

A COMPREHENSIVE STATE-OF-THE-ART  
EVALUATION FOR ALL TYPES OF DUST  
COLLECTION EQUIPMENT THAT MAY BE  
APPLICABLE IN UNDERGROUND COAL MINES

(Contract No. S0100231)

Bureau of Mines Open File Report 4-71

for

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Pittsburgh Mining Research Center  
U. S. Bureau of Mines  
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by

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NATIONAL TECHNICAL  
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## FOREWORD

The United States Bureau of Mines has funded this investigation to determine the state-of-the-art of dust collection technology and the applicability of said technology to underground coal mines. As part of this program pilot plant tests were conducted on several dust collectors employing various mechanisms. The results of these tests were determined according to the procedures set forth herein, and the collectors were operated at conditions recommended by the manufacturers. For illustrative purposes the various collectors have been compared to an arbitrary criterion that reflects the authors' conservative estimate of the performance necessary to meet mine health and safety regulations.

The purpose of these tests was not to determine the relative merits of the collectors or their manufacturers, but rather to demonstrate that the state-of-the-art of dust collection technology is sufficient to explain the performance of various collection mechanisms on coal dust. Most of the companies who volunteered equipment for this investigation manufacture a range of collection equipment for applications of varying degrees of difficulty. The collectors tested were selected to demonstrate various mechanisms, and the results can in no way be construed as an indication of the relative expertise of the companies involved.

The United States Bureau of Mines and the Garrett Research and Development Company extend their thanks to the many companies who cooperated with and contributed to this investigation.



## ABSTRACT

Basic dust collection mechanisms are reviewed, and inertial collection is selected as the most applicable to the respirable coal mine dust problem. Coal mine dust data are evaluated and an estimate is made of the respirable dust loading and size distribution typical of the continuous miner environment. Manufacturers of dust collection equipment are surveyed and several units selected for pilot plant tests with coal dust. The experimental results indicate that the collection mechanisms can be characterized by the state-of-the-art technology. Recommendations are presented for the design of a dust collection system for the coal mine environment.

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## INTRODUCTION

The two main reasons for controlling dust in underground coal mines are to reduce the explosion hazard of the dust and to prevent the exposure of workmen to harmful concentrations of airborne dust. Although the explosion hazards have long been recognized, it is only recently that the magnitude of the problem of "coal miner's pneumoconiosis" or "blacklung" has become clear. A statistical study of death rates for U.S. coal miners, based on records for 1950, indicated that the rate was about twice that of the general working male population. Their death rate from diseases of the respiratory system was about five times that of the general working male population. In addition, the costs being incurred by state governments for compensations due to pneumoconiosis and silicosis are quite significant. The compensation awards for these diseases during the period 1950-1962 were approximately \$70,000,000 just for the states of Pennsylvania and West Virginia.

Techniques have been developed which provide at least partial dust control for almost every operation in a mine. Personal respirators have been developed, and significant efforts have been made in the areas of dust control on roof bolt, drills, conveyor loading, and transfer stations. The only significant exception is the continuous mining machine. These units have very great productivity, and therefore generate large amounts of respirable dust. Their use is increasingly dominating underground coal production, and they account for one-half of underground bituminous coal production.

The use of continuous mining machines aggravates the dust problem in another way. As mining becomes more mechanized, "full-seam" mining is becoming more prevalent. This means that the partings in the coal are mined with the coal. If the partings contain free silica, the dust will be more harmful to breathe. In certain types of continuous mining the roof and floor may also be cut. Since these materials contain large amounts of free silica, and these dusts are apparently finer than coal dust, the problem may be further aggravated.

Considerable effort has been expended in a search for an efficient means of controlling the dust generated by these machines. The methods studied fall into five basic categories: treating the coal before it is mined to prevent dust from being generated, control of fragmentation, dust suppression, collecting the dust at the mining face immediately after it is generated, and increasing the mine ventilation to dilute the respirable dust to an acceptable level.

