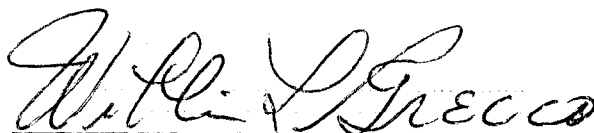


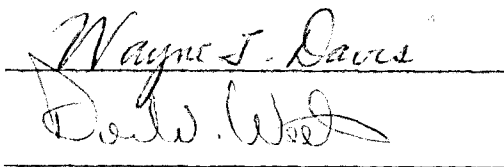
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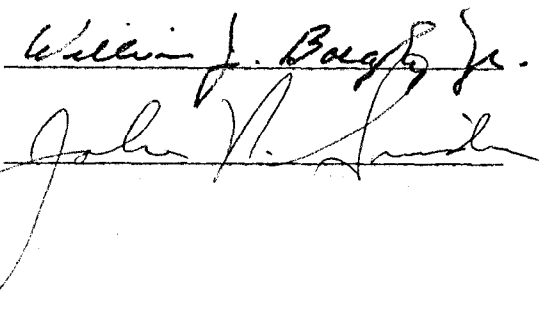
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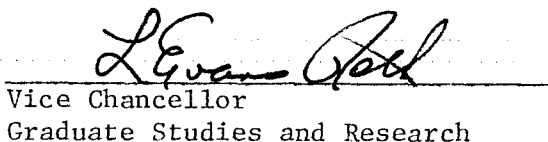
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PRESSURE DROP EFFECTS OF PARTICLE SIZE DISTRIBUTION
MODIFICATION ON THE PERFORMANCE OF FABRIC
FILTRATION DUE TO CYCLONE PRECLEANING
OF GAS FLOWS

A Dissertation
Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Frank Richard Kurzynske

June 1978

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ABSTRACT

The primary objective of this research was to examine the effects of particle size distribution modification, resulting from the cyclonic precleaning of dust-laden gas flow, on the pressure drop performance of fabric filtration media. Moreover, the relationship of overall cyclone collection efficiency on system pressure drop (summation of pressure losses across both fabric filter and precleaning cyclone) was studied.

This study, in part performed on laboratory scale equipment, revealed that there was a minimum system pressure drop value associated with cyclone and fabric media type and operating conditions which was obtained for a given inlet dust size distribution at a specific cyclone efficiency. At this optimum cyclone efficiency, the system pressure drop savings of a cyclone/fabric filter combination as compared to a fabric filter alone were generally found to be substantial. However, as cyclone efficiency exceeded its optimum value, system pressure drop rose rapidly and not only quickly negated any pressure drop savings achieved through the use of a precleaner, but increased operating pressure losses above those values at which a fabric filter would operate without a precleaner. For this reason the establishment of an optimum precleaner efficiency for a cyclone/fabric filter control device is deemed important.

A modeling technique was derived in this study to predict system pressure drop as a function of cyclone efficiency. Using laboratory generated data, graphical relationships were generated which through data interpolation provided inputs to the developed model. A unique

relationship was found between the geometric mass mean diameter, d_{pg} -out, of the particulate penetrating through the cyclone, and the operating pressure drop across the fabric filter dust cake as a function of dust loading. This empirical relationship was then used to predict fabric filter pressure loss as a function of cyclone efficiency.

An optimization capability was added to the derived cyclone/fabric filter model with the development of a theoretical subroutine to predict the previously found graphical model inputs (with the exception of the fabric pressure loss/ d_{pg} -out relationship which must be empirically found). With the incorporation into the expanded model of a pressure loss expression for a commercial series of cyclone sizes, the expanded model with optimization routine was used to predict the optimum cyclone inlet velocity for each cyclone size which resulted in the optimum cyclone efficiency and the minimum system pressure drop for a given inlet dust size distribution, cyclone and fabric media type, and operating conditions.

Results of the modeling analysis substantially delineated the effect that a cyclone precleaner has on cyclone/fabric filter system pressure drop. Effects of varying cyclone diameter, inlet particle size distribution, and cyclone inlet velocity were studied. This modeling technique should be useful as a tool to aid in the optimum design of cyclone/fabric filter collectors with a minimum annualized cost.

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LIST OF SYMBOLS

- A = cyclone parameter based on physical characteristics of the collector, the particles, and the gas flow.
- A_c = area of cyclone interior collecting surface.
- A_p = surface area of particle.
- A_s = surface area of cyclone exposed to gas (for practical purposes equivalent to A_c).
- a = height of cyclone gas inlet.
- B = diameter of cyclone conical section at collected dust exit.
- B = constant dependent upon type of inertial collection device.
- B = constant defined by Equation V-7.
- b = width of cyclone gas inlet.
- b' = constant in Equation V-6.
- b'' = constant in Equation V-7.
- c = variable in Equation II-12 dependent on cyclone dimension ratios and defined by Equation II-13.
- c_i = effective dust loading to filter.
- c_i -inlet = inlet dust loading to cyclone.
- D = diameter of cyclone body.
- D_e = diameter of cyclone gas exhaust exit.
- d_c = diameter of cyclone conical section at farthest distance the vortex extends below the gas exit duct.

d_{crit} = size of particle calculated to be collected with 100% efficiency.

d_p = particle diameter.

d_{pg} = geometric mass mean diameter of particle size distribution.
distribution.

d_{pg-in} = particulate geometric mass mean diameter into cyclone.

d_{pg-out} = particulate geometric mass mean diameter penetrating through cyclone.

d_{p50} = size of particle calculated to be collected with 50% efficiency.

d_{vs} = specific surface mean diameter.

d_w = particle weight corresponding to the interval $d(\ln(d_p))$ of particle sizes.

E = cost of electricity per kilowatt-hour.

E_f = efficiency of filter in retaining dust cake.

F_r = frictional resistance to flow.

F_s = centrifugal separating force on particle.

G = friction constant (0.005 for cyclones).

g = gravitational acceleration constant.

H = total height of cyclone (cylinder + cone).

H = resistance of dust cake on fabric filter as expressed by Equation II-48.

h = height of cylindrical body of cyclone.

h_r = number of control device operating hours per year.

K = filtration bed permeability.

$\bar{K}$ = constant with a unitless value of 16 as expressed in Equation II-33.

- K_1 = initial resistance of clean fabric.
 K_2 = specific dust resistivity (theoretically determined).
 K_2' = operating dust resistivity (measured).
 k = Carmen-Kozeny constant.
 L = depth of dust deposit on filter.
 L' = filtration bed depth.
 M = constant defined by Equation V-6.
 m' = constant in Equation V-6.
 m'' = constant in Equation V-7.
 N = number of spiral flow revolutions in cyclone.
 n = dimensionless exponent describing vortex strength.
 n = number of items from 1 to i .
 $\overline{Pt}$ = integrated penetration.
 Q = gas flow rate.
 Q_6 = flow reference capacity at six inch pressure drop for
 Fisher-Klosterman XQ series cyclones.
 R = radius of rotation.
 R_p = radius of cyclone body.
 r_p = particle radius.
 S = distance outlet exhaust dust protrudes into cyclone
 interior.
 S_s = specific surface.
 S_v = surface area exposed to flow per unit volume.
 S_w = surface area exposed to flow per unit weight.
 T = absolute temperature in degrees Kelvin.
 t = elapsed time of fabric filter operation.

V = filtration velocity through fabric filter.

V_e = gas velocity at entrance to exit pipe.

V_i = inlet cyclone gas velocity.

V_p = volume of particle.

V_t = tangential velocity of cyclone vortex at a given radius of rotation (R).

V_{tmax} = maximum tangential velocity.

V_{tp} = particle tangential velocity at cyclone body wall.

W = weight of dust deposit on filter.

W_c = total weight of particulate sample.

w = migration velocity of particles to cyclone wall.

x = value defined by Equation II-1.

y = farthest distance the vortex extends below the gas

z = transformation defined by Equation II-27.

α = ratio of bulk density to true density.

α' = variable defined by Equation II-38.

β = dimensionless volume shape factor.

ΔH = pressure loss expressed as a number of inlet velocity heads.

ΔP_c = pressure drop across cyclone handling only clean air.

ΔP_{cyc} = pressure drop across cyclone.

ΔP_d = pressure drop across cyclone which takes into account the effect of dust loading on cyclone pressure drop.

$\Delta P_{dustcake}$ = pressure loss across bed of accumulated particulate.

ΔP_{fabric} = pressure loss across the woven fiber strands composing fabric.

ΔP_{ff} = pressure loss due to combination of
 $\Delta P_{fabric} + \Delta P_{dustcake}$ (total pressure loss across
 fabric filter).

ΔP_{sav} = attainable pressure drop savings.

ΔP_{sys} = total system pressure loss resulting from the
 combination of $P_{cyc} + P_{ff}$.

ϵ = volumetric porosity of filtration bed.

ϵ_e = value defined by Equation II-35.

ϵ_i = value defined by Equation II-36.

η = fractional efficiency value.

λ = particle shape correction factor.

μ = absolute gas viscosity.

μ = micron (unit of length).

ρ_b = bulk particle density.

ρ_g = density of gas.

ρ_p = true particle density.

ρ_L = density of liquid.

σ_g = geometric standard deviation.

τ = unitless cyclone friction factor of approximately
 0.02.

v = particle velocity with respect to gas.

ψ = inertial impaction parameter.

T = friction factor defined by Equation II-7.

CHAPTER I

INTRODUCTION

I. STATEMENT OF PROBLEM

Precleaning devices, most frequently dry cyclones, may be used in dust-laden air flow to classify particulate, to remove abrasive particles, to decrease the percent of combustible carbonaceous material, and/or to reduce dust loading prior to the inlet side of high efficiency dust collectors. Cyclones and other precleaning devices accomplish this by removing the larger, heavier fraction of the dust distribution. By adjusting the dimensions and/or the flow rate of a cyclone, an increasing or decreasing fraction of the dust distribution can be collected. This size distribution modification inherently effects the performance of the final collector.

The fabric filter is one type of high efficiency dust collector whose pressure loss and efficiency performance is affected by a precleaner. A primary benefit of a precleaner prior to fabric filtration is to reduce the amount of particulate the fabric filter must handle. This particulate reduction results in a reduction in the weight of the dust cake formed on the fabric per unit of time which results in lower resistance across the fabric to air flow. However, the corresponding reduction in the particulate mass mean diameter by the precleaner results in an increase in the rate at which filtration resistance increases with time. This tendency of filtration resistance to rise more rapidly on a fabric

filter using a precleaner is due to the formation of a particle filtration bed with smaller particles. Consequently, precleaners affect fabric filters by competing mechanisms; one reducing pressure loss as a function of dust loading, and the other increasing pressure loss as a function of particle size. For a given dust, the system pressure drop (the sum of pressure losses across a cyclone precleaner and a fabric filter) may reach a point, depending on the efficiency of the cyclone, that exceeds the pressure drop that would occur across a fabric filter alone. Thus, the pressure drop savings benefit from reduced particulate loading on the fabric filter is eradicated.

Fabric conditioning with the smaller particles additionally produces a higher fabric residual pressure drop (the pressure drop to which a fabric filter returns after cleaning). This is due to the fabric's greater retention of smaller particles. Any incremental increase in residual pressure drop raises the system pressure drop by the same increment. In conclusion, by precleaning particle laden gas streams with high efficiency cyclones, the particle size distribution can be so modified as to potentially make precleaning highly undesirable due to creation of unacceptable pressure losses.

Presently, the effect on system pressure drop resulting from the cyclone/fabric filter relationship is not well understood. Designers of particulate control systems need a tool which they can use in evaluating the effects cyclone precleaner size and collection efficiency have on system pressure drop. It is evident from field experience reports that cyclone/fabric filter combinations are resulting in unacceptable system pressure losses.

II. FIELD EXPERIENCE

Incidents of bag blinding due to high efficiency mechanical collectors ahead of baghouses have been reported in the literature. McKee (1) has reported unacceptably high pressure losses across an industrial boiler baghouse which were attributed to a too efficient cyclone precleaner. Billings (2) reported a savings of 1.3 inches water across a coal-fired boiler baghouse by reducing multiclone pre-cleaner efficiency from 78% down to 70% with no noticeable reduction in overall cyclone/fabric filter collection efficiency. Billings also cited bag blinding problems on the East Bridgewater Associates Resource Recovery Facility where two large cyclone precleaners were installed ahead of a 70,000 cubic feet per minute baghouse used for controlling municipal refuse combustion emissions. Lukyanov and Lelyuk (3) revealed problems with increased resistance on Russian fabric filter installations due to cyclonic separation of dust loadings prior to the baghouse.

Helfritch and Beach (4) claim bag failure on a boiler baghouse as the result of a too efficient multiclone precleaner. Identical bags were installed on each of two similar baghouses with one house having a more efficient cyclone precleaner. The more efficient precleaner resulted in higher pressure drops across the companion baghouse which reportedly caused the bags to be pulled onto the cage wires more severely resulting in accelerated abrasive wear of the fiberglass bags.

III. OBJECTIVES

Little consideration has been given in the literature to analyzing the effects of precleaners on fabric filters. Moreover, the pressure loss

consequences of size distribution modification of dust by the use of precleaners on fabric filtration has not been delineated. It was the purpose of this dissertation to study the effect of particle size modification by a cyclone precleaner on the pressure loss across a fabric filter. More specifically, the objectives of this dissertation were to:

1. Determine if there is a practical optimum cyclone precleaner efficiency which results in minimum system pressure loss across a cyclone/fabric filter collection device.
2. Develop a tool for analyzing the effect of modifying inlet particle size distribution on cyclone/fabric filter system pressure loss.
3. Develop an optimization technique for predicting optimum cyclone inlet velocity and cyclone size for a given inlet dust size distribution which will result in the lowest system pressure loss.

IV. SIGNIFICANCE OF RESEARCH

With the increased attention being given fabric filtration as a means for controlling coal fired boiler emissions, the objectives of this dissertation become even more apropos. Significant fan energy savings, reduction in air handling equipment size, and increased bag life are among the potential benefits that may be derived from analyzing the effects precleaner efficiency and size have on cyclone/fabric filter system pressure losses due to modification of particle size distribution.

V. APPROACH

To achieve the determined objectives the following approach was used:

1. A literature review was conducted to determine any historical information that might pertain to the problem.
2. A bench scale laboratory test unit composed of a three inch diameter cyclone and a fabric filter was assembled and operated. System pressure drop was evaluated as a function of cyclone efficiency. Laboratory data was acquired in order to (a) determine if there is an optimum cyclone efficiency which resulted in a minimum system pressure loss, (b) develop a data base from which modeling constants could be derived, and (c) establish a relationship between the geometric mass mean diameter of the particulate penetrating the cyclone and fabric filter design parameters.
3. A cyclone/fabric filter model was developed to predict the system pressure drop as a function of cyclone efficiency. Using the obtained laboratory data, graphical relationships were generated which through interpolation provided data inputs to the model. The model was then used to analyze the effect of modifying inlet particle size distribution on cyclone/fabric filter system pressure loss.
4. An optimization technique was established by the development of a theoretical package for the basic cyclone/fabric filter model. Whereas, the model had been dependent on graphically

interpolated real data inputs for a specific cyclone, the theoretical package allowed analysis of a cyclone/fabric filter relationship without having to develop graphically determined inputs from empirical cyclone data. This made possible the development of an optimization technique for predicting optimum cyclone inlet velocity and cyclone size for a given inlet dust size distribution, cyclone and fabric media type, and operating conditions.

CHAPTER II

REVIEW OF RELATED LITERATURE

I. PREFACE

Historical information dealing with the effects of particle sized distribution modification by precleaners on fabric filters was very limited. Moreover, the approach taken in reviewing the literature was to review those historical parameters used to predict the performance of cyclones and fabric filters as independent units. Thus, an understanding of the relationship between cyclone precleaners and fabric filters could be synthesized.

II. HISTORICAL PERSPECTIVE OF PRECLEANING DEVICES

Introduction

Gravity and inertial separation devices have been used both as sole collection devices, and as precleaning devices prior to higher efficiency collectors. These simple, economical devices were once considered efficient enough in controlling emissions. As emission regulations became more stringent, these devices were generally either replaced or converted to precleaners preceding a more highly efficient collection device such as a fabric filter. Sunbury Steam Plant of Pennsylvania Power and Light Company is a case in point where existing cyclonic collectors were retained as precleaners on a fabric filter installation (5).

Reasons for using gravity and inertial precleaners prior to fabric filtration have been found to be threefold. First, precleaners can serve to substantially reduce the dust loading that a baghouse must handle, thereby providing potential savings in design and operating expenses. Secondly, a precleaner can be used to remove a troublesome type particulate. For the design of new collection systems for boilers, Booth (6) notes that large quantities of unburned, sometimes glowing, carbon (more than 20% of the collected ash) represent a possible fire hazard in a fabric filter. To avoid this, a precleaner can be used to remove the larger, heavier carbonaceous particulate. Other troublesome type particulate, noted in the literature as affecting fabric filtration, and removable with the use of precleaners, include large, abrasive particles and filamentous strands intermingled within particulate matter (7). Thirdly, inertial separators are used in separating industrial process emissions. In some circumstances it is desirable to separate certain weight fractions of the particulate emission from the gas flows for process reuse or sale allowing the remaining particulate to be collected by fabric filtration.

Gravity Settling Chambers

Particles suspended in flowing gas streams are acted on by gravity and possess inertia and momentum. These properties may be used to separate particles from gas streams.

The gravity settling chamber is probably the simplest and earliest type of dust collector, consisting essentially of an open compartment through which the dust-laden stream passes. Gas velocity in the chamber is reduced to permit the dust particles to settle out

by the action of gravity. Lapple (8) recommended that gas velocity not exceed 600 feet per minute due to dust re-entrainment problems. Pressure losses are very low but excessive chamber area requirements and poor efficiency generally make them unsuitable as precleaners.

Inertial Separators

Inertial separators are devices which separate particles from gas streams by causing sudden changes in the direction of the gas stream. Separation occurs by a combination of the inertia of the dust particle, impaction on a target, and centrifugal forces.

The specific designs of inertial collectors vary from the rather simple momentum separator to the more sophisticated Aerodyne[®] tubes and Rotoclones[®]. The range of performance for these more sophisticated units is similar to that of high efficiency cyclones (9). Although, the theory of inertial separation has been well developed (10,11), theoretical approaches have afforded little insight into evaluating commercial inertial separators on the market. Empirical formulations have been found to be the most practical approach to efficiency and pressure drop determinations (10).

Cyclones

The most frequently used inertial device for precleaning is the cyclone. The first known application of a cyclone for the separation of solids from gases was probably a cyclone constructed by the Knickerbocker Company about 1885 (12). All the essential elements in design of contemporary cyclones are found in this earliest cyclone.

There are many different types of cyclones in use. Cyclone flow may be straight throughput or reverse flow. Entries to cyclones may be by helical, wraparound or axial configurations. Dust discharges may be axial or peripheral. All, however, transform inlet gas velocities into a confined vortex from which centrifugal forces tend to drive the suspended particles to the wall of the cyclone body.

Cyclone geometry is generally expressed in dimensionless form, as a multiple of the diameter, D . In the literature there are seven dimension ratios using D ; a/D , b/D , D_e/D , S/D , h/D , H/D , and B/D (13). These dimensions are defined in Figure II-1. Thus, the geometric similarity of several cyclones can be compared by analyzing their dimension ratios.

A number of standard cyclone designs, which have specific dimension ratios have been suggested in the literature by Stairmand (14), Lapple (8), and Swift (15). Table II-1 is a comparison of these designs. A comparison of the designs showed that the dimension ratios differed according to the purpose for which the cyclone was to be used. High efficiency cyclones tend to have smaller gas inlet areas (a/D and b/D) and gas exit areas (D_e/D) than do the high throughput designs. Gas exit duct length (S/D) is less in the high efficiency designs. According to Stairmand (14), higher efficiency can be traded off somewhat against higher throughput. A high efficiency cyclone of standard design will process only about one-half as much flow as a high throughput design of the same diameter and height operating at the same pressure drop. General purpose standard designs appear to be a compromise between high efficiency and high throughput.

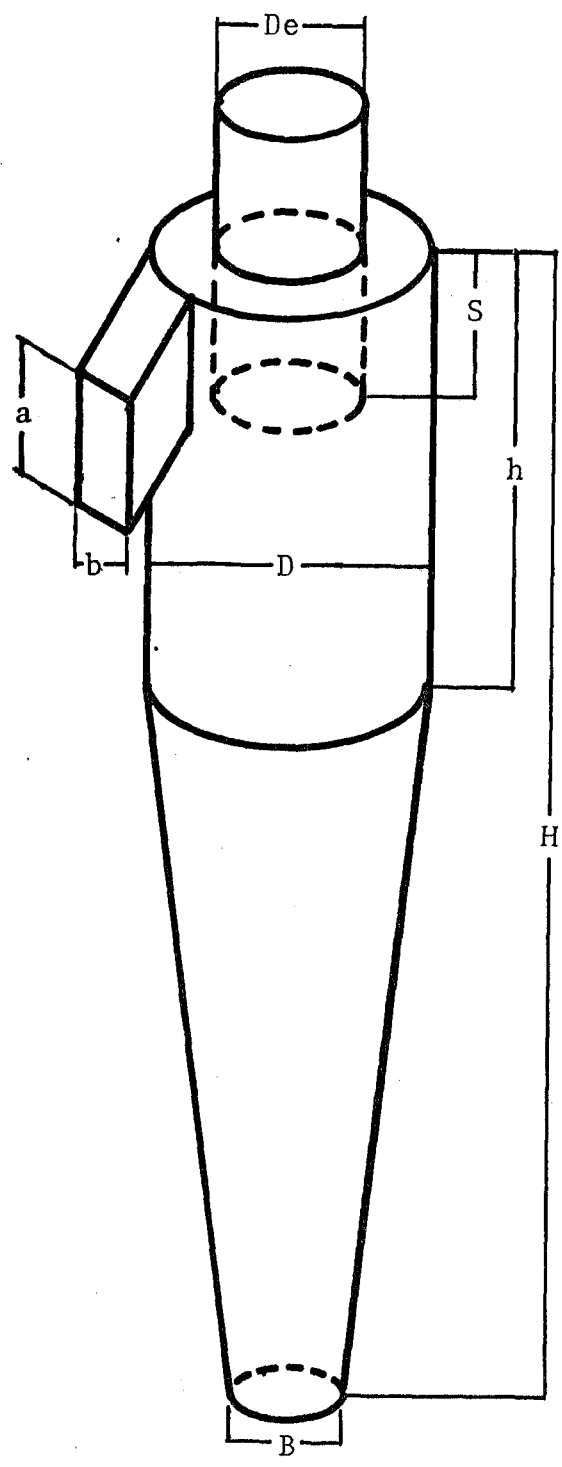


Figure II-1. Cyclone Dimensions (13).

Table II-1

Cyclone Standard Designs (15)

Source	Recommended Duty	D	a/D	b/D	De/D	S/D	h/D	H/D	B/D
Stairmand (1951)	high efficiency	1	0.5	0.2	0.5	0.5	1.5	4.0	0.375
Swift (1969)	high efficiency	1	0.44	0.21	0.4	0.5	1.4	3.9	0.4
Lapple (1951)	general purpose	1	0.5	0.25	0.5	0.625	2.0	4.0	0.25
Swift (1969)	general purpose	1	0.5	0.25	0.5	0.6	1.75	3.75	0.4
Stairmand (1951)	high throughput	1	0.75	0.375	0.75	0.875	1.5	4.0	0.375
Swift (1969)	high throughput	1	0.8	0.35	0.75	0.85	1.7	3.7	0.4

III. DETERMINATION OF PARTICLE SIZE DISTRIBUTION

Particle Size Measurement

Particle size determinations are undertaken to obtain necessary information about the size characteristics of the particulate matter to be collected. Perry (16) lists several acceptable methods of measuring particle size which can be summarized into two categories; those conducted by laboratory analysis, and those conducted in situ in a flowing gas sample.

In the laboratory, the particle size of a collected sample is usually measured by microscopic count, or by resuspension and classification in either an air stream or liquid. Microscopic count is a technique where the sizes of particles are measured visually and the number in each size range counted on an area basis, or mass basis if assumptions are made about particle volume and density.

The Whitby centrifuge is another laboratory method which classifies by measuring settling rate due to gravity or centrifugal force in a liquid medium. A Coulter Counter[®], likewise, uses a liquid medium to measure the effect that a particle's size has on an electric field. The resulting size analysis is based on particle volume which allows for a more accurate determination of particle size on a mass basis. However, dispersing the particulate sample in a liquid does create a problem. Airborne particles often flocculate, producing agglomerates held together by electrostatic charges. When these particles are dispersed in a liquid, these charges can be substantially different than in the original airstream. This problem has been

partially overcome by use of various electrolytic liquid solutions and anti-electrostatic additives.

The Bahco dry classifier is another recognized laboratory method developed for particle size analysis. Using the Bahco classifier, the sample can be sized into fractions between one and forty-four microns. A number of questions arise concerning the Bahco technique since particles may not be resuspended in the same size range that they had initially in the gas flow. Perry commented that there was a tendency for finer particles to be lost from the sample through embedment in the pores of the collection filter.

Whenever possible, an in situ measurement of particle sizes while suspended in the original gas stream is preferred. One method of in situ sampling is by use of a cascade impactor. Pilat et al. (17) reported on the field use of this inertial impaction device. Limits of impactors included short sampling periods when dust loadings are high and laborious effort in determining impactor stage efficiencies.

Optical methods such as light scattering are becoming more predominant in in situ sampling. Shofner et al. (18) reported on a low intensity laser device which measured single particles passing through a sampling volume of such small size that the probability of occupancy by a particle in the size range of interest was near unity. If there is a particle in the sampling volume at the instant of laser pulse, the light scattered by the particle will be collected and converted to a signal which registers, depending upon signal strength, as a specific size count.

Analysis of Particle Size Data

Cadle (19) and Hatch (20) reported that most dusts, especially particulate substances produced by crushing or grinding, are log normally distributed. That is, particle sizes of the dusts are normally distributed when plotted on log-probability paper. Table II-2 shows a representative example of a frequency analysis on the particle mass size measurements obtained by laboratory or in situ measurement of a log-normal dust (21). By plotting cumulative percent by weight versus particle diameter on Cartesian coordinates, an S-type distribution curve can be obtained from the frequency analysis as shown in Figure II-2. Replotting the data in terms of frequency versus diameter expresses the data in terms of a normal frequency distribution. As evidenced in Figure II-3, there is a positive skewness for log normal distributions plotted on normal distribution coordinates. This skewness indicates that the diameters themselves are not normally distributed, rather, the logarithms of the diameters are normally distributed. This fact is evidenced by Figure II-4 which is a plot of frequency versus log of particle diameter producing a normal or Gaussian type symmetrical distribution. Knowing that a Gaussian distribution is obtained indicates that the data will result in a straight line when plotted on logarithmic-probability coordinates as shown in Figure II-5. From these graphical analyses, size distribution is readily available.

The particular diameter with the greatest frequency is referred to as the mode and it occurs for the sample data at three microns (21). The mean value occurs at 50% probability on a log probability plot and is referred to as the geometric mass mean diameter, d_{pg} , for log-normal distributions analyzed on a mass basis.

Table II-2

Typical Particle Size Mass Distribution Frequency Analysis (21)

Mass Frequency %	Diameter Size Range, μ	Range Average Diameter, μ	Cumulative % by Wt.	Less than Diameter, μ
1	1.0		96.0	18
1	1.0-1.2		95.2	16
3	1.2-1.6	1	93.0	14
4.5	1.6-2.0		89.6	12
27.5	2-4	3	84.0	10
23	4-6	5	75.0	8
15	6-8	7	60.0	6
9	8-10	9	37.0	4
5.6	10-12	11	9.5	2
3.4	12-14	13	5.0	1.6
2.2	14-16	15	2.0	1.2
0.8	16-18	17	1.0	1.0
4	>18			

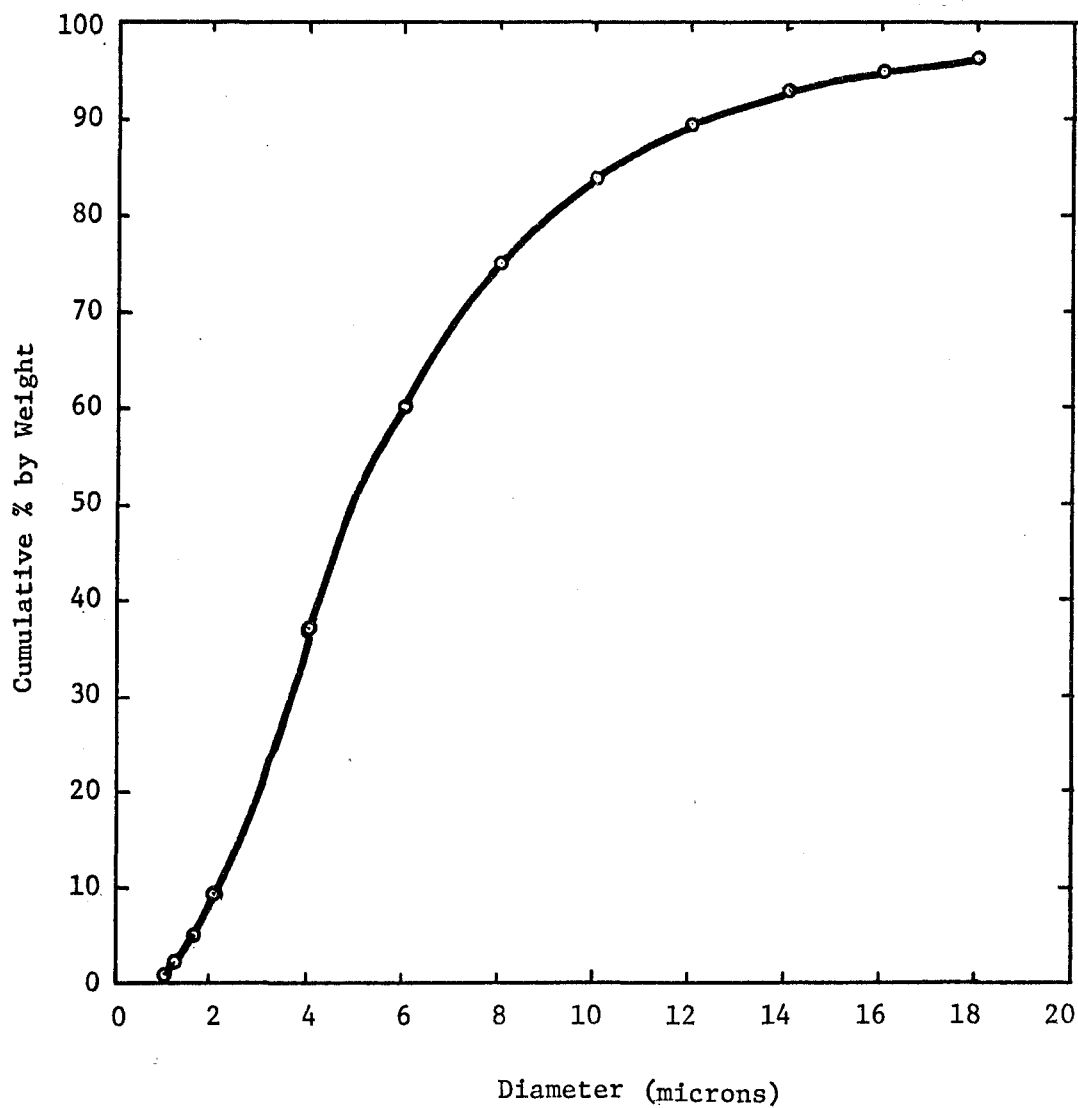


Figure II-2. Typical Particulate Distribution on Cartesian Coordinates (21).

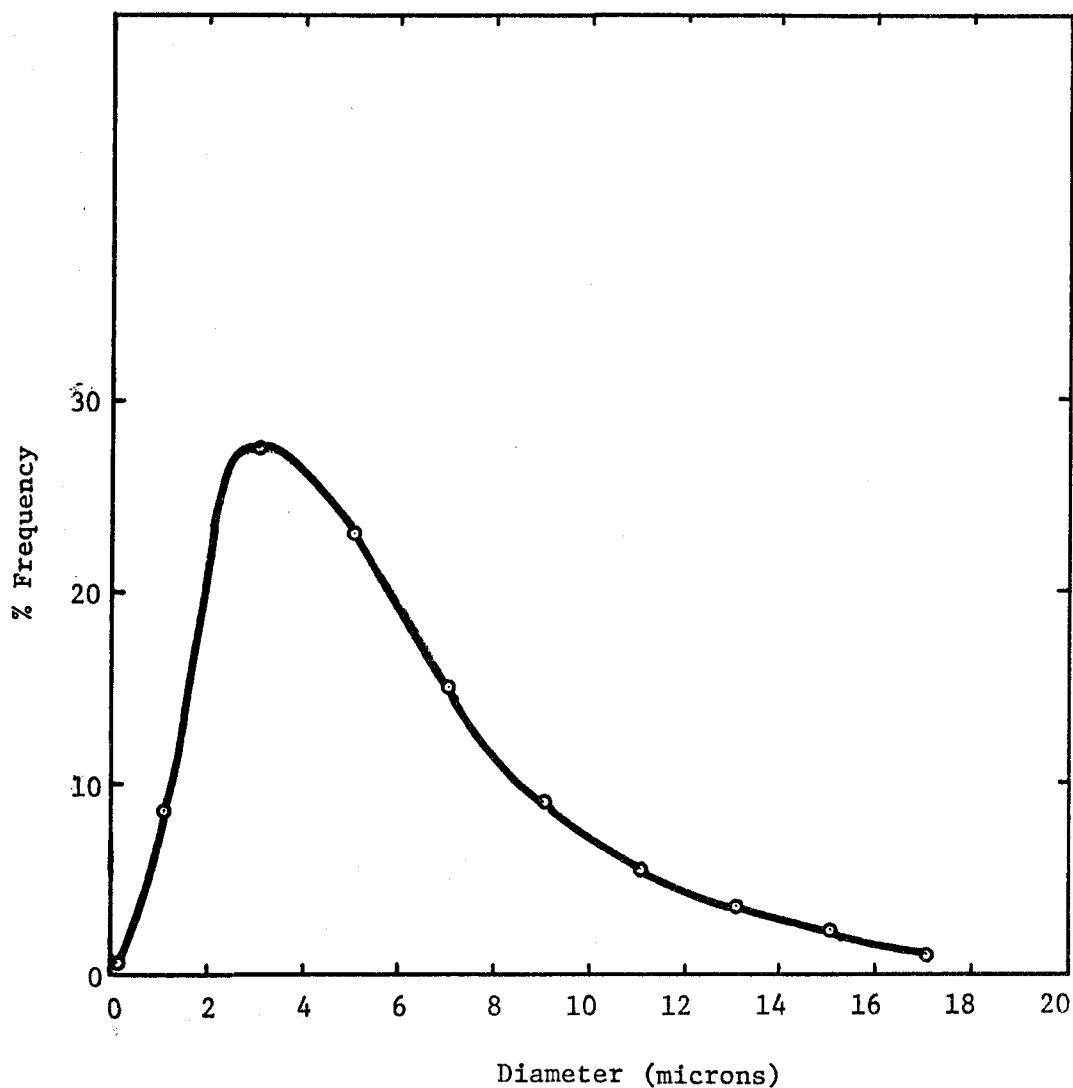


Figure II-3. Typical Particulate Distribution Plotted as Normal Frequency Distribution on Cartesian Coordinates (21).

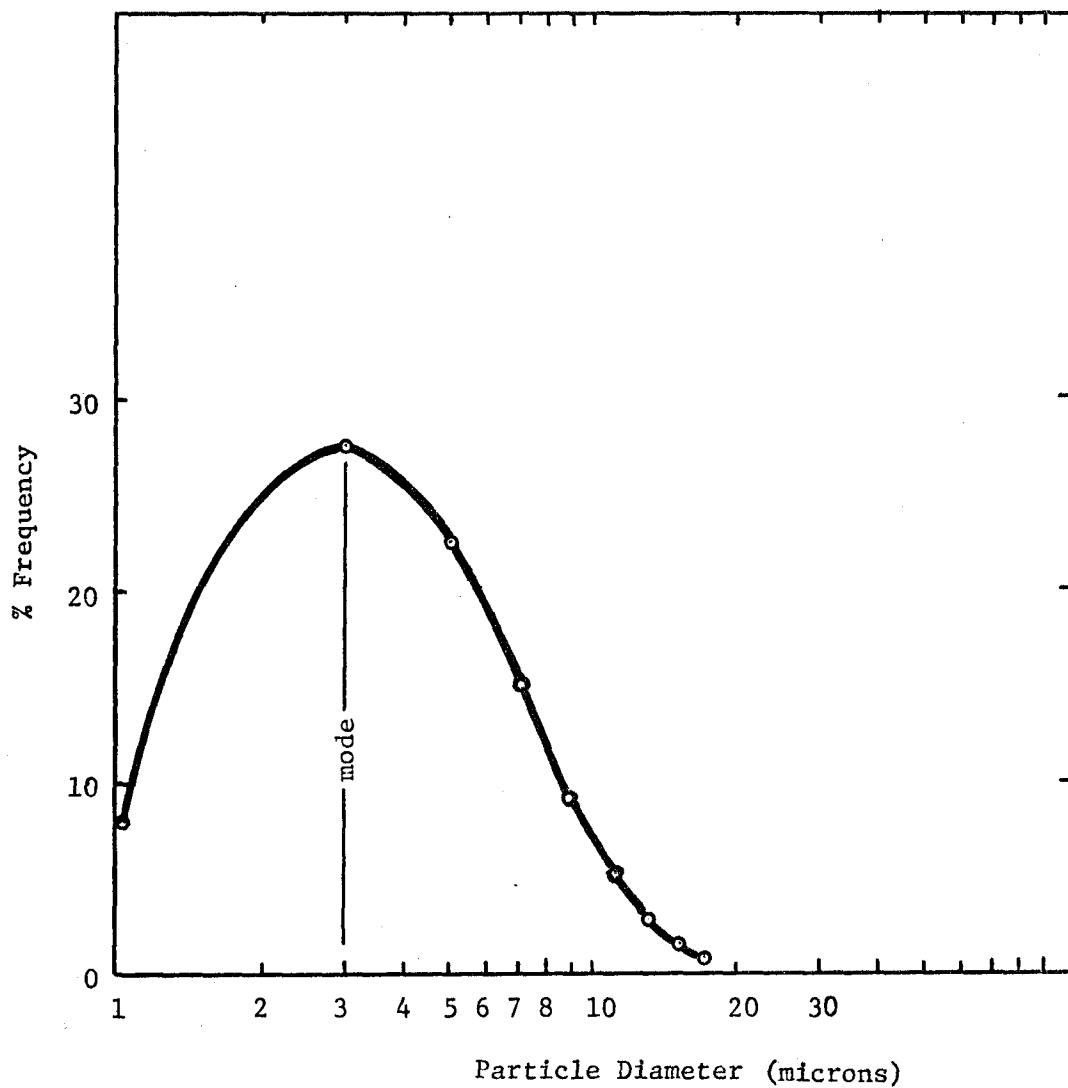


Figure II-4. Typical Particulate Distribution Plotted as Log Normal Frequency Distribution (21).

