s
ρ_p = particle density, kg/m^3
ρ_w = density of water, kg/m^3
ΔP = pressure drop, cm W.C.
ΔP_d = dry pressure drop, cm W.C.

PERFORMANCE AND DESIGN MODELS FOR SCRUBBERS

INTRODUCTION

Scrubbers are devices which utilize a liquid in the separation of particulate or gaseous contaminants from a gas stream. The liquid may be used to contact the gas and particles directly, or may be used to clean solid surfaces on which the particles or gases have been collected.

Scrubbers are used extensively for the control of air pollution emissions. There are so many different scrubber systems offered by manufacturers that it is often difficult to choose the right scrubber for a particular job.

The optimum scrubber system for a particular job will not depend only on the system costs. The major consideration should be whether the scrubber is capable of removing the pollutants to the degree required. An inexpensive, simple scrubber which does not meet the efficiency requirements is not only useless, but a waste of money and time. It is, therefore, of primary importance to provide as sound a basis as possible for predicting performance.

Design models based on fundamental engineering concepts provide the best approach for evaluating the performance and cost of scrubber systems. This report summarizes the best available engineering models for particulate scrubbers.

COLLECTION MECHANISMS

Currently available scrubbers can be grouped into a number of categories: plate, massive packing, fibrous packing, preformed spray, gas-atomized spray, centrifugal, baffle, impingement and entrainment, mechanically aided, moving bed, and various combinations (Calvert, et al. 1972 and Calvert, 1977). No matter what type of scrubber is being evaluated, it is convenient to consider dust particles to be separated from the gas by one or more unit mechanisms, the basic particle collection elements which account for the scrubber performance. 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. Table 1 summarizes the scrubber groups and the important unit mechanisms for each group.

For each of the unit mechanisms, 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.

DESIGN EQUATIONS

There are two basic approaches for developing design equations for scrubbers. One approach 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. The second approach is to determine the deposition velocity of a particle experiencing a specific deposition force, such as electrical attraction. These two approaches are discussed below.

Unit Mechanism Approach

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

$$-\frac{dc}{c} = \frac{|u_r|}{Q_G} \eta \; dA_c \qquad (1)$$

"η" is the overall collection efficiency of a unit mechanism.

Inertial impaction is the collection of moving particles by impingement on some target. The relative effect of inertial impaction for different particles and flow conditions is characterized by the inertial impaction parameter, K_p, defined as:

$$K_p = \frac{C' \rho_p d_p^2 u_G}{9 \mu_G d_c} \tag{2}$$

Figure 1 shows the theoretical and experimental target efficiencies for a single sphere and a single cylinder as related to the inertial impaction parameter.

Equation (1) has been solved for various scrubber systems which involve collection by inertial impaction. The results are tabulated in Table 2.

Equation (1) also may be applied to other collection mechanisms if an expression for "η" is known. Table 3 presents expressions for the single drop and single cylinder collection efficiencies resulting from various collection mechanisms.

Deposition Velocity Approach

The particle deposition velocity is the component of its velocity in the direction towards the collecting surface. If the particle deposition velocity is constant and the gas and particles are well mixed everywhere in the scrubber, the particle collection can be predicted from the following equation:

$$Pt_d = 1 - E = \frac{c_o}{c_i} = \exp\left[- \frac{u_{pD} A_D}{Q_G} \right] \tag{3}$$

"u_{pD}" 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 is a list of theoretical equations predicting the deposition velocity for each collection mechanism. The scrubber collection efficiency can be calculated by using equation (3) coupled with the appropriate deposition velocity and the total deposition area of the scrubber.

Pressure Drop

Along with particle collection efficiency, the scrubber power requirement is also an important consideration in designing the optimum pollution control system. The power requirement 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 scrubbers are summarized in Table 5.

PERFORMANCE PREDICTION AND SCRUBBER DESIGN

Air pollution control regulations generally specify a maximum mass rate of emissions and often set a concentration limit as well. By knowing the particulate 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 penetration will depend on the size distribution and on the penetration for each size. The overall penetration, $\overline{Pt}$, of any device collecting a dust with any size distribution will be:

$$\overline{Pt} = \int_{0}^{W} \frac{Pt_d \, dW}{W} = \int_{0}^{\infty} Pt_d \, f(d_p) dd_p \qquad (4)$$

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.

In designing a scrubber, the maximum allowable penetration, $\overline{Pt}$, and size distribution, $f(d_p)$, in the process stream must be known. The only variable in equation (4) is "Pt_d" which is a function of scrubber geometry and scrubber operating conditions. One must first choose the scrubber geometry and operation condition, then evaluate "Pt_d" by means of the design equations presented in Table 2 and integrate equation (4) to obtain the overall penetration, $\overline{Pt}$. If the calculated "$\overline{Pt}$" 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 "$\overline{Pt}$." 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" from the appropriate design equations. Then "$\overline{Pt}$" may be calculated from equation (4) to check whether it is acceptable.