Pre-treating the coal would be an attractive solution to the problem, but no consistent and economical technique has yet been set forth for doing this. Neither increasing mine ventilation nor providing protective equipment for mine operators really solves the dust problem. However, with the wide variety of high-efficiency dust removal equipment available, some selected equipment might be modified for use in the specific case of coal mine dust.

On September 18, 1969, the Garrett Research and Development Company contracted with the United States Bureau of Mines to conduct a comprehensive state-of-the-art evaluation for all types of dust collection equipment that may be applicable in underground coal mines.

#### SUMMARY

The objectives of this investigation were to make a detailed study of dust collecting equipment including geometry, operating characteristics, and costs; collect mine dust samples and determine the size and composition of the dust; conduct performance tests on various types of dust collecting equipment as required; and finally, report the results of these investigations and make recommendations for any further work necessary. The investigation can be summarized as follows:

1. Basic dust collection mechanisms were reviewed including gravitational, inertial, diffusional, electrostatic, porous filtration, radiation and thermal gradient, magnetic, diffusophoretic, agglomeration, and particle buildup.
2. Coal mine dust samples were taken and dust data taken by other investigators were evaluated. Based on this evaluation an estimate was made of the respirable dust loading and size distribution typical of the continuous miner environment.
3. A survey of 35 major manufacturers of dust collection equipment was conducted. From this survey eight pilot plant scale units were selected for performance tests. These units were selected based on the review of the relative merits of the basic dust collection mechanisms noted above.
4. A pilot plant system was designed and constructed to test collectors in the 1,500 to 3,000 cfm range. The pilot system included a coal dust generation section designed to provide respirable coal dust to the collection system and sampling equipment for determining the concentration and size distribution of the dust in the inlet and outlet air streams.

5. Data were taken for the eight collectors to determine penetration as a function of particle diameter for various coal dusts of known size distribution and various collector operating conditions. The results were related to the theoretical performances for the several mechanisms tested.

### CONCLUSIONS

The results and conclusions of this investigation are as follows:

1. Respirable coal mine dust was estimated on the basis of the AEC sampler as having a loading ranging from an average of  $5.0 \text{ mg/m}^3$  to a maximum of  $10.0 \text{ mg/m}^3$ , and a logarithmic normal size distribution with a mass mean diameter of 2.55 microns and a geometric standard deviation of 1.7. In order to reduce this dust to a loading of  $2.0 \text{ mg/m}^3$  based on the MRE sampler ( $0.81 \text{ mg/m}^3$  based on the AEC sampler) a collection efficiency of from 84 to 92% will be required on the AEC respirable dust.
2. Based upon the investigation of basic dust collection mechanisms, it is apparent that a collector based on an inertial mechanism will be most likely to meet the above collection criterion.
3. There appears to be no commercially available dust collector that can satisfy both the physical constraints of the mine environment and the designated collection criterion.
4. Experimental results indicate that the state-of-the-art knowledge of dust collection mechanisms is sufficient to serve as a basis for design of an appropriate collection system. The results further indicate that a co-current atomizing, or venturi scrubber is one type which could achieve the desired efficiency.
5. The collection efficiency for a given collector on a given dust can be explained entirely in terms of inertial parameters such as particle diameter and density and the operating conditions of the collector. Information on surface characteristics, composition, and other physical properties is not necessary for the design of a dust collection system.

6. Since there is presently no satisfactory commercial collector available for the coal mine dust application, a collection system will have to be designed and constructed specifically for the mine conditions. The design of this collection system will be dependent upon the nature of the entire air system in the vicinity of the continuous mining entry. It is therefore necessary that the air system be specified before the design parameters of the dust collector can be determined. This air system must in turn conform to the design constraints for the dust collector set forth in this report.

#### RECOMMENDATIONS FOR FUTURE RESEARCH

Since it has been demonstrated that the state-of-the-art knowledge of dust collection mechanisms is sufficient to serve as a basis for design of an appropriate collection system, future research should be devoted to developing an optimal air system for the continuous mining operation. The design of this air system will dictate the operating conditions for the dust collector.