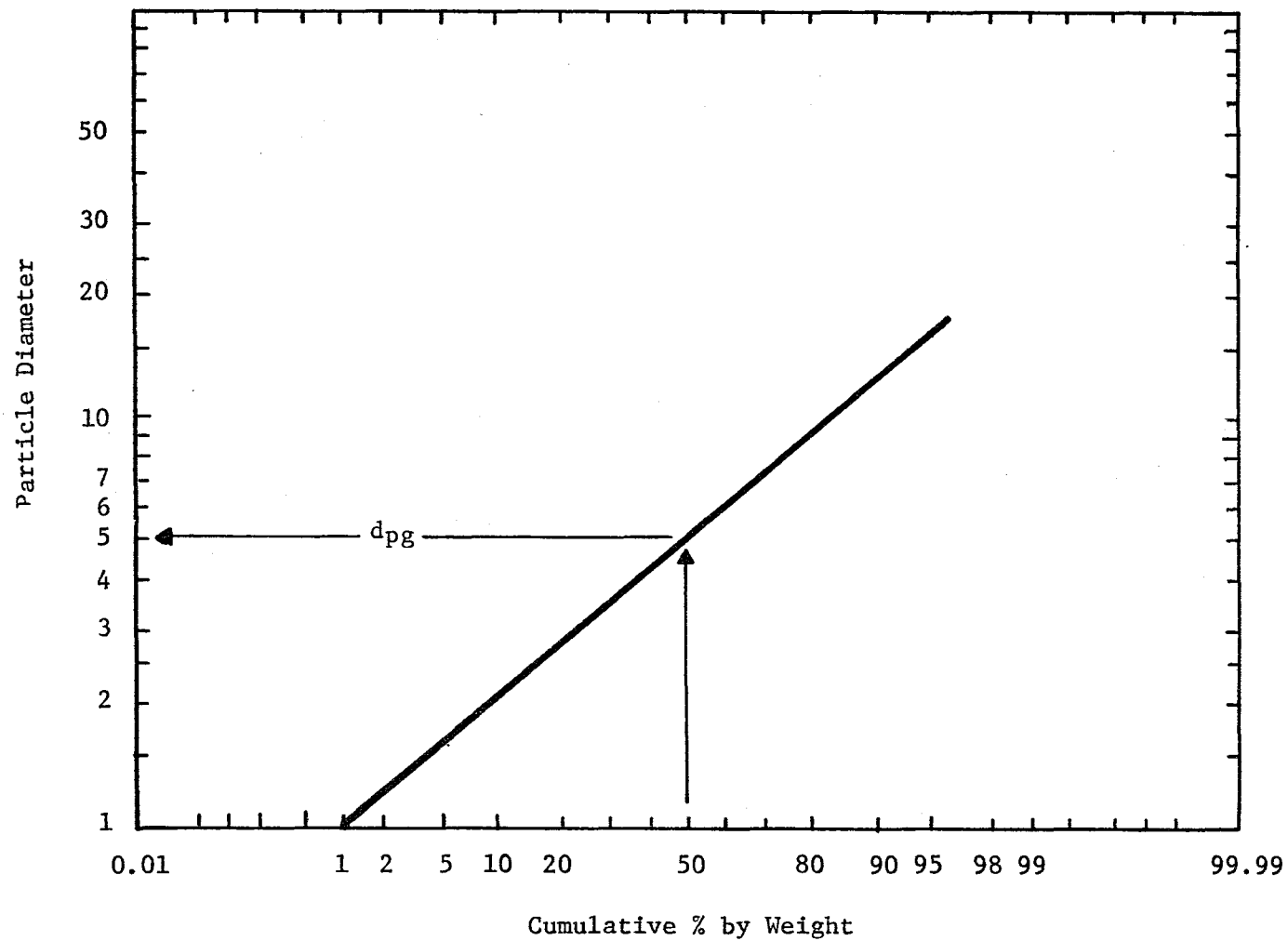


Figure II-5. Typical Particulate Distribution Plotted on Log Probability Coordinates (21).

The standard deviation, or geometric standard deviation for log-normal distributions, is a measure of the distribution of the data about the mean. The geometric standard deviation, σ_g , can be obtained for a log-normal distribution either directly from Figure II-5, or it may be obtained mathematically by taking the square root of the variance (19):

$$\log \sigma_g = \left[\sum_{i=1}^n \frac{(X_i - \bar{X})^2}{n} \right]^{0.5} \quad (\text{II-1})$$

where

$\bar{X}$ = the log of the geometric mean = $\sum X/n$.

X_i = the log value of $n = i$.

Geometric standard deviation is obtained most simply from the log-probability plots either by dividing the diameter which occurs at the probability distribution of 84.13% by d_{pg} , or by dividing d_{pg} by the diameter which occurs at the probability distribution of 15.87%. A geometric standard deviation of one would indicate that all particles in the distribution would be of the same size. Thus, theoretically σ_g goes to unity as an increasing percent of the larger particle sizes in the distribution are removed until only one particle size remains.

Cadle (19) points out that one of the important advantages of plotting size distribution data on log-probability paper is that it is often possible to transpose plots of weight distribution to count and specific surface distribution, and vice versa. For example, given the geometric mass mean diameter, d_{pg} , and the geometric standard deviation, the specific surface mean diameter (which has the same standard deviation as does the mass distribution) can be calculated from the following equation:

$$d_{vs} = \log d_{pg} - 1.151 \log^2 \sigma_g \quad (\text{II-2})$$

Discussion of transformation equations from the mass distribution basis to other size distribution bases can be found in Hatch (20).

IV. PRINCIPLES OF CYCLONE OPERATION

Cyclone Flow

Cyclones alter inlet particle size distributions by removing the larger, heavier particulate fractions. The reverse flow, tangential entry cyclone is generally considered to be the "common-type" cyclone. It will be used as the basis for describing the mechanism of cyclone operation which consists of two distinct vortices; a large diameter descending helical current in the body and cone, and an ascending helix of smaller diameter extending up from the dust outlet section through the gas outlet. (See Figure II-6.)

Gas entering the tangential inlet at the top of the cylindrical body creates a spiral flow downward between the walls of the gas discharge outlet and the body of the cyclone. This "large vortex" continues below the walls of the gas outlet, and at some point near the bottom of the cone, the vortex reverses its direction of axial flow but maintains its direction of rotation, so that an inner vortex cone is formed traveling upward to the gas outlet. Particle velocities can be resolved into three velocity components; tangential velocity, radial drift velocity, and axial velocity.

Stern et al. (22) reported that the tangential velocity of gas in the vortex, V_t , increases with decreasing radius from the radius

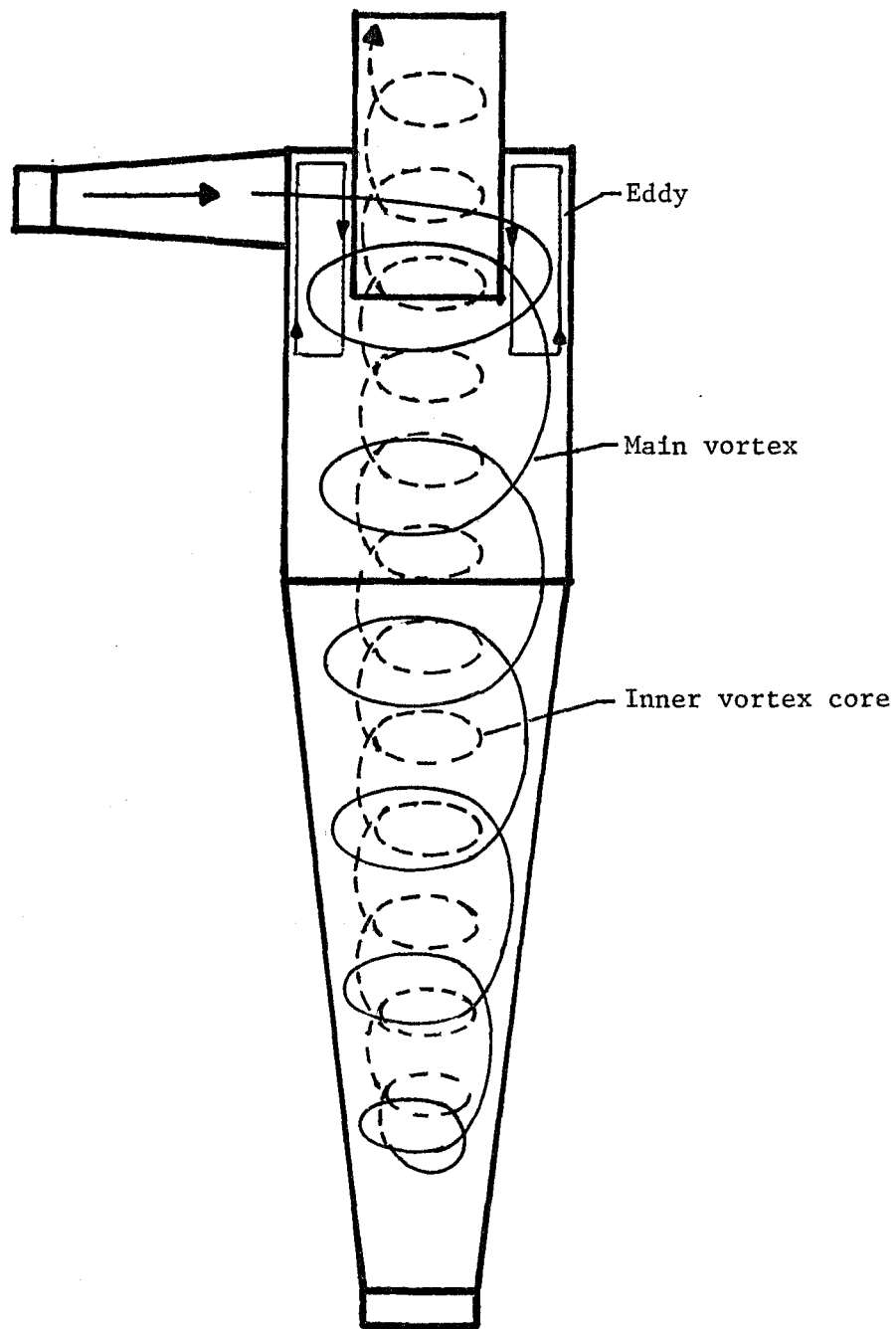


Figure II-6. Cyclonic Vortex Flows on Reverse Flow, Tangential Entry Cyclone.

of the cylindrical body, R_p , to a maximum at some intermediate radius; and from this intermediate point inward to the axis of the cylinder, the tangential velocity decreases. Chan and Lippmann (23) pointed out that flow near the cyclone wall is assumed to be laminar; although it is usually somewhat turbulent. Between the two vortices, there is a transitional boundary of zero vertical or horizontal velocity. Fuchs (24), and Wagner and Murphy (25) have claimed this boundary to be of great importance since it permits mass transport between these turbulent vortices. Fuchs has referred to this phenomenon as turbulent mixing.

Stern (22) stated that in the main vortex:

$$V_t = V_{tp} \left(\frac{R_p}{R} \right)^n \quad (\text{II-3})$$

where

V_t = tangential velocity at radius R (ft/sec)

V_{tp} = tangential velocity at body wall (ft/sec)

R_p = radius of cyclone body (ft)

R = radius of rotation (ft)

n = dimensionless exponent

Values of n vary between 0.5 and 1 depending upon the radius of the cyclone body and gas temperature and reflect the strength of the vortex. Strauss (26) found experimental values of n to range between 0.5 and 0.7.

First (27) reported that the inner vortex core is generally smaller in diameter than the gas outlet, the core radius being between

0.2 and 0.4 times the radius of the gas outlet. The radius of maximum tangential velocity was found by First to be from 0.4 to 0.8 times the radius of the gas outlet.

At the point where the flow inlet joins the cyclone body, an annular space exists inside the cyclone between the cyclone body wall and the gas outlet pipe extending down into the cyclone cavity. The tangential gas velocity increases uniformly from the body wall to the outlet wall and there is generally downward vortex flow. Caplan (28) hypothesized that since the radius of the gas outlet pipe is greater than the radius of maximum tangential velocity, the maximum tangential gas velocity is not obtained in the annular space that is later obtained in the main body of the cyclone. In addition, Caplan has reported that in the annular space near the top of the cyclone, there is upward gas flow along the body wall surface which results in eddies at the top circulating down the gas outlet wall and up the body wall. From these eddies dust particles are lost into the gas outlet. Downward extension of the gas outlet projection results in more pronounced eddies.

Forces in Particle Collection

Particles are separated from the gas stream by centrifugal force which drives them across flow stream lines to the cyclone wall. Caplan (28) expresses this radial force on the particle as:

$$F_s = \frac{\beta \rho_p d_p^3 v_{tp}^2 R_p^{2n}}{gR^{(2n+1)}} \quad (\text{II-4})$$

where

F_s = centrifugal separating force

d_p = particle diameter

ρ_p = particle density

β = dimensionless volume shape factor

n = dimensionless exponent reflecting vortex strength

g = gravitational acceleration constant.

Since it can be assumed that the particles are in the Stokes law range, fluid resistance to the centrifugal separating force can be calculated from:

$$F_r = 3\pi\mu d_p v \quad (\text{II-5})$$

where

F_r = frictional resistance to flow

μ = gas viscosity

v = particle velocity with respect to gas

It is readily observed from Equations II-4 and II-5 that separating force increases with diameter cubed and wall tangential velocity squared, while the resistance force increases only with linear diameter.

V. CYCLONE PERFORMANCE

Performance Parameters

An evaluation of cyclone performance is based upon two parameters:

Parameter 1: the efficiency of a cyclone in removing particulate

Parameter 2: pressure loss across a cyclone during its operation

The first parameter can be evaluated in terms of both cyclone fractional efficiency and cyclone overall efficiency. Cyclone fractional efficiency is expressed as the weight of particles of a stated size collected by the cyclone, divided by the total weight of particles of that size going to the cyclone. On the other hand, cyclone overall efficiency is expressed as the total percent by weight of the particulate

collected. Cyclone efficiency may also be defined in terms of integrated penetration, $\overline{Pt}$, which is equivalent to 1.0 minus the cyclone overall efficiency. Thus, integrated penetration expresses the total percent by weight of the particulate penetrating or passing through the cyclone.

Cyclone Fractional Efficiency

Many equations are found in the literature which are purported to permit calculation of cyclone fractional efficiency. Chan and Lippman (23) have reported on 10 different cyclone fractional efficiency equations found in the literature which they have classified into four different types.

Conventional approach. The first type of fractional efficiency equation is what Chan and Lippman have called the conventional approach where the particle size diameter collected at a specific fractional efficiency is calculated. For example the particle size calculated to be collected with 50% efficiency or particle "cut size," d_{p50} , is the particle size which results in one-half of the particulate of that specific diameter being collected and one-half penetrating through the cyclone. A nomograph for determining particle cut size diameter has been developed by Kuong (29). Particle cut size equations have been presented by Strauss (26) and Lapple (8). Strauss' equation for d_{p50} has been reported as:

$$d_{p50} = \frac{3}{V_i T} \left[\frac{Q \mu D_e}{2\pi(\rho_p - \rho_g)(H - S)D} \right]^{0.5} \quad (\text{II-6})$$

where

V_i = gas inlet velocity

T = friction factor

Q = flow through cyclone

Stairmand (14) has defined the friction factor as:

$$T = - \frac{\left[\frac{D_e}{2(D-b)} \right]^{0.5} + \left[\frac{D_e}{2(D-b)} + \frac{4GA_s}{ab} \right]^{0.5}}{\frac{2GA_s}{ab}} \quad (\text{II-7})$$

where

G = friction constant (0.005 for gas cyclones)

A_s = surface area of cyclone exposed to gas

ab = cross sectional area of inlet duct

Lapple has expressed particle cut size as follows

$$d_{p50} = \left[\frac{9\mu b}{2\pi N V_i (\rho_p - \rho_p)} \right]^{0.5} \quad (\text{II-8})$$

where

b = inlet width (ft)

N = effective number of flow revolutions in cyclone

The number of turns, N , that a particle makes within the cyclone is an important parameter in equations similar to Lapple's and must be estimated. Friedlander (10) and Lapple (8) reported an average value of N to be five with a range of 0.5 to 10. Crawford (30) has stated that $N=6$ for a cyclone of Lapple's standard proportions.

Particle "critical size," d_{crit} , is that specific particle size that is calculated to be collected with 100% efficiency. Particle

critical size equations have been presented by Davies (31), Rietema (32), and Rosin et al. (33). The use of particle cut size equations is more prevalent in the literature.

Semiempirical approach. The second type of fractional efficiency equation as categorized by Chan and Lippman is the semiempirical approach. This approach is represented by equations developed by Sproull (34) and Leith and Licht (35). Sproull's expression for predicting fractional efficiency values has been published as follows (34):

$$\eta = 1 - \exp \left(\frac{-w A_c}{Qg} \right) \quad (\text{II-9})$$

where

g = gravitational constant

w = migration velocity of particles to cyclone wall

$$= \frac{d_p^2 \rho_p V_t^2}{18 \mu D} \quad (\text{II-10})$$

A_c = interior collecting surface area of cyclone which is for practical purposes equivalent to the value of A_s in Equation II-7.

$$= \pi D h + \frac{\pi}{2} (D + B) \left[(H-h)^2 + \left(\frac{D-B}{2} \right)^2 \right]^{0.5} \quad (\text{II-11})$$

Leith and Licht have predicted fractional efficiency values using the following equation (35):

$$\eta = 1 - \exp [-2(C\psi)^{1/(2n+2)}] \quad (\text{II-12})$$

where

C = variable dependent on cyclone dimension ratios

$$= \frac{\pi D^2}{ab} \left[2 \left(1 - \left(\frac{D_e}{D} \right)^2 \right) \left(\frac{S}{D} - \frac{a}{2D} \right) + 1/3 \left(\frac{S + Y - h}{D} \right) \right] \left[1 + \frac{d_c}{D} + \left(\frac{d_c}{D} \right)^2 \right] + \frac{h}{D} - \left(\frac{D_e}{D} \right)^2 Y/D - S/D \quad (\text{II-13})$$

ψ = modified inertial impaction parameter

$$= \frac{\rho_p d_p^2 V_i}{18 \mu D} (n - 1) \quad (\text{II-14})$$

n = dimensionless parameter reflecting vortex strength

$$= 1 - \left[1 - \frac{(0.394 D)^{0.14}}{2.5} \right] \left(\frac{T}{283} \right)^{0.3} \quad (\text{II-15})$$

In Equation II-15, D is the diameter of the cyclone in centimeters and

T is the absolute temperature in degrees K.

The term Y/D in Equation II-13 was defined as follows:

$$\frac{Y}{D} = 2.3 \frac{D_e}{D} \left(\frac{D^2}{ab} \right)^{1/3} \quad (\text{II-16})$$

Here, Y is the farthest distance the vortex extends below the gas exit

duct. And finally, the term d_c/D in Equation II-13 was defined by

Leith and Licht as follows:

$$\frac{d_c}{D} = \frac{D - (D - B)[(S + Y - h)/(H - h)]}{D} \quad (\text{II-17})$$

Here, d_c is the diameter of the conical section at point Y.

Theoretical approach. The third type of fractional efficiency equation as categorized by Chan and Lippman is what they call the purely

theoretical approach. This approach has been exemplified by an expression derived by Beeckmans (36) which, due to its complexity, requires computer solution.

Empirical approach. The fourth type of fractional efficiency equation is the empirical approach as used in expressions developed by Wagner and Murphy (25) and Stairmand (14). Stairmand has developed grade efficiency curves which express fractional efficiency values as derived from a series of tests on specific size cyclones of Stairmand standard proportions. The relative dimensions of both Stairmand's high efficiency and high throughput cyclones can be seen in Table II-1 (p 12). Using grade efficiency curves, one can determine what percent of a specific particle size should be collected for the stated cyclone operating conditions. Figure II-7 is a grade efficiency curve for a high throughput eight inch diameter cyclone of Stairmand standard proportions with a 50 ft/min inlet velocity carrying particles with a specific gravity of two at 20°C. From this grade efficiency curve it can be seen for the given conditions that approximately 90% of the 20 micron particles would be expected to be collected while only 65% of the 10 micron particles would be expected to be collected.

To find the performance of a cyclone for conditions other than those for which Stairmand obtained experimental fractional efficiency data, a method of transposing the curves was developed as follows: For changes in dust density, multiply the dust size obtained from the curve by the ratio:

$$\left(\frac{\text{density of test dust}}{\text{density of new dust}} \right)^{0.5} \quad (\text{II-18})$$

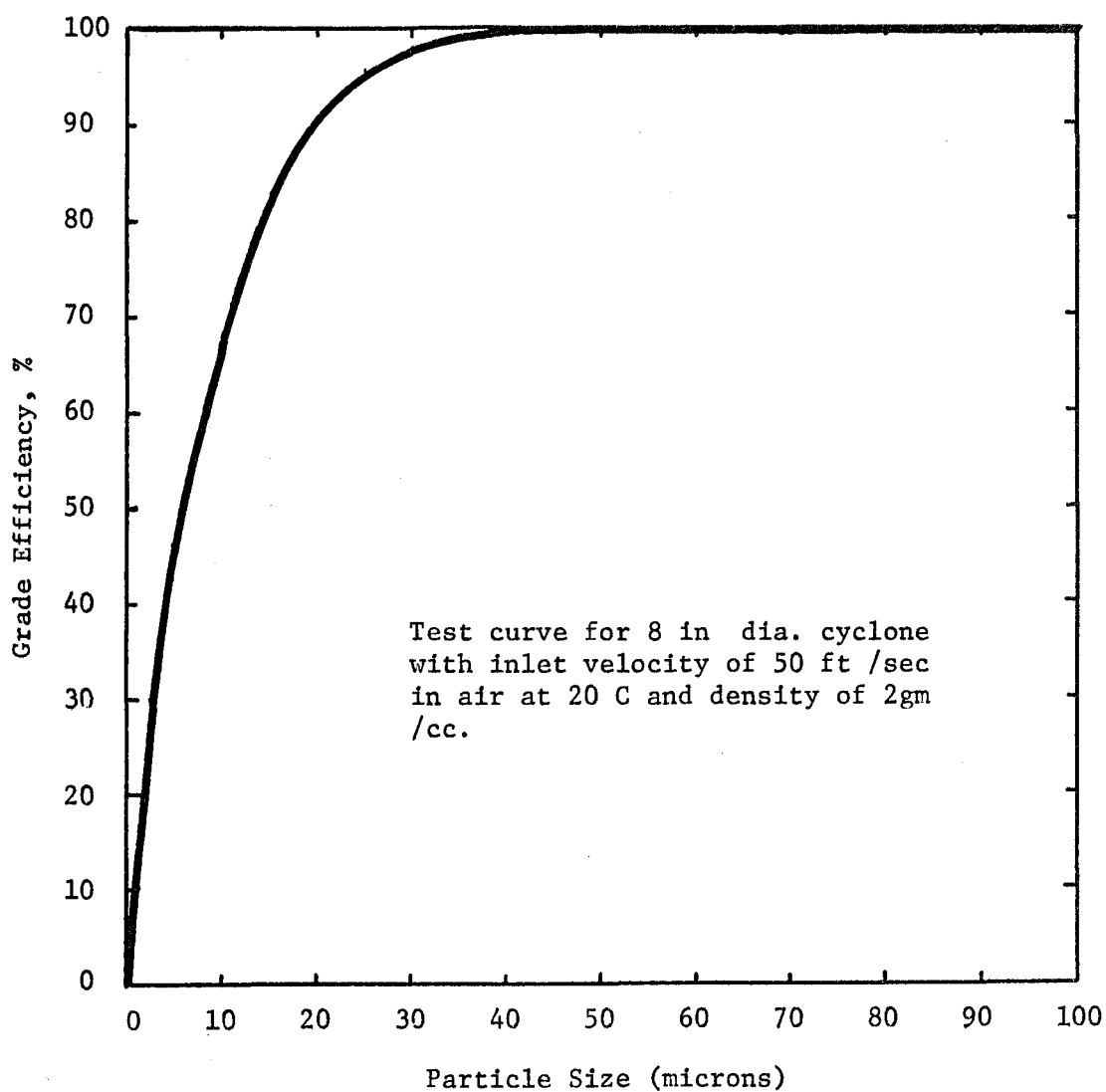


Figure II-7. Grade Efficiency Curve for High Gas Rate Cyclone (14).

For changes in the flow volume multiply by:

$$\left(\frac{\text{test flow}}{\text{new flow}} \right)^{0.5} \quad (\text{II-19})$$

For changes in gas viscosity multiply by:

$$\left(\frac{\text{new viscosity}}{\text{test viscosity}} \right)^{0.5} \quad (\text{II-20})$$

For changes in cyclone diameter multiply by:

$$\left(\frac{\text{diameter of new model}}{\text{diameter of test model}} \right)^{0.5} \quad (\text{II-21})$$

Cyclone Overall Efficiency

Overall cyclone collection efficiency can be determined for a cyclone if both the grade efficiency curve and particle size distribution are known. Grade efficiency curves can be constructed from empirical data or from theory using equations such as Equation II-9 or II-10 (p 29). Caplan (28), Danielson (37), and Stairmand (14) have presented similar methods for determining overall collection efficiency but they require laborious effort. Stairmand's (14) method for prediction of overall collection efficiency and grading of exit dust is presented in Table II-3.

Calvert (38) has studied the effects of particle size distribution on the performance of inertial collectors and has developed a unique theoretical approach for determining overall collection efficiency. Although it has been assumed frequently in the past that the average overall penetration (1.0 minus overall efficiency) calculated based upon d_{pg} is close to the integrated penetration obtained when size distribution is taken into account, Calvert has theoretically shown

Table II-3

Prediction of Overall Efficiency of Collection and Grading of Exit Dust (14)

(1) Size of grade (microns)	(2) % in grade inlet*	(3) Efficiency at mean size ⁺ (%)	(4) Overall collection <u>(2) X (3)</u> 100 (%)	Grading of exit	
				(5) (As % of feed) (2) - (4) (%)	(6) Actual <u>(5) X 100</u> (1 - efficiency) (%)
30	7.5	99.4	7.5	Nil	Nil
25-30	2.5	99.1	2.5	"	"
20-25	3.5	98.6	3.4	0.1	0.4
15-20	8.0	97.4	7.8	0.2	0.8
10-15	14.5	93.6	13.6	0.9	3.5
8-10	10.4	86.6	9.0	1.4	5.5
5-8	13.1	79.4	10.4	2.7	10.6
2-5	16.8	67.7	11.4	5.4	21.3
0-2	23.7	38.2	9.0	14.7	57.9
	100.0		74.6	25.4	100.0

* From particle size distribution analysis

+ From grade efficiency curve

that this assumption errors significantly as the value of σ_g increases and has developed a graphical means for determining integrated penetration as a function of particle size distribution taking σ_g into consideration.

Calvert's approach in developing his graphs relating integrated penetration to particle size distribution is based upon the following semiempirical equation which is of the general form used in predicting penetration for many types of inertial collection equipment:

$$\overline{Pt} = \exp(-Ad_p^B) \quad (II-22)$$

where A is a characteristic collection parameter based on physical characteristics of the collector, the particles, and the gas flow, and B is a constant dependent upon the particular type inertial collection device. Equation II-22 can be expressed in terms similar to Equation II-9 (p 29) as follows:

$$\eta = 1 - \exp(-Ad_p^B) \quad (II-23)$$

Calvert states that the log-normal particle distribution density can be expressed by:

$$\frac{1}{W_c} \frac{d_w}{d(\ln(d_p))} = f(d_p) = \frac{1}{(2\pi)^{0.5} \ln(\sigma_g)} \exp \left[- \left(\frac{\ln(d_p) - \ln(d_{pg})}{(2)^{0.5} \ln(\sigma_g)} \right)^2 \right]$$

where

σ_g = geometric standard deviation of particulate

d_{pg} = geometric mass mean diameter of particulate

$f(d_p)$ = size frequency

W_c = total weight of particulate sample

d_w = particle weight corresponding to the interval $d(\ln(dp))$

of particle sizes.

The overall (integrated) penetration, $\overline{Pt}$, of any device on a dust of any type of size distribution can then be expressed by:

$$\overline{Pt} = \frac{1}{W_c} \int_0^w \overline{Pt} dw \quad (II-25)$$

Calvert uses Equations II-22 and II-24 to write an expression for integrated penetration:

$$\overline{Pt} = \frac{1}{(\pi)^{0.5}} \int_{-\infty}^{+\infty} \exp \left[-Z^2 - Ad_{pg}^B \exp(BZ(2)^{0.5} \ln(\sigma_g)) \right] dZ \quad (II-26)$$

where Z and dZ are transformations:

$$Z = \frac{\ln(d_p) - \ln(d_{pg})}{(2)^{0.5} \ln(\sigma_g)} \quad (II-27)$$

$$dZ = \frac{1}{(2)^{0.5} \ln(\sigma_g)} d(\ln(d_p)) \quad (II-28)$$

Knowing that particle size, d_p , is called d_{p50} when its penetration is 50%, Equation II-22 can be written as:

$$\ln(0.5) = Ad_{p50}^B \quad (II-29)$$

Combining Equation II-29 and II-26, Calvert obtained the following equation:

$$\overline{Pt} = \frac{1}{(\pi)^{0.5}} \int_{-\infty}^{+\infty} \exp \left[-Z^2 - \ln(2) \left(\frac{d_{pg}}{d_{p50}} \right)^B \exp((Z)^{0.5} Z B \ln(\sigma_g)) \right] dZ \quad (II-30)$$

Integrating Equation II-30 by digital computer, Calvert produced a plot of $\overline{Pt}$ vs $(d_{p50}/d_{pg})^B$ with $B \ln(\sigma_g)$ as a parameter as shown in Figure II-8. Figure II-9 is another computer plot produced by Calvert of $\overline{Pt}$ vs (d_{pg-out}/d_{pg-in}) with σ_g as a parameter.

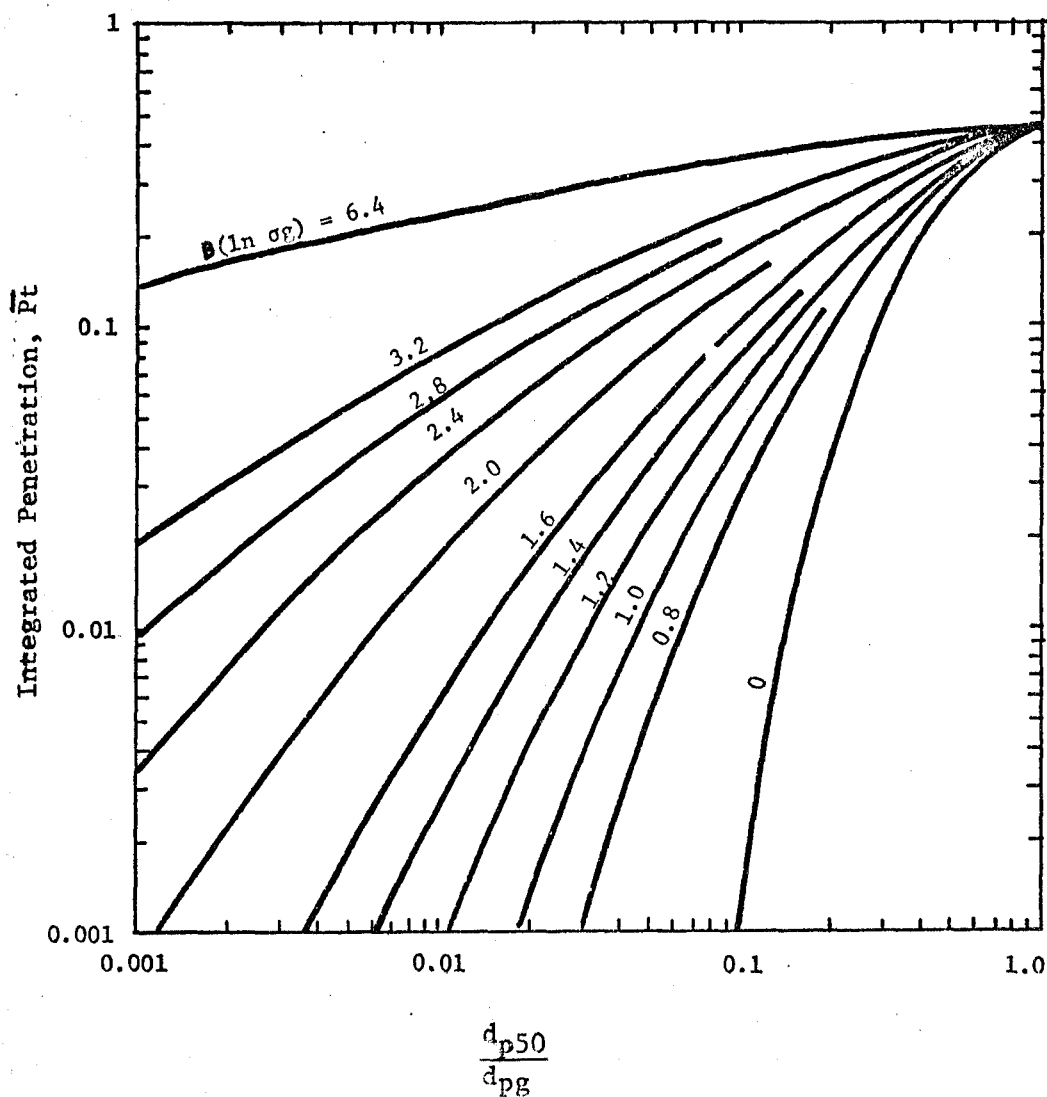


Figure II-8. Relationship Between Integrated Penetration and $\frac{d_{p50}}{d_{pg}}$ with $B(\ln \sigma_g)$ as a Parameter (38).

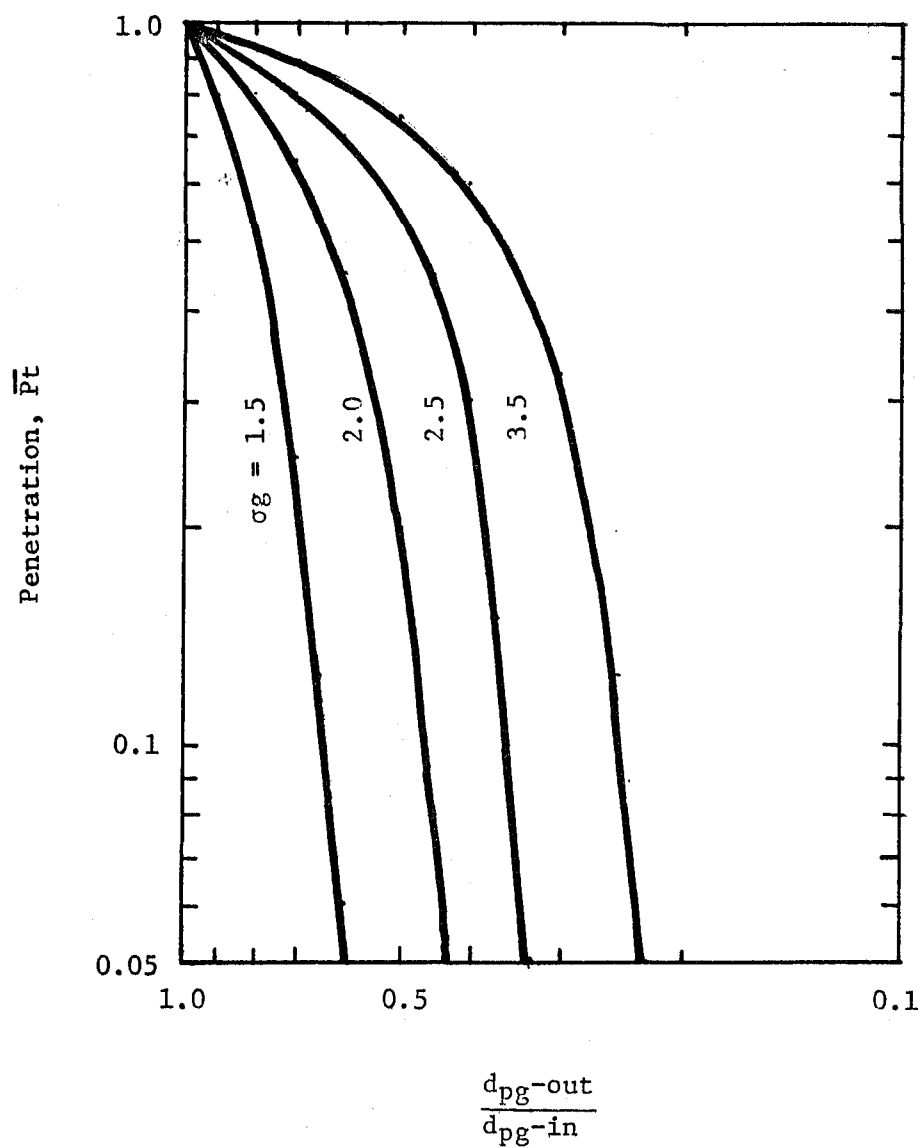


Figure II-9. Relationship Between Average Particle Size Entering and Leaving a Collection Device (38).

Knowing d_{p50} , d_{pg} , B and σ_g , a value of integrated penetration (or overall efficiency) can be found for a cyclone. Crawford (30) recommends that a value of $B=2$ be used for cyclones.

Cyclone Pressure Losses

Pressure drops across a cyclone have been attributed to a number of factors:

1. Losses due to expansion of gas when it enters the cyclone.
2. Losses due to wall friction.
3. Losses as kinetic energy of rotation in the cyclone.
4. Losses at the entrance to the exit pipe.