This design method is precise but time-consuming. A much simpler method, called the "cut diameter" method, has been developed to provide quick designs when precision is not required. The "cut diameter" method has been described in the "Scrubber Handbook" and other publications.

CUT DIAMETER METHOD FOR PERFORMANCE PREDICTION AND SCRUBBER DESIGN

Cut Diameter

A very convenient parameter for describing the capability of a particle scrubber is the diameter of the particle for which the scrubber is 50% efficient. 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 size at 50% efficiency.

The great utility of cut diameter stems from the fact that a curve of collection efficiency versus 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.

Integrated Penetration

Most scrubbers that collect particles by inertial impaction perform in accordance with the following relationship:

$$Pt_d = \exp\left(-A\ d_{pa}^{\ B}\right) = \frac{c_o}{c_i} \qquad (5)$$

"B" is an empirical constant. Packed-bed and plate type scrubber performance are described by a value of "B = 2.0" whereas for centrifugal scrubbers of the cyclone type, B = 0.7. Gas-atomizing scrubber performance fits a value of "B = 2.0" over a large portion of the usual operating range. Therefore, we use a value of "B = 2.0" as representative of most scrubbers operating in the inertial impaction regime. Figure 2 plots collection efficiency against the ratio of aerodynamic particle diameter to performance cut-diameter, showing one line based on equation (5) and another for a venturi scrubber under typical operating conditions.

Most industrial particulates have approximately a log-normal size distribution. Hence, the two basic parameters of the log-normal distribution adequately describe the size distributions of particulate matter. These parameters are the mass median diameter, d_{pg}, and the geometric standard deviation, σ_g. If the size distribution is log-normal, a plot of the percent of particles less or greater than a stated diameter versus the diameter, on logarithmic probability graph paper, will yield a straight line. The 50% value of "d_{pa}" equals "d_{pg}" and the ratio of the particle diameter at about 84.1% undersize to "d_{pg}" is equal to "σ_g."

One can integrate equation (4) with "Pt_d" given by equation (5) and "$f(d_p)$" by log-normal distribution. The results are presented in graphical form in Figure 3. The overall penetration ($\overline{Pt}$) for the entire size distribution is plotted against the ratio of required cut diameter to mass median diameter, with geometric standard deviation as the parameter.

Figure 3 can be used to determine what "d_{RC}," the required cut diameter, must be in order to get a specific "$\overline{Pt}$" for a given size distribution. For example, suppose the size distribution has "d_{pg} = 10 µmA" and "σ_g = 3.0," and one needs 99% collection efficiency. The penetration is 100% minus the percent collection efficiency, or 1%, which corresponds to "$\overline{Pt}$ = 0.01" in fractional units.

The diameter ratio corresponding to "Pt = 0.01" and "σ_g = 3.0" is "d_{RC}/d_{pg} = 0.063." Since "d_{pg} = 10 µmA, d_{RC} = 0.63 µmA." This means that one will need a scrubber with a cut diameter of 0.63 µmA or less to achieve 99% collection of the particles in question.

Cut/Power Relation

Mathematical models for scrubber performance and the cut-diameter approach developed in the "Scrubber Handbook" led to the concept that performance cut diameter could be related to gas-phase pressure drop, or power input to the scrubber. The results of subsequent performance tests on a variety of scrubbers in industrial installations, combined with mathematical modeling, enabled the refinement of the cut/power relationship shown in Figure 4. The curves give the cut diameter (µmA) as a function of either power input (W/m³/min) or gas-phase pressure drop (cm W.C.) for a number of typical installations such as sieve-plate column, packed column, fibrous packed bed, gas-atomized spray, and mobile fluidized bed.

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

One can see from Figure 4 that the only "unaided" scrubbers capable of giving a 0.6 μmA cut diameter are the gas-atomized and fibrous-packed-bed types. A gas-phase pressure drop of about 33 cm W.C. would be required for the gas-atomized scrubber. The fibrous packing would need 56 cm W.C. for 100 μm fiber diameter and about 15 cm W.C. for 50 μm fibers.

It would take about 75 μm fiber diameter to achieve a "d_{RC} = 0.6 μmA" at slightly less pressure drop than for the gas-atomized scrubber. This is quite fine fiber or wire, and serious questions would arise regarding its structural stability, and susceptibility to corrosion and plugging. The safe approach would be to choose the gas-atomized scrubber unless extensive pilot tests could be done with fine fiber beds.

Other types of scrubbers could 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.

Power and Cost

The equivalent power axis plotted on the top of the cut/power plot is based on 50% efficiency for a fan and motor combination. The theoretical power requirement is approximately 1.63 $W/m^3/min$ for each centimeter of water pressure drop. Power costs can be approximated as twice the theoretical power required for 50% efficiency.

Equipment costs are best estimated from vendor's quotations. As usual, one must be sure that all prices for competing units are on the same basis. Materials, ducting, electrical work, foundations, supporting structure, etc., must be specified as included or not.