The development of this air system should take place in three phases:

1. A preliminary evaluation of the relative merits of alternative air intake systems should be conducted. The two major alternatives for consideration are a machine mounted system and a system located in the last open crosscut. The machine mounted system offers the advantages of mobility and immediate proximity to the working face and the disadvantage of limited capacity. A system in the last open crosscut offers the advantages of large capacity, increased working space at the face, and enhanced methane dilution and the disadvantages of comparative immobility and higher operating costs.
2. The alternative air systems should be evaluated experimentally in an above ground simulation of a continuous mining entry. This investigation should lead to the determination of operating parameters that will allow the design and construction of a dust collection prototype system.
3. The prototype system should be tested in a mine to determine both its mechanical effectiveness and its effect on mine operating conditions.

Two other areas of investigation are worthy of note. First, a continuing effort is needed to more accurately determine dust loadings and size distributions. The design of a dust collection system can be based on the conservative estimate of the respirable dust set forth in this report, but an improved knowledge of the dust would obviously allow improvements in the operating criteria for the dust collection system.

Second, the long range dust control objective should be control of the source. While the immediate problem created by the continuous miner deserves primary attention, research must continue to improve mining machine designs so that less dust will be generated.

## BASIC MECHANISMS OF DUST COLLECTION

Small dust particles are usually kept suspended in air for long times by the viscous force or drag of the air, which resists any forces tending to precipitate them. Sometimes forces due to electrostatic charge, radiation flux, and other phenomena may also act to keep dust suspended.

As a rule, the dust suspension (also referred to as an "aerosol") is not a stable state and it will become separated in time. Practical processes for dust separation (or collection) are methods for making that time as short as possible. Let us first review the basic mechanisms which can cause dust to move relative to air and then describe the types of devices embodying these mechanisms and their performance characteristics.

The major mechanisms which can be used for particle collection are:

1. Gravitational
2. Inertial
3. Diffusional
4. Electrostatic
5. Porous filtration
6. Radiation and thermal gradient
7. Magnetic
8. Diffusophoretic
9. Agglomeration
10. Particle buildup

Gravitational separation occurs continuously due to the attraction of the earth for the dust particles. The dust settles at a velocity such that the gravitational force is just balanced by the drag force exerted by the air. Since the drag force increases with velocity, a dust particle initially at rest falls increasingly faster until it reaches its terminal settling velocity. For respirable particles this takes a very short time and the dust may usually be assumed to reach terminal velocity instantaneously. A two micron diameter coal particle settling in air will reach a velocity of about 0.4 in./min.

Inertial forces tend to keep the particle moving in the same direction. Thus, if the air is moving in a curved path, the particle's inertia causes it to deviate from that path. The particle will move at some velocity relative to the air such that the drag force (plus any other resistive forces) will balance the inertial force.

Diffusion of particles is caused by their bombardment by gas molecules. A dust particle whose size is on the order of the mean free path of the gas molecules (about  $10^{-5}$ cm) or smaller will experience random collisions which will cause it to move along an erratic path. This phenomenon is known as "Brownian motion" and it tends to keep the aerosol mixed.

If particles are removed from one region of the suspension, say by sticking to a wall, other particles will diffuse toward the region where the concentration has been lowered. This process of Brownian diffusion has the same effect as gaseous diffusion, and it is important for particles smaller than a few tenths of a micron in diameter.

Electrostatic charges on dust particles makes them susceptible to the forces in a charge gradient. Charged particles will be attracted by unlike charges and repelled by like charges. Thus a negatively charged particle in an aerosol of like-charged particles will be repulsed by the "cloud" but would be attracted by a positively charged plate. In some special situations the "space charge" effect or the imposition of a charge gradient can cause particles to remain suspended indefinitely.