Most pressure drop theories consider factors two and three to be the most significant. First (27) and Iinoya (39) found that increases in wall friction result in the reduction of cyclone pressure losses at the expense of decreased efficiency which leads to a questioning of the second factor's importance. Caplan (28) has pointed out that a survey of cyclone pressure drop equations by Stern, et al. (22) concluded that there was no satisfactory method for predicting cyclone resistance which was accurate over a wide range of different types of construction. Moreover, for commercial units, pressure drop should be determined experimentally. Most cyclone manufacturers have developed empirical cyclone pressure drop expressions. For example, Fisher-Klosterman Corporation (40) has developed for a series of proprietary cyclones the following predictive equation which requires an experimentally found reference capacity provided by the manufacturer:

$$\Delta P_{cyc} = 318 \left[\frac{V_{1ba}}{Q_6} \right]^2 (\rho_g)^{0.84} (\mu)^{0.16} \quad (II-31)$$

where

ΔP_{cyc} = cyclone pressure drop (inches of water)

b = diameter of cyclone inlet (ft)

a = height of cyclone inlet (ft)

Q_6 = tabulated reference capacity at 6.0" pressure drop (cfm)

ρ_g = density of gas (lbs/ft³)

μ = absolute viscosity of gas at operating conditions (lbs/ft-sec)

V_i = cyclone inlet velocity (ft/min)

Whenever empirical data does not exist, however, a number of theories exist which express cyclone pressure loss as a number of inlet velocity heads, ΔH . In turn, inlet velocity heads can be converted to pressure drop in terms of static pressure head, ΔP , by:

$$\Delta P = \frac{V_i^2 \rho_g \Delta H}{2g\rho_L} \quad (\text{II-32})$$

where, ρ_L , is the density of the liquid used as the measurement reference (typically water).

Equations by Shepherd and Lapple (41), Stairmand (42), Alexander (43), First (27), and Barth (44) represent a portion of the myriad of cyclone pressure drop equations reported in the literature. Shepherd and Lapple have developed the following velocity head equation taking into consideration only the kinetic energy losses in a cyclone:

$$\Delta H = K \frac{ab}{D_e^2} \quad (\text{II-33})$$

where $K = 16$ for a cyclone with tangential entry.

Barth (44) expressed cyclone pressure drop as a function of pressure loss factors 1-4:

$$\Delta H = \left(\frac{V_{tmax}}{V_e} \right)^2 \left(\frac{4ab}{\pi D_e^2} \right)^2 (\epsilon_e + \epsilon_1) \quad (II-34)$$

where ϵ_e reflects cyclone entrance, internal friction, and kinetic energy losses.

$$\epsilon_e = \frac{D_e}{D} \frac{1}{\left[1 - \frac{V_{tmax}}{V_e} (H-S) (2/D_e) T \right]^2} \quad (II-35)$$

The factor ϵ_1 results from losses of the gas outlet and is defined as follows:

$$\epsilon_1 = \frac{4.4}{\left(\frac{V_{tmax}}{V_e} \right)^{2/3}} + 1 \quad (II-36)$$

where

$$\frac{V_{tmax}}{V_e} = \frac{(D_e/2)(D-b)\pi}{2ab\alpha + (H-S)(D-b)\pi T} \quad (II-37)$$

$$\alpha' = 1 - 1.2 b/D \quad (II-38)$$

V_e is the velocity at the entrance to the exit pipe and T is a friction factor of approximately 0.02.

Stairmand (42), likewise, has presented a method of calculating a pressure drop through a cyclone by:

$$\Delta H = 1 + 2T^2 \left[\frac{2(D-b)}{D_e} - 1 \right] + 2 \left(\frac{4ab}{\pi D_e^2} \right)^2 \quad (II-39)$$

where T is described by Equation II-7 (p 28).

A comparison of the above five mentioned pressure drop equations has been published by Leith and Metha (13). Table II-4 presents their

Table II-4

Comparison of Experimental and Theoretical Cyclone Pressure Drop (13)

Test No.	Source*	D	D_e	S	h	H	a	b	Expt'l ΔH	Calculated $\Delta H^\dagger$				
										1	2	3	4	5
1	A	2	1	3	4	8	0.5	0.25	3.38	2.0	1.9	1.8	2.7	2.9
2	A	2	1	3	4	8	1	0.5	5.55	8.0	7.6	7.1	5.3	7.6
3	A	5	2.5	7.5	10	20	3	1.25	10.6	9.6	9.1	9.6	6.1	8.8
4	A	5	2.5	7.5	10	20	2.5	1.25	6.4	8.0	7.6	8.0	5.3	7.6
5	A	15	5	6	17	29.5	10	2	11.4	12.8	19.6	20.0	14.4	16.7
6	A	10	2.5	7.33	9.5	22	3.66	1.17	9.36	10.9	15.5	18.3	12.5	16.7
7	B	1	0.5	1.17	1.3	3.2	0.62	0.23	3.71	9.1	10.2	7.5	6.7	9.1
8	B	0.75	0.43	0.67	0.98	2.46	0.5	0.25	6.15	10.8	11.9	8.4	5.7	9.3
9	B	1.1	0.62	1	1.5	3	0.67	0.35	7.25	9.8	11.9	7.8	5.7	9.3
10	C	0.94	0.49	1.5	2	4	0.5	0.22	7.19	7.2	6.6	5.6	4.8	6.6
11	C	0.94	0.49	1.5	2	4	0.5	0.146	4.68	4.8	4.4	3.8	4.2	4.7
12	C	0.94	0.49	1.5	2	4	0.5	0.10	3.68	3.4	3.1	2.7	3.6	3.7

* A, Stairmand (1949); B, Stern, Caplan and Bush (1955); C, Shepherd and Lapple (1940).

† 1. Shepherd and Lapple (1940); 2, First (1950); 3, Alexander (1949); 4, Stairmand (1949); 5, Barth (1956).

B assumed to 0.25D. All dimensions in ft.

findings. It is evident from an analysis of Table II-4 that there is substantial variation between predicted values of ΔH and experimental values of ΔH . Barth's equation does appear to predict more accurately, than the other methods, the experimentally found values of ΔH , albeit, the prediction is not strong. Correlation coefficients for the five cyclone pressure drop equation methods based on the contents of Table II-4 have been determined by Leith and Metha as follows:

<u>Method</u>	<u>Correlation Coefficient</u>
Barth	0.80
Stairmand	0.77
Shepherd and Lapple	0.77
Alexander	0.55
First	0.53

VI. EFFECTS OF CYCLONE OPERATING VARIABLES

Dust Loading

The amount of dust present in the cyclone gas flow is referred to as dust loading and has been reported to be an important operating variable by Briggs (45) and Shepherd and Lapple (41). Typical dust loadings for cyclones range from 1 to 100 grains per cfm (46, 47).

Briggs (45) has reported that increased inlet dust loading to a cyclone causes the pressure drop to be lower and the efficiency to be increased. More specifically, Briggs states that the fractional decrease in the pressure drop, for a given flow rate was found to vary as the square root of the dust concentration as shown in the following equation:

$$\Delta P_d = \frac{\Delta P_c}{1 + 0.013 (C_{i-\text{inlet}})^{0.5}} \quad (\text{II-40})$$

where

P_d = pressure drop with dust load

P_c = pressure drop with clean air

$C_{i-\text{inlet}}$ = inlet dust concentration (grains/ft³) .

The effect of dust concentration upon collection efficiency, was found by Briggs to be small, but not to be neglected for accurate work.

Sproull (48) believed that Briggs' observations are the result of a rather large reduction in gas viscosity due to dust cloud presence. Soo (49) has, likewise, found that the friction factor for turbulent flow in a pipe is less for dusty gas than for clean. Reductions in viscosity as shown in Equations II-10 (p 29) and II-14 (p 30) will have an effect on cyclone efficiency. As viscosity is decreased friction forces on the dust particle, which must be driven to the cyclone wall, are decreased.

Inlet Gas Velocity

Pressure drop theoretically varies with the square of the inlet velocity as shown in Equation II-32 (p 40). Likewise, collection efficiency increases with increasing inlet velocity up to 4000 - 5000 fpm where internal turbulence causes a loss of efficiency (28).

Stairmand (14) reported that a typical cyclone inlet velocity design is 50 fps with a range of 30 - 100 fps (1800 - 6000 fpm) unless the unit is being used as a precollector for coarse dusts, where low spinning velocities of 5 - 10 fps (300 - 600 fpm) were more desirable.

Leith and Metha (13) have recommended that inlet velocities be kept between 10 - 13 fps (600 - 780 fpm) on cyclones to prevent reentrainment of collected dust from the cyclone wall.

Caplan (28) has determined a quantitative relationship of efficiency with inlet velocity by analysis of data provided by First (27). This relationship is shown in Figure II-10. For typical, wall dispersed dusts the rate of increase in efficiency was by far the greatest for the inlet velocity range between 5 - 20 fps. Caplan has concluded that as inlet velocity increases from zero, there appears to be a linear increase in efficiency until about 70% of maximum efficiency obtainable is reached, after which the slope decreases rapidly. Figure II-10 indicates that a typical cyclone inlet design velocity of 50 fps (3000 fpm) as recommended by Stairmand can be undesirable due to cyclone operation in the flat portion of the curve. It is also evident as theory suggests, that the initial slope of the line is steeper for larger particles and for smaller cyclones than it is for finer particles and larger cyclones.

VIII. CYCLONE LITERATURE SUMMARY

Methods have been published that can be used to predict cyclone performance. Fractional efficiency curves can be generated for a cyclone using equations such as II-9 and II-12. (p.29). Using in situ or laboratory methods of particle size analysis, the size distribution of the dust to be collected can be ascertained. With the fractional efficiency curve of the cyclone known and the particle size distribution known, an

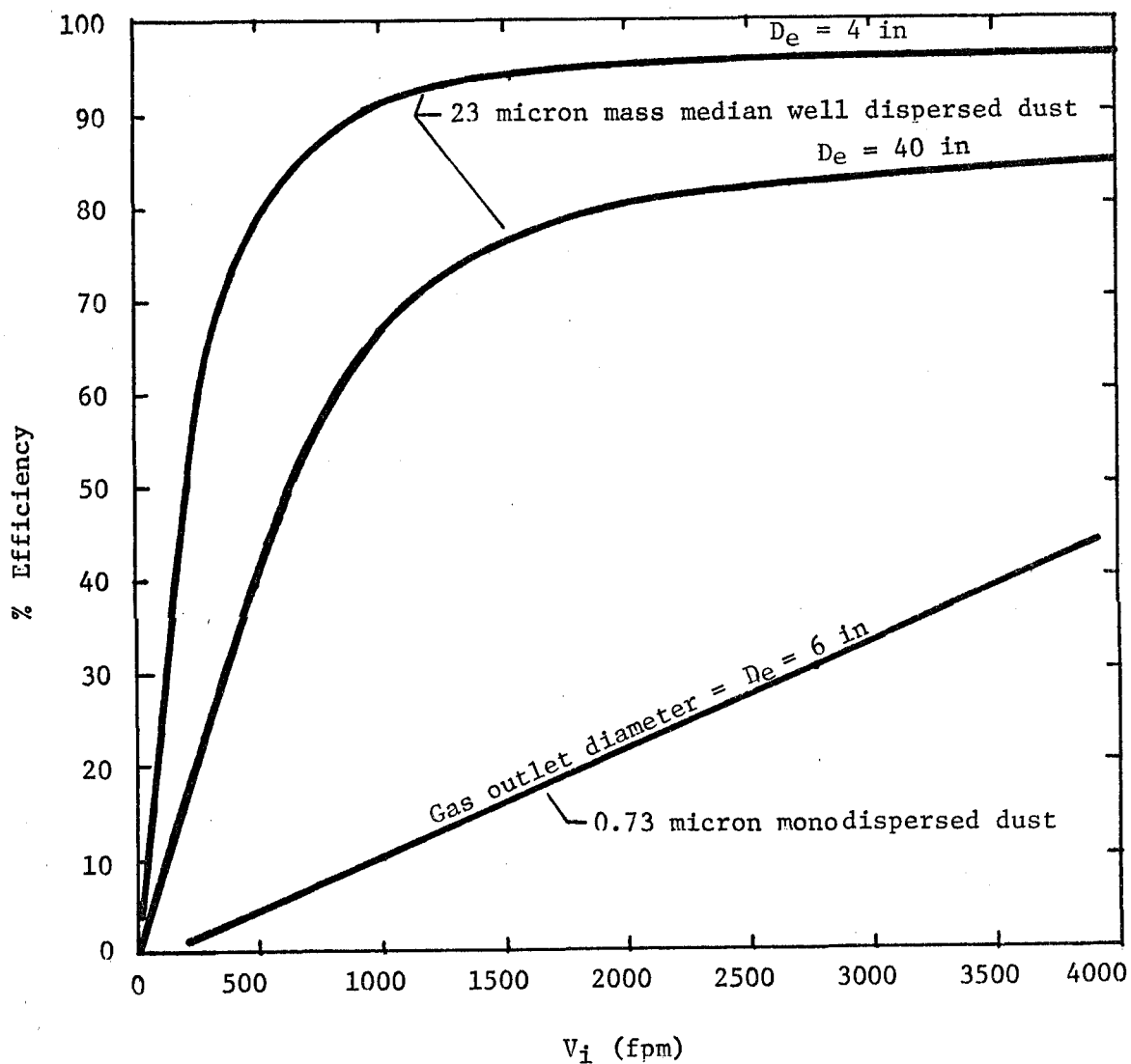


Figure II-10. Relationship of Cyclone Inlet Velocity on Efficiency (28).

overall collection efficiency and the geometric mass mean diameter of the particulate penetrating the cyclone, d_{pg-out} , may be calculated using the procedure presented by Stairmand (14). A simple theoretical method of calculating overall cyclone efficiency has been derived by Calvert (38). Calvert's method requires that a particle cut size value, d_{p50} , be determined using equations such as II-6 (p 27) and II-8 (p 28). Knowing the size distribution of the dust (d_{pg} and σ_g) to be collected, Figure II-8 (p 37) can be entered and an integrated penetration value, $\overline{Pt}$, can be found. Using another figure developed by Calvert, Figure II-9 (p 29), a d_{pg-out} value can be determined when $\overline{Pt}$ and dust size distribution are known. Thus, a means is available for theoretically determining the particle size of the dust penetrating the cyclone which is to be collected by a second control device.

Cyclone pressure drop can be determined theoretically using Equation II-32 (p 40), which expresses pressure loss in terms of velocity heads. Pressure losses were shown to be a function of cyclone inlet velocity squared. Theoretical equations which predict velocity head values have not proven to be satisfactory as evidenced by Table II-3 (p 34) and as concluded by Stern, et al. (22) and by Leith and Metha (13).

Dust loading is reported to have an inverse effect on cyclone pressure drop; an increase in cyclone grain loading results in a decrease in pressure drop. Equation II-40 (p 44) predicts a 12% decrease in pressure drop across a cyclone with a dust loading of 100 grains per cfm as compared to a cyclone operating with clean air.

Literature suggests that cyclone inlet velocities of 5-20 fps represent a realistic design range. Figure II-10 (p 46) indicates for a dispersed dust that there is a cyclone inlet velocity value above which any increase in inlet velocity results only in a minimal cyclone efficiency gain.

VIII. PRINCIPLES OF FABRIC FILTRATION

Introduction

A fabric filter is a particulate control device traditionally made up of a woven or felted textile material generally in the shape of a cylindrical bag or flat supported envelope. The textile material is contained in a sheet metal "baghouse" having inlet and outlet gas flow connections. A method of cleaning the material and means of storing the collected dust are incorporated into the control unit. Early designs of patented fabric filters date back to 1852 (50).

Figure II-11 illustrates a typical flow schematic for a tubular bag fabric filter. In initial operation, dusty gases pass through the filter fabric depositing dust particles on individual fibers and yarn surfaces at the start of filtration. As the time of operation increases, additional particles deposit and accumulate on already deposited particles forming aggregate structures which project from the fabric surface. As deposition and accumulation continue, openings between the individual yarns and fibers become constricted by aggregates, in effect, reducing the size of the interstitial openings through which the gases can flow. Eventually a continuous deposit forms over the fabric media surface and becomes so thick that its resistance to flow becomes excessive

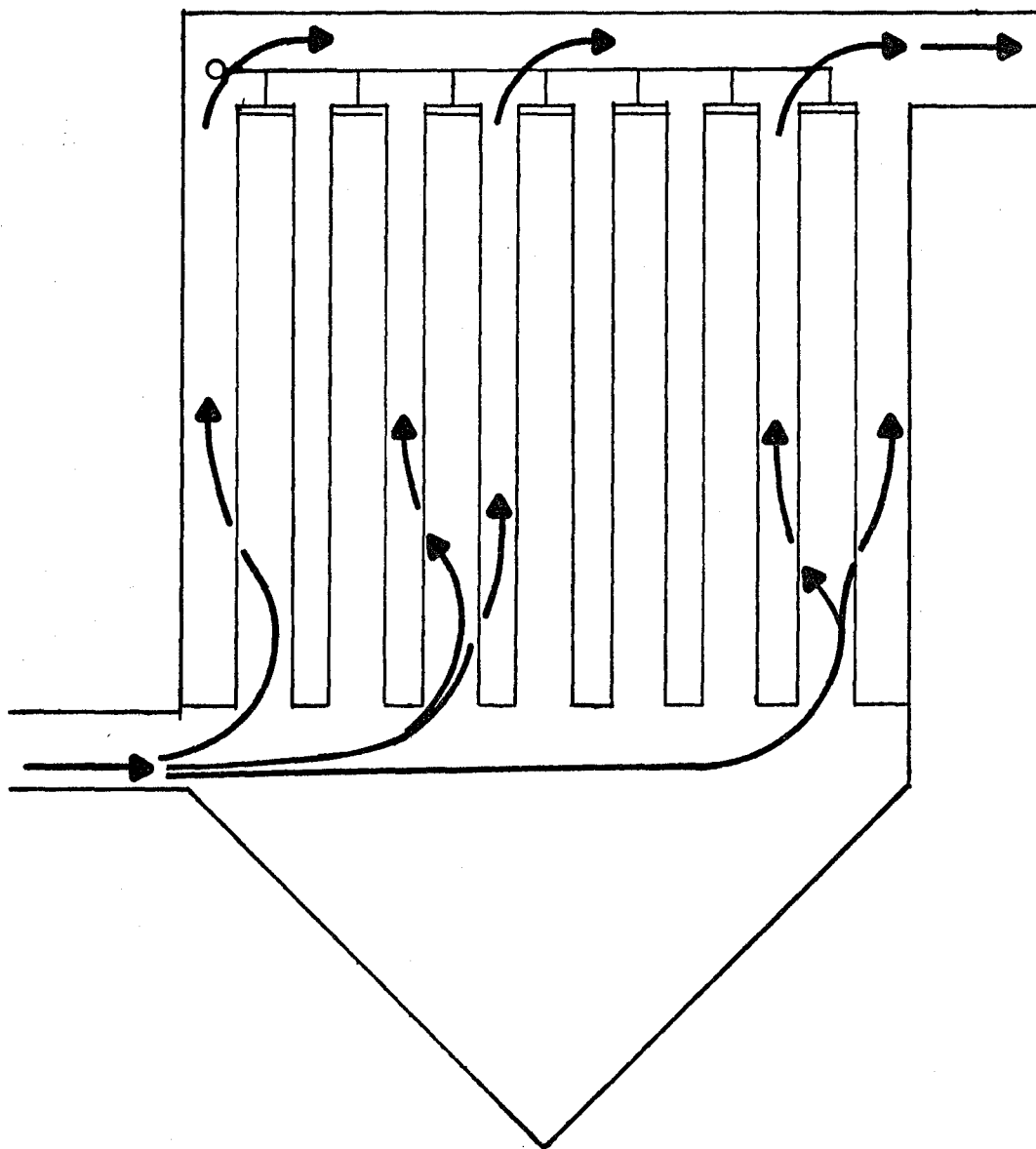


Figure II-11. Schematic of Baghouse Filtration.

necessitating cleaning of the filter. Thus, fabric filtration operation involves both a filtration cycle and a cleaning cycle.

Filtration Cycle

Filtration, in essence, occurs through both fibrous textile media and porous granular media. The filtration process can be broken down into three distinct phases (50):

1. initial or early deposition when particles deposit on individual fibers or filaments of the yarn;
2. intermediate deposition when particles accumulate on previously deposited particles forming filamentous aggregates which bridge interweave and interstitial spaces;
3. continued deposition of particles on the granular matrix resulting in the formation of a filter cake.

Stratification effects enter into the filtration process. As the dirty gas stream enters the entrance of a bag, the velocity of flow is high carrying with it larger, more dense particulate matter. As the flow proceeds through the bag, the velocity progressively decreases resulting in only the finer fraction of particulate matter being carried in the stream flow to the distal end of the bag (50).

The average velocity at which the gas stream actually passes through the filter media is referred to as the air to cloth ratio or filtration velocity. This velocity is a critical factor in system design, and the proper choice of its value depends upon the type of fabric, method of cleaning, and particle properties. Usual values range between 1-12 cubic feet per minute/square foot of fabric surface area (51).

The temperature of gas flow is currently limited to 550°F with Teflon[®] and Fiberglass[®] fabrics being the most heat resistant fabrics yet developed for industrial air filtration.

A substantial amount of the dust deposited remains within the fabric interstitial spaces after the cleaning cycle. This residual deposit produces a residual pressure drop across the filter which gradually reaches an equilibrium value after numerous filtration and cleaning cycles. At this point of conditioned status, all the dust deposited during the filtration cycle is effectively removed during the cleaning cycle. This residual dust deposit provides for a fairly high initial overall particle collection efficiency (greater than 99%) upon resumption of dusty gas flow after cleaning since the individual particles and aggregates act also as collection bodies (52). Particle collection in filtration occurs as the result of three primary mechanisms: inertial impaction, direct interception, and diffusion. An in-depth study of these filtration mechanisms and others can be found in the literature (26, 50, 53, 54).

Permeability

The relationship between pressure drop across the fabric-dust cake filter and the filtration velocity through the filter is of major importance in determining the economics of any fabric filtration system. As filtration velocity increases, pressure drop across the filter increases. This pressure/velocity relationship has been expressed as Darcy's law written simply as (52):

$$\frac{\Delta P}{L'} = \frac{\mu V}{K} \quad (\text{II-41})$$

where

L' = filtration bed depth

V = filtration velocity

K = permeability of the bed

All factors except K are readily obtained.

Permeability, K , is fairly well understood for rigid porous beds. A good description of permeability would be to describe it as the openness of a material to the transmission of fluid. Consequently, the prediction of permeability is based upon a knowledge of particle sizes, shapes, and arrangements. Carmen-Kozeny, Brinkman, and others (55) have proposed permeability theories for rigid beds. The Carmen-Kozeny expression states that (50):

$$K = \frac{\epsilon^3}{k S_s^2 (1-\epsilon)^2} \quad (\text{II-43})$$

where

ϵ = volumetric porosity of filtration bed

S_s = specific surface of the porous material

k = Carmen-Kozeny constant.

The value of the constant, k , is dependent on bed structure. Carmen has calculated that an approximate value of five is appropriate for estimating permeability in beds of spherical particles.

Billings (50) states that the Carmen-Kozeny theory is not accurate for values of filtration bed porosity greater than 0.7, but that Brinkman's model, based on a bed of spheres not quite touching but so close together as to effect fluid drag on each other, should apply to those near spherical particles in very loose, high porosity beds.

Brinkman's expression for permeability is (50):

$$K = \frac{r_p^2}{18} \left[3 + \frac{4}{(1-\epsilon)} - 3 \left(\frac{8}{1-\epsilon} - 3 \right)^{0.5} \right] \quad (\text{II-44})$$

where r_p is the particle radius. Unlike Carmen-Kozeny, Brinkman does not take into consideration bed structure (k and S). For this reason the Carmen-Kozeny equation is more universally used.

In filtration practice the concept of bed resistance is preferred to permeability values. Bed resistance has the common engineering units of inches of water per fpm/pound per foot squared and is related to permeability as follows (50):

$$\text{Bed resistance} = \left(\frac{1}{K} \right) \left(\frac{\mu}{\rho_p (1-\epsilon)} \right) . \quad (\text{II-45})$$

IX. PREDICTION OF PRESSURE DROP ACROSS FABRIC FILTERS

Development of Equations

Williams et al. (56) have theorized, for ideal conditions of particle filtration through a fabric, that bed resistance equals:

$$\Delta P_{\text{total}} = \Delta P_{\text{filter}} + \Delta P_{\text{dust cake}} . \quad (\text{II-46})$$

For real conditions, this simple summation of individual resistance is not totally accurate due to the interaction of dust penetrating into the fabric.

In general, gas flow through fabrics is viscous at low velocities and pressure drop is directly proportional to flow as described by:

$$\Delta P_{\text{filter}} = K_1 V \quad (\text{II-47})$$

where

ΔP = pressure drop across fabric (inches of water)

V = filtration velocity (fpm)

K_1 = resistance of fabric (inches of water/fpm) .

K_1 is the coefficient of resistance to flow for a clean fabric and is reported by manufacturers as air flow permeability; a value equal to the air flow through the fabric in cfm/ft^2 at a 0.5 inch water pressure drop (50). For simple weave fabrics, Robertson (57) has developed an expression using fabric parameters to predict K_1 . In operating fabric filters the initial fabric resistance is usually negligible compared to the pressure drop of the dust-laden fabric.

Fair and Hatch (58) have developed an expression for predicting pressure drop resulting from water flowing through a sand bed. This expression has been used to predict the additional resistance ($\Delta P_{\text{dust cake}}$) that occurs during filtration as a layer of dust forms on the fabric and is as follows:

$$\frac{H}{L} = \frac{k \mu V}{g \rho_a} \left(\frac{A_p}{V_p} \right)^2 \frac{(1-\epsilon)^2}{\epsilon^3} \quad (\text{II-48})$$

where

H = resistance of dust layer (cm of fluid flowing)

L = depth of dust deposit (cm)

k = Carmen-Kozeny constant

$\frac{A_p}{V_p}$ = surface area to volume ratio = $S_v (\text{cm}^{-1})$

ρ_a = density of air (gm/cm^3)

g = acceleration due to gravity (980 cm/sec^2)

μ = viscosity of gas stream (g/cm-sec) .

Williams, Hatch and Greenburg (55) modified Equation II-48

by expressing bed depth, L , in terms of dust weight, W , as follows:

$$W = L\rho_p(1-\epsilon) \quad . \quad (\text{II-49})$$

This expression was further modified to include time by substituting for dust weight the following expression:

$$W = C_i V t E_f \quad (\text{II-50})$$

where

C_i = dust loading to the filter (gm/cm^3)

t = elapsed time of filter operation at above loading (second)

E_f = efficiency of filter in retaining the dust cake (generally assume unity) .

With these substitutions, the equation for pressure loss across the cake becomes:

$$\rho_a g H(t) = \Delta P(t) = \left[\frac{k\mu}{\rho_p} \left(\frac{A_p}{V_p} \right)^2 \frac{1-\epsilon}{\epsilon^3} \right] C_i V^2 t \quad (\text{II-51})$$

where the pressure drop has dimensions of force/unit area.

The bracketed term is called the dust resistance coefficient and is dependent upon the specific surface and porosity properties of the granular layer. The dimensions of the resistance coefficient are sec/cm . To convert the dimensions of Equation II-51 (dynes/cm^2) to an equivalent expression in common engineering units, the equation becomes:

$$\Delta P_{\text{dust cake}} = \left[\left(\frac{k_{\mu}}{\rho_p} \right) \left(\frac{A_p}{V_p} \right)^2 \left(\frac{1-\epsilon}{\epsilon^3} \right) \left(\frac{1 \text{ in. H}_2\text{O}}{5.2 \text{ lbs/ft}^2} \right) \left(\frac{1 \text{ min}}{60 \text{ sec}} \right) \right] \left(\frac{1 \text{ lb}}{7000 \text{ grains}} \right) C_i V^2 t \quad (\text{II-52})$$

where

- $\Delta P_{\text{dust cake}}$ = pressure loss (in. H₂O)
 C_i = dust loading (grains/ft³)
 V = filtration velocity (ft/min)
 t = time elapsed (min)
 μ = fluid viscosity (lbm/ft-sec) .

The bracketed bed resistance factor is now referred to as the specific dust resistance coefficient or specific dust resistivity, K_2 , and has the following dimensions:

$$K_2 = \frac{\text{in. H}_2\text{O/fpm}}{\text{lbs/ft}^2} \quad (\text{II-53})$$

Maintaining consistent engineering units Equation II-52 can be reduced to the following expression:

$$\Delta P_{\text{dust cake}} = K_2 \frac{C_i V^2 t}{7000} \quad (\text{II-54})$$

The following equation, reported by Billings (50), has been synthesized from Equations II-47 (p 54) and II-54 to predict the pressure loss performance across a fabric filter:

$$\Delta P_{\text{total}} = K_1 V + K_2 \frac{C_i V^2 t}{7000} \quad (\text{II-55})$$

Equation II-55 approximates pressure loss performance across a fabric filter as a linear function which is not true. Equation II-55 fails to express how the initial interaction of particulate matter on the

clean fabric effects fabric filter pressure drop. Fabric filter performance curves show initial pressure losses to generally be a non-linear function.

Generation of Performance Curves

Graphical representations have been used extensively in analysis of the pressure loss performance of fabric filters (54). These graphical solutions to Equation II-46 (p 53) are plots of filter resistance, $\Delta P/V$, versus the accumulation of dust on the filter per unit area of filter, $C_1 Vt$. A schematic diagram of the performance curve is shown in Figure II-12.

The performance curve is typically divided into two zones:

1) the cake repair zone, and 2) the deposition of homogeneous dust cake zone. Filtration begins at the residual drag value which is that value of total resistance that exists after a dust fabric combination has been cleaned. Filter drag or resistance increases rapidly as voids in the porous cake and fabric media are filled. The linear or homogeneous dust cake portion of the curve is the predominant section of the curve with its slope being the measured value of specific dust resistivity called the operating dust resistivity, K_2' .

Davis (54,59) has used the performance curve concept to develop a predictive performance model for fabric filtration by modeling each of the zones. Inputs to this parametric model are the operating dust resistivity, the fabric type, dust loading, filtration velocity, and the total time of filtration. Other predictive performance models have been offered by Billings (50) and Fraser (60). Both of these models,

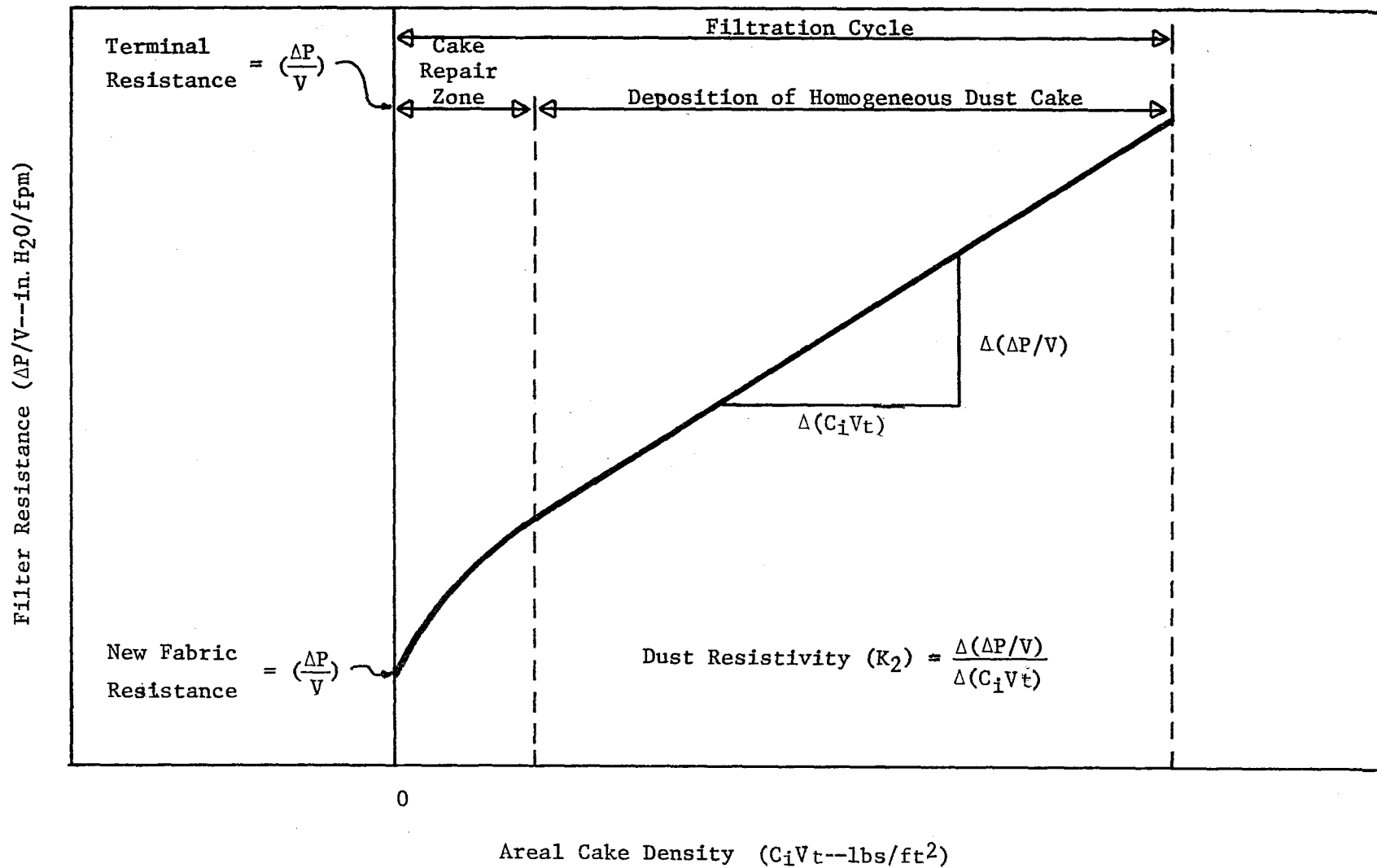


Figure II-12. Basic Performance Curve of Fabric Filter.

likewise, require an input of the specific or operating dust resistivity. Davis' model, unlike Billing's and Fraser's, has the ability to predict pressure drop values in the cake repair zone.

X. PROPERTIES OF FILTRATION BED AFFECTING RESISTANCE

Introduction

As revealed in Equation II-52 (p 56), values of specific or operating dust resistivity, K_2 and K_2' , are predominantly dependent upon the geometric properties of the filtration bed. More specifically, Davis (59) has reported that the value of K_2' was found to be statistically dependent on the geometric properties of the dust cake alone for the 44 data sets of fabric/dust combinations he tested. The non-linear portion of the performance curve (the cake repair zone) was reported to be statistically dependent on both the dust cake and fabric media.

Based upon these observations it can be concluded that the specific or operating dust resistivities are determined by the way particle geometric properties influence dust cake characteristics. Billings (50) has listed the following parameters which effect the characteristics of a filtration bed, and consequently, have an influence on its resistance and permeability:

1. porosity
2. specific surface
3. particle shape factor
4. pore size and structure.

Parameters 3 and 4 have a determining influence on the values of the first two parameters.

Large deviations between K_2' (measured) and K_2 (theoretical), as reported in the literature (50, 54), reflect the difficulty of measuring or establishing the effective particle shape, specific surface, porosity, pore size and structure, and other appropriate parameters in a dust deposit on an operating fabric filter.

Porosity

Porosity, or void fraction, is simply the percent of open space in the porous filtration bed and is defined as:

$$\epsilon = 1 - \alpha \quad (\text{II-46})$$

where α is referred to as the packing density and described as the fraction of solids in the filter determined by the ratio of bulk density, ρ_b , to true density of the material, ρ_p ; that is:

$$\alpha = \frac{\rho_b}{\rho_p} \quad (\text{II-57})$$

Typical values of the porosity of a dust cake range from 0.4 to greater than 0.9. Factors effecting porosity include particle size distribution, particle shape, and pore geometry.

The effect of particle size on porosity is shown by Dallavalle (61) using Roller's data in Figure II-13. It should be noted, however, that these values were not for dusts filtered; rather, Roller's data was obtained by packing, under mechanical force, dust into a container and as such may not be representative of voids for filter cakes. This figure reveals that particles below about 30 microns tend to form more bulky aggregates resulting in higher porosity. Figure II-14 by Billings (50) illustrates the calculated relationship of porosity

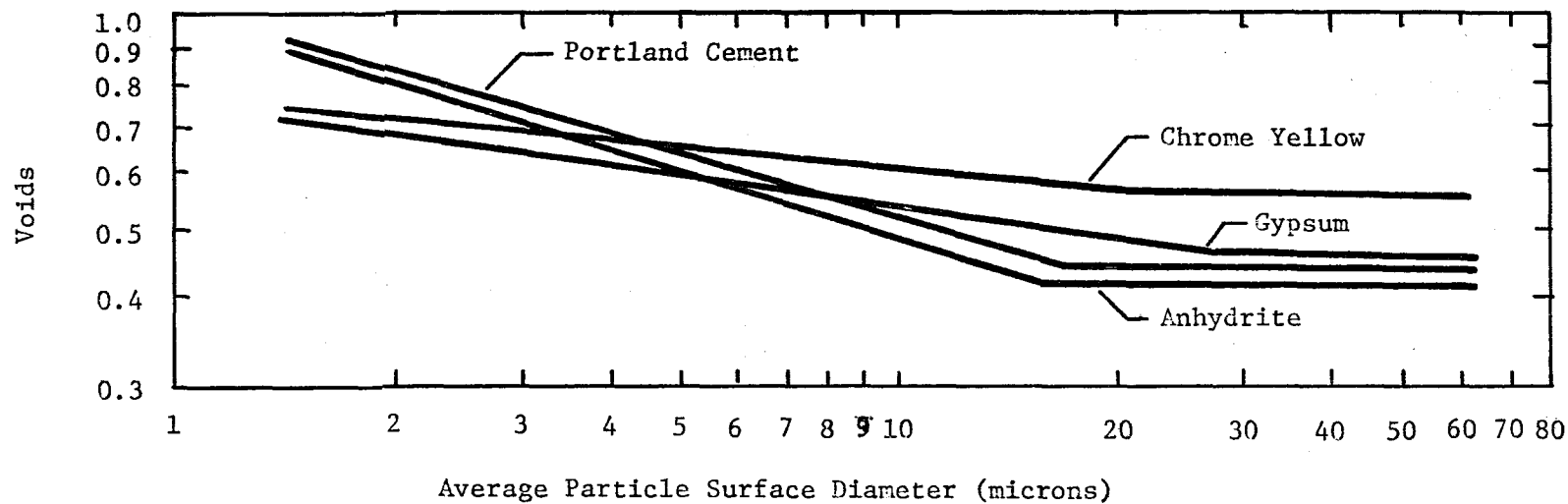


Figure II-13. Porosity as a Function of the Average Particle Surface Diameter for Four Powders (61).