TABLE 1. SCRUBBER CLASSIFICATIONS

Geometric Type	Unit Mechanism for Particle Collection
Plate	Jet impingement, bubbles
Massive packing	Sheets (curved or plane), jet impingement
Fibrous packing	Cylinders
Pre-formed spray	Drops
Gas-atomized spray	Drops, cylinders, sheets
Centrifugal	Sheets
Baffle and secondary flow	Sheets
Impingement and entrainment	Sheets, drops; cylinders, jets
Mechanically aided	Drops, cylinders, sheets
Moving bed	Bubbles, sheets
Combinations	

TABLE 2. DESIGN EQUATIONS FOR VARIOUS SCRUBBER TYPES

SCRUBBER TYPE	DESIGN EQUATIONS
Sieve Plate	$Pt_d = \exp[-40\, F^2 K_p],\; K_p = \frac{d_{pa}^2\, u_h}{9\, \mu_G\, d_h}$, $0.38 < F < 0.65$
Massive Packing	$Pt = \exp\left[-\frac{7}{\varepsilon}\frac{Z}{d_c} K_p\right]$
Fibrous Packing	$Pt_d = \exp\left[-\frac{4\ell}{d_f}\; \alpha\; \eta_{cylinder}\right]$ $\eta_{cylinder} = f(K_p)$, from Figure 2
Venturi and Gas-Atomized Spray	$Pt_d = \exp\left[\frac{2\, Q_L\, u_{Gt}\, \rho_L\, d_d}{55\, Q_G\, \mu_G}\; F(K_{pt}, f)\right]$ $F(K_{pt}, f) = \frac{1}{K_{pt}}\left[1.4 \ln\left(\frac{K_{pt} f + 0.7}{0.7}\right) + \frac{0.49}{0.7 + K_{pt} f} - (K_{pt} f + 0.7)\right]$
Preformed Spray	$Pt_d = \exp\left[-\frac{3\, Q_L\, u_t\, Z}{2\, Q_G\, d_d\, (u_t - u_G)}\; \eta_{drop}\right]$, vertical countercurrent flow $Pt_d = \exp\left[-\frac{3\, Q_L\, h}{2\, Q_G\, d_d}\; \eta_{drop}\right]$, cross-flow $\eta_{drop} = f(K_p)$, from Figure 2
Impingement and Entrainment	$Pt_d = \exp\left[\frac{2(\Delta P_d)\, d_d}{55\, u_G\, \mu_G}\; F(K_{pt}, f)\right]$ $F(K_{pt}, f) = \frac{1}{K_{pt}}\left[1.4 \ln\left(\frac{K_{pt} f + 0.7}{0.7}\right) + \frac{0.49}{0.7 + K_{pt} f} - (K_{pt} f + 0.7)\right]$
Centrifugal (cyclone)	$Pt_d = \exp\left[-2(C\,\psi)^{1/(2n+2)}\right]$ $\psi = \frac{\rho_p\, d_p^2\, u_G}{18\, \mu_G\, D_c}\,(n+1)$ $n = 1 - \left[1 - \frac{(0.00394\, D_c)^{0.14}}{2.5}\right]\left(\frac{T}{283}\right)^{0.3}$
Centrifugal (cyclone with spray)	$Pt_d = \exp\left[-2\,(C\,\psi)^{1/2n+2} - \frac{3\, Q_c\, (R_c - R_s)}{2\, Q_G\, d_d}\; \eta_{drop}\right]$ $\eta_{drop} = f(K_p)$, from Figure 2 ψ and n same as that for the cyclone
Baffle Type Collector	$Pt_d = \left[1 - (\eta_{cp} + \eta_{drop})\right]^n$ $\eta_{cp} = 1 - \exp\left[\left(\frac{A_p}{A_t}\right) K_p\right]$ $\eta_{drop} = f(K_p)$, from Figure 2