The Millikan oil drop experiment to determine the charge on the electron is an example of the latter case, where gravitational force is just balanced by the force due to a charge gradient between two plates. Particle charge and the electrostatic field can be controlled so that the particles can be caused to move relative to the gas at a velocity determined by the balancing of drag and motive forces.

Porous filtration, as used here, means the blocking of particle movement by means of a screen with pores of the same magnitude as the particle or smaller. It is distinguished from filtration by fibrous media such as paper and glass wool where the collection mechanism is inertial impaction on the fibers which may be spaced many particle diameters apart. After some particles have been collected they may form a "cake" which will act as a porous filter and will generally increase the filtration efficiency and pressure drop.

Radiational and thermal forces due to the flux of light or heat can cause particles to move relative to air. The unequal bombardment experienced on the hot and cold or light and dark sides of the dust particles causes them to move away from the heat or light source. Thermal precipitation or thermophoresis has been used as the mechanism for particle collection in dust sampling instruments.

Magnetic force can be used to cause particle movement relative to fluids. An important requirement is that the particles be susceptible to magnetic attraction. Since this is frequently not the case, this mechanism is not utilized, to our knowledge.

Diffusion of a gas relative to the bulk of the air stream can cause a drag force on dust particles which will tend to move them relative to the air stream. The evaporation of water from a drop or sheet of water would tend to move dust particles away from the water surface. On the other hand, condensation of water would tend to move dust particles toward the water surface. In coal mines the evolution of methane from the coal surface tends to move dust particles away from the surface. The general phenomenon is known as diffusophoresis or sweep diffusion.

Agglomeration is a phenomenon which, while it will not of itself remove dust particles from air, will make them much more susceptible to removal by other mechanisms, such as gravitational sedimentation. Brownian motion causes the dust particles to move relative to the air and this random motion will cause the particles to collide with one another. When the particles collide, they tend to stick together and form agglomerates or clusters of particles. The temperature of the gas has a strong influence on agglomeration (as well as diffusivity) because the gas molecules move a higher velocity at higher temperatures. The turbulence of the air stream also has an effect upon agglomeration in that it will cause more violent motion of the particles, and this may be significant if the scale of the turbulence approaches the size of the particles.

Particle buildup by condensation of a gas, such as water vapor, can also make the dust easier to remove from suspension. The introduction of steam and/or the cooling of a humid air stream has been employed to build up the size of the dust particles so that they are easier to remove by sedimentation or inertial impaction. Chemical reactions may also be employed to build up the size or density of particles.

A final mechanism for removal of dust particles is their conversion into gaseous form by some type of chemical reaction. The combustion of carbon particles is an example of this. Evaporation of particles is a related mechanism for converting them to the vapor state. In some instances, such as the elimination of fog from stack plumes, it is feasible to heat the flue gas so that the water vapor will not condense as the plume leaves the stack and be diluted in ambient air rapidly enough so that it will not condense as it is cooled outside the stack.

#### Useful Mechanisms for Underground Coal Dust

Most of the basic mechanisms for dust collection can be set aside as either impractical, dangerous, or improbable for use in the control of coal dust underground. As a means of simplifying the discussion of control equipment the basic mechanisms for dust control will be separated into those which can be disregarded and those which should be considered.

Gravitational collection can be eliminated on the basis of the volume of the equipment which would be necessary to collect dust particles in the respirable range to the degree necessary. As will be discussed later, a satisfactory dust collector will have to be capable of 50% efficiency on coal dust of about 0.65 to 1.35 microns in diameter. A gravitational separator, even of the multiple tray type with spacing of one centimeter between trays, would have to have a volume of 1,500 cubic feet in order to clean 3,000 CFM of air. This would doubtless be excessively large for use on a continuous coal mining machine.

Diffusional collection is not very effective on particles larger than 0.3 to 0.5 micron diameter. The bulk of the respirable dust is much larger than this; the mass median diameter is likely to be about 2.5 microns in diameter. Since less than 0.1 percent would be in the size range below 0.5 micron diameter, it is obvious that diffusional collection cannot account for a sufficient reduction of the respirable mass fraction. A word of caution should be placed here, in that it may be determined someday that the extremely small particle sizes have a disparately large effect on health and may therefore be more important than their proportionate mass fraction would indicate.