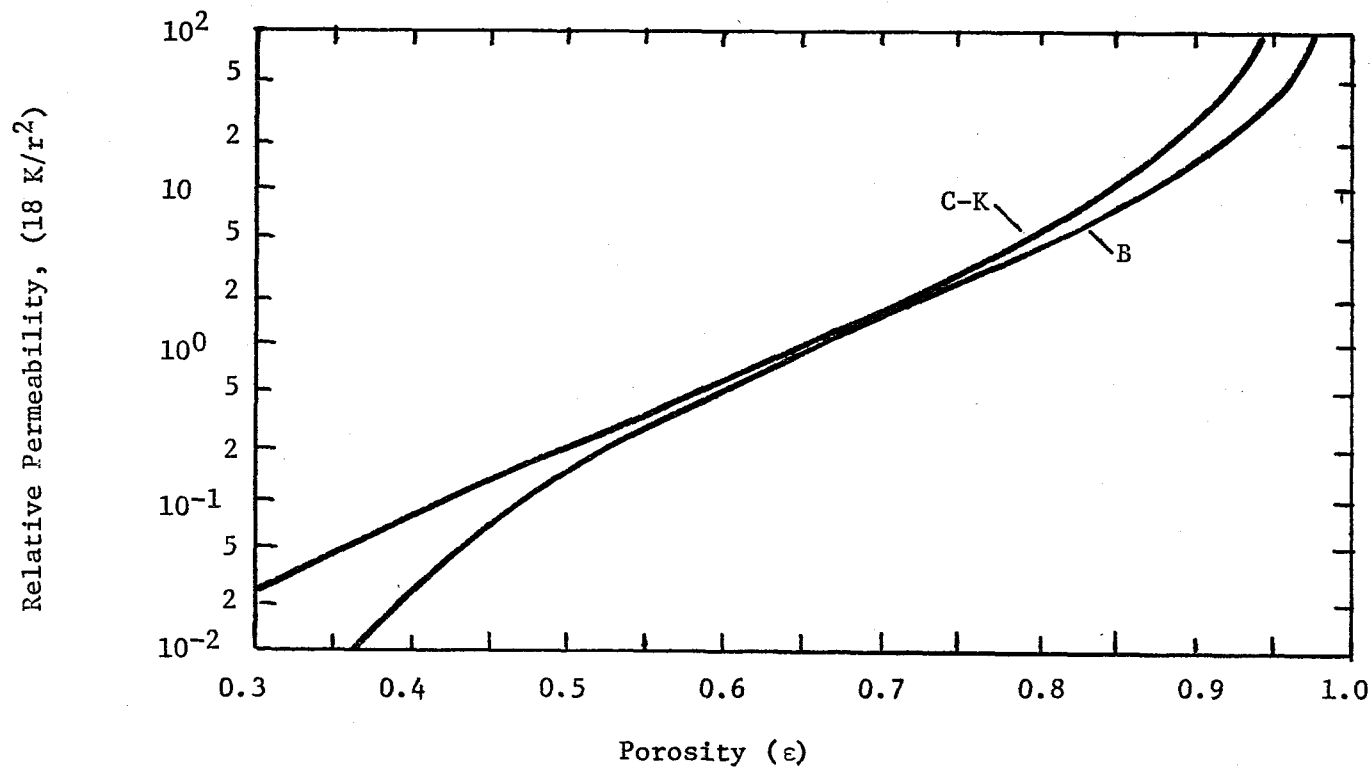


Figure II-14. Relationship of Porosity on Permeability as Determined from the Carman-Kozeny and Brinkman Models (50).

on permeability for the Carmen-Kozeny and Brinkman predictive models. The importance of porosity is evidenced by the fact that permeabilities may vary by a factor of 1000 over the range of porosities expected in fabric filtration.

The theoretical Equation II-48 (p 53) shows pressure drop across a granular bed to be very sensitive to the porosity function. Table II-5 presents the porosity function, $\frac{1-\epsilon}{\epsilon^3}$, resulting from various values of ϵ . As porosity decreases the porosity function is seen to increase which results in higher resistance.

The relationship between the geometric standard deviation of the dust size distribution, σ_g , and the resulting dust cake porosity has been reported in the literature. Bo, et al. (62) concluded that powders with wider size ranges have lower porosity values than similar dusts having narrower size limits. Similarly, Sohn and Moreland (63) reported that the packing density $(1-\epsilon)$ of a polydispersed size particle bed increases as σ_g increases.

Sohn and Moreland have stated that for a particle distribution composed of varying spherical particle sizes ($\sigma_g > 1$); that is, a polydispersed dust, interstitial spaces between larger particles will be filled by smaller particles as illustrated in Figure II-15. Larger values of σ_g reflect greater variation of particle sizes. Greater variation in particle sizes results in increased opportunity for smaller particulate to accumulate within interstitial spaces producing decreased porosity and, conversely, increased packing density.

Figure II-16, developed by Sohn and Moreland, shows the variation of packing density with geometric standard deviation for two sand types,

Table II-5
Values of Porosity Function
For Given Porosity

ϵ	$\frac{1-\epsilon}{\epsilon^3}$
.90	.14
.85	.24
.80	.39
.75	.60
.70	.88
.65	1.27
.60	1.85
.55	2.70
.50	4.0
.45	6.0
.40	9.4
.35	15.1
.30	25.9

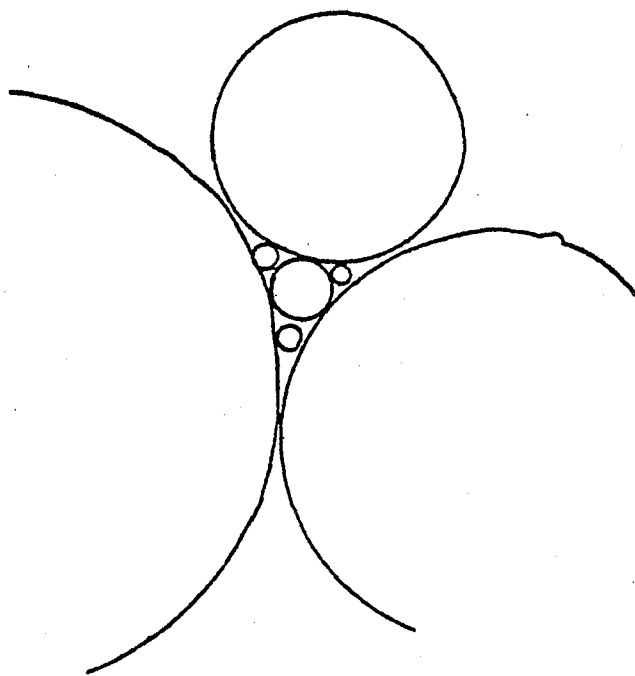


Figure II-15. Depiction of Smaller Particles
Accumulating in Interstitial Spaces.

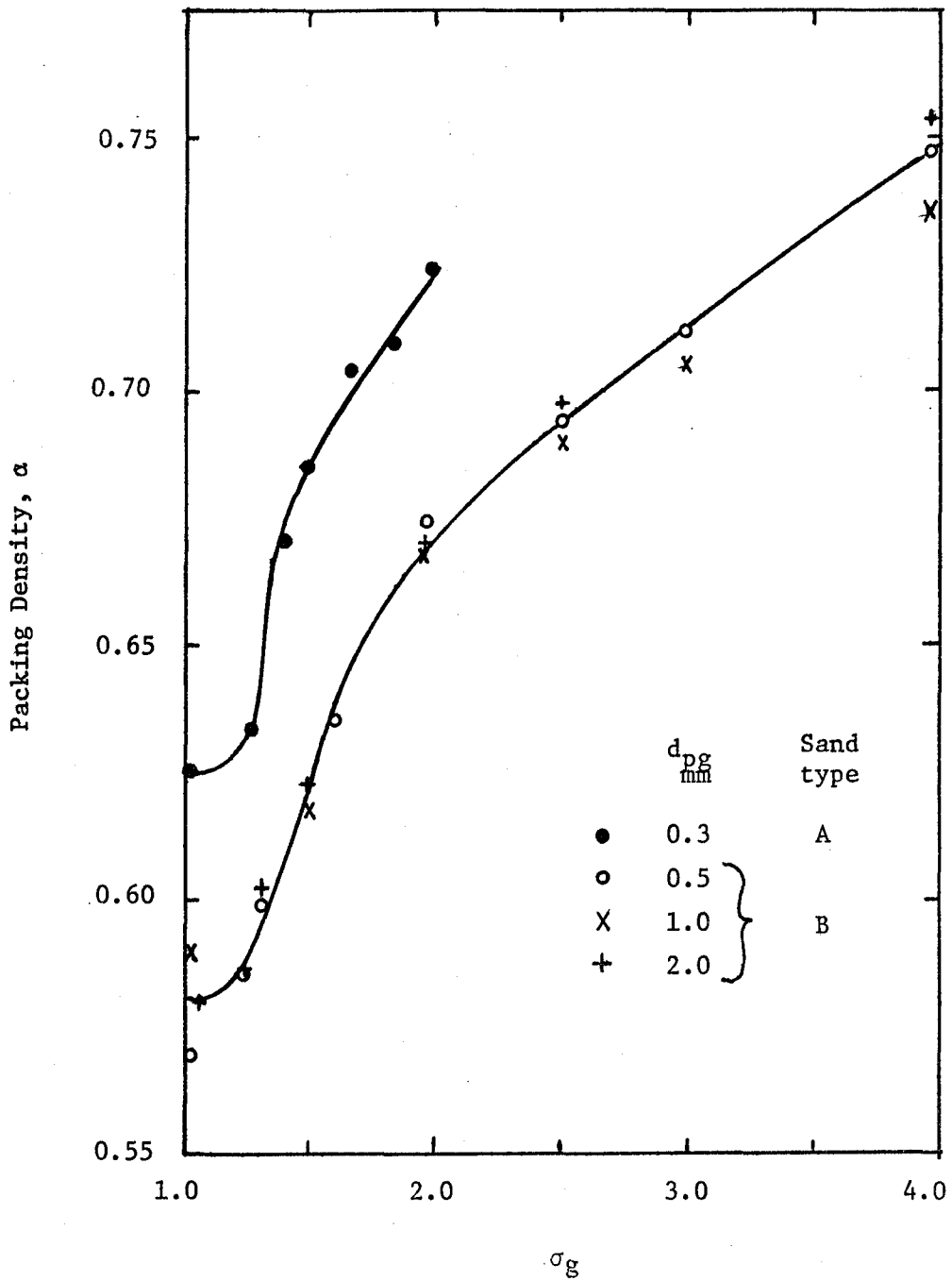


Figure II-16. Relationship of Geometric Standard Deviation on Packing Density (63).

A and B, with A type being of higher sphericity. As σ_g for both sand types increases, packing density is shown to increase. Packing densities are also shown to be higher for the more spherical particles. Thus, it may be inferred that spherical particles pack more tightly than other shaped particles. Three different mass mean diameters of type B sand were used in developing Figure II-16. The scatter of data is relatively small inferring that packing density is independent of mass mean diameter.

Sohn and Moreland have also reported that for a monodispersed particulate ($\sigma_g=1$) of spherical shape, porosity is independent of particle size. Thus, a monodispersed particulate bed of three micron particles would have the same porosity as a monodispersed particulate bed of thirty micron particles.

Specific Surface

Specific surface is defined as the surface area exposed to the fluid flow per unit weight or per unit volume of solid material and is expressed for spherical particles by (19,50):

$$S_v = \frac{\text{surface area of solids in a given total volume}}{\text{volume of solids in a given total volume}}$$

$$= \frac{\text{surface area of one particle}}{\text{volume of one particle}} = \frac{A_p}{V_p} = \frac{6}{d_p} \quad (\text{II-58})$$

$$S_w = \frac{6}{d_p \rho_p} = \text{surface area per unit weight} \quad (\text{II-59})$$

Table II-6 presents computational values of (A_p/V_p) for spherical particles ranging from 500 to 0.5 microns. It can be seen from this table that specific surface values increase dramatically with decreasing particle size. It can be concluded from Table II-6 that

Table II-6

Values of A_p/V_p for Spherical Particles in
Fabric Filter Dust Cake

Particle Size μm	cm	A_p/V_p^* cm^{-1}	$(A_p/V_p)^2$ cm^{-2}
500	5×10^{-2}	1.2×10^2	1.44×10^4
300	3×10^{-2}	2×10^2	4×10^4
200	2×10^{-2}	3×10^2	9×10^4
100	10^{-2}	6×10^2	3.6×10^5
50	5×10^{-3}	1.2×10^3	1.44×10^6
30	3×10^{-3}	2×10^3	4×10^6
20	2×10^{-3}	3×10^3	9×10^6
10	10^{-3}	6×10^3	3.6×10^7
5	5×10^{-4}	1.2×10^4	1.44×10^8
3	3×10^{-4}	2×10^4	4×10^8
2	2×10^{-4}	3×10^4	9×10^8
1	1×10^{-4}	6×10^4	3.6×10^9
0.5	5×10^{-5}	1.2×10^5	1.4×10^{10}

$$*S_o = (A/V) = 6 \pi D_p^2 / \pi D_p^3 = 6/D_p, \text{ cm}^{-1}$$

specific surface is a highly significant parameter in determining specific or operating dust resistivity.

An interesting observation is the fact that a large amount of surface area can exist per unit mass. For example, a cubic centimeter of unit density material distributed as one micron spheres will have a specific surface of $6.0 \text{ m}^2/\text{gram}$. Specific surface values per unit weight range from below $0.01 \text{ m}^2/\text{gram}$ for certain sand types to above $1000 \text{ m}^2/\text{gram}$ for specific porous carbon compounds (19).

Particle Shape Factors

Most prediction methods for determining pressure loss across a dust cake assume the deposited particulate matter to be spherical in shape. Naturally, this is not always the case and a means for compensating is required for determining specific surface factors. For particles which are not spherical, the specific area/volume relationship is given as (64):

$$\frac{A_p}{V_p} = \lambda 6/d_p \quad (\text{II-60})$$

where the particle shape factor, λ , is a correction factor. Values of λ based on geometric similarity, can be calculated using the following equation by Leva (64):

$$\lambda = 0.205 A_p/V_p^{2/3} \quad (\text{II-61})$$

where A is the surface area of a particle of arbitrary shape and V is the volume of that particle.

Care should be taken in discussing particle shape factors. The term "shape factor" can be understood relative to different methods of

determination such as geometrical similarity, aerodynamic similarity, and surface property similarity. Herdan (65) treats this matter in detail.

Pore Size and Structure

The physical shape and size of pores in granular media is related in part to particle size distribution, particle shape, packing arrangement, and the degree of compaction or compression applied (50). Increases in velocity of filtration, V , do increase compaction forces which compress bed structures thereby decreasing porosity and increasing K_2 as found by Sapite and Walsh (66). Other factors affecting compaction include pressure drop, drag forces on the deposited aggregates, and effects of adhesion, humidity and electrostatic forces (50).

Pore size and structure will vary according to the way the particulate packs. Billings (50) reported that the porosity of beds of uniform spheres varies upward from a value of about 0.259 found for a rhombohedral packing arrangement. Naturally, rhombohedral packing is not a type of packing expected to be found under field conditions. Packing of particulate in fabric filtration is a random process which results in a random arrangement of the particles. This randomness produces various size and structure interstitial pore openings.

Particle shape also effects pore size and structure. Packing of nonspherical particles tends to result in bridging which produces large pore openings (50). Thus, porosity is increased only to be offset partly by the tendency of smaller particles to accumulate in the larger interstitial spaces.

XI. FABRIC FILTER LITERATURE SUMMARY

Fabric filtration involves the filtering of dust-laden air through both a dust cake and a fabric media. Pressure loss across the fabric/dust cake filter can be described in terms of a permeability factor or a bed resistance factor. In filtration practice, the concept of bed resistance is preferred to permeability values.

The most predominant term found in the literature for describing bed resistance across a dust cake was specific or operating dust resistivity, K_2 or K_2' . The dust cake properties controlling specific (theoretical) or operating (measured) dust resistivity are expressed by Equation II-52 (p 56). The porosity and specific surface properties appear to have the most significant effect upon the bed resistance terms. In turn, porosity was found to be primarily a function of both the distribution of particle size and of particle shape. Specific surface was found to be a function of particle size.

Calculated values of specific dust resistivity have been reported to vary substantially from real data (50,54). Consequently, empirically developed values of operating dust resistivity are preferred. By developing a performance curve for a fabric/dust combination, a value of operating dust resistivity can be found as illustrated in Figure II-12 (p 58).

Pressure drop performance models for fabric filters have been developed by several individuals (50,54,63). Davis' model is the only mentioned model that predicts values of fabric filter pressure drop in the cake repair zone. All of these models require in input form a value

of specific or, preferably, operating dust resistivity. The determination of K_2' is a highly important parameter in assessing the performance of a fabric filter.

CHAPTER III

DESCRIPTION OF DESIGN AND PROCEDURAL TECHNIQUES FOR EXPERIMENTS PERFORMED

I. INTRODUCTION

Preface

Analysis of Equations II-8 (p 28), II-32 (p 40), and II-52 (p 56) can provide a theoretical acquaintance for the complex interaction of cyclones on fabric filters and the resulting system pressure drop. As a cyclone progressively becomes more efficient, mass mean diameter and σ_g of the outlet dust distribution decrease resulting in higher cake porosity values. Higher porosity values, in turn, result in higher permeability and lower resistance factors which equates to lower pressure loss. Likewise, by decreasing dust loading to the fabric, pressure loss across the fabric may be reduced for a given cycle time, t .

On the other hand, cyclones tend to increase fabric filter pressure losses by increasing specific surface values. (See Table II-5 (p 64) for the effect of particle size on specific surface.) Reduction in dust loading has also been reported to raise fluid viscosity values which has a detrimental effect on fabric filter pressure loss. Associated with the reduction of dust loading is the removal of the denser particulate fractions which theoretically increases specific dust resistivity and pressure losses.

Although cyclone precleaners may lower fabric filter pressure losses, they do so at the expense of pressure losses across themselves.

Higher cyclone particulate removal efficiencies are the result of increased inlet flows to the cyclone with pressure drop being a function of the flow squared. Thus, theoretically, there is a point at which system pressure loss for a cyclone/fabric filter combination; that is, the summation of pressure losses occurring across both a cyclone and fabric filter in combination, will exceed pressure loss for a fabric filter operating by itself.

Objective of Laboratory Testing

In order to better understand the relationship of cyclone efficiency on system pressure drop and how the relationship varies with inlet dust size, laboratory experiments were conducted to study the system pressure drop effects of modifying inlet dust size distributions to a fabric filter by varying the efficiency of a precleaning cyclone. Laboratory data was collected in order to determine if there is a pragmatic optimum cyclone efficiency for cyclone/fabric filter collectors. Restated, does a minimum system pressure loss occur at a value of cyclone efficiency that can be reasonably obtained, and that can result in sufficient pressure loss savings to make attainment of optimum cyclone efficiency justifiable?

Laboratory testing was also conducted for the establishment of a data base from which modeling constants could be derived, and for the establishment of a unique method for expressing the operating dust resistivity as a function of some cyclone/fabric filter operating parameter.

Experimental Facility

In order to accomplish the objectives of laboratory testing, a bench scale fabric filtration test unit was utilized. A schematic of the bench scale unit is shown in Figure III-1. A test dust was deposited on a rotating table and metered to the filtration chamber using a variable speed table feeder. Dust feed from the table was by a pickup tube under negative pressure. The dust entrained in the pickup tube air flow passed to the filtration chamber where it was dispersed by a diffuser before contacting the fabric.

The bench scale test facility could be operated with or without a cyclone precleaner. For each dust type to be tested an initial filtration test was performed without a cyclone in-line. To modify the size distribution of the dust fed to the filtration chamber, a three inch diameter cyclone of Stairmand high efficiency medium throughput design was installed between the table feeder and filtration chamber. The dimensions of this cyclone are illustrated in Figure III-2. A quart size glass jar was fitted to the bottom of the cyclone to serve as the collection bin. Tapered reductions were placed on both cyclone inlet and outlet to provide attachment points for Tygon[®] tubing connecting the cyclone in-line with the table feeder and filtration chamber.

Pressure drop across the fabric was monitored with the use of an inclined manometer to ± 0.005 inch water gauge sensitivity. The same manometer was also used to determine cyclone pressure drop.

Flow through the test unit was produced by a constant volume displacement pump with the flow being controlled by a manual regulator

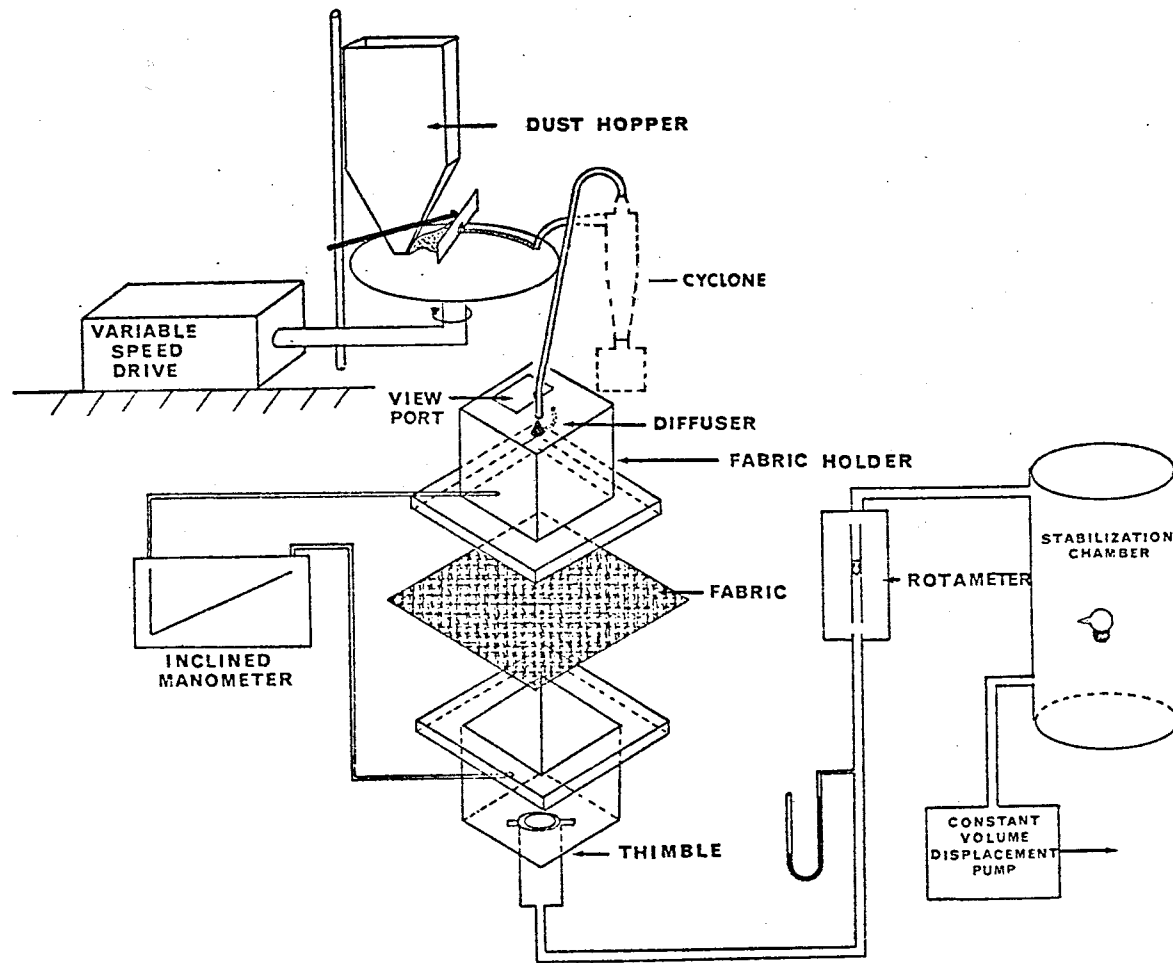


Figure III-1. Schematic Diagram of Bench Scale Test Unit.

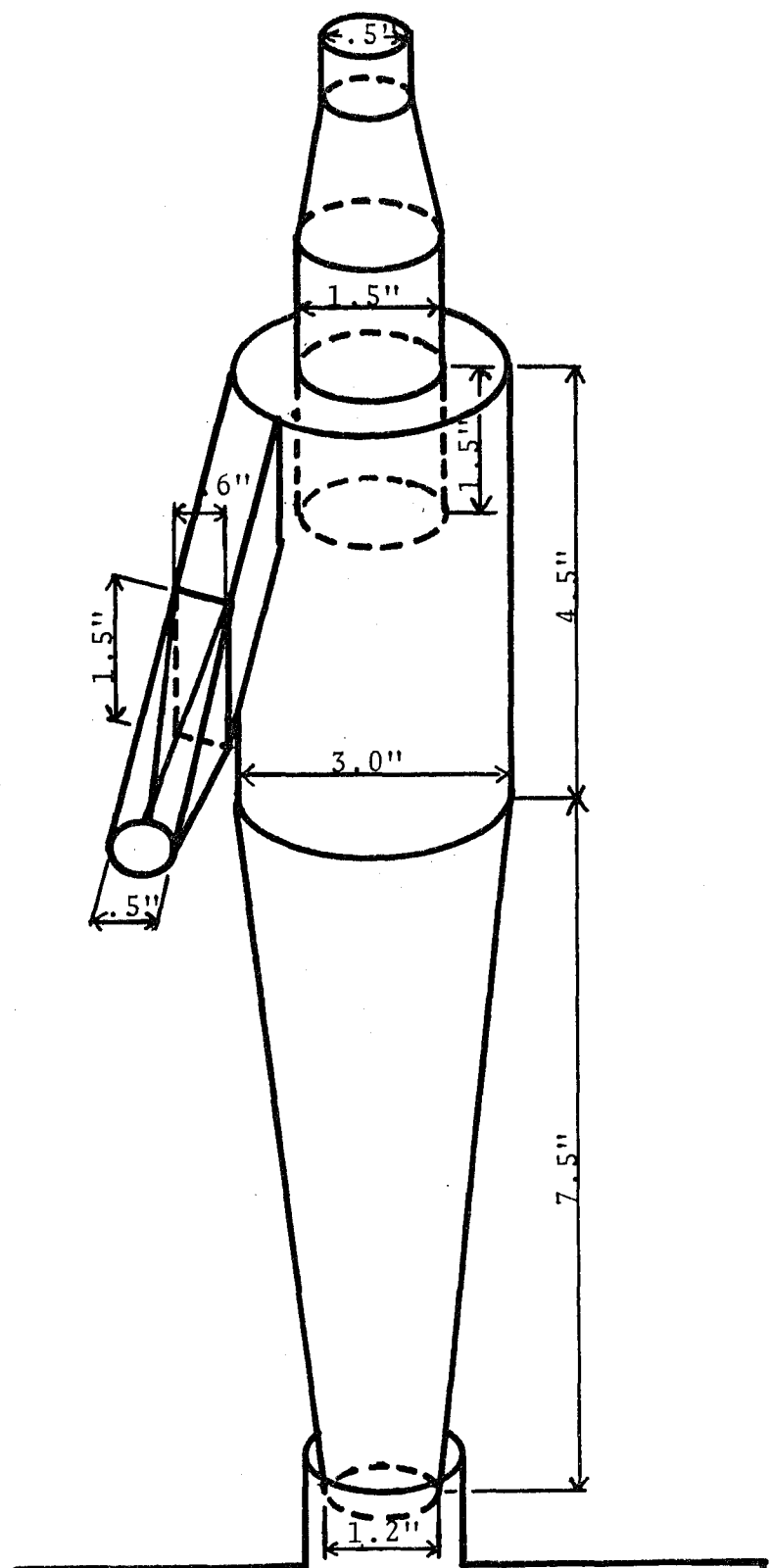


Figure III-2. Dimensions of Laboratory Cyclone.

placed between the rotameter and the pump. To control flow fluctuations within the system, a stabilization chamber with a bleed-in damper was installed between the regulator and displacement pump. The amount of negative pressure placed upon the test unit was monitored with a mercury manometer so that flow corrections across the rotameter could be made when needed.

II. EXPERIMENTAL DESIGN

Test Dusts

Six different talc dusts as shown in Table III-1 were used to provide a range of mass mean diameters from 3.86 microns to 15.29 microns. All dusts were of the same published density, 2.85 grams per cubic centimeter as determined by the manufacturer. The approximate standard geometric deviation (σ_g) of the six inlet talc dusts was two. Measurements of the size distribution by mass were performed on a Model TA Coulter Counter [®] (courtesy of Oak Ridge National Laboratory).

Test Fabric

A Fiberglass [®] filament fabric of bulk warp and bulk fill was used as the filtration medium. Fabric areal density (weight/area) was 14.0 - 14.9 ounces per square yard. This fabric is typical of the industrial fabrics currently being installed on high temperature applications such as coal fired boilers.

Test Description

An air to cloth ratio of four was used for all tests. An initial run with each of the six inlet dust types was performed without the cyclone in-line. Three additional runs were performed on each dust

Table III-1
Dusts Used in Experiments

Dust #	Description	d_{pg}	σ_g
1	Microtalc	3.86	1.97
2	Nytral 400 (talc)	5.68	1.94
3	Nytral 300 (talc)	8.18	1.87
4	Nytral 200 (talc)	10.36	2.10
5	Ceramitalc	13.09	2.02
6	Ceramitalc 10A	15.29	2.03

at different cyclone efficiencies. All runs were of 90 to 120 minute duration or until the pressure drop range across the manometer was exceeded ($\geq$ 11 inches water).

Varying cyclone efficiency values were generated by altering inlet velocities to the cyclone; or consequently, flows through the cyclone. In order to maintain a constant air to cloth ratio across the fabric, each specific cyclonic flow required a corresponding fabric surface area which would result in the four feet per minute filtration velocity. To achieve this, three additional bench scale unit tops of specified size were constructed of Plexiglass[®] in order to provide the approximate fabric area for maintaining the air to cloth ratio. Table III-2 specifies run number, flow, and top dimensions.

To determine if the different top dimensions would alter the performance of the fabric filter, all three tops were tested to determine if there was any substantial change in filtration performance. Using a single dust, Nytal 400, the average pressure drop across the filtration area between the three tops varied no more than plus or minus eight percent for a given areal dust density on the fabric. Likewise, the average slope of the performance curves for the three tops varied by no more than plus or minus one percent. Figure III-3 presents a comparison of the performance curves for the three tops. It was concluded that the method was a satisfactory one for testing the effect of cyclonic efficiency on the performance of fabric filters.

Two basic calibrations were required prior to performing any of the experiments. First, the table feed rate was calibrated to the rotational speed of the table. A dust loading of 5 grains per cubic

Table III-2

Specification of Run Number, Flow, and Top Dimensions for Laboratory Tests Performed.

Run #	Cyclone use	Cyclone flow (cfm)	Cyclone inlet velocity		Unit top	Top dimensions			
			(fpm)	(fps)		Width (in)	Breadth (in)	Height (in)	Fabric area (in ²)
1	No	None	-	-	A	12.0	12.0	12.0	144.0
2	Yes	4.0	640	10.67	A	12.0	12.0	12.0	144.0
3	Yes	2.0	320	5.33	B	8.5	8.5	12.0	72.0
4	Yes	1.0	160	2.67	C	6.0	6.0	12.0	36.0

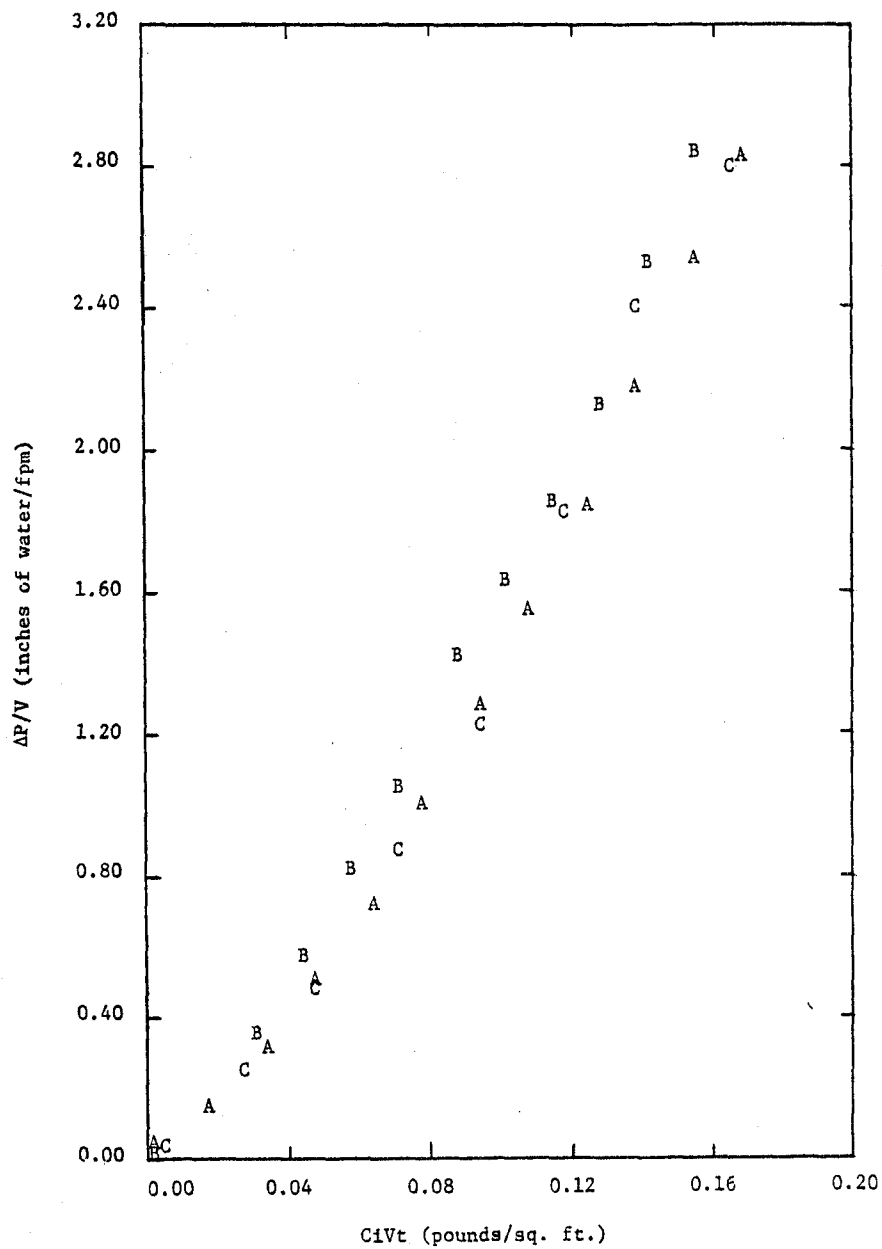


Figure III-3. Comparison of Performance Curves for Bench Scale Unit Tops A, B, and C.

foot from the feeder was prescribed but due to variations of dust deposition upon the table, dust loadings over the span of 24 runs ranged from 3 to 9.5 gr/ft³. Thus it was necessary to determine the average loading after each test. Secondly, system flow was calibrated. A cylindrical four inch by four foot long flow chamber was mounted in line with the bench scale unit. By traversing this chamber using a Type 8500 Alnor hot wire anemometer, the flow measuring rotameter was calibrated for the desired test flows.

To maintain a constant carrying velocity between the feeder table and cyclone, and between the cyclone and filtration chamber, the system tubing was sized for each flow so that an approximate carrying velocity of 2500 fpm was sustained.

Test Procedure

After assembling the test unit for each test, a leak test was performed. By restricting flow through the cyclone inlet, a seven inch mercury pressure differential could be placed across the unit. Any flow through the system could be monitored by the rotameter. Extra care was taken to prevent any leakage on the tests involving low flow rates.

Before injecting dust into the test unit, initial fabric pressure drop readings were recorded. Thereafter, fabric pressure drop and efficiency were monitored as a function of filtration time. Pressure drop values were generally recorded at five minute intervals. As resistance across the fabric increased, the regulator value had to be adjusted to maintain constant flow. Cyclone pressure drop values were taken while the cyclone was operating under a dust loading so as to

reflect the effect of grain loading on cyclone pressure losses. Ambient laboratory temperature was maintained at $24^{\circ}\text{C} \pm 2^{\circ}$, and relative humidity was controlled to $35\% \pm 5\%$.

III. ANALYSIS TECHNIQUES

Determination of Cyclone Efficiency

Each piece of fabric to be used as a filter was preweighed before being assembled into the filtration chamber. After a test run, the dust captured in the cyclone and collection jar was weighed. The fabric filter was carefully removed and weighed to determine the weight of the dust passing through the cyclone to the fabric. To this weight was added the weight of any dust accumulations found in the test system between the cyclone outlet and fabric filter. These dust accumulations were generally considered to be negligible. Since fabric filters generally exceed 99.5% collection efficiency by mass, no measurable amount of particulate was expected to penetrate through the filter as was the case. By gravimetric analysis the initial grain loading into the system, cyclone efficiency, and effective grain loading to the fabric were ascertained.

Determination of Cyclone Inlet and Outlet Size Distributions

Attempts to obtain in situ size distributions using a GII Model 226 Source Cascade Impactor[®] and a ESC PILLS VI[®] optical particle size-concentration monitor proved unsatisfactory due to the inability of these instruments to sample from the small duct size carrying the dust-laden air flow. Samples of the cyclone outlet dust collected from the fabric filter were hermetically stored from each test run. These were analyzed

along with inlet dust samples using a Model TA Coulter Counter [®]. Isotron II [®] was used as the electrolytic dispersant. A typical graphical output is shown in Figure III-4. By analyzing these graphs, geometric mass mean diameter and standard geometric deviation were obtained.

Figure III-5 is a typical photomicrograph taken of a dust sample visually delineating changes in particle size distribution with increasing cyclone efficiency.

Determination of Dust Resistivity

Data recorded for each run were in the form of pressure loss across the fabric versus time. Performance curves were constructed from each data set by transforming the fabric pressure loss data to normalized resistance, $\Delta P/V$, and time data to areal cake density, $C_i Vt$. Since effective grain loading, C_i , and bag velocity, V , were constants for a given run, the transformation to $\Delta P/V$ versus $C_i Vt$ represented a plot of real data (multiplied only by a constant). A computer program with plotter routine was used to transform all data and plot the performance curve for each test run. Inputs to the program were C_i , V , ΔP and t . Figure III-6 is a plotter printout of a typical computer data analysis showing the performance curve. By graphically determining the slope of the linear portion of each performance curve, the operating dust resistivity, K_2' , was found.