TABLE 3. SINGLE DROP AND SINGLE CYLINDER COLLECTION EFFICIENCY DUE TO VARIOUS COLLECTION PHENOMENA

COLLECTION PHENOMENA	DROP	CYLINDER
Interception	$\eta_I = \left(1 + \frac{d_p}{d_c}\right)^2 - \left(\frac{d_c}{d_c + d_p}\right)$	$\eta_I = 0.0518 \left(\frac{C_D\ N_{Ref}}{2}\right) \frac{d_p}{d_f}$, laminar flow $= 1 + \frac{d_p}{d_f} - \frac{d_f}{d_p + d_f}$, turbulant flow
Diffusion	$\eta_D = \frac{4\ D_p}{\lvert u_G - u_d \rvert\ d_d} \left[2 + 0.552\ N_{Red}^{0.5} \left(\frac{\nu_G}{D_p}\right)^{1/3}\right]$	$\eta_D = 0.75 \left(\frac{C_D\ N_{Ref}}{2}\right)^{0.4} N_{Pe}^{-0.6}$
Gravity Settling	$\eta_G = \frac{\eta_{vis} + \eta_{pot}\left(\frac{N_{Red}}{60}\right)}{1 + \frac{N_{Red}}{60}}$	$\eta_G = \frac{u_t}{u_G} = \frac{C'\ d_p^2\ \rho_p\ g}{18\ \mu_G\ u_G}$
Electrostatic Precipitation	$\eta_E = \frac{4\ C'\ q_p\ q_c}{3\pi\ \mu_G\ d_p\ u_o\ \varepsilon_o}$, charged particle charged drop $= \left(\frac{30\ \pi}{24}\ \frac{\varepsilon - 1}{\varepsilon + 2}\ \frac{C'\ d_p^2\ q_c^2}{\mu_G\ u_o\ d_c\ \varepsilon_o}\right)^{0.4}$, uncharged particle charged drop	$\eta_E = 1.5 \left[\frac{\left(\frac{\varepsilon - 1}{\varepsilon + 1}\right) q_p^2\ C'}{12\ \pi^2 \varepsilon_o\ d_f^2 \mu_G\ d_p\ u_o}\right]^{0.5}$

TABLE 4. 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	$u_{PD} = \frac{C' \mu_o H q_p \mu_G}{3 \pi \mu_G d_p}$

TABLE 5. PRESSURE DROP

Scrubber Type	Pressure Drop
Sieve Plate	$\Delta P = h_w + h_{ow} + h_{dp} + h_r$ h_w = weir height ≈ 5 cm $h_{ow} = 0.157 \frac{Q_L}{w_\ell}$ $h_{dp} = 1.14\ [0.4\ (1.25-f_h)+(1-f_h)^2]\ \frac{\rho_G\ u_h^2}{\rho_L\ 2g}$ $h_r = 0.13 \frac{\rho_w}{\rho_L}$
Massive Packing	Generalized pressure drop correlation for packed bed (Perry, 1973).
Fibrous Packing	$\Delta P = 6.5 \times 10^{-4} \frac{\ell(1-\varepsilon)\ \rho_G\ C_D\ u_G^2}{d_f}$
Venturi and Gas Atomized Spray	$\Delta P = 8.24 \times 10^{-4}\ u_{Gt}^2 \left(\frac{Q_L}{Q_G}\right)$
Centrifugal (cyclone)	$\Delta P = 0.000513\ \rho_G \left(\frac{Q_G}{A}\right)^2 \left(\frac{7.5\ A}{d_e^2}\right)$, with inlet vanes $= 0.000513\ \rho_G \left(\frac{Q_G}{A}\right)^2 \left(\frac{16\ A}{d_e^2}\right)$, without inlet vanes
Baffle	$\Delta P = \sum_{i=1}^{n} 1.02 \times 10^{-3}\ f_D\ \rho_G \frac{u_G^2}{2 \cos^2\theta} \frac{A_p}{A_t}$

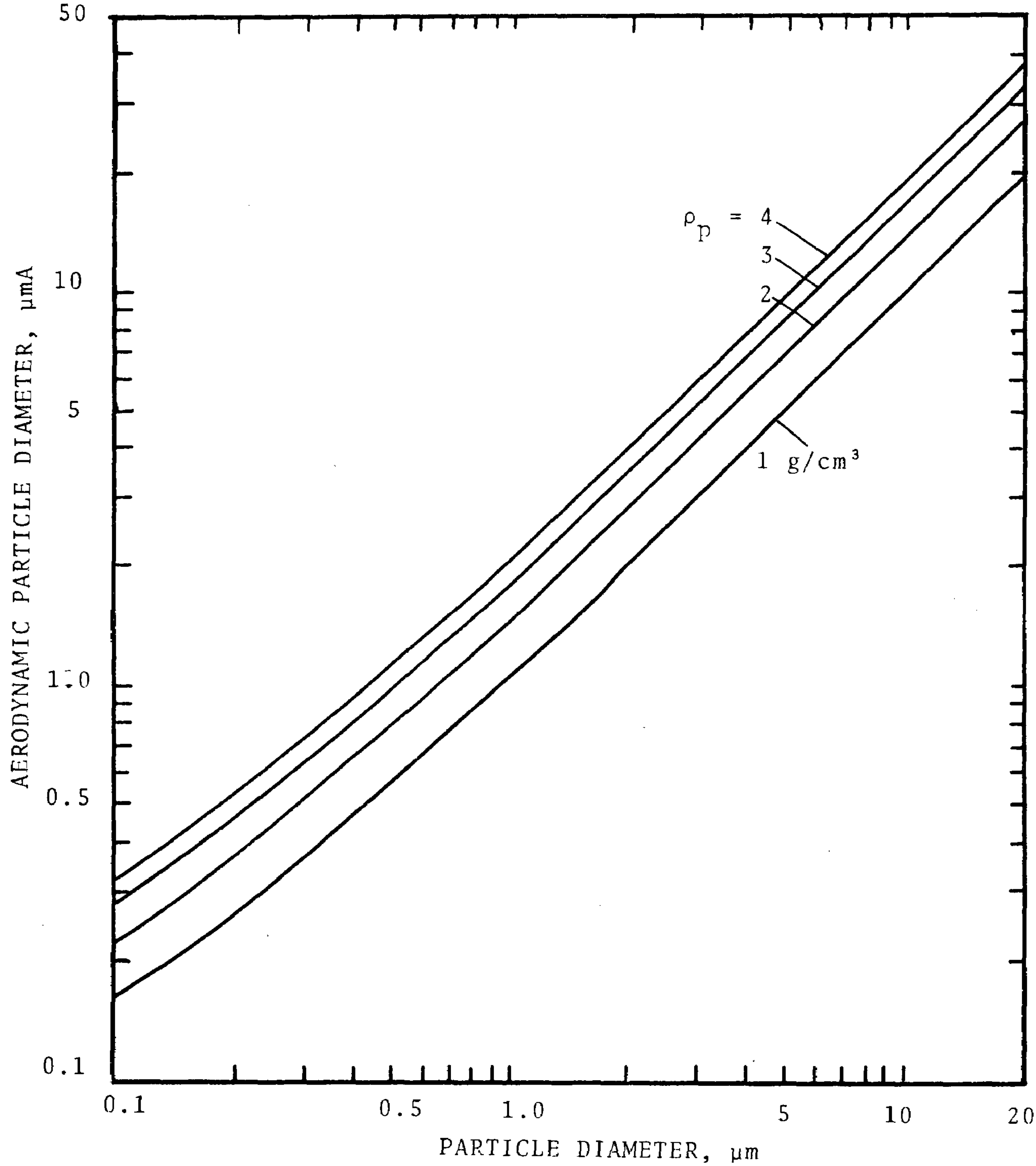
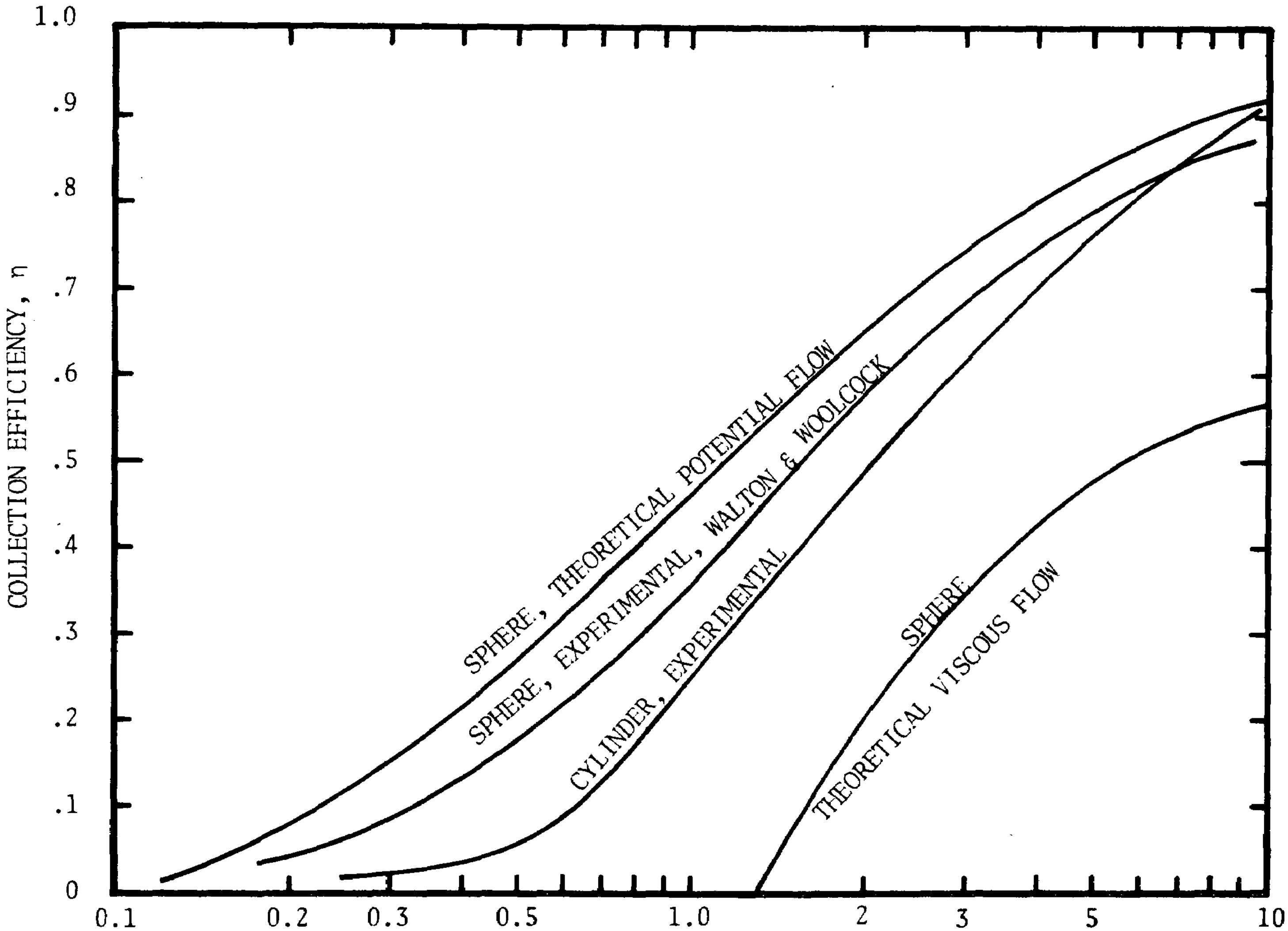