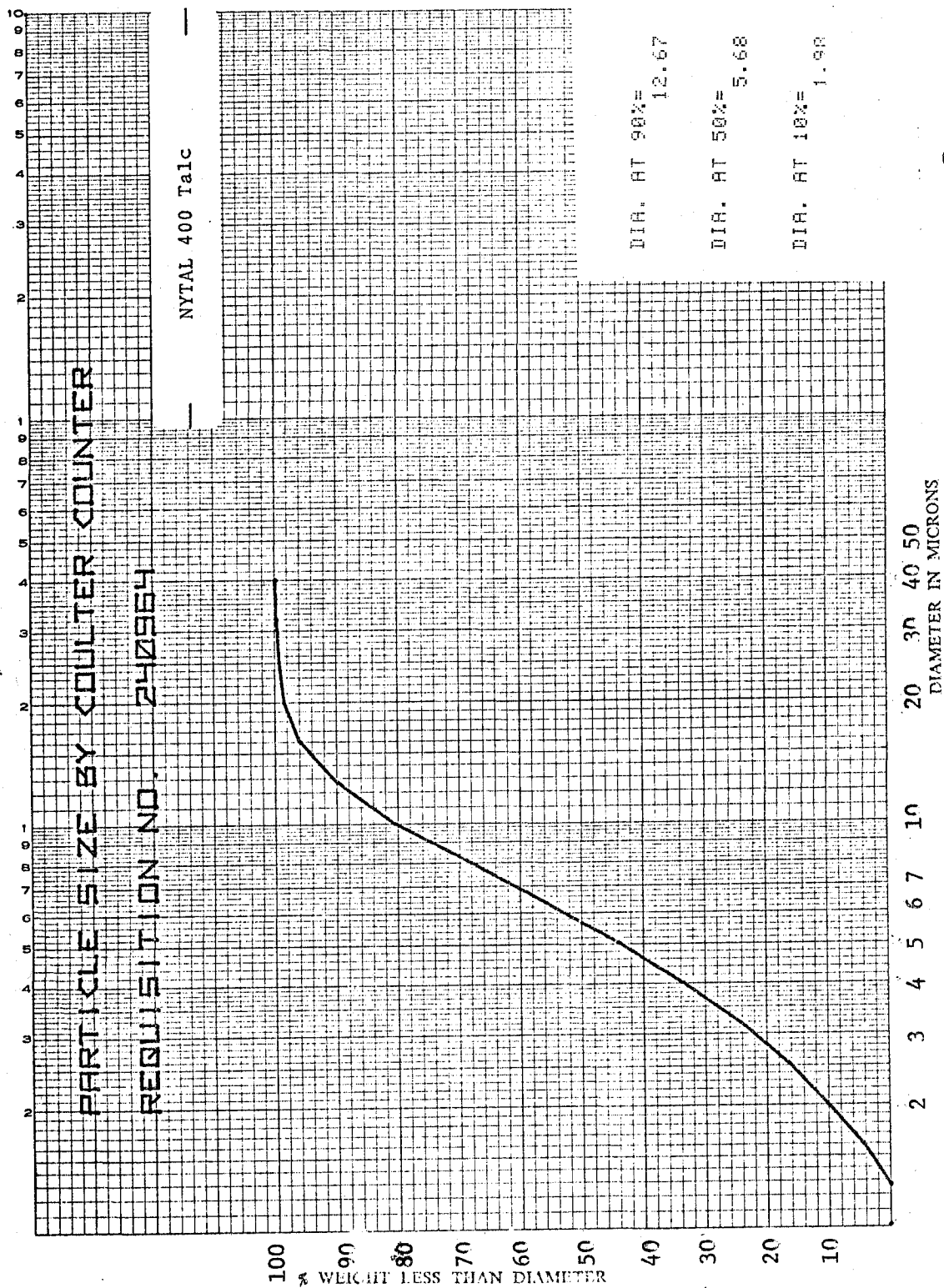
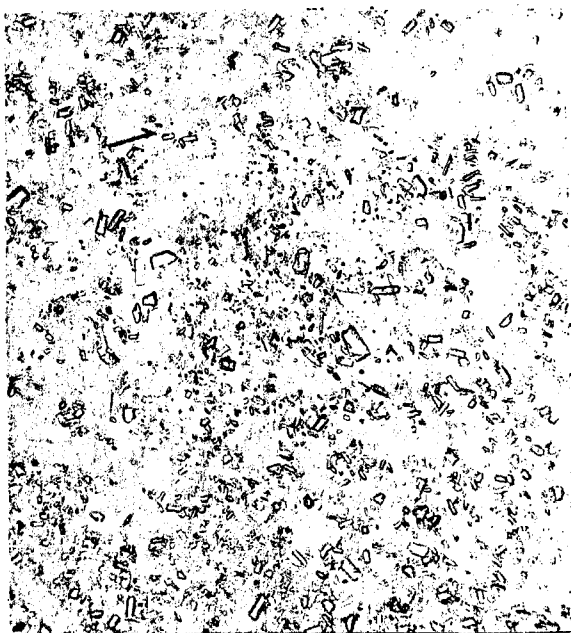
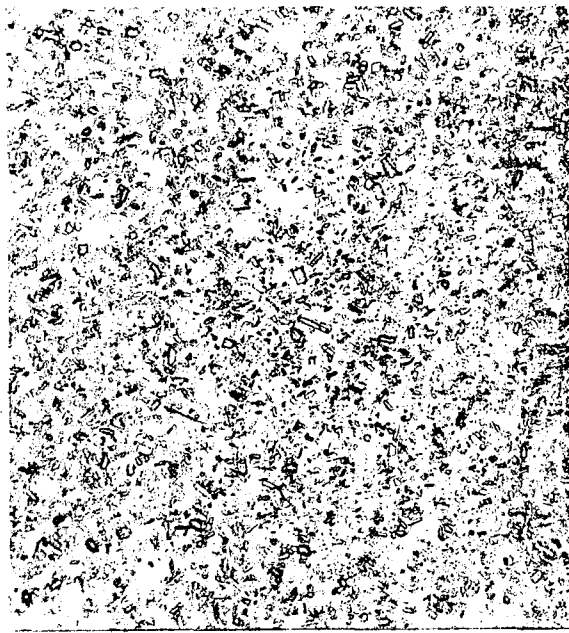


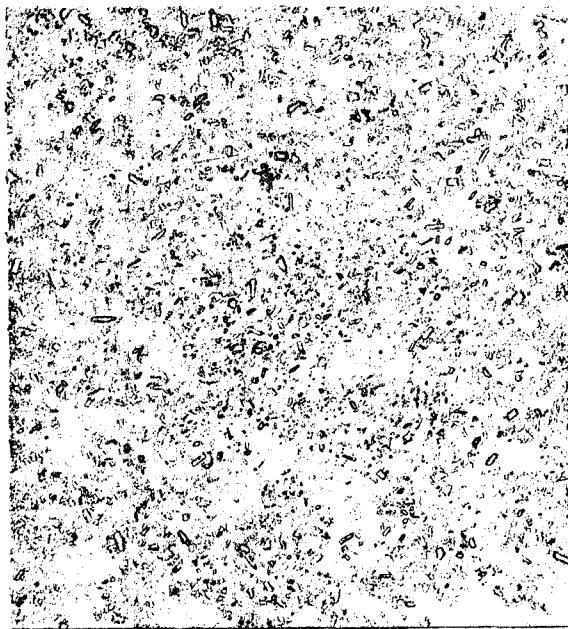
Figure III-4. Typical Graphical Output of Model TA Coulter Counter®.



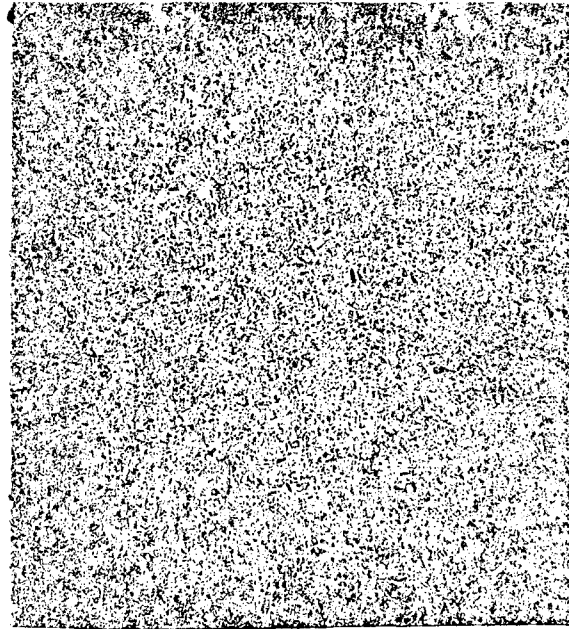
Zero Particulate Removal
100 X



64% Particulate Removal
100 X



70% Particulate Removal
100 X



82% Particulate Removal
100 X

Figure III-5. Effect of Cyclone Efficiency on Outlet Particle Size Distribution Using Dust #2.

RESISTANCE VS. AERIAL DUST DENSITY
DUST TYPE IS NYTAL 300
GRAIN LOADING= 7.25 GRAINS/SCF
A/C RATIO=4. FT/MIN
FABRIC TYPE=0004
EXPERIMENT NO. IS SFA-1/27/77

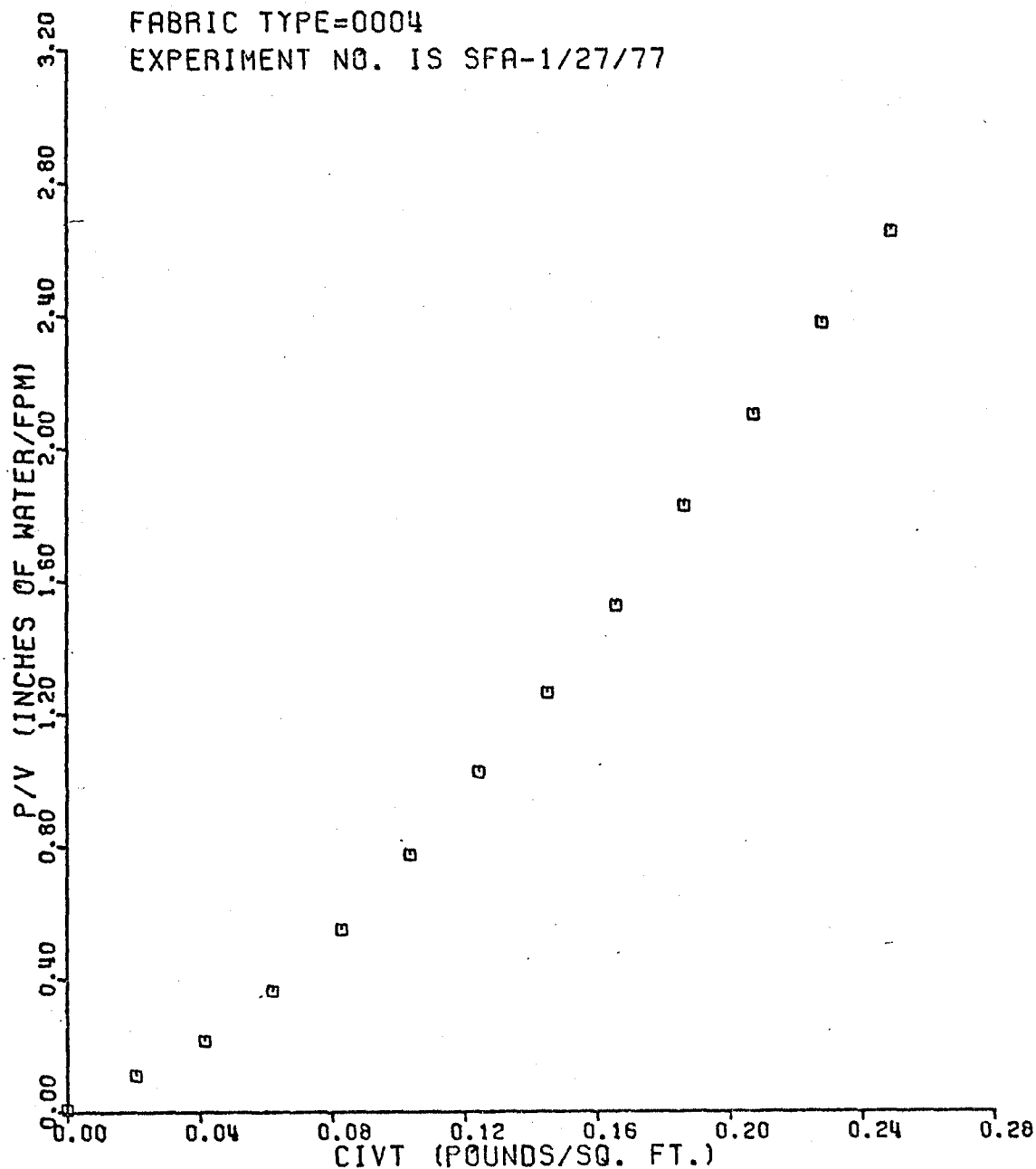


Figure III-6. Typical Computer Printout of Performance Curve.

CHAPTER IV

RESULTS AND DISCUSSION OF LABORATORY EXPERIMENTS

I. RAW DATA EVALUATION

Introduction

As described in Chapter III a bench scale test unit composed of a cyclone in-line with a fabric filter was used to generate system pressure drop data as a function of cyclone efficiency. Four experimental runs of varying cyclone efficiencies were performed for each of the six dust types. The results of these 24 runs are presented in Table IV-1. Run 1 for each dust type was performed without a cyclone in-line.

Analysis of the raw data involved determining the performance curve for each of the 24 runs. Graphs of filter resistance, $\Delta P/V$, versus areal cake density, $C_i Vt$, were generated. For any given value of $C_i Vt$, the fabric filter pressure loss could be obtained. Assuming a constant inlet dust loading to the cyclone, C_i -inlet, the effective dust loading to the fabric filter, C_i , would decrease with increasing cyclone efficiency. For the same length of filtration time, runs with the higher cyclone efficiencies had lower values of $C_i Vt$.

Normalization of $C_i Vt$ Values

Constant C_i -inlet values were not obtained. Inlet dust loadings to the test unit varied because of dissimilar dust depositions on the feeder table. Thus, a comparative analysis of the raw data for the 24 runs based on time in filtration would be in error. To correctly compare

Table IV-1
Results of Laboratory Experiments

V = 4 fpm for all runs	Run 1	Run 2	Run 3	Run 4	Run 1	Run 2	Run 3	Run 4	Run 1	Run 2	Run 3	Run 4
	Microtalc				Nytal 400				Nytal 300			
V_i (fpm)	+	640	320	160	+	640	320	160	+	640	320	160
C_i -inlet (gr/ft ³)	2.9	3.65	3.61	3.84	5.29	5.88	6.09	7.8	7.25	8.23	8.09	10.88
d_{pg} -in (microns)	3.86	3.86	3.86	3.86	5.68	5.68	5.68	5.68	8.18	8.18	8.18	8.18
d_{pg} -out (microns)	3.86	2.89	3.32	3.42	5.68	2.69	3.58	3.98	8.18	2.63	3.05	5.05
σ_g (microns)	1.97	1.59	1.78	1.8	1.94	1.56	1.82	1.93	1.87	1.56	1.74	2.12
η_{cyc} (%)	+	68.5	47	41	+	82	70	64	+	87	84	73
$\overline{P_t}$ (%)	+	31.5	53	59	+	18	30	36	+	13	16	27
C_i -effect (gr/ft ³)	2.9	1.15	2.17	2.13	5.29	1.04	2.13	2.55	7.25	1.09	1.31	2.46
K_2 $\frac{\text{inches H}_2\text{O}/\text{fpm}}{\text{lbs}/\text{ft}^2}$	42	62.5	58	56	21.5	41	37	43	13.5	44	39	34
Normalized $C_i V_t$	0.129	0.041	0.068	0.076	0.129	0.023	0.038	0.046	0.129	0.017	0.021	0.035
ΔP_{ff} @ norm. $C_i V_t$	18.9	7.52	12.5	15.0	8.15	2.88	3.52	3.76	4.32	1.61	1.92	2.24
ΔP_{cyc} (inches H ₂ O)	0	4.75	1.46	0.52	0	4.75	1.46	0.52	0	4.75	1.46	0.52
ΔP_{sys} @ norm. $C_i V_t$	18.9	12.27	13.96	14.93	8.15	7.63	4.98	4.28	4.32	6.36	3.38	2.76

Table IV-1 (Continued)

V = 4 fpm for all runs	Run 1	Run 2	Run 3	Run 4	Run 1	Run 2	Run 3	Run 4	Run 1	Run 2	Run 3	Run 4
	Nytal 200				Ceramitalc 1				Ceramitalc 10A			
V_i (fpm)	+	640	320	160	+	640	320	160	+	640	320	160
C_i -inlet (gr/ft ³)	9.0	9.29	10.17	12.08	7.49	8.33	9.59	8.94	9.57	9.63	11.82	12.8
d_{pg} -in (microns)	10.36	10.36	10.36	10.36	13.09	13.09	13.09	13.09	15.29	15.29	15.29	15.29
d_{pg} -out (microns)	10.36	2.31	3.74	4.63	13.09	2.65	3.25	4.72	15.29	2.59	3.38	4.04
σ_g (microns)	2.1	1.54	2.0	2.15	2.02	1.64	2.0	2.3	2.03	1.7	1.95	2.13
η_{cyc} (%)	+	90	83	81	+	86	83	80	+	91	86	86
$\bar{P}_t$ (%)	+	10	17	19	+	14	17	20	+	9	14	14
C_i -effect (gr/ft ³)	9.1	0.9	1.77	2.15	7.48	1.18	1.59	1.55	9.57	0.9	1.66	1.60
K_2 $\frac{\text{inches H}_2\text{O/fpm}}{\text{lbs/ft}^2}$	11	48	36	32	18.5	52	55	51	9.5	41	28	16
Normalized $C_i V_t$	0.129	0.013	0.022	0.024	0.129	0.018	0.022	0.026	0.129	0.012	0.018	0.018
ΔP_{ff} @ norm. $C_i V_t$	3.6	1.32	2.48	2.4	6.2	2.32	3.56	3.2	3.52	1.19	1.24	1.2
ΔP_{cyc} (inches H ₂ O)	0	4.75	1.46	0.52	0	4.75	1.46	0.52	0	4.75	1.46	0.52
ΔP_{sys} @ norm. $C_i V_t$	3.6	6.07	3.94	2.92	6.2	7.07	5.02	3.72	3.52	5.94	2.70	1.72

+ Data values not applicable due to absence of in-line cyclone.

the data, an analysis must be based on normalized areal dust density, that is, all laboratory data had to be evaluated at the same effective inlet grain loading to the cyclone. By data normalization, all inlet dust loadings were adjusted to 5.0 grains per cubic foot. Effective dust loadings to the filter were determined by multiplying C_i -inlet by the cyclone penetration, $\overline{Pt}$. With values of $C_i Vt$ normalized for C_i , a comparative analysis of the laboratory data could be made for a specific effective time, t , in filtration.

Figure IV-1 is a graph, using normalized laboratory data, of system pressure drop as a function of cyclone collection efficiency for all six dust types. Values of $C_i Vt$ were based on the following:

$$V = 4 \text{ ft/min}$$

$$t = 45 \text{ min}$$

$$C_i\text{-inlet} = 5.0 \text{ gr/ft}^3.$$

It is hard to visualize in Figure IV-1 a graphical line representing the relationship between system pressure drop and cyclone efficiency for each dust type. However, Figure IV-1 does provide sufficient data representing the relationship between system pressure drop and cyclone efficiency to indicate that there is an optimum cyclone efficiency that can result in significant system pressure loss savings. A minimum system pressure drop value can be observed at some intermediate cyclone efficiency for all dust types except dust #1. Another important observation from Figure IV-1 is that system pressure drop values in the higher cyclone efficiency ranges tended to be greater than system pressure drop values occurring with no precleaning of the dust-laden gas flows for dust types #3 through #6. This indicates, in terms

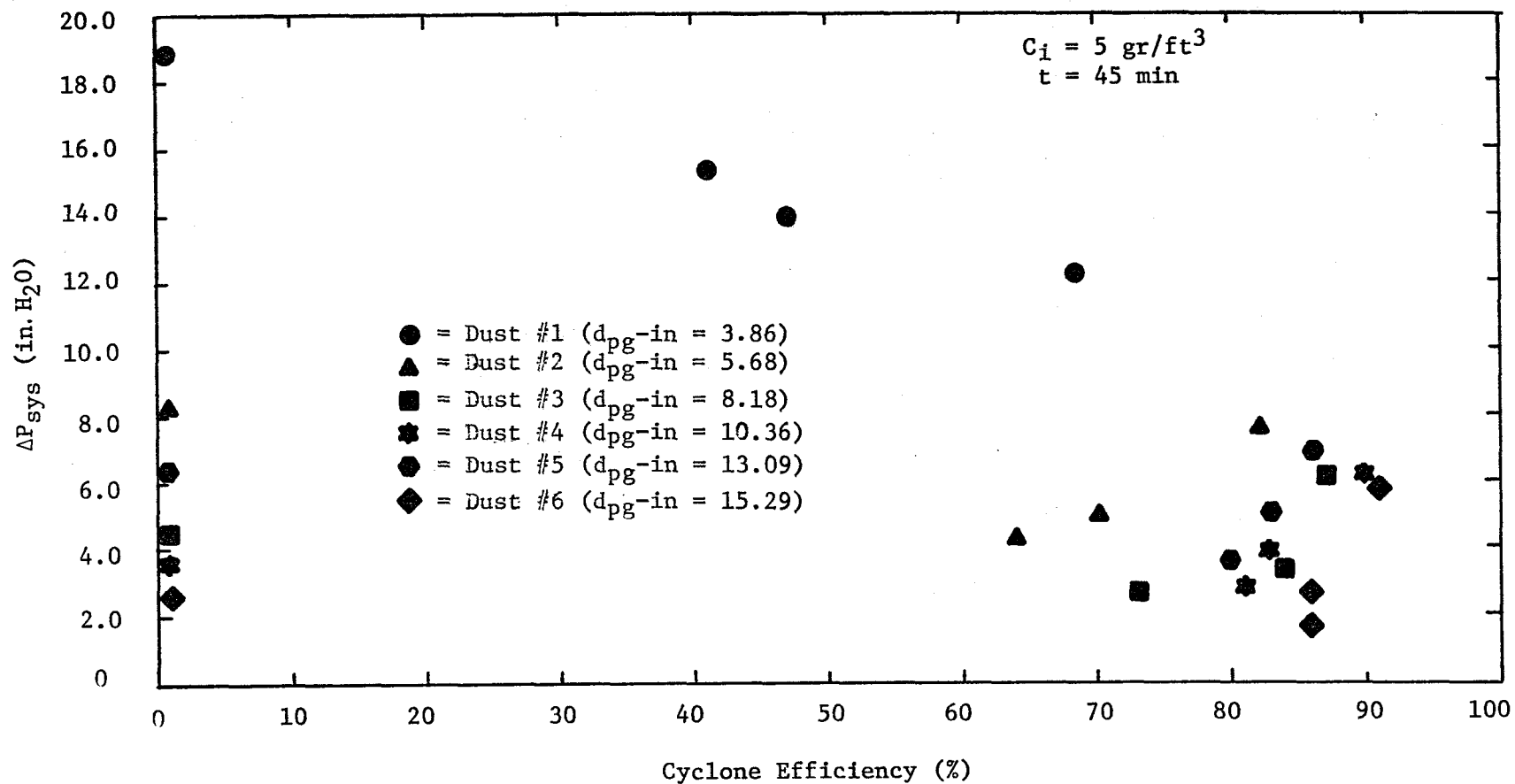


Figure IV-1. Plot of Normalized Laboratory Data Relating System Pressure Drop to Cyclone Efficiency.

of system pressure loss, that no precleaning of these dust-laden flows would be better than high efficiency precleaning.

II. DETERMINATION OF DATA RELATIONSHIPS

Relation of $\overline{Pt}$ with V_i

In order to more fully visualize the shape of the curves in Figure IV-1, a cyclone/fabric filter pressure drop model was developed to generate additional data values (the development of this model will be discussed in Chapter V). Values of cyclone integrated penetration, $\overline{Pt}$, and operating dust resistivity of the fabric filter, K_2' , were required inputs to the model. To generate these values, graphical relationships were found between the data that allowed interpolation of the inputs. Graphical relationships found for each dust type were: 1) the relationship between integrated cyclone penetration and cyclone inlet velocity, 2) the relationship between geometric mass mean diameter of particulate passing through cyclone and integrated cyclone penetration, and 3) the relationship between operating dust resistivity and geometric mass mean diameter of particulate passing through the cyclone.

Figure IV-2 is a semi-log plot of integrated cyclone penetration versus cyclone inlet velocity. Knowing that cyclone penetration must equal a value of 1.0 at $V_i=0$, a freehanded "best fit" line was drawn through the data points of each dust type. A smooth curve was assumed between the cyclone inlet velocity values of zero and 160 feet per minute as the actual shape of this line segment is unknown. Fortunately, the values of integrated penetration resulting from cyclone inlet velocities below 160 fpm were not pertinent for the determination of

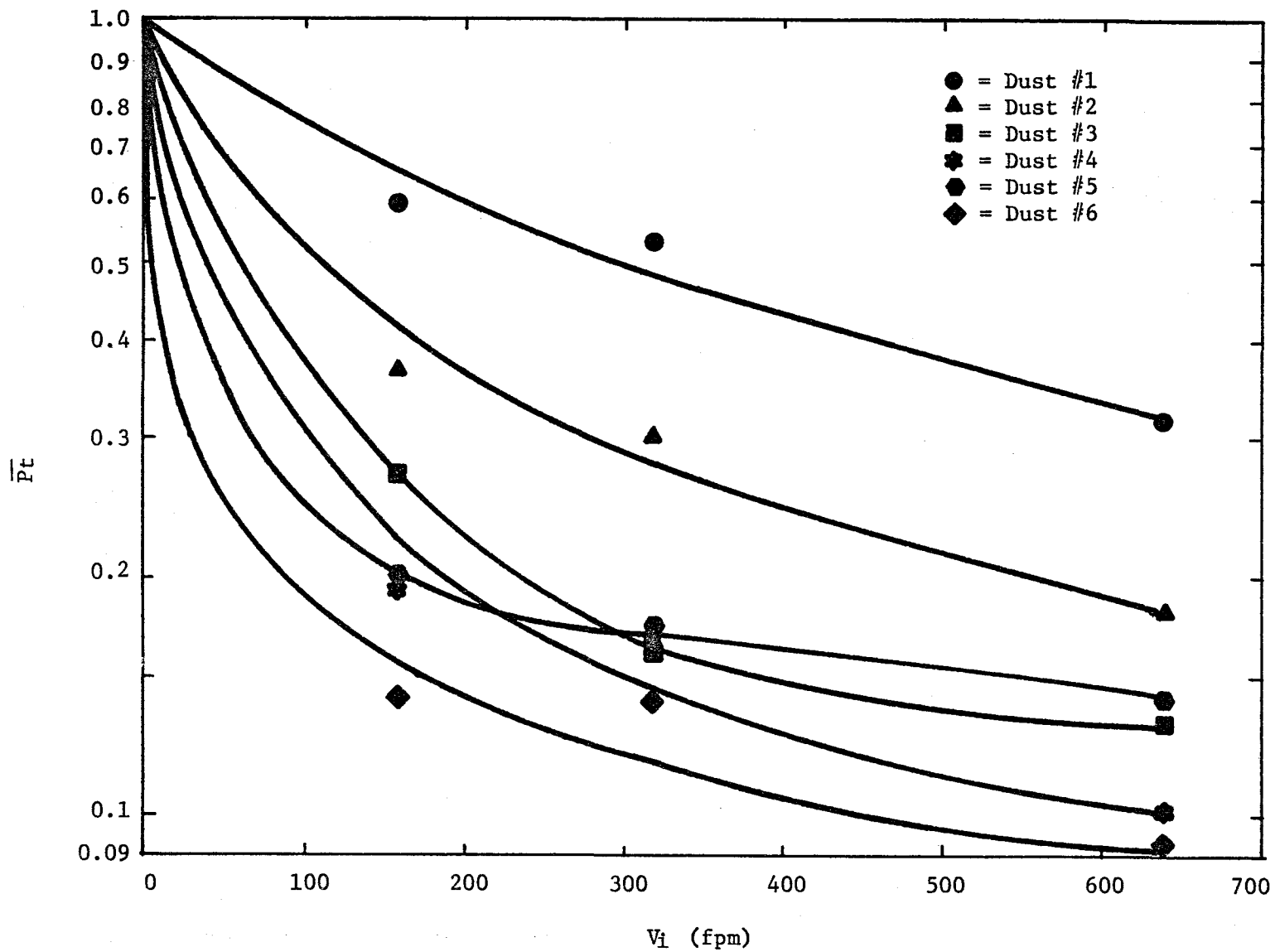


Figure IV-2. Relationship Between Integrated Cyclone Penetration and Cyclone Inlet Velocity.

optimal cyclone efficiency. Using Figure IV-2 a graphical estimation of $\overline{Pt}$ can be made for a given inlet velocity and dust type.

Relation of d_{pg} -out with $\overline{Pt}$

Figure IV-3 is a semi-log plot of the geometric mass mean diameter out of the cyclone, as determined by particle size analysis using a Coulter Counter, versus integrated cyclone penetration for each dust type. All dust types, except type #5, appear analogous in shape. Smooth curves were again graphically obtainable on a freehanded "best fit" basis. Having obtained the percent by mass of the dust penetrating through the cyclone from Figure IV-2, the geometric mass mean diameter of the penetrating dust can be approximated over the range of values graphically represented using Figure IV-3.

Relation of K_2' with d_{pg} -out

Historical theoretical predictions of K_2 by Williams, et al. (56), Billings (50), and Frazer, et al. (60) have proved cumbersome and inaccurate. For this reason, a method was sought whereby empirically determined operating dust resistivity values could be used as inputs into the cyclone/fabric filter pressure drop model. Such a method was found by plotting K_2' values as a function of d_{pg} -out. This relationship is unique in that it provides a means separate from historical theory to predict values of K_2' .

Figure IV-4 is a semi-log plot of operating dust resistivity versus geometric mass mean diameter of the particulate penetrating through the cyclone for each dust type. Values of K_2' were obtained over a range of geometric mass mean diameter values for each dust using

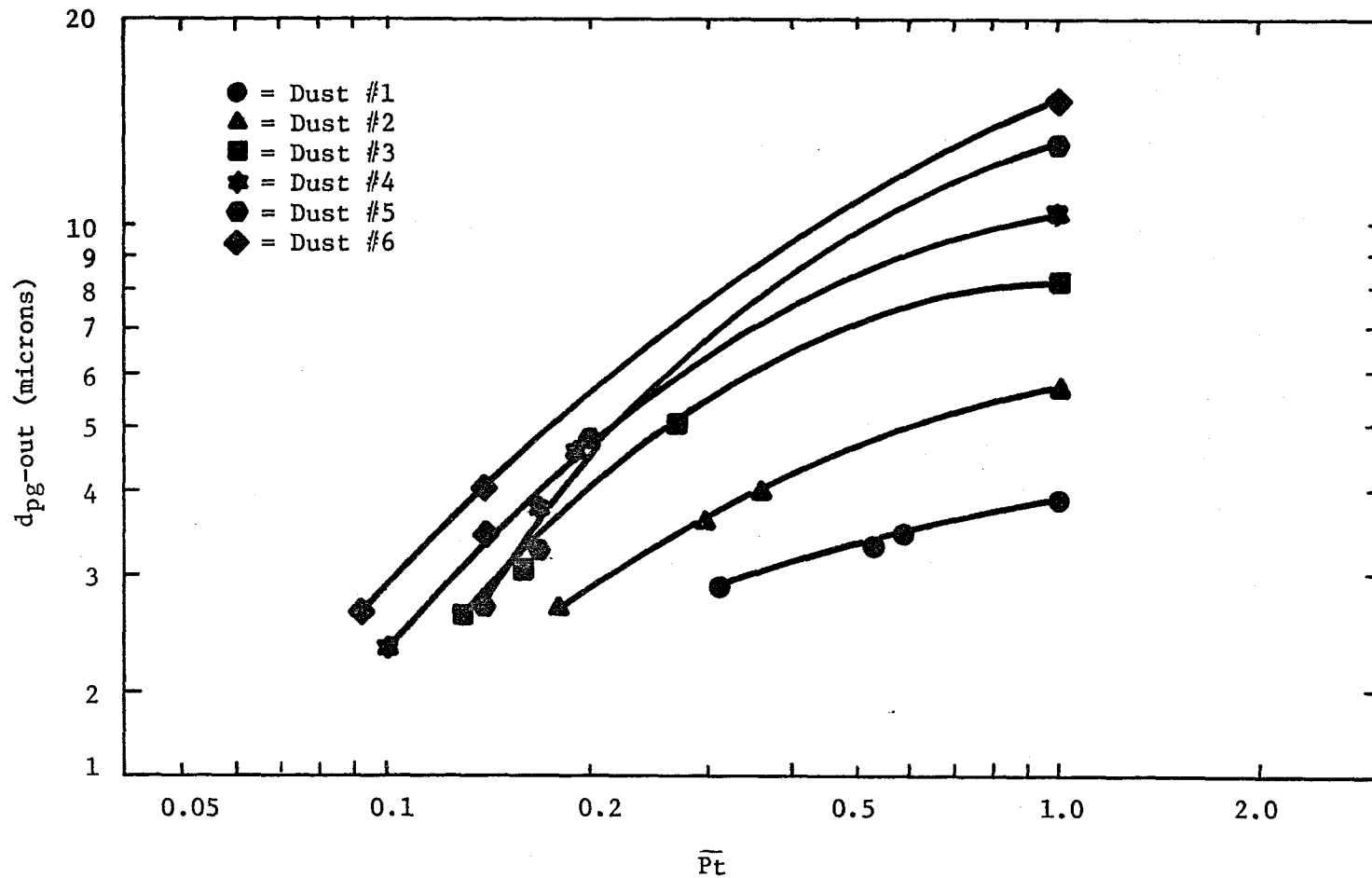


Figure IV-3. Relationship Between Mass Mean Diameter Out of Cyclone and Integrated Cyclone Penetration.

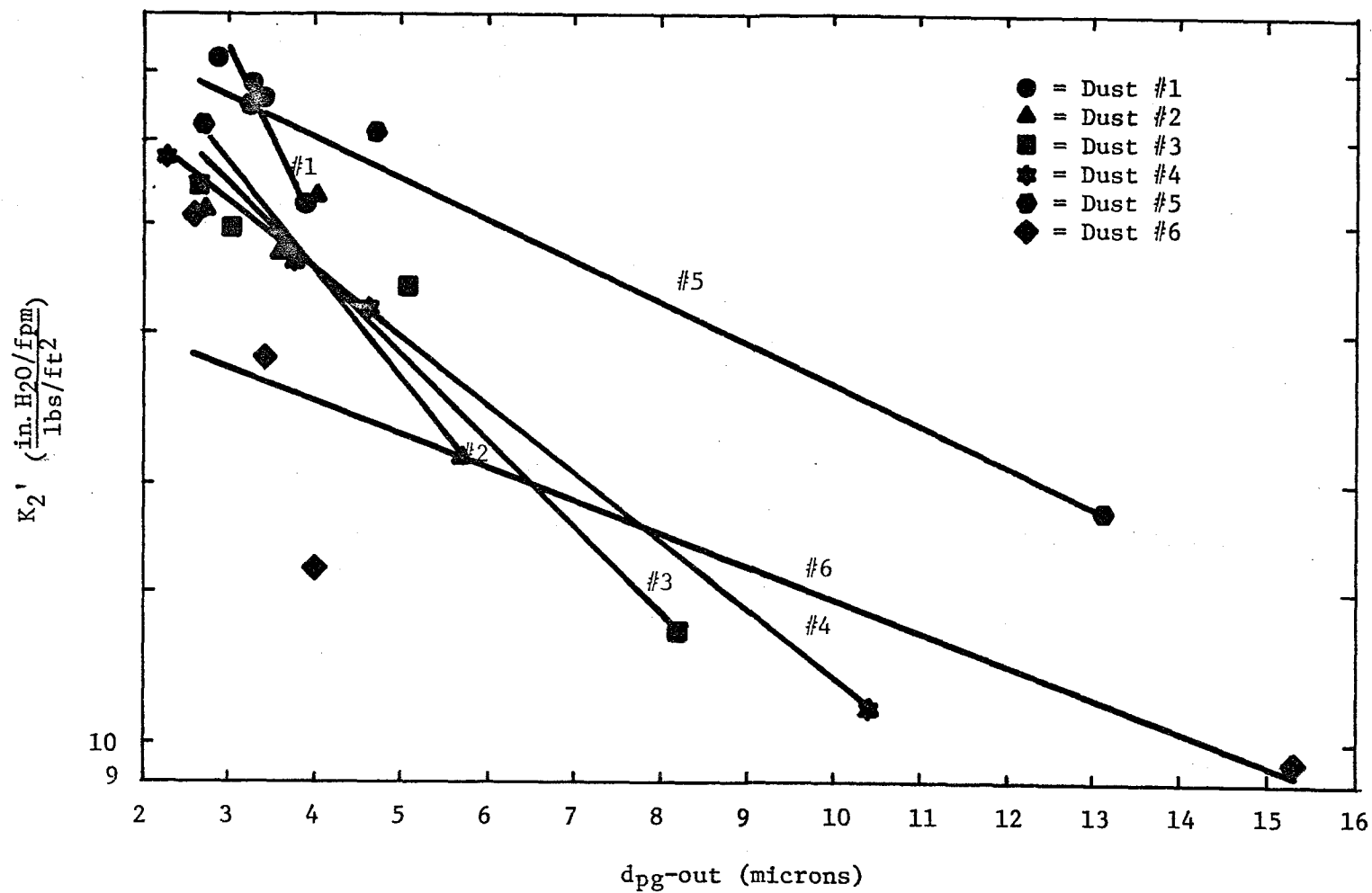


Figure IV-4. Relationship Between Dust Resistivity and Mass Mean Diameter Out of Cyclone.

the K_2' determination procedure and bench scale cyclone/fabric filter test unit as described on page 85 in Chapter III.

A regression analysis of $\ln(K_2')$ on d_{pg} -out was performed on the laboratory data obtained for each of the six dust tested. Table IV-2 reports the results of that analysis. A relationship of the form:

$$K_2' = \exp [a(d_{pg}\text{-out}) + b] \quad (IV-1)$$

was found to describe K_2' as the function of d_{pg} -out for each of the six dusts with correlation coefficients ranging between 0.85 and 0.99+. Four of the dusts had correlation coefficients greater than 0.94. Using the relationship expressed in Equation IV-1, regression lines were fitted to the data points of each dust type in Figure IV-4.

The ability to define the relationship of d_{pg} -out on K_2' is a significant attainment. By finding the geometric mass mean diameter of the particulate penetrating the cyclone from Figure IV-3, a value of the operating dust resistivity can be approximated. Consequently, for a given cyclone inlet velocity value, Figure IV-2, IV-3, and IV-4 can be used to graphically obtain values of $\overline{Pt}$, d_{pg} -out, and K_2' for each dust.