Figure 1. Relation between physical and aerodynamic particle diameter.



$$K_p = \frac{C' \rho_p d_p^2 U_o}{9 \mu_G d_c}$$

Figure 2. Experimental and calculated collection efficiencies for sphere and cylinder.

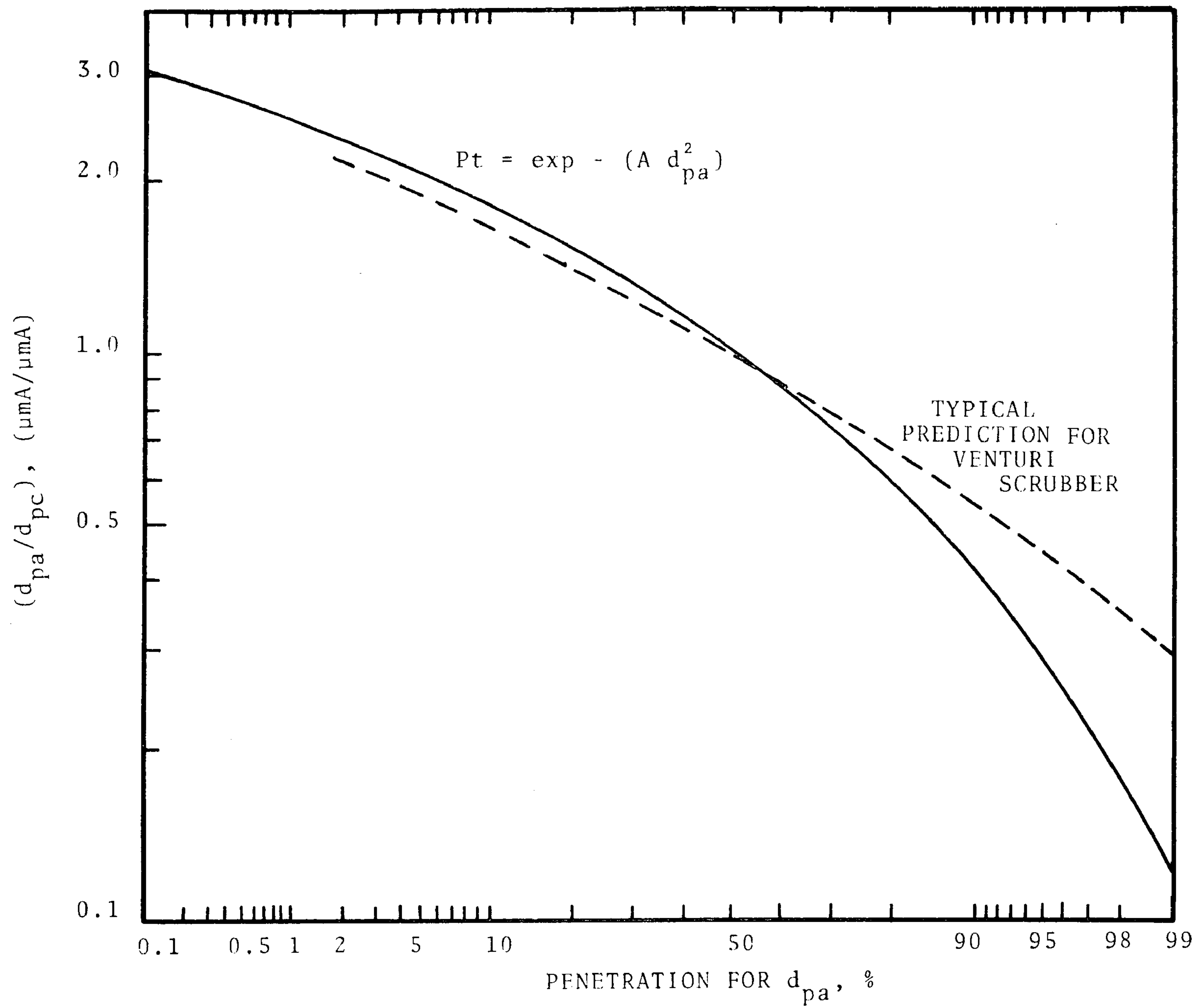


Figure 3. Predicted particle diameter, penetration relationship for inertial impaction (Calvert, 1974).

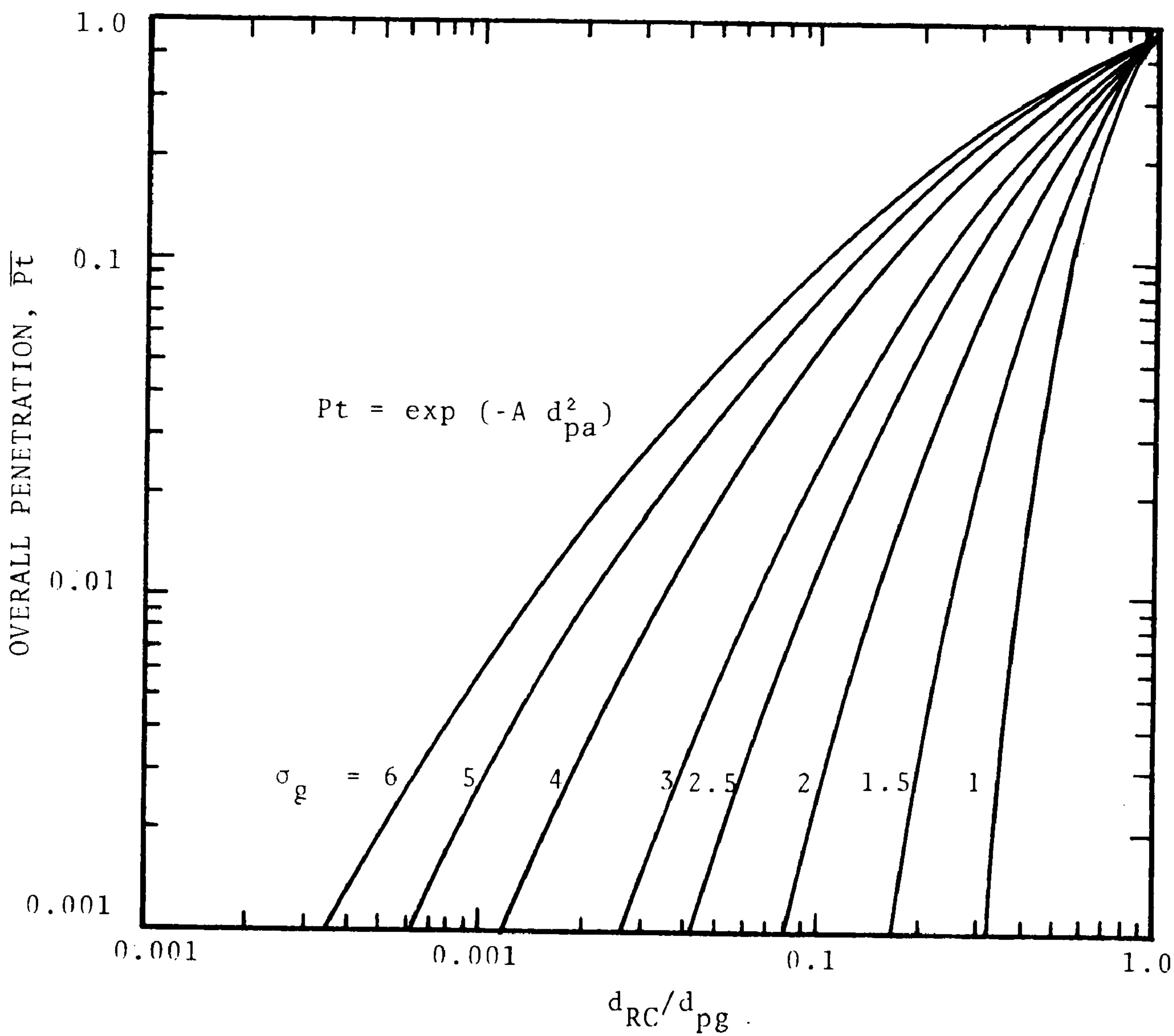


Figure 4. Integrated (overall) penetration as a function of cut diameter and particle parameters.