Relation of ΔP_{cyc} with V_i

Laboratory cyclone pressure drop data was analyzed as a function of inlet velocity in order to develop an equation for predicting laboratory cyclone pressure losses. This capability of empirically predicting cyclone pressure drop was incorporated into the cyclone/fabric filter pressure drop model that was used to generate additional laboratory data values.

Table IV-2

Results of Regression Analysis Performed on Each Dust Type in Figure IV-4

Dust Number	Dust Symbol	Dust Name	Slope of line (a)	Intercept of line (b)	Correlation coefficient
1	●	Microtalc	-.410	5.373	.938
2	▲	Nyral 400	-.224	4.429	.877
3	■	Nyral 300	-.206	4.367	.969
4	✱	Nyral 200	-.182	4.288	.999
5	●	Ceramitalc	-.107	4.334	.987
6	◆	Ceramitalc 10A	-.091	3.592	.852

Little, if any, effect on cyclone pressure drop was expected for the dust loading values used in the laboratory experiments. Nevertheless, in order to compensate for any effect of dust loading on cyclone pressure drop, cyclone pressure drop data was collected while the cyclone was operating under a dust loading of approximately five grains per cubic foot.

Figure IV-5 is a log-log plot of cyclone pressure drop versus cyclone inlet velocity for the experimental data obtained. An expression of the following form was found by linear regression analysis to fit the line with a correlation coefficient of 0.99+:

$$\Delta P_{\text{cyc}} = \exp [(1.6535 \ln(V_1)) - 9.1406] \quad (\text{IV-2})$$

Thus, for the range of inlet velocities expressed in Figure IV-5, the corresponding value of cyclone pressure drop could be predicted.

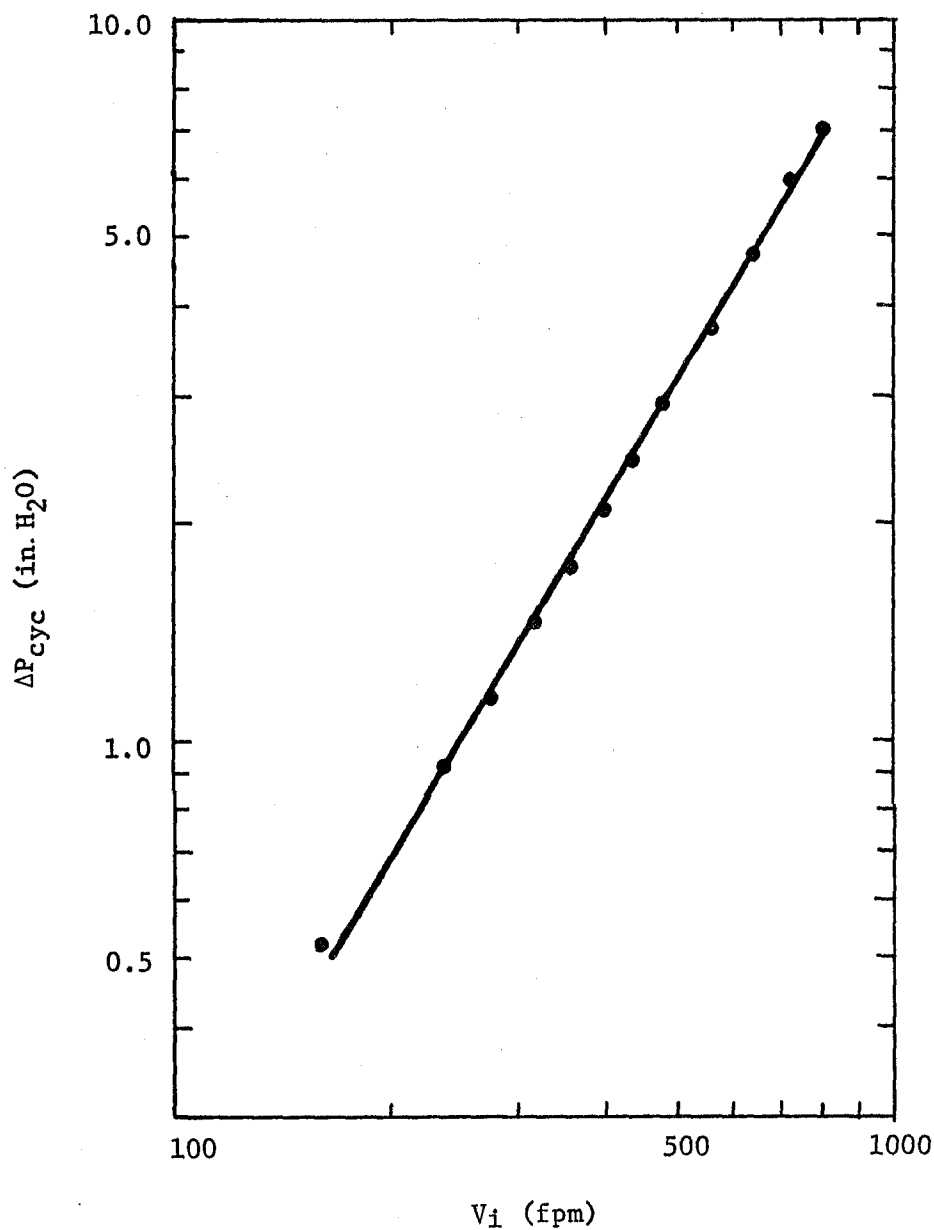


Figure IV-5. Relationship Between Pressure Drop and Inlet Velocity for the Laboratory Cyclone.

CHAPTER V

DEVELOPMENT OF CYCLONE/FABRIC FILTER

SYSTEM PRESSURE DROP MODEL

I. MODEL DEVELOPMENT

Introduction

As previously mentioned only four data points showing the relationship between system pressure drop and cyclone efficiency were generated empirically for each dust tested. These four data points per dust were not sufficient to establish a meaningful relationship between system pressure drop and cyclone efficiency. Additional values of system pressure drop were needed as a function of cyclone efficiency for each dust type in order to determine graphically the shape of the curve representing each relationship. Continued experimental generation of data points was considered unfeasible due to laboratory equipment and time limitations. It was decided that a more feasible approach was to extend the data by empirical modeling.

Modeling Approach

Two purposes existed in the development of a cyclone/fabric filter pressure drop model. The first purpose was to establish a modeling technique to generate missing laboratory data values using in input form as much empirical data as possible. To achieve this purpose the "basic model" was created which used the empirical data relationships developed in Figures IV-2 (p 95), IV-3 (p 97), and IV-4 (p 98). Empirically derived input values of integrated

penetration, $\overline{P_t}$, and the geometric mass mean diameter of that penetration, d_{pg} -out, as obtained from Figures IV-2 (p 95) and IV-3 (p 97) are referred to as graphically determined inputs.

Incorporated into the basic model was a fabric filter pressure drop modeling routine developed by Davis (54,59). Davis' model was selected over other published models due to: 1) the ability of the model to predict fabric filter pressure drop values in the cake repair zone of the performance curve, 2) the dependence of the model on empirically generated constants, and 3) the degree of familiarity and confidence with the model.

The prediction of fabric filter pressure drop using Davis' model can be accomplished for both unconditioned (new) fabrics and conditioned fabrics. Davis (59) claims a higher level of model confidence for predicted fabric filter pressure drops when using his expression for unconditioned fabrics.

The second purpose existing in the development of a cyclone/fabric filter pressure drop model was to provide a modeling technique that could be expanded to predict the relationship between system pressure drop and cyclone efficiency for field-type cyclone/fabric filter installations without having to generate input values from empirical data. This purpose was accomplished with the development and addition of a theoretical subroutine to the basic model for the prediction of the data relationships found in Figures IV-2 and IV-3. The theoretically predicted values of $\overline{P_t}$ and d_{pg} -out obtained from the theoretical subroutine are referred to as theoretically derived inputs. Thus, theoretically derived inputs can be used in lieu of graphically determined inputs. This

expanded modeling technique made possible the generation of optimization curves for predicting optimum cyclone inlet velocity and cyclone size for a given inlet dust size distribution, cyclone and fabric media type, and operating conditions.

It should be noted that both the basic model and the expanded version of the basic model require the empirically derived K_2'/d_{pg-out} relationship. This relationship was incorporated into the model using Equation IV-1 (p 99). Values of the variables a and b for each dust type are shown in Table IV-2 (p 100).

Development of Basic Model

In order to develop the basic model, two pressure drop parameters had to be evaluated. These parameters were:

Parameter 1: Pressure drop across the cyclone as a function of cyclone efficiency

Parameter 2: Pressure drop across the fabric filter as a function of cyclone efficiency.

Evaluation of Parameter 1

By analysis of laboratory data it was possible to define a relationship between pressure drop of the laboratory cyclone and its inlet velocity, V_i . Moreover, it was also possible to determine the relationship between the cyclone's inlet velocity and its efficiency for each dust type. Thus, the value of cyclone pressure drop for a given cyclone efficiency was obtainable for the range of data values collected.

Evaluation of Parameter 2

The evaluation of the second parameter was more difficult. No satisfactory relationship for determining the pressure drop across the fabric filter as a function of cyclone efficiency could be found from the empirical data alone. However, by using the fabric filter pressure drop model developed by Davis (54,59) as a subroutine in the cyclone/-fabric filter system pressure drop model, pressure drop could be predicted across a fabric filter if some empirically derived modeling constants expressing the relationship between dust characteristics and fabric type were known. Sufficient laboratory data was available to determine the needed modeling constants for Davis' model.

The evaluation of the second parameter was also dependent on the ability to determine how cyclone precleaning effects values of areal cake density ($C_1 Vt$) and operating dust resistivity (K_2'). The value of K_2' was determined as a function of the geometrical mass mean diameter of the particulate penetrating through the cyclone as discussed in Chapter IV. The value of areal cake density for a cyclone/fabric filter combination was subsequently determined from the following variables:

$\overline{Pt}$ = overall dust penetration through cyclone (%)

$C_{1\text{-inlet}}$ = inlet dust loading to system (lbs/ft³)

V = filtration velocity (ft/min)

t = length of filtration cycle (min)

where the multiplication of $\overline{Pt}$ times $C_{1\text{-inlet}}$ provides the effective dust loading, C_1 , to the filter.

Flow Chart of Basic Model

Figure V-1 is a simplified flow diagram of the basic model used in simulating system pressure drops across a cyclone/fabric filter combination. The model is composed of two sections:

1. prediction of pressure drop across the cyclone
2. prediction of pressure drop across the fabric filter.

Holding cyclone dimensions, operating parameters, and particle characteristics fixed, cyclone pressure drop and cyclone efficiency in terms of $\overline{Pt}$ and d_{pg} -out can be determined as a function of cyclone inlet velocity (V_i). Thus, for a given cyclone inlet velocity there is a specific value of $\overline{Pt}$, d_{pg} -out, and cyclone pressure drop. Likewise, for each dust type there is a specific K_2'/d_{pg} -out relationship. Consequently, there is a specific value of K_2' corresponding to a specific value of d_{pg} -out for a given inlet velocity and dust type.

For specified fabric filter characteristics and operating parameters, Davis' model can be used to predict fabric filter pressure drop as a function of K_2' . The summation of the predicted fabric filter pressure drop and the cyclone pressure drop occurring at the same cyclone inlet velocity results in a value of system pressure drop. At some value of cyclone inlet velocity, the system pressure drop value passes through a minimum. At this specific value of V_i , an optimum cyclone efficiency value is obtained. This optimum efficiency value has been expressed in terms of the percent of total mass collected.

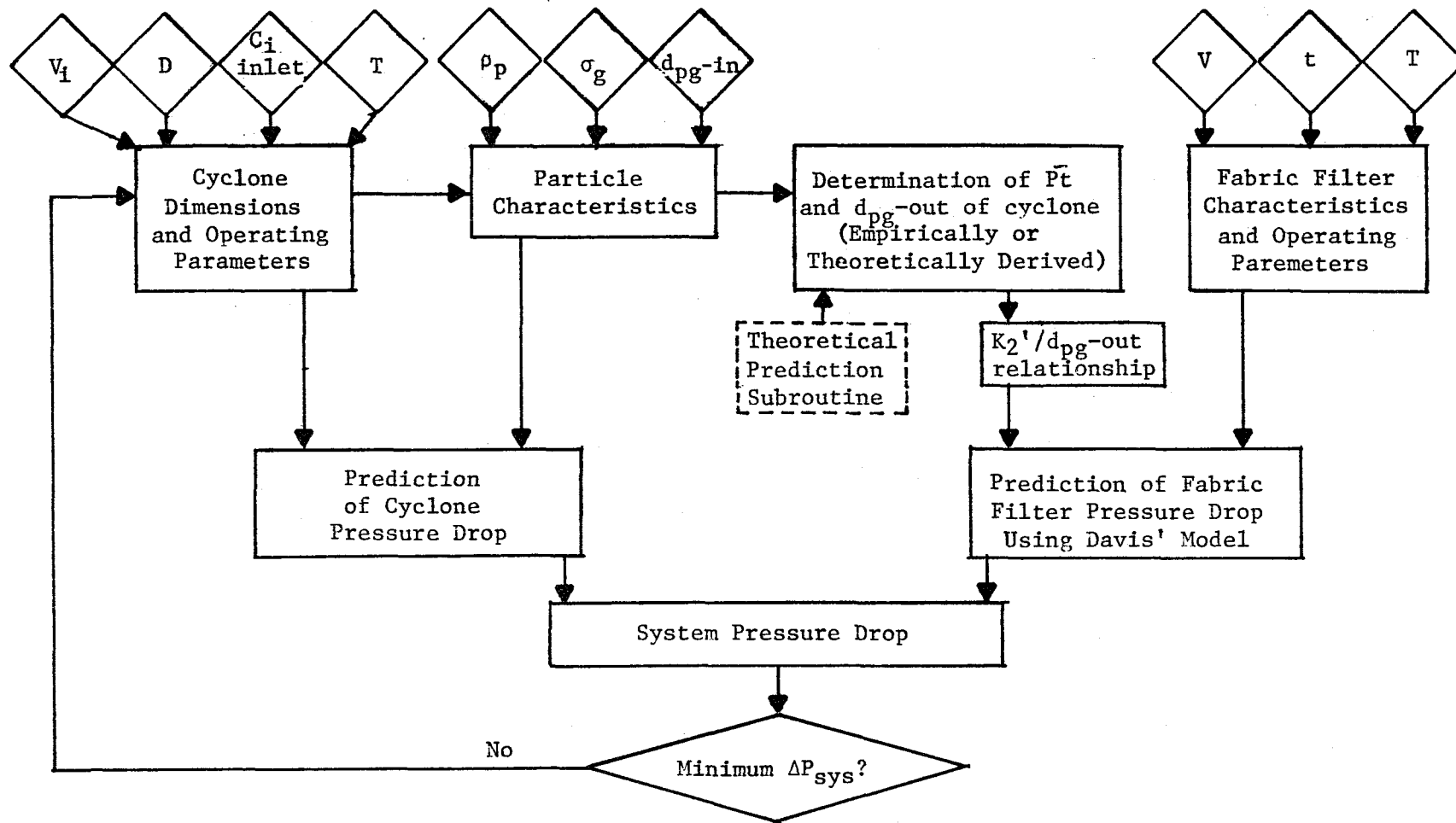


Figure V-1. Flow Diagram of Basic Model Used in Simulating System Pressure Drops Across a Cyclone/Fabric Filter.

II. PREDICTION OF CYCLONE PRESSURE DROP

Predictive Model for Laboratory Cyclone

The capability of predicting cyclone pressure drop was desired for two applications. Those applications were:

1. pressure loss across the experimental laboratory cyclone
2. pressure loss across a commercial, field-installation cyclone.

Pressure loss, for both applications was determined as a function of inlet velocity.

Cyclone pressure drop can be predicted from empirically derived expressions, theoretical formulations, or a mixture of both. Theoretical predictions by Stairmand (42), Shepherd and Lapple (41), and Barth (44) underestimated laboratory obtained experimental values. This underprediction was partially attributed to the fact that the above three theoretical formulations were derived on much larger cyclones than the three inch diameter laboratory cyclone. Since sufficient experimental data was available, an empirically derived expression was used as the predictive tool for modeling the laboratory cyclone pressure drops. Equation IV-2 (p 101) was derived from the data and incorporated into the basic model.

Predictive Model for Commercial Cyclones

For development of theoretical system pressure drop optimization curves, to be discussed in Chapter VI, a model was sought for pressure loss prediction across a commercial, field-installation cyclone. A predictive equation developed by Fisher-Klosterman, Inc. was selected (40).

This equation was based on both Barth's theoretical predictions and on empirical data, and was designed specifically for Fisher-Klosterman XQ series cyclones (67). An empirically found reference capacity provided by Fisher-Klosterman was required for each size cyclone of Fisher-Klosterman design that was to be modeled. Their predictive equation was used in the following form:

$$\Delta P_{\text{cyc}} = 6 \left(\frac{V_i b a}{Q_6} \right)^2 \quad (\text{V-1})$$

where

ΔP_{cyc} = cyclone pressure drop (inches of water)

b = diameter of cyclone inlet (ft)

a = height of cyclone inlet (ft)

Q_6 = tabulated reference capacity at 6.0" pressure drop (cfm)

V_i = cyclone inlet velocity (ft/min).

Equation V-1 can be used when it is assumed that the gas flow is air at standard conditions. No pressure drop corrections were made for dust loading.

Values of pressure drop predicted by Fisher-Klosterman were compared to theoretically obtained values using expressions by Stairmand, and Shepherd and Lapple. Theoretical expressions underpredicted Fisher-Klosterman by a factor of two. As previously mentioned, Stern, et al. (22) have reported the lack of satisfactory theoretical methods for predicting cyclone pressure drop over the range of different types of commercial cyclone constructions.

III. PREDICTION OF FABRIC FILTER PRESSURE DROP

Description of Constants in Davis Model

The second part of the cyclone fabric filter system pressure drop model relies upon the ability of Davis' model to predict the performance curves of fabric filters.

Davis (59) states that the initial performance curve of a fabric/dust combination can be described by the following equations:

$$\Delta P/V = \exp [M \ln(C_1 Vt) + B] \quad (V-2)$$

for $0.01 \leq C_1 Vt < 0.05 \text{ lbs/ft}^2$

$$\Delta P/V = \exp [M \ln(0.05) + B] + K_2 [C_1 Vt - 0.05] \quad (V-3)$$

for $C_1 Vt \geq 0.05 \text{ lbs/ft}^2$.

Davis also states that an estimation can be made of the residual resistance of fabrics caused by retention of dust on the fabric that can not be effectively removed. This estimation is made by assuming an effective value of residual areal cake density which Davis observed to approximately 0.02 lbs/ft^2 . Based on this assumption, the prediction of the resistance of conditioned fabrics as a function of time is described by the following equations:

$$\Delta P/V = \exp [M \ln(C_1 Vt + 0.02) + B] \quad (V-4)$$

for $C_1 Vt \leq 0.03 \text{ lbs/ft}^2$

$$\Delta P/V = \exp [M \ln(0.05) + B] + K_2' [C_1 Vt - 0.03] \quad (V-5)$$

for $C_1 Vt > 0.03 \text{ lbs/ft}^2$.

In order to use predictive Equations V-2 through V-5 it was necessary to determine the dependence of constants M, B, and K_2'

obtained from each data set on the fabric and dust characteristics.

Davis found the following expressions to show the relationship of M and B on fabric and dust type in the cake repair zone of the operating curve for values of areal cake density between 0.01 and 0.05 lbs/ft²:

$$M = m' \ln(K_2) + b' \quad (V-6)$$

$$B = m'' \ln(K_2) + b'' \quad (V-7)$$

Determination of Constants from Laboratory Data

By regression analysis of the operating curves for each laboratory data set, 24 values of M, B, and K_2' were found. In turn, by regressing M on K_2' and B on K_2' for the 24 values; the constants in Equations V-6 and V-7 were found to be as follows:

$$m' = 0.1591$$

$$b' = 0.5631$$

$$m'' = 1.2640$$

$$b'' = -0.9372 .$$

Thus, the equations for determining M and B as a function of the fabric type and the six talc dust types used in the laboratory experimentation were:

$$M = 0.1591 \ln(K_2) + 0.5631$$

$$B = 1.2640 \ln(K_2) - 0.9372 .$$

Inserting these values of M and B into Davis' equations provided the tool for predicting fabric filter pressure drop. Correlation coefficients for equations describing M and B were 0.91 and 0.97 respectively.

Determination of Operating Parameters

Inlet dust loading to the system, filtration velocity, and length of filtration cycle were predetermined parameters in the fabric filter pressure drop model. In order to simulate the normalized laboratory data, operating parameters inserted into the fabric filter model were specified at an inlet dust loading (C_i -inlet) of 5.0 grains per cubic foot, a filtration velocity of 4.0 feet per minute, and a filtration cycle time of 45 minutes. The resulting values of areal dust density ($C_i Vt$) were a function of cyclone efficiency as determined by the effective amount of the inlet dust loading (C_i) actually reaching the fabric filter.

Determination of K_2'

The key element in the development of the basic cyclone/fabric filter pressure drop model was the establishment of the K_2'/d_{pg} -out relationship. This relationship as previously discussed provided the means for determining the value of the operating dust resistivity at a given cyclone inlet velocity. This K_2'/d_{pg} -out relationship was established for the specified filtration velocity of four. The derivation of this relationship has been discussed in Chapter IV.

IV. THEORETICAL PREDICTION SUBROUTINE

Introduction

Ability to theoretically determine $\overline{Pt}$ and d_{pg} -out significantly increases the value of the cyclone/fabric filter pressure drop model. Empirical data is usually not readily available for determining

relationships between cyclone inlet velocity, integrated penetration and geometric mass mean diameter of the penetrating dust. Therefore, an approach has been developed using established theory to predict the above relationships as a function of cyclone inlet velocity. The developed approach requires the prediction of:

1. cyclone particle cut diameter (d_{p50})
2. integrated cyclone dust penetration
3. geometric mass mean diameter of dust penetrating cyclone .

Figure V-2 is a flow diagram of the theoretical subroutine to predict d_{p50} , $\overline{Pt}$, and d_{pg-out} .

Prediction of Cyclone Particle Cut Diameter

Cyclone particle cut diameter, d_{p50} , is the diameter of a particle collected with 50% efficiency. To predict d_{p50} , an equation of the following form presented by Lapple (8) was used.

$$d_{p50} = \left[\frac{9\mu b}{2\pi N V \left(\frac{\rho_p - \rho_g}{\rho_p} \right)} \right] \quad (V-8)$$

where N = the number of turns the gas makes in the cyclone. A value of $N=5$ was chosen as Friedlander (10) and Lapple (8) have reported an average value of N to be five.

Holding dust density and the diameter of the cyclone constant, a specific particle cut diameter can be found as a function of cyclone inlet velocity. As inlet velocity increases, the value of d_{p50} decreases. Consequently, integrated cyclone dust penetration and the mass mean diameter of that penetration decrease as d_{p50} decreases. Furthermore, a dust of small mass mean diameter penetrating to the fabric filter results in high values of dust resistivity occurring during filtration.

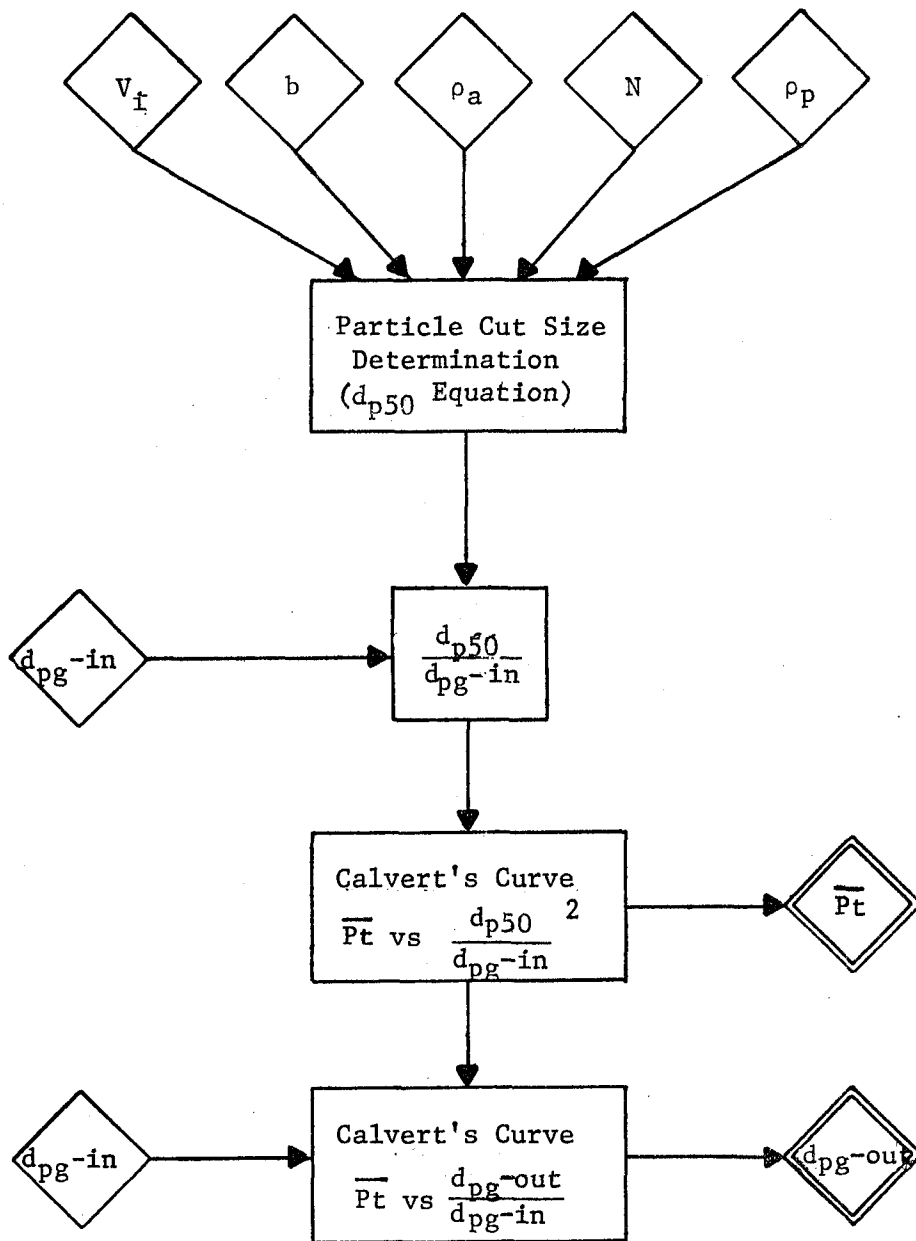


Figure V-2. Flow Diagram of Theoretical Prediction Subroutine.

As previously determined in the laboratory data analysis, model input values of $\overline{Pt}$ and d_{pg-out} can be expressed as a function of cyclone inlet velocity. Accordingly, cyclone inlet velocity was chosen as the variable input parameter upon which the theoretical values of the other variables in the model were determined.

Prediction of Integrated Cyclone Penetration

Calvert's (38) theoretical work dealing with the effect of particle size distribution on the efficiency of particulate control equipment can be used to predict integrated cyclone penetration. Calvert, in Figure II-8 (p 37), has theoretically predicted integrated penetration as a function of the ratio of cyclone cut diameter to geometric mass mean inlet diameter squared, $(d_{p50}/d_{pg-in})^2$, with $B \ln(\sigma_g)$ as a parameter. By knowing the inlet dust size distribution and the value of B , and by calculating the value of d_{p50} , the theoretical integrated penetration (equivalent to 1.0 minus overall collection efficiency) of a cyclone was found. As mentioned in Chapter II, Crawford (30) stated that a value of $B = 2.0$ should be used for cyclones.

Since a significant number of dusts, including the six dust types used in the laboratory testing, have a geometric standard deviation of approximately two; Calvert's curve for the $B \ln(2.0)$ parameter was incorporated into the theoretical subroutine to predict $\overline{Pt}$. Unfortunately, Calvert's curve does not predict values above 45% integrated penetration. (See Figure II-8.) Consequently, values of $\overline{Pt}$ cannot be predicted using Calvert's method for cyclones operating below 55% collection efficiency.

Prediction of Mass Mean Diameter Out of Cyclone

The theoretical mass mean diameter of dust penetrating the cyclone and depositing on the fabric filter can be expressed as a function of the integrated cyclone penetration. As the value of $\overline{Pt}$ decreases so does the value of d_{pg} -out. Using theoretical curves, again developed by Calvert, the relationship between an average particle size entering and leaving a collection device was determined as a function of $\overline{Pt}$ with dust geometric standard deviation as a parameter. (See Figure II-9, p 38.)

Having previously determined the value of $\overline{Pt}$, d_{pg} -in, and σ_g , Calvert's curve can be utilized to obtain the ratio of d_{pg} -out/ d_{pg} -in. Thus, d_{pg} -out is established in the theoretical subroutine after having determined theoretical values for d_{p50} and $\overline{Pt}$.

In summation, the theoretical prediction subroutine provides a means to predict the particle cut size (d_{p50}) as a function of cyclone inlet velocity; integrated penetration ($\overline{Pt}$) through the cyclone as a function of d_{p50} ; and the geometric mass mean diameter of the dust penetrating the cyclone (d_{pg} -out) as a function of $\overline{Pt}$. Having predicted the value of d_{pg} -out, and knowing the empirical relationship between K_2' and d_{pg} -out, one can predict the operating dust resistivity value for a given cyclone inlet velocity.

III. MODEL GENERATION OF DATA

Input Selection

As previously explained, either graphically or theoretically obtained values of $\overline{Pt}$ and d_{pg} -out can be input into the basic

cyclone/fabric filter system pressure drop model. An analysis was undertaken to judge the validity of the model in predicting the relationship of cyclone efficiency on system pressure drop, and to examine the potential ability of using theoretically derived inputs as compared to empirically obtained graphical inputs. Figures V-3 through V-8 are graphical comparisons between real data (C_i -inlet normalized to 5.0 gr/ft³), predicted data using graphically determined inputs, and predicted data using theoretically derived inputs for all six laboratory dust types. For low values of cyclone collection efficiency the actual shape of the curve representing the relationship between system pressure drop and cyclone efficiency could not be ascertained from existing laboratory data or the cyclone/fabric filter model. Therefore, no graphical representation of the relationship was attempted for cyclone efficiencies below 40%. For cyclone efficiency values between 40 and 55%, the cyclone/fabric filter model was dependent upon graphically determined inputs alone. As previously noted, the cyclone/fabric filter system pressure drop model using theoretically derived inputs cannot predict system pressure drop values for cyclone collection efficiencies below 55%; hence, graphical representation of the relationships determined from the model using theoretically derived inputs can be provided only for cyclone efficiencies greater than 55%.

The prediction of the relationship between system pressure drop and cyclone efficiency using graphically determined inputs generally simulated real data satisfactorily. For both input types those predicted values of system pressure drop occurring with no cyclone precleaner in-line or stated, for practical purposes, as occurring

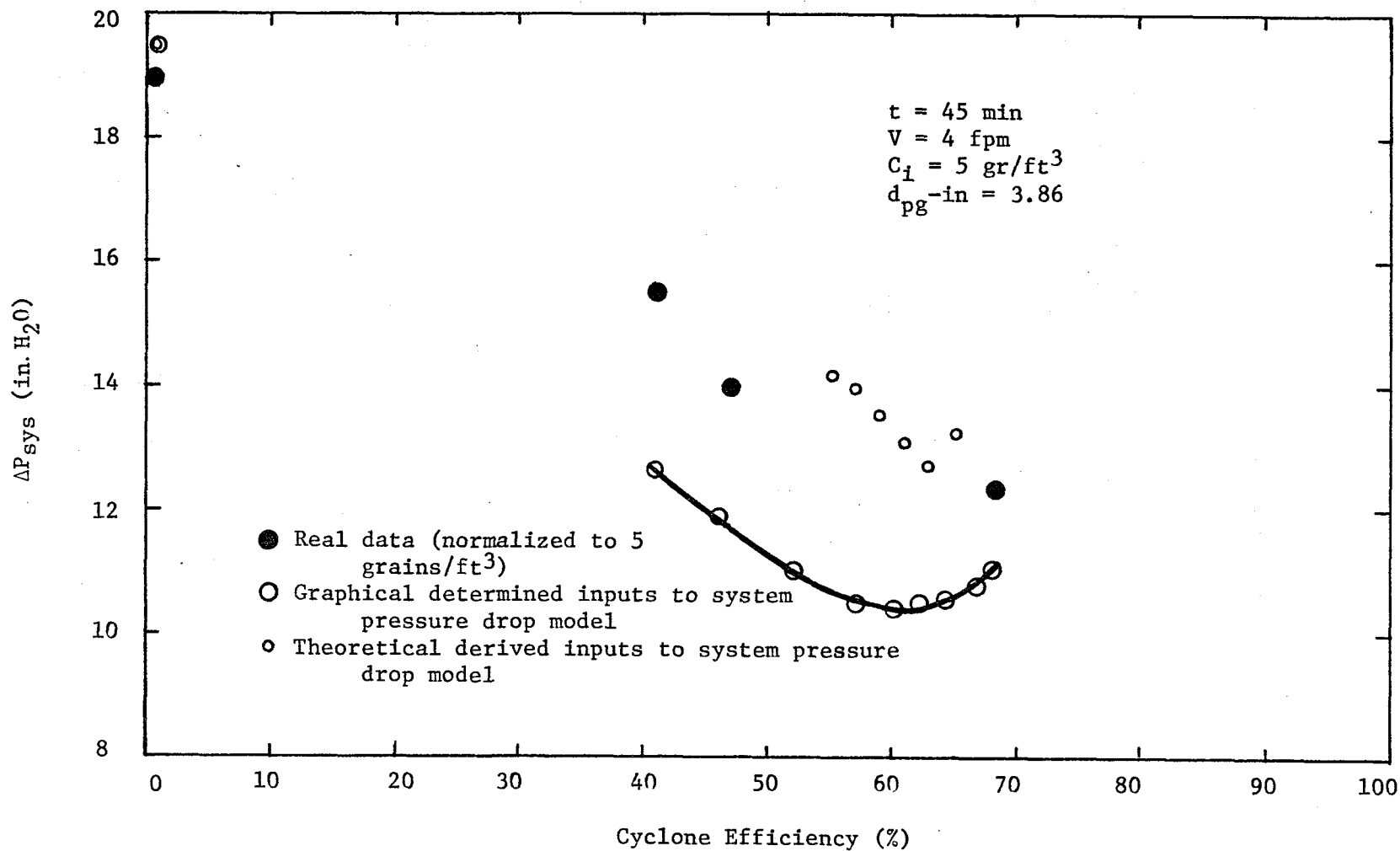


Figure V-3. Comparative Analysis Between Real and Predicted Initial System Pressure Drops for Dust #1.

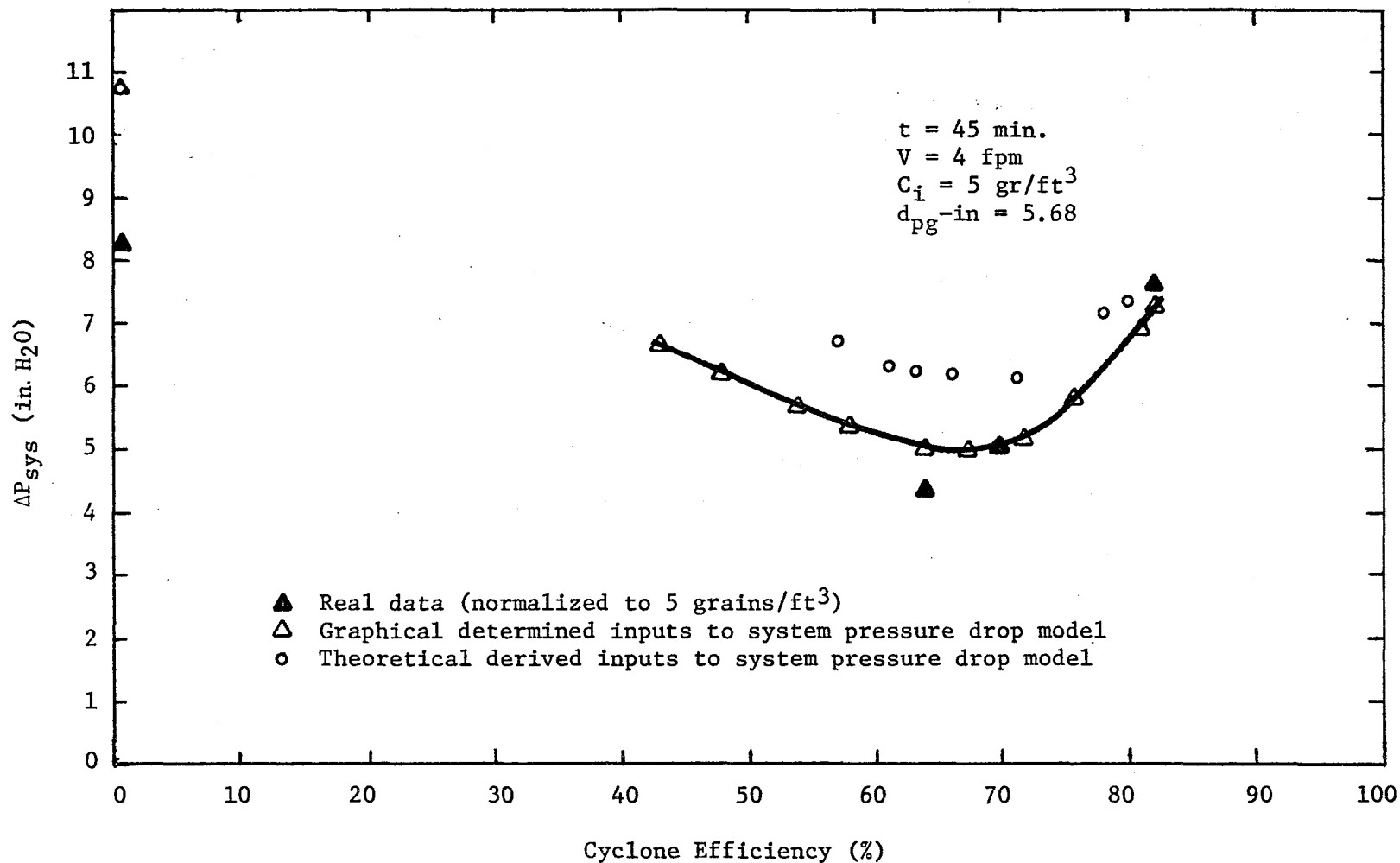


Figure V-4. Comparative Analysis Between Real and Predicted Initial System Pressure Drops for Dust #2.

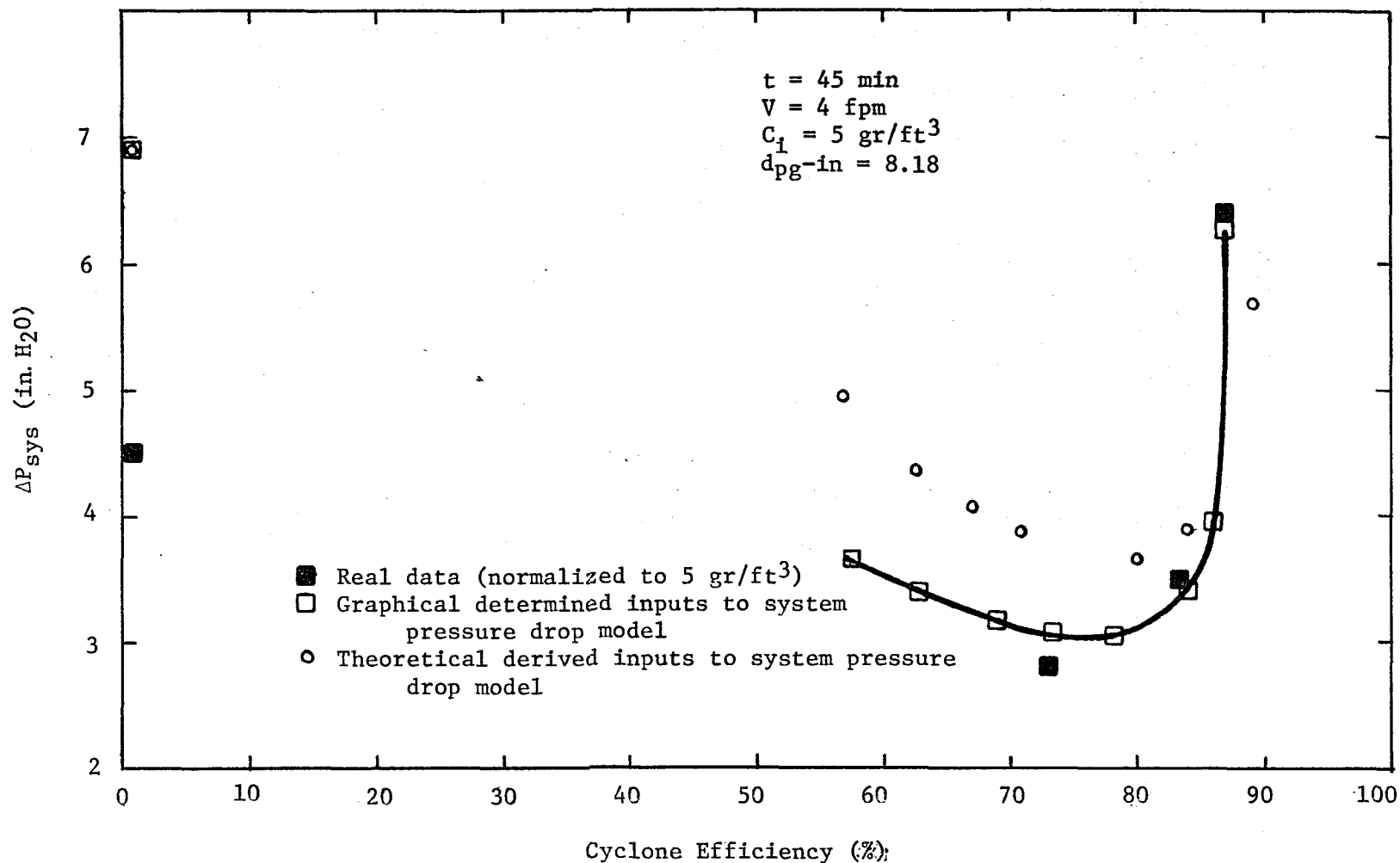


Figure V-5. Comparative Analysis Between Real and Predicted Initial System Pressure Drops for Dust #3.

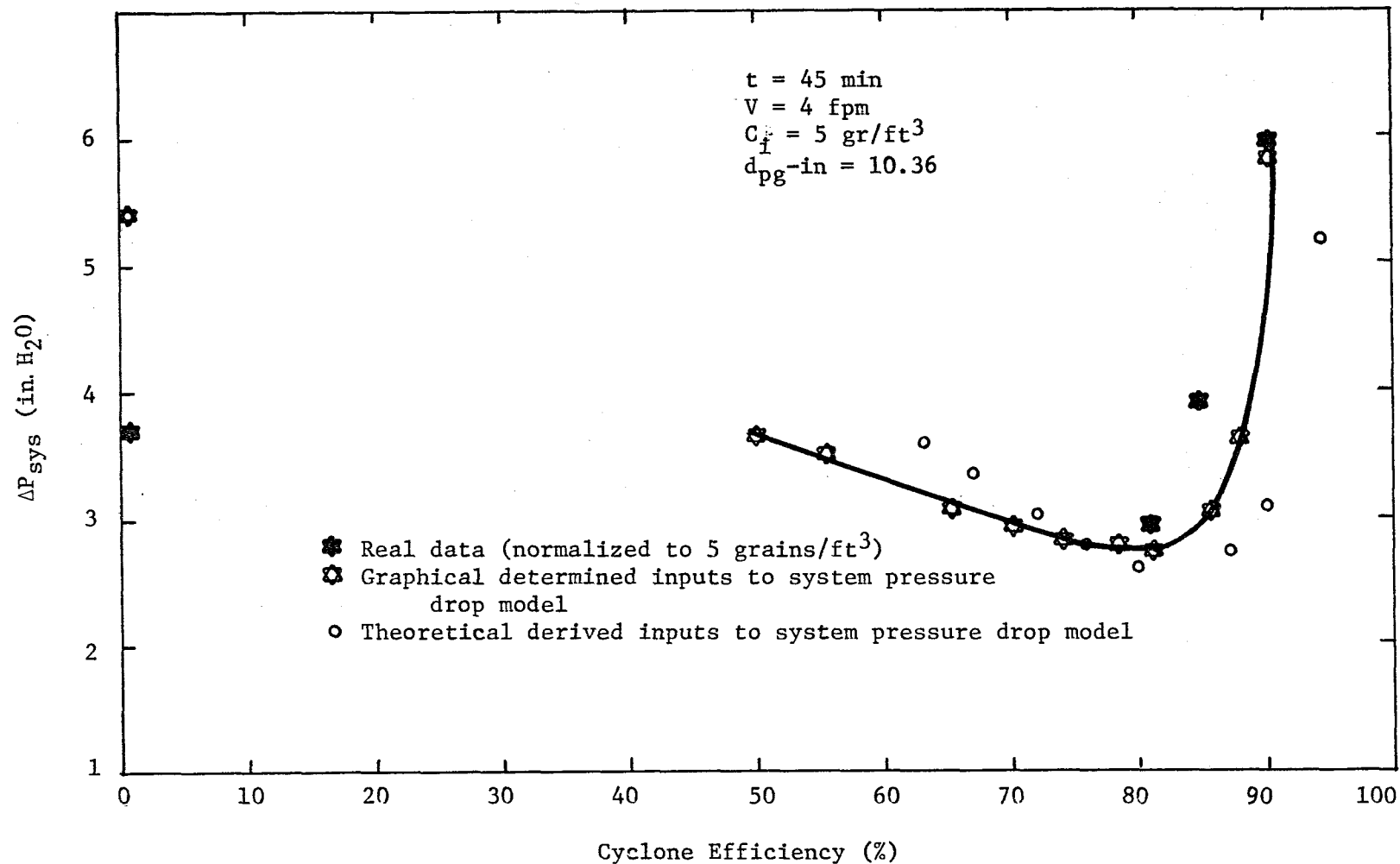


Figure V-6. Comparative Analysis Between Real and Predicted Initial System Pressure Drops for Dust #4.

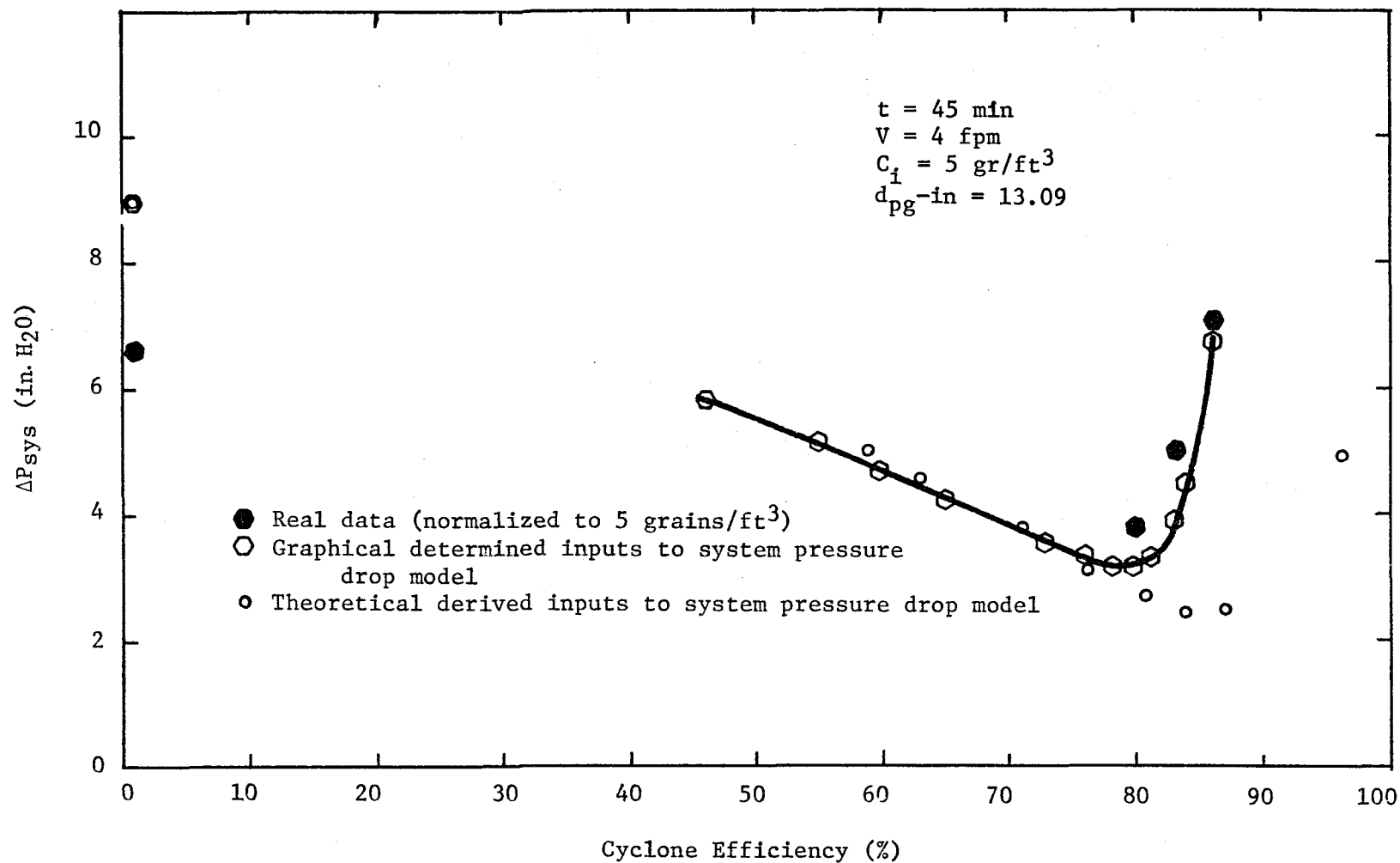


Figure V-7. Comparative Analysis Between Real and Predicted Initial System Pressure Drops for Dust #5.

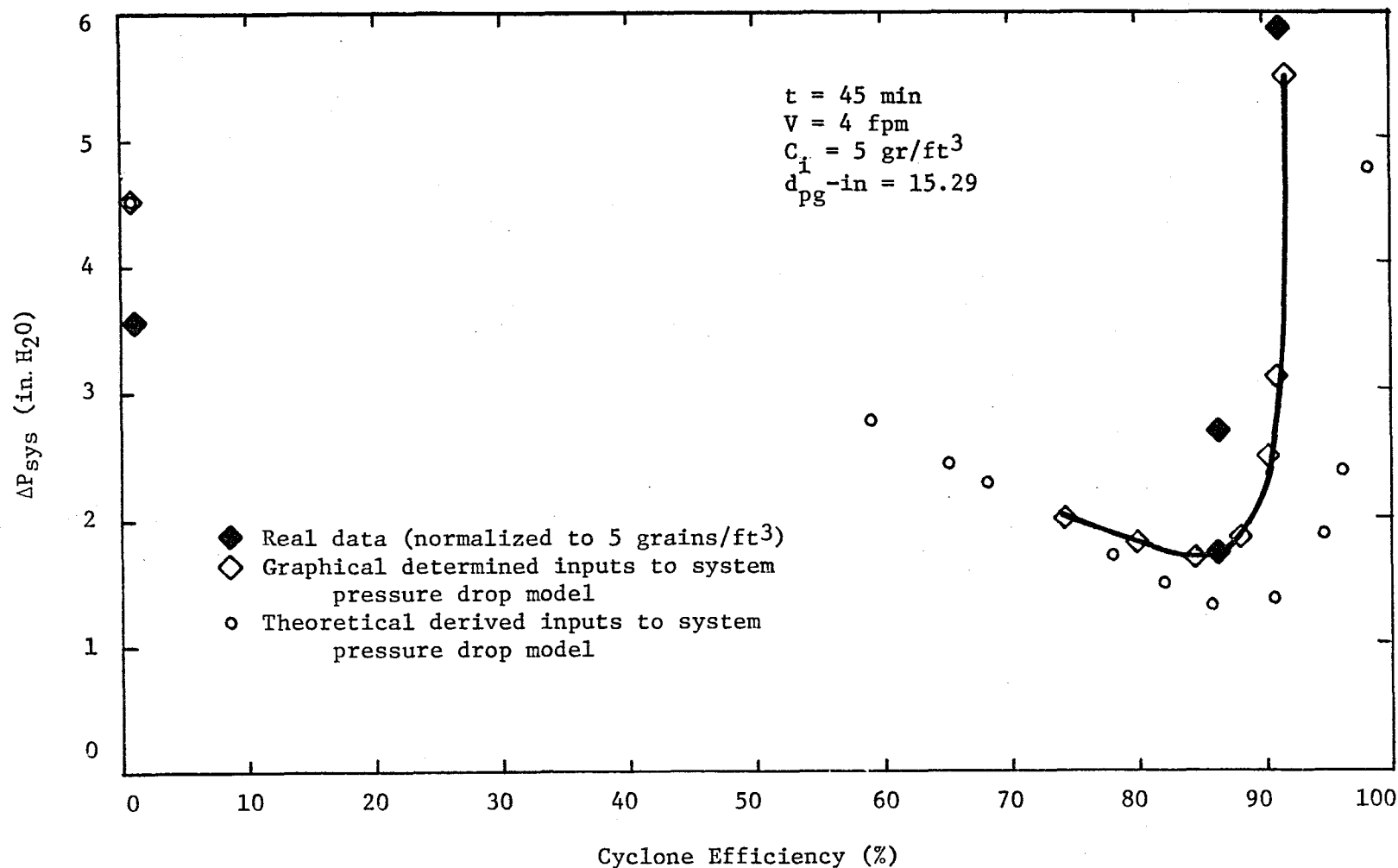


Figure V-8. Comparative Analysis Between Real and Predicted Initial System Pressure Drops for Dust #6.

at zero cyclone efficiency deviation from real data. It should be noted that to infer a cyclone to be operating at zero cyclone efficiency rather than no cyclone to be present could imply the presence of an infinitely large cyclone or an infinitely small inlet velocity. Such an occurrence would turn the collector into a gravity settling chamber with a resultant collection efficiency. Hence, all references to zero cyclone efficiency imply that no cyclone has been used to preclean or modify the inlet dust distribution.

The variance between predicted system pressure drop values and real data values at zero cyclone efficiency was found to be the result of the inappropriate selection of the areal dust density value in the fabric filtration model which divided the fabric filter performance curve into its two regions: the cake repair zone and the zone of deposition of homogeneous dust cake. The average areal density value dividing the performance curve zones, as found by Davis after analyzing 106 performance curves, was 0.05 pounds per square foot. However, the areal density values dividing the performance curve zones of the laboratory data generated at zero cyclone collection efficiency were generally found to be in excess of 0.05 lbs/ft^2 . Only the performance curves for dust types #1 and #6 at zero cyclone efficiency approximated the average dividing areal density value found by Davis. Moreover, the dividing areal density values for dust types #2 through #5 were found to approach 0.10 lbs/ft^2 . It should be noted for dust types #1 and #6 that predicted values of system pressure drop at zero cyclone collection efficiency simulated satisfactorily real data.

Since Davis' average value of areal dust density dividing the zones of the performance curve was obtained from an analysis of 106 performance curves, Davis' value of 0.05 lbs/ft^2 was deemed more statistically significant and therefore retained in the model. Further testing is needed to substantiate the higher atypical laboratory found values of areal dust density that separate the two performance curve zones before any adjustment of the average dividing value used in the model can be made. Accuracy in predicting values of system pressure drop at zero cyclone efficiency is desirable for predicting pressure drop savings achievable with the use of a cyclone precleaner. However, the accuracy of the model in predicting the point of optimal cyclone efficiency is more important since this region of the curve is where the operating minimum system pressure drops are found. The cyclone/fabric filter model, using both types of inputs, appeared to satisfactorily predict values of optimum cyclone efficiency.

Predicted values of optimum cyclone efficiency using theoretical inputs had greater variation from real data than predicted values using graphical inputs. Nevertheless, the predicted values derived from theoretically determined inputs generally simulated equivalent optimum cyclone efficiency and equivalent pressure drop savings as did the predicted values using graphically determined inputs. Differences in the value of predicted optimum cyclone efficiency between the graphical and theoretical type inputs for the six laboratory dusts varied by no more than $\pm 5\%$ with the average difference in prediction varying $\pm 2\%$.

Initial System Pressure Drop Curves

Figure V-9 is a summary graph comparing predicted data points derived using graphically determined inputs and normalized real data for all six laboratory dust types. Again the simulation of predicted data using graphically derived inputs on real data generally appears to be close.

With the curve now visible representing the relationship between the initial system pressure drop and cyclone efficiency, a predicted optimal cyclone efficiency for each of the six inlet dust size distribution becomes evident.

Analysis of Figure V-9 indicates that as the mass mean diameter of the inlet dust size to the system increases, the value of optimal cyclone efficiency, likewise, increases. Secondly, greater system pressure drop savings may be realized using a cyclone precleaner on the smaller mass mean diameter dusts than on the larger dusts. Furthermore, system pressure drop appears to increase rapidly as cyclone efficiency increases past the optimum value. Based on this observation it is prudent to error on the low side in the selection of a design value for optimum cyclone efficiency.

Effect of Filtration Time on Curves

Using graphical inputs and the system pressure drop model for conditioned fabric filtration operation, Figures V-10, V-11 and V-12 have been generated. System pressure drop for conditioned operation varies from system pressure drop for initial fabric filter operation in that the former takes into account residual resistance in its

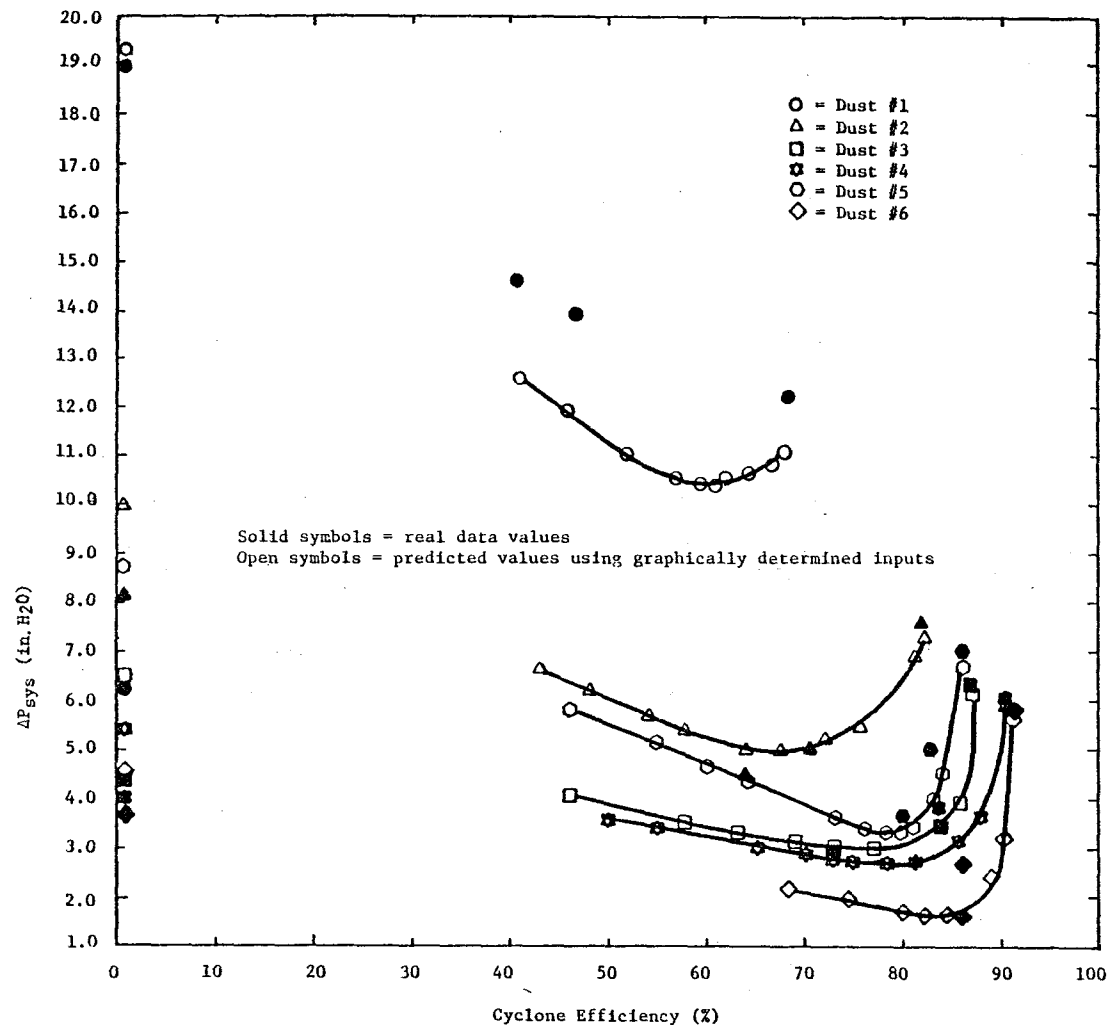


Figure V-9. Comparative Analysis Between Normalized Real Data and Predicted Initial System Pressure Drop Using Graphically Determined Inputs for All Laboratory Dust Types.

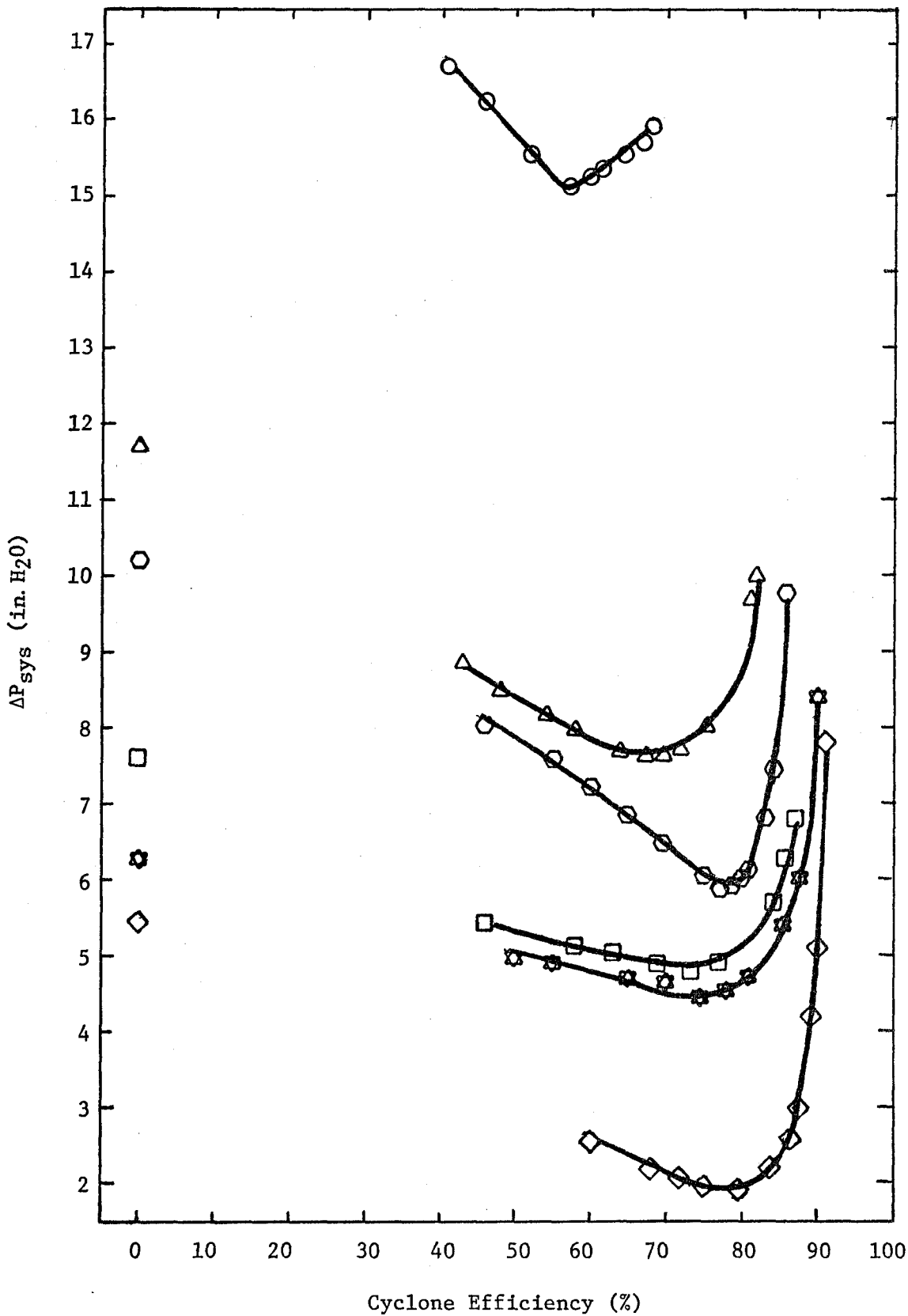


Figure V-10. Conditioned System Pressure Drop Versus Integrated Cyclone Efficiency for Filtration Time of 45 Minutes.

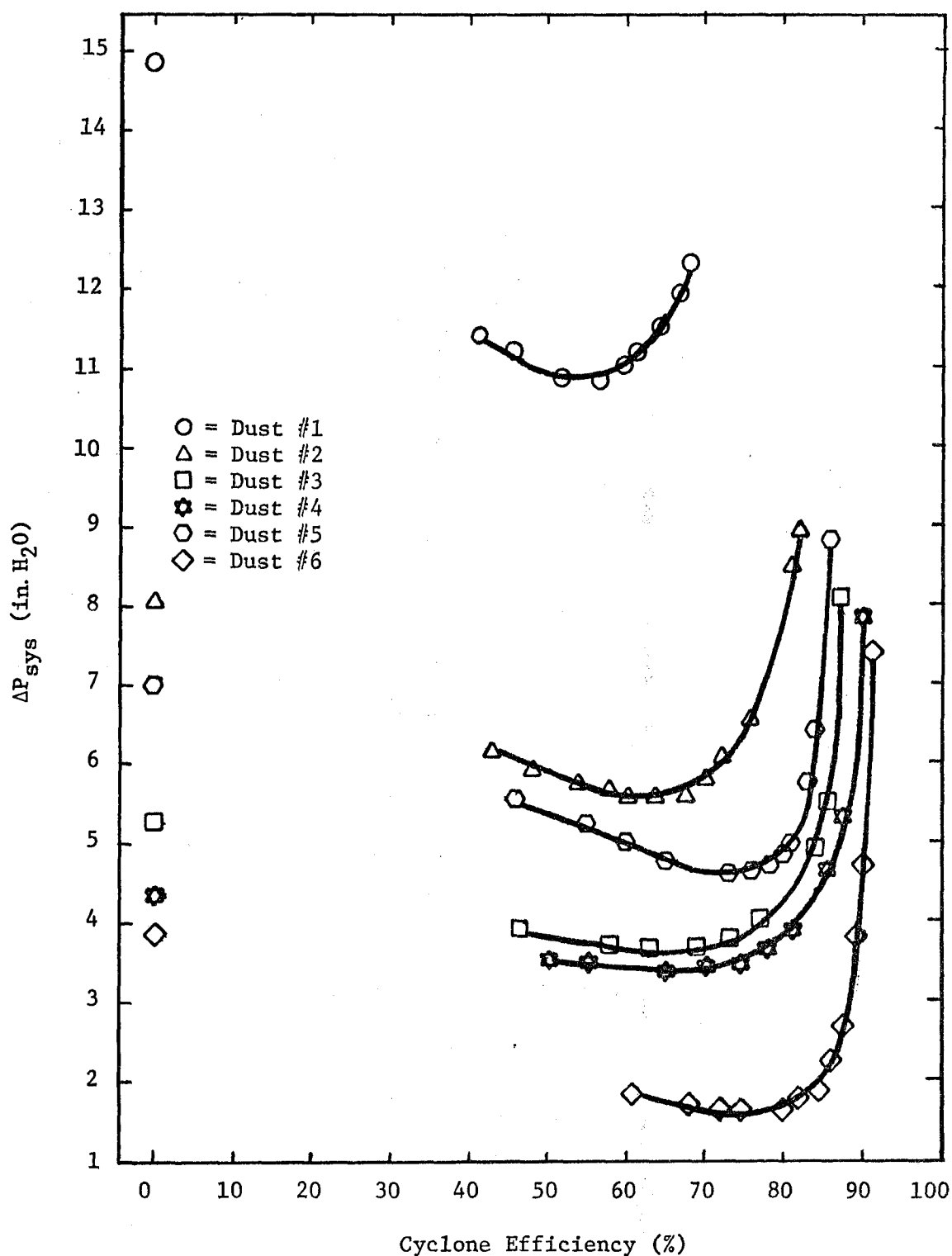


Figure V-11. Conditioned System Pressure Drop Versus Integrated Cyclone Efficiency for Filtration Time of 30 Minutes.

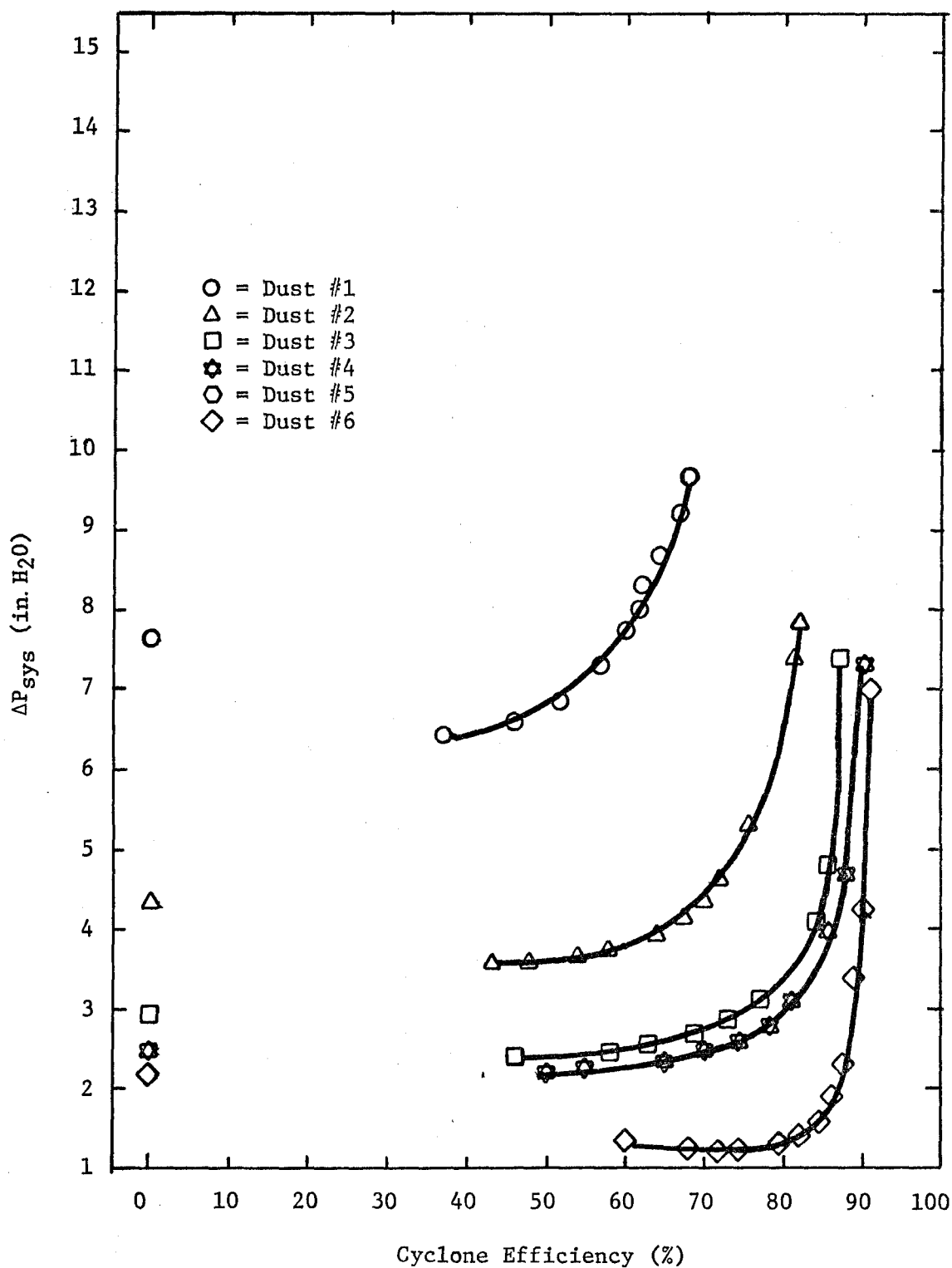


Figure V-12. Conditioned System Pressure Drop Versus Integrated Cyclone Efficiency for Filtration Time of 15 Minutes.

prediction of fabric filter pressure drop. Residual resistance accrual is due to the bag conditioning process; not all of the dust impregnating the bag is released during cleaning.

The three figures vary in the length of filtration time prior to cleaning. For shorter filtration time periods, the system pressure drop savings realized with a cyclone precleaner are predicted to be minor. Because of the short time, t , areal dust cake densities are low resulting in unelevated pressure losses across the fabric filter. Consequently, any pressure drop values across a cyclone will have a pre-dominant effect on the system pressure losses.

A comparison of the optimum cyclone efficiency values between the filtration time periods of 30 and 45 minutes showed no significant deviation in the optimum efficiency value for each of the dust types. Extending the filtration cycle time beyond 45 minutes is not expected to significantly change the optimum cyclone efficiency values since the rate at which pressure drop increases across a fabric filter (as measured by values of K_2') remains constant.

CHAPTER VI

DEVELOPMENT OF SYSTEM PRESSURE DROP OPTIMIZATION CURVES

I. USE OF PREDICTIVE MODEL

Introduction

In the design phase of a cyclone/fabric filter collector, a tool has been needed to aid the engineer in determining the most desirable cyclone precleaner efficiency. Using established theory and an empirically derived relationship, a method has been developed to theoretically predict the optimal cyclone collection efficiency which results in the minimum system pressure drop for a given inlet dust size distribution under specific cyclone/fabric filter operating conditions, and for both a specific cyclone type and fabric media type.

The basis of this optimization method is the cyclone/fabric filter system pressure drop model as delineated in Chapter V. Using this model, optimization curves have been generated. Analysis of these modeled relationships between system pressure drop and cyclone efficiency have resulted in a graphical optimization technique for predicting optimum cyclone inlet velocity and cyclone size for a given inlet dust size distribution which will result in the lowest system pressure loss. Also, the analysis of these optimization curves provides significant insight into the cyclone/fabric filter relationship. A plethora of data is available using the model for studying through trend analysis the effects of varying cyclone/fabric filter parameters.

System Pressure Drop Model

Using theoretically derived input values, the cyclone/fabric filter system pressure drop model can be used to develop a graphical relationship between cyclone efficiency and system pressure drop as a function of cyclone inlet velocity for specified cyclone sizes, fabric media, and dust types. Theoretical input values of $\overline{P_t}$ and d_{pg-out} can be determined using the theoretical prediction subroutine. Prediction of K_2' can be accomplished by using an empirically derived relationship between K_2' and d_{pg-out} for a specified filtration velocity. Thus, for a given cyclone inlet velocity, the model can predict an overall cyclone efficiency and the corresponding initial or conditioned system pressure loss.

Model Constraints

Certain limitations constrict the use of the model in its present form. Firstly, as discussed in Chapter V, the system pressure drop model relies on a parametric cyclone pressure loss expression established for a proprietary brand of cyclones. This expression was chosen over a theoretical expression due to a need of higher accuracy of prediction. Any alternative cyclone pressure drop expression can be readily substituted into the model.

Secondly, dust parameters bounding the developed model limit its predictability to dusts having a standard geometric deviation of two, a common σ_g of industrial dusts. However, the model can be easily programmed to handle other geometric standard deviations.

Thirdly, the model cannot predict system pressure losses for cyclones operating at overall collection efficiencies less than 55%.

At penetration values greater than 45%, the model incorrectly assumes a zero efficient cyclone. This problem can be overcome by increasing the integration range of Equation II-30 (p 36) for values of

$(d_{pg}/d_{p50})^2$ greater than one.

Another constraint is that the K_2'/d_{pg} -out relationship is limited to the operating conditions at which the data was taken. Filtration velocity is especially critical. If the fabric filter collector is to be run at a filtration velocity of four, the empirical relationship must be developed at a filtration velocity of four.

Finally, model constants for predicting either the initial or conditioned resistance across the fabric filter are specific for fabric type. If the modeling of additional fabrics is desired, constants for these fabrics must be derived. Laboratory testing to determine the K_2'/d_{pg} -out relationship usually provides sufficient data for determination of these constants.

II. OPTIMIZATION ILLUSTRATION

Data Generation

To illustrate the optimization method, dust types #1, #2, #4, and #6 were run on the model. Each dust type was evaluated over a range of commercially available Fisher-Klosterman cyclone sizes. Cyclone diameters varied from 4 to 32 inches. Operating conditions simulated were a filtration cyclone time of $t = 45$ minutes, filtration velocity of $V =$ four feet per minute, and temperature of $T = 25^\circ\text{C}$. The K_2'/d_{pg} -out relationships established for the four dust types during laboratory testing were incorporated into the model for lack of more reliable field data. Filter media type was the same

Fiberglass [®] fabric for which model constants were developed using laboratory data as explained in Chapter V.