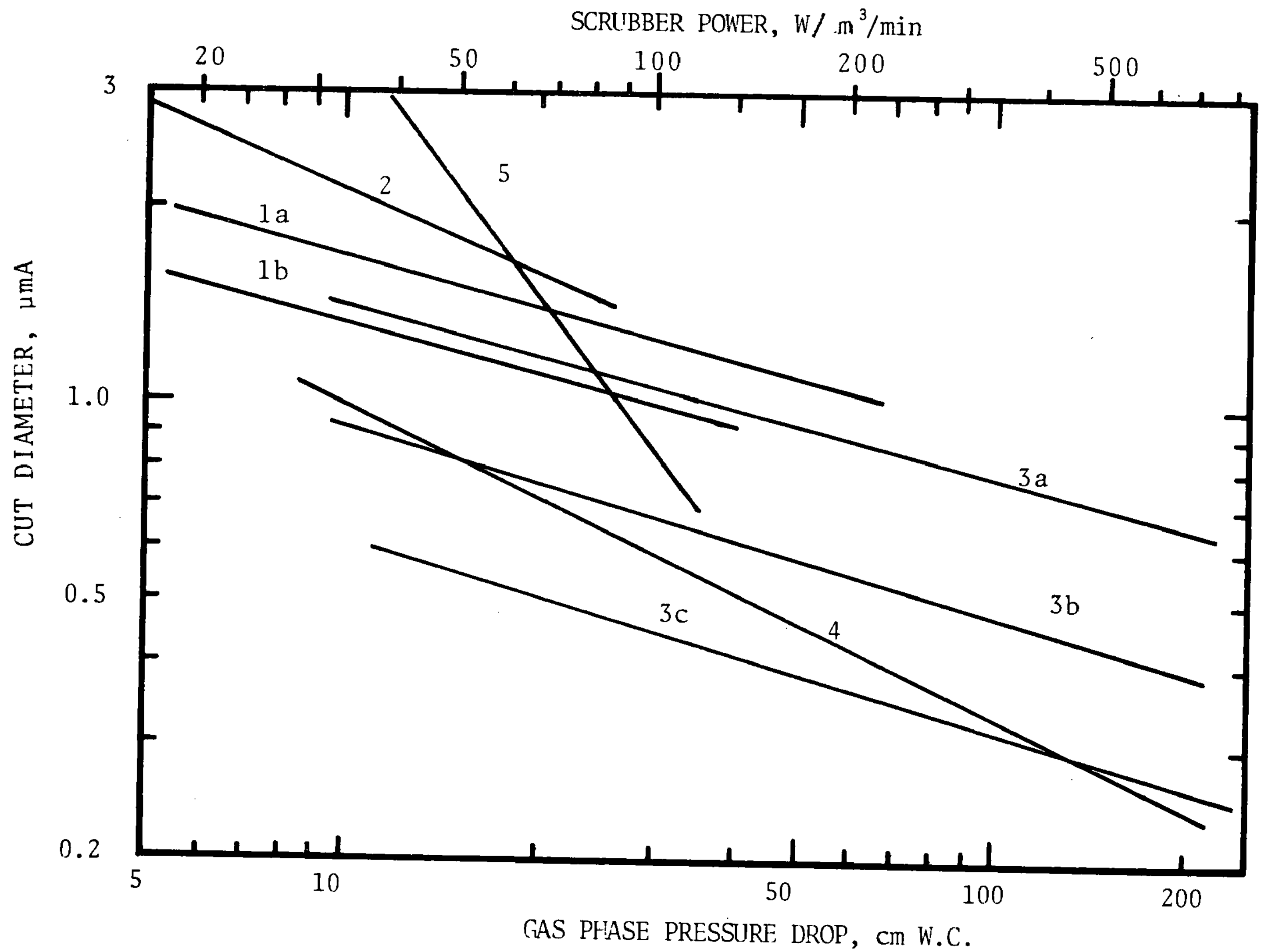


Figure 5. A.P.T. cut/power plot.

1a. Sieve-plate column with foam density of 0.4 g/cm³ and 0.5 mm hole dia. The number of plates does not affect the relationship much (Experimental data and mathematical model.)

1b. Same as 1a except 3.2 mm hole dia.

2. Packed column with 1-in. rings or saddles. Packing depth does not affect the relationship much. (Experimental data and mathematical model.)

3a. Fibrous packed bed with 0.3 mm dia. fiber, any depth. (Experimental data and mathematical model.)

3b. Same as 3a except 0.1 mm dia. fibers.

3c. Same as 3a except 0.05 mm dia. fibers.

4. Gas-atomized spray. (Experimental data from large venturis, orifices, and rod-type units, plus mathemtical model.)

5. Mobile bed with 1 to 3 stages of fluidized hollow plastic spheres. (Experimental data from pilot plant and large-scale power plant scrubbers.)

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16. ABSTRACT The report gives a capsule summary of the best available design models for wet scrubbers and their application to fine particulate control. Details of the models are reported in the Scrubber Handbook and other EPA publications listed in the bibliography. When EPA initiated its Wet Scrubber Systems Study in 1970, the state-of-the-art was largely empirical. Each application was considered to be a special case which could only be dealt with on the basis of long and specific experience. Engineering design was based on a primative, cut-and-try approach and often resulted in an expensive overdesign to cover the wide range of uncertainty. There was also very little scrubber performance information available. In the Wet Scrubber Systems Study all available information concerning wet scrubber theory and practice was reviewed and evaluated. The best available engineering design methods were evaluated and, where necessary, new or revised methods were developed to provide as sound a basis as possible for predicting performance. The Scrubber Handbook, published in 1972, resulted from this study.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Pollution Control	13B
Dust	Stationary Sources	11G
Scrubbers	Particulate	07A
Gas Scrubbing		13H
Mathematical Models		12A

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