Results

Table VI-1 is a data print-out from the system pressure drop model for dust #1 in combination with a four inch diameter cyclone. Inlet cyclone velocities range from 0 to 5400 fpm (0-90 fps) in increments of 300 fpm (5 fps).

Figures VI-1 through VI-4 are optimization curves for each of the four dust types developed by plotting data from the model print-outs. Predicted system pressure drop values for zero cyclone efficiency have been deleted from Figures VI-2 and VI-3 (dust types #2 and #4) since these values are thought to be erroneously high for reasons previously mentioned. Laboratory found real data values of system pressure drop at zero cyclone efficiency have been plotted for each dust type.

Discussion of Results

The system pressure drop optimization curves theoretically predict the effect of varying cyclone diameter and inlet dust size on the optimal cyclone efficiency and system pressure drop. The graphical display of such relationships appear to be of significant value in the design of a cyclone precleaner used prior to fabric filtration. Several observations from the optimization curves are evident.

First, the curves predictively reveal that optimal cyclone efficiency decreases as cyclone diameter increases. The larger cyclones tend to be less efficient sending a greater dust loading to the fabric

Table VI-1

Typical System Pressure Drop Model Data Printout.

V_1	d_{p50}	R	Pt	d_{pg-out}	K_2	$C_1 V_t$	ΔP_{ff}	ΔP_{cyc}	η	ΔP_{sys}
0.0		3.680	1.000	3.860	44.241	0.129	19.637	0.000	0.000	19.637
300.000	6.723	3.033	1.000	3.860	44.241	0.129	19.637	0.049	0.000	19.685
600.000	4.754	1.517	1.000	3.860	44.241	0.129	19.637	0.195	0.000	19.832
900.000	3.881	1.011	1.000	3.860	44.241	0.129	19.637	0.439	0.000	20.075
1200.000	3.361	0.758	0.410	2.239	86.038	0.053	10.612	0.780	59.000	11.392
1500.000	3.007	0.607	0.370	2.181	88.106	0.048	9.253	1.219	63.000	10.472
1800.000	2.745	0.506	0.330	2.104	90.941	0.042	8.192	1.755	67.000	9.947
2100.000	2.541	0.433	0.310	2.073	92.101	0.040	7.634	2.389	69.000	10.023
2400.000	2.377	0.379	0.280	2.038	93.423	0.036	6.770	3.120	72.000	9.891
2700.000	2.241	0.337	0.250	2.007	94.614	0.032	5.906	3.949	75.000	9.855
3000.000	2.126	0.303	0.230	1.980	95.669	0.030	5.347	4.876	77.000	10.222
3300.000	2.027	0.276	0.210	1.957	96.582	0.027	4.786	5.899	79.000	10.686
3600.000	1.941	0.253	0.200	1.942	97.196	0.026	4.514	7.021	80.000	11.535
3900.000	1.865	0.233	0.180	1.911	98.435	0.023	3.973	8.240	82.000	12.213
4200.000	1.797	0.217	0.170	1.891	99.218	0.022	3.709	9.556	83.000	13.265
4500.000	1.736	0.202	0.160	1.872	100.006	0.021	3.447	10.970	84.000	14.417
4800.000	1.681	0.190	0.150	1.853	100.801	0.019	3.186	12.482	85.000	15.668
5100.000	1.631	0.178	0.140	1.833	101.603	0.018	2.928	14.090	86.000	17.018
5400.000	1.585	0.169	0.130	1.814	102.410	0.017	2.672	15.797	87.000	18.469

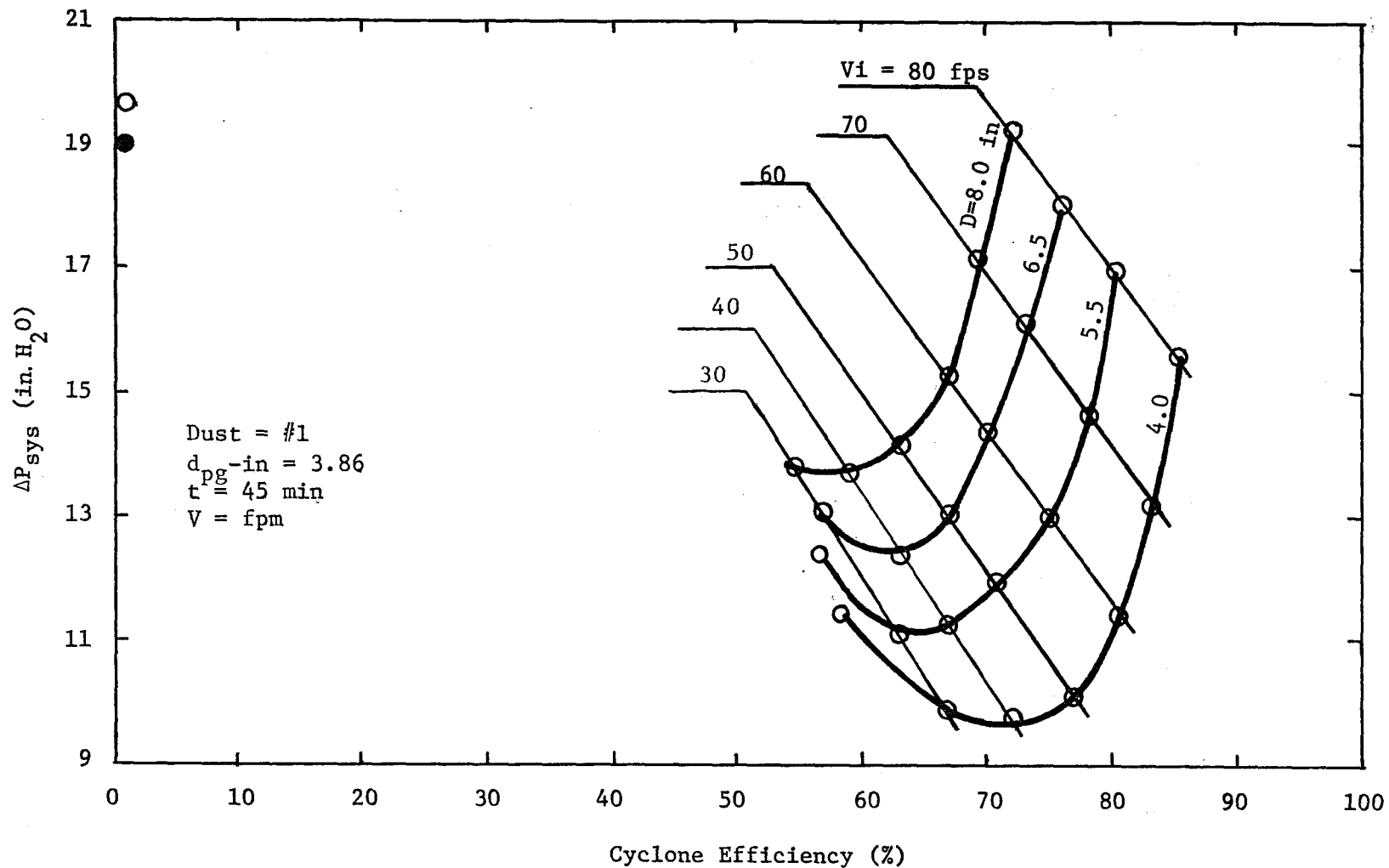


Figure VI-1. Predicted System Pressure Drop for Selected Cyclones Using Dust #1.

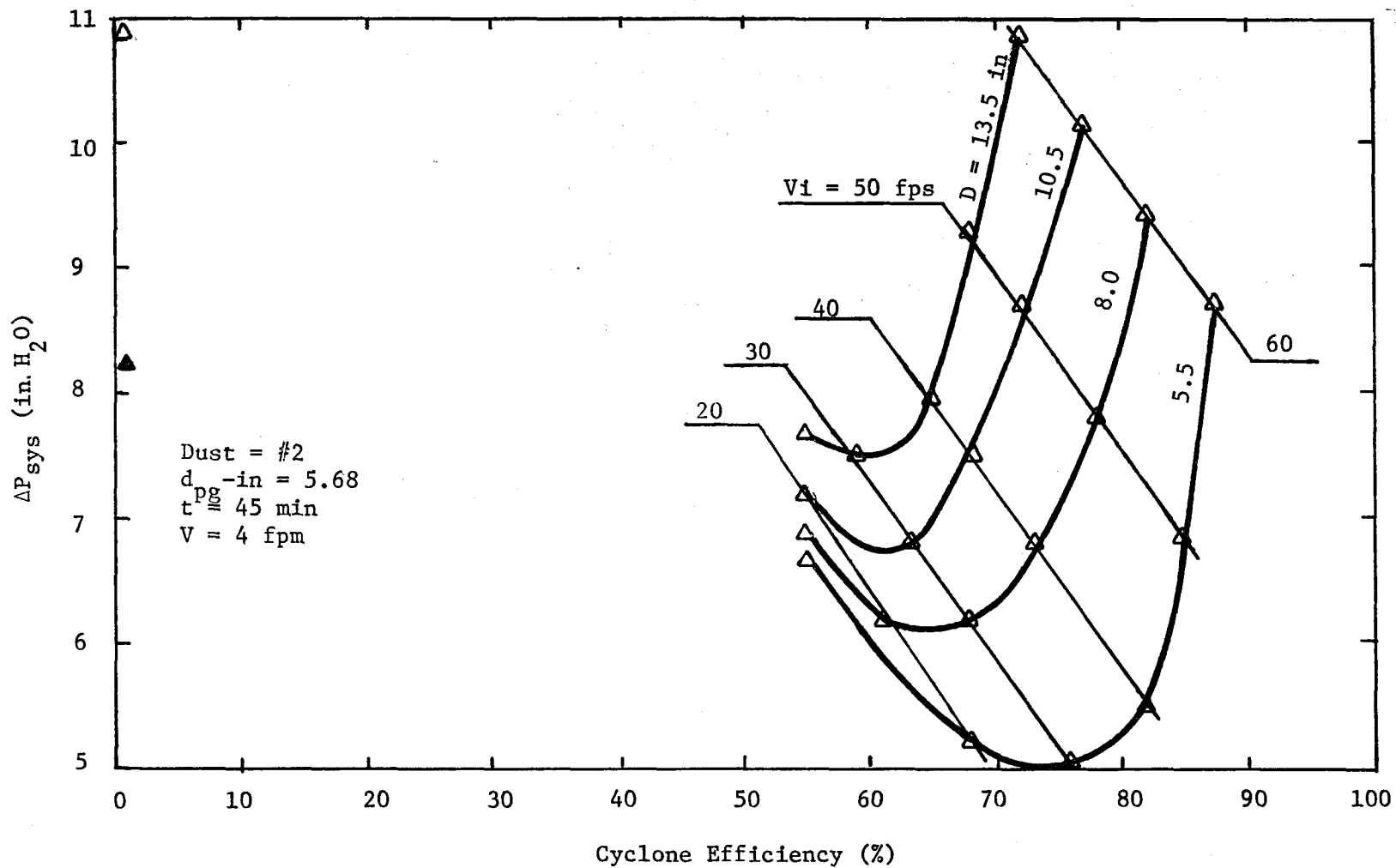


Figure VI-2. Predicted System Pressure Drop for Selected Cyclones Using Dust #2.

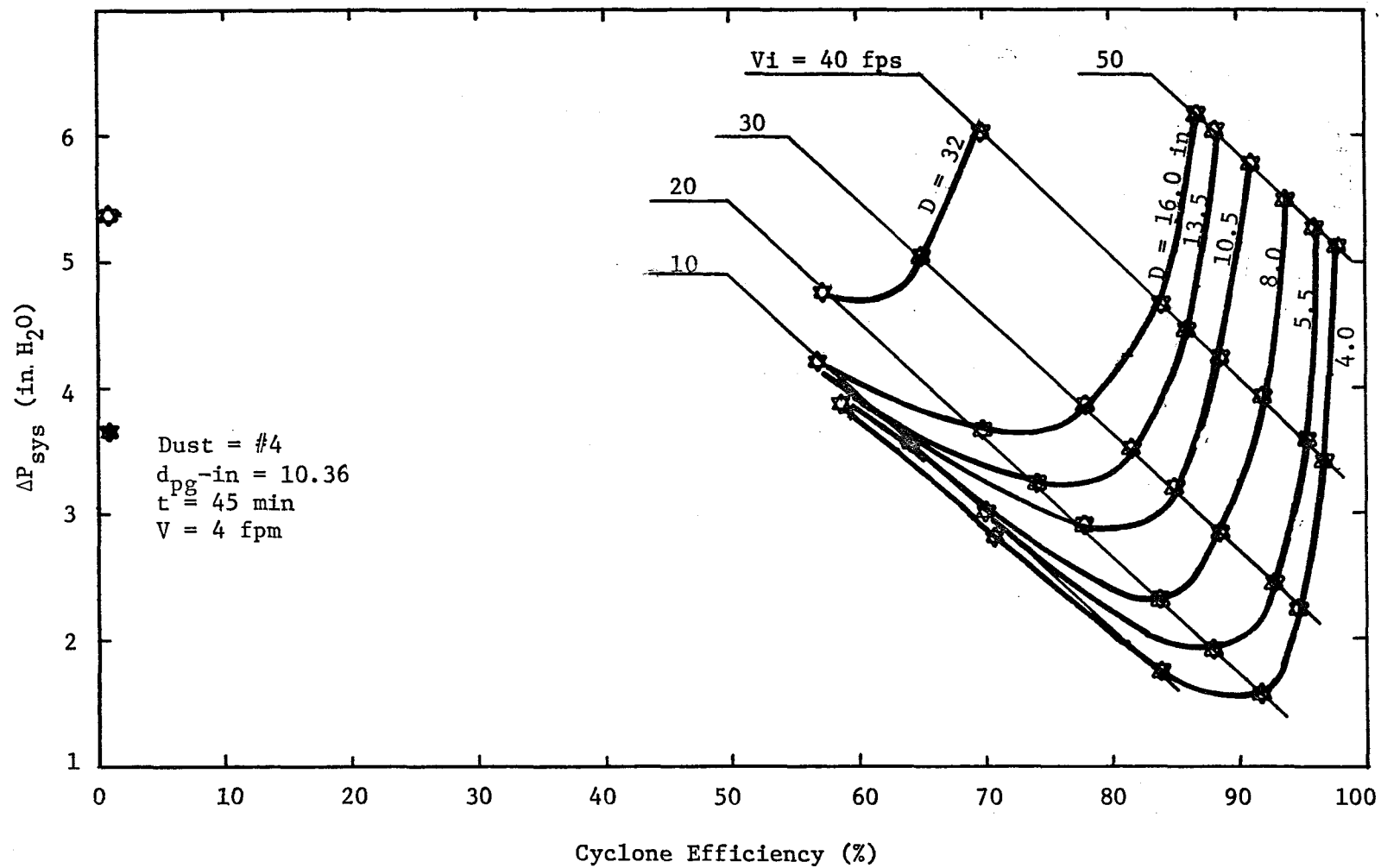


Figure VI-3. Predicted System Pressure Drop for Selected Cyclones Using Dust #4.

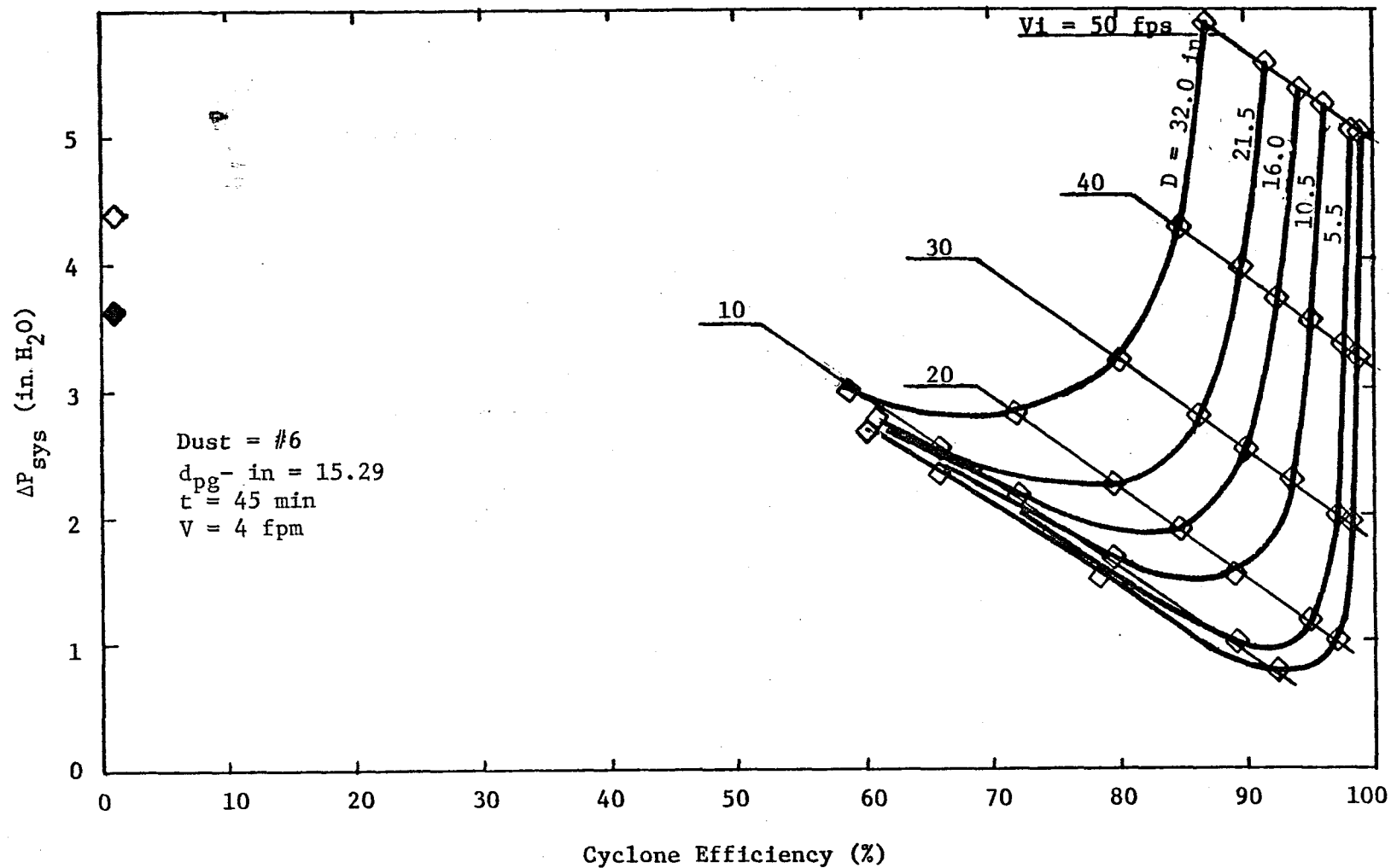


Figure VI-4. Predicted System Pressure Drop for Selected Cyclones Using Dust #6.

filter than a smaller one operating at the same pressure drop. Consequently, the larger cyclones operate at a higher optimal system pressure drop for a given dust. Also, for each dust type there appears to be a maximum cyclone diameter size above which no reduction in system pressure drop can be obtained. Rather, the use of a cyclone exceeding this maximum diameter results in excessive system pressure losses. Furthermore, the value of maximum diameter cyclone size appears to be directly related to inlet particle size. As inlet particle size increases, the maximum diameter cyclone size value increases.

Secondly, optimal cyclone efficiencies increase as inlet dust size increases. Comparing the curves of the four dust types reveals that optimal cyclone efficiencies for the larger dust sizes are greater than for smaller dusts.

Thirdly, for a given dust, optimal cyclone inlet velocities appear to remain relatively constant over the range of cyclone diameters. This implies for the proprietary series of cyclones tested that there is one specific optimal inlet velocity for a given inlet dust size distribution. The selection of cyclone diameter then becomes a balancing of system pressure drop savings with the increasing fabrication-installation costs of progressively smaller cyclones operating at the optimum inlet velocity.

Another observation from the optimization curves reveals that optimal cyclone inlet velocity decreases as inlet dust size increases. Figure VI-5 presents the derived relationship between optimum cyclone inlet velocity and cyclone inlet mass mean diameter for a dust with a

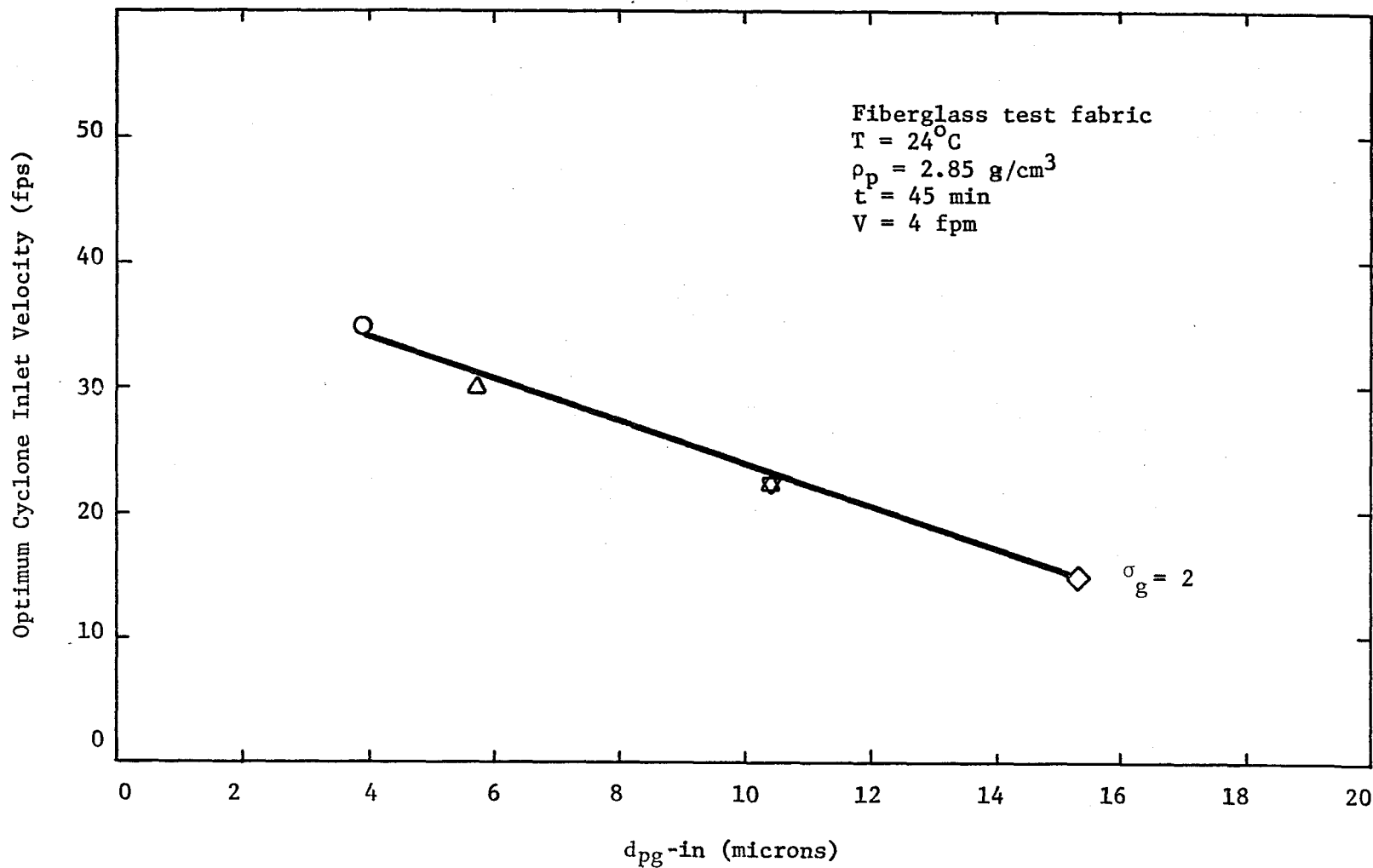


Figure VI-5. Relationship Between Optimum Cyclone Inlet Velocity and Cyclone Inlet Mass Mean Diameter for Fisher-Klosterman XQ Series Cyclones Operating Under Specified Conditions.

standard deviation of two, a density of 2.85, and for specified operating conditions, cyclone type, and fabric type. As seen in Figure VI-5, larger inlet dust sizes require lower inlet velocities in order to achieve the optimal system pressure loss. This naturally results in less flow through the cyclone when precleaning larger inlet dust sizes. Consequently, more cyclone capacity is theoretically required for optimal performance of a system collecting a large mass mean diameter dust distribution as compared with a small mass mean diameter dust distribution.

Further observations indicate that cyclones of decreasing diameter result in greater predicted system pressure drop savings. Also, system pressure drop savings tend to increase more dramatically between cyclone sizes with decreasing inlet dust size. Figure VI-6 shows the relationship between the minimum system pressure drop and cyclone diameter as a function of inlet dust size. The effect of cyclone diameter on the minimum system pressure loss is much greater for dust #1, as evidenced by its steeper slope, than for dust #6. Thus, system pressure loss is observed to be more sensitive to cyclone size for smaller dust sizes. This again can be observed by comparing pressure loss differences between the 4.0 and 5.5 inch diameter cyclones for dusts #1 and #6. The predicted pressure drop differential between the two cyclone sizes for the 15.3 micron dust approximated only 0.25 inches. Whereas, the predicted pressure drop differential between the two cyclones for the 3.86 micron dust was approximately 1.5 inches. Thus, the value of a 4.0 inch diameter cyclone over a 5.5 inch for precleaning a 15 micron mass mean diameter dust distribution is predicted to be inconsequential while

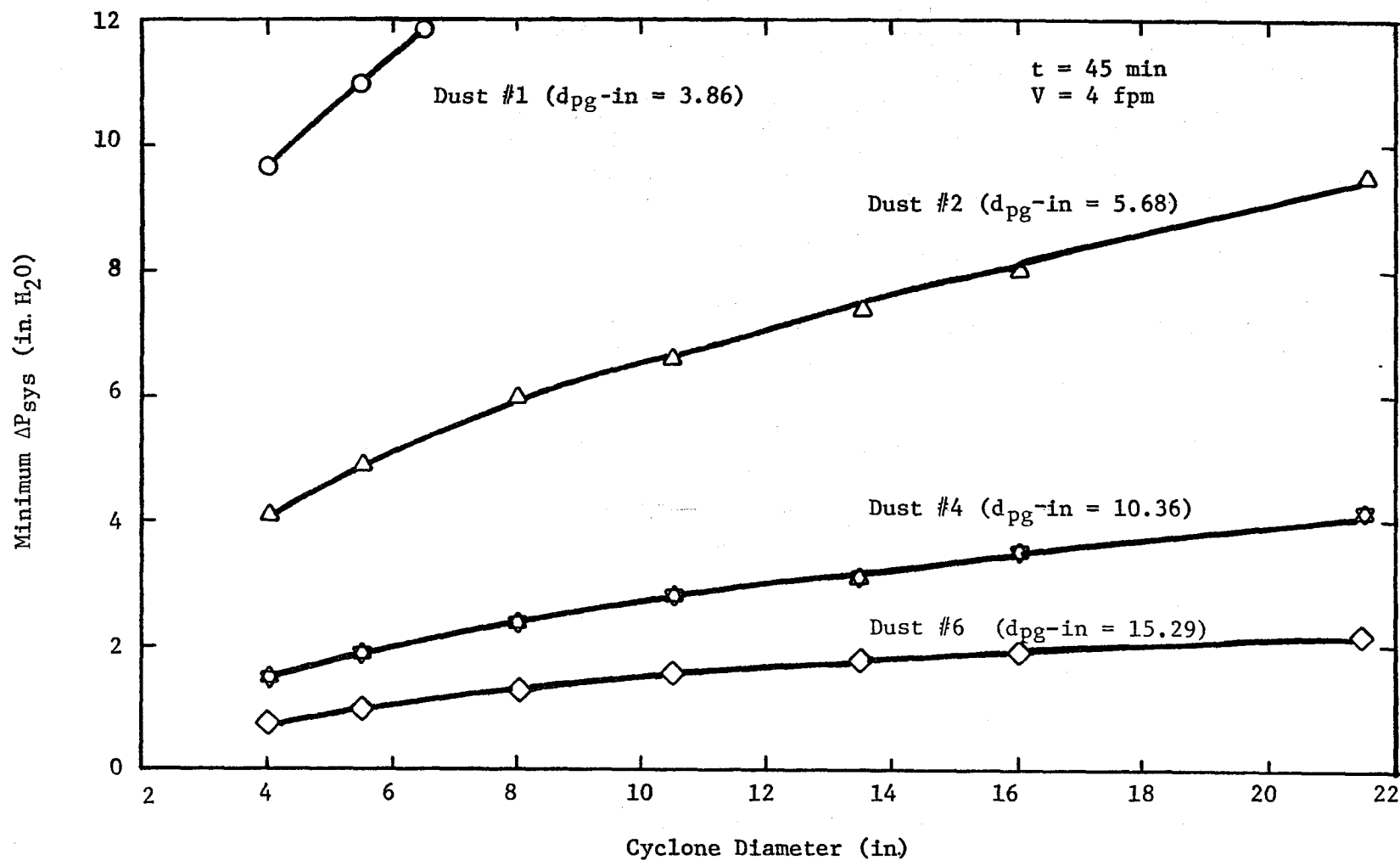


Figure VI-6. Relationship Between Minimum System Pressure Drop and Cyclone Diameter As a Function of Inlet Dust Size.

1.5 inches might be saved by using a 4.0 inch over a 5.5 inch diameter cyclone when precleaning a 4 micron dust.

An ancillary to the above observation predicts increased pressure drop savings when using precleaners on smaller dust sizes. Figure VI-1 indicates for the given operating conditions that the use of a cyclone/-fabric filter collector could theoretically result in a ten inch pressure drop savings over the use of a fabric filter collector alone for dust type #1. The same comparison for dust type #6 (Figure VI-4) indicates a smaller, 3.50 inch, predicted system pressure drop savings for the cyclone precleaner/fabric filter combination as opposed to the fabric filter alone.

Graphical Optimization Technique

Figures VI-5 and VI-6 are of exceptional significance since they represent a technique that can be used for predicting the optimum cyclone inlet design velocity for the given geometric mass mean diameter of the inlet dust. Figures developed by this technique are specific for the dust's geometric standard deviation, cyclone and fabric media type, dust density, and operating parameters such as temperature and filtration velocity.

For the given conditions in Figure VI-5, a designer can readily determine an appropriate cyclone inlet velocity as a function of the geometric mass mean diameter of the particulate he desires to collect. Using Figure VI-6 along with a cost analysis of cyclone fabrication/-installation expenses, a designer could determine the optimum cyclone diameter for the dust type in question.

CHAPTER VII

SUMMARY AND CONCLUSIONS

I. EXISTENCE OF AN OPTIMUM PRECLEANER EFFICIENCY

Real Data

Laboratory data has revealed that there is an optimum cyclone efficiency for a given inlet dust size distribution and system operating conditions at which there exists a minimum system pressure loss across a cyclone/fabric filter particulate control device. System pressure drop savings were achieved using a cyclone precleaner for all dusts tested. Particle size, shape and distribution of the test dusts, and dust loading were fairly typical of a large segment of industrial emissions. Laboratory data values of system pressure drop savings varied from 0.68 inches of water to 6.6 inches of water with the smallest micron test dust resulting in the greatest savings.

Simulated Data

To determine the predicted point of minimum system pressure drop and the corresponding optimal efficiency, and to better understand the relationship of cyclone precleaner efficiency on system pressure drop, a model was developed to simulate cyclone/fabric filter performance. Inputs to the model could be empirically or theoretically derived. Using graphically interpolated inputs of empirical data, optimum cyclone efficiencies were predicted for each of the dust types tested in the laboratory on the bench scale unit. Resulting predicted maximum system

pressure drop savings varied from 2.5 inches of water to 8.3 inches of water with the smallest micron test dust again resulting in the greatest savings. However, a note of caution should be observed concerning these predicted values of maximum system pressure drop savings. For zero cyclone efficiency values, the cyclone fabric/filter model appeared to significantly overpredict values of system pressure loss for some of the test dusts, especially, dust types #2, #3, and #5. Thus, the actual value of maximum system pressure drop savings may be smaller for the test dust types in question.

Both real and simulated data revealed that system pressure losses were very sensitive to increased cyclone efficiency values above the optimum value. As the efficiency exceeded this optimum value, system pressure drop rose rapidly and not only quickly negated any pressure loss savings achieved through use of the precleaner, but increased operating pressure losses above those values at which a fabric filter would operate without a precleaner. For this reason the establishment of an optimum precleaner efficiency for a cyclone/fabric filter control device is deemed important.

Operational Savings

Substantial annual fan electricity cost savings can be realized by operating a cyclone/fabric filter collector near the optimum cyclone efficiency. Using the following cost expression developed by Fraser and Foley (68), which assumes an overall energy conversion efficiency of 55 percent for fan and motor, a savings analysis can be made:

$$\text{Annual Fan Energy Cost, dollars} = 0.0002125 \, h_r Q_{AP} \frac{E}{\text{sav}}$$

where:

h_r = number of control device operating hours per year

ΔP_{sav} = pressure loss savings achieved (in H_2O)

Q = gas flow rate (acfm)

E = cost of electricity per kilowatt hour (\$).

For example, assuming a 200,000 acfm cyclone/fabric filter control device, 100 hours per week operation, and \$0.03 per kwh energy costs; an energy savings of \$33,150 a year can theoretically be expected if a five inch pressure loss can be avoided by optimizing the precleaner's efficiency. Likewise, initial capital savings can be realized by the installation of smaller air handling units due to decreased system resistance.

II. PRESSURE LOSS OPTIMIZATION

Optimization Technique

Incorporation of a commercial cyclone pressure loss expression and a theoretical input prediction package into the model developed for simulating laboratory cyclone/fabric filter performance, allowed for the evolvment of optimization curves which simulate field conditions. Using K_2'/d_{pg} -out relationships derived from the laboratory tests, optimization curves for four of the test dusts were generated. Effects of differing cyclone sizes, inlet particle sizes, and inlet cyclone velocities were analyzed.

Effect of Cyclone Size

Cyclone size was found to be directly related to system pressure drop; the smaller the cyclone, the lower the pressure drop. Cyclone size was also found to be indirectly related to the optimum cyclone

efficiency value for a given dust; as cyclone size decreased, the optimum value of cyclone efficiency increased. Consequently, cyclone size selection must involve an economic analysis between decreasing pressure losses and increasing fabrication-installation costs of smaller cyclones. Differences in savings of pressure loss between cyclone sizes became less sensitive to cyclone size as inlet dust size increased. Thus, one can conclude that the selection of cyclone size is more critical for smaller inlet particle sizes.

Effect of Inlet Particle Size

Decreasing inlet particle size resulted in overall higher system pressure drops for cyclone/fabric filters (a phenomenon naturally occurring with fabric filtration); on the other hand, decreasing inlet particle size generally resulted in increased opportunity for pressure loss savings using a precleaner. Model prediction indicates that it might be profitable to give more attention to the precleaning of small micron dust distributions.

Cyclone Inlet Velocity

Optimization curves revealed that for each of the four dusts tested, there was a specific optimum inlet velocity which held constant over the entire range of cyclone sizes examined. Thus, for a given inlet dust size distribution, cyclone and fabric media type, and operating conditions, there is one specific inlet velocity that can be designed for regardless of cyclone size. This optimum inlet velocity will result in the optimum cyclone efficiency value for a given cyclone size.

Optimum inlet velocity was also found to be indirectly related to particle size, that is, optimum inlet velocities were lower for the larger dust sizes. Predicted optimum inlet velocities ranged from 35 fps (dust #1) to 15 fps (dust #6). These velocities are lower than the average design velocity of 50 fps which one source suggests. However, laboratory data and other sources confirm the lower predicted optimum inlet velocities as realistic.

III. SUMMATION OF CONCLUSIONS

Results from this study analyzing the effects of a cyclone precleaner on a fabric filter can be summarized by the following nine conclusions:

1. There is a readily obtainable optimum cyclone efficiency for a given inlet dust size distribution which results in a minimum system pressure drop.
2. System pressure drop is very sensitive to increases in cyclone efficiency above the optimal value. Cyclone efficiencies above this optimal value can quickly eradicate any system pressure loss savings achieved by a precleaner and can result in unacceptable excessive system pressure losses.
3. Decreasing inlet particle size results in increased opportunity for pressure loss savings using a precleaner. Cyclones may be of great value in the precleaning of inlet distributions of small particle size.
4. For a specific inlet dust distribution cyclone and fabric media type, and operating conditions, there is an optimum

inlet velocity independent of cyclone size. This optimum inlet velocity will result in the minimum system pressure loss for a given cyclone size.

5. Optimum inlet velocity is indirectly related to inlet particle size; the larger the inlet dust size, the lower the optimum inlet velocity.
6. Cyclone size is directly related to system pressure drop for a given particle size inlet distribution, the smaller the cyclone, the lower the system pressure loss.
7. There is a specific maximum diameter cyclone size for a given inlet dust size, cyclone and fabric media type, and operating conditions above which no system pressure drop savings can be realized using a cyclone precleaner. This value of maximum diameter cyclone size decreases with decreasing inlet particle size.
8. As cyclone size decreases, the optimal value of cyclone efficiency increases for a given particle size inlet distribution. That is, a cyclone precleaner operating at the optimal inlet velocity will remove an increasingly greater percent of the particulate from the gas flow as cyclone size decreases.
9. The selection of cyclone size is more critical for smaller dust size distributions. The opportunity for greater pressure drop savings realization exists between cyclone sizes when precleaning smaller particle size inlet distributions.

IV. SUGGESTED RESEARCH

Model Validation

To increase confidence in the optimization model, research should be conducted to validate the model on a full scale unit. A compartmented baghouse and controllable grain loading would lend to a lesser complicated study.

Trade Off Analysis

Research into the economic analysis of trade off between decreasing energy costs due to decreasing cyclone size, and increasing capital investment due to increasing fabrication-installation costs would facilitate design decisions concerning optimum cyclone size.

Abrasiveness of Particles

Bag failure has been reported by Helfritch and Beach (4) as a result of a too efficient precleaner. A closer look may be needed at the abrasive property of small particles leaving a precleaner with respect to their effect on fabrics.

Effect of Precleaning on Efficiency

Further research is needed to study the effect of dust particles size distribution modification on the efficiency of fabric filtration. Precleaning may result in a slight deterioration in efficiency due to the decreased size of the particulate being collected by the fabric filter.

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