The amount of development work required to make electrostatic precipitation permissible for use in coal mines makes its utilization in coal mines doubtful in the reasonable future.

Radiation and thermal forces are not likely to be useful in the near future, because no practical devices based on these mechanisms are presently available. The maintenance of the necessary thermal gradient, for instance, would require a considerable heat source and heat sink in addition to a heat exchanger.

Magnetic forces would not be useful on coal dust. Diffusophoresis is a mechanism which may conceivably aid the collection of dust by a device such as a scrubber utilizing cold water, but it is not envisioned as a primary mechanism of collection. It is further conceivable that the use of steam for particle buildup might be developed into a useful device. If so, the condensation of steam might cause some diffusophoresis effect.

Agglomeration might also aid the collection of coal dust in a variety of devices by increasing the particle size. It is unlikely that diffusion could be used as a primary means for obtaining the necessary collection efficiency and still remain within the space constraints of the underground situation.

These considerations leave inertia and porous filtration as the major mechanisms for coal dust collection underground. Porous filtration is technically suitable and capable of providing very high efficiency. However, the space requirements cause porous filtration to appear less likely than inertial collection as a basis for an optimum underground coal dust collector.

### INERTIAL DUST COLLECTION

Inertial collection is the basis, or at least the principal mechanism, for the collection of dust by a large number of devices. These will be described very briefly below. There are a number of excellent texts and articles dealing with particle collection, and the reader requiring more detail is referred to the list of selected references in the bibliography of this report.

#### Cyclones

Cyclone separators are devices which employ a rotary motion of the entire gas stream to spin out dust particles under the influence of centrifugal force. The rotation is caused by the air entering the collector either through a tangential opening or through propeller-like guide vanes which cause it to rotate. The dust particles are spun to the wall of the cylindrical collector and then are conveyed

along the wall either by gravitational force or by drag forces to some form of collection hopper and removal system. The cleaned air leaves through some form of centrally located opening.

Smaller diameter cyclones are more efficient than large ones, and this has caused the development of a variety of multiple small-diameter cyclones operated in parallel. Typical collection efficiencies for large high-efficiency cyclones and small-diameter high-efficiency multiple cyclones are given in Figure 1 and Table 1.

The collection efficiency of the cyclone increases with air velocity through the cyclone, and the pressure drop also increases with the air velocity. Thus higher efficiency must be paid for in terms of pressure drop, which means higher fan horsepower. There is an upper limit to the air velocity which can be used; this being the velocity at which re-entrainment of dust from the cyclone walls becomes appreciable.

For the particular case of a cyclone with an axial inlet or a "hub" at the center, the efficiency,  $E$ , for particles of diameter  $D_p$  is given by:

$$E = \frac{1 - [1 - (D_p/C)^2]^{1/2}}{1 - X^2} \quad (1)$$

where  $X = D_h/D_o$ , the ratio of diameters of the cyclone hub and the cyclone outer wall; and  $C$  is a coefficient depending on the cyclone dimensions, the flow rate, and the physical properties of the air stream and the dust particles (3).

When  $D_p \geq C$ , the efficiency is 100%. The cut diameter, or diameter for which the penetration is 50%, is:

$$d_c = \frac{C}{2} [(1-X)(3+X)]^{1/2} \quad (2)$$

### Curved Passages

A variety of dust collectors utilize essentially the same principle as the cyclone separator, but the gas is caused to turn by curved passages of some sort. Examples of this type of collector are louvered or deflector collectors, zig-zag or corrugated passages, and beds packed with massive shapes (as distinguished from fibers). In the packed beds the essential mode of collection is caused by the flow of the

FIGURE 1

TYPICAL EFFICIENCY CURVES  
FOR HIGH EFFICIENCY SINGLE AND  
MULTIPLE CYCLONES (1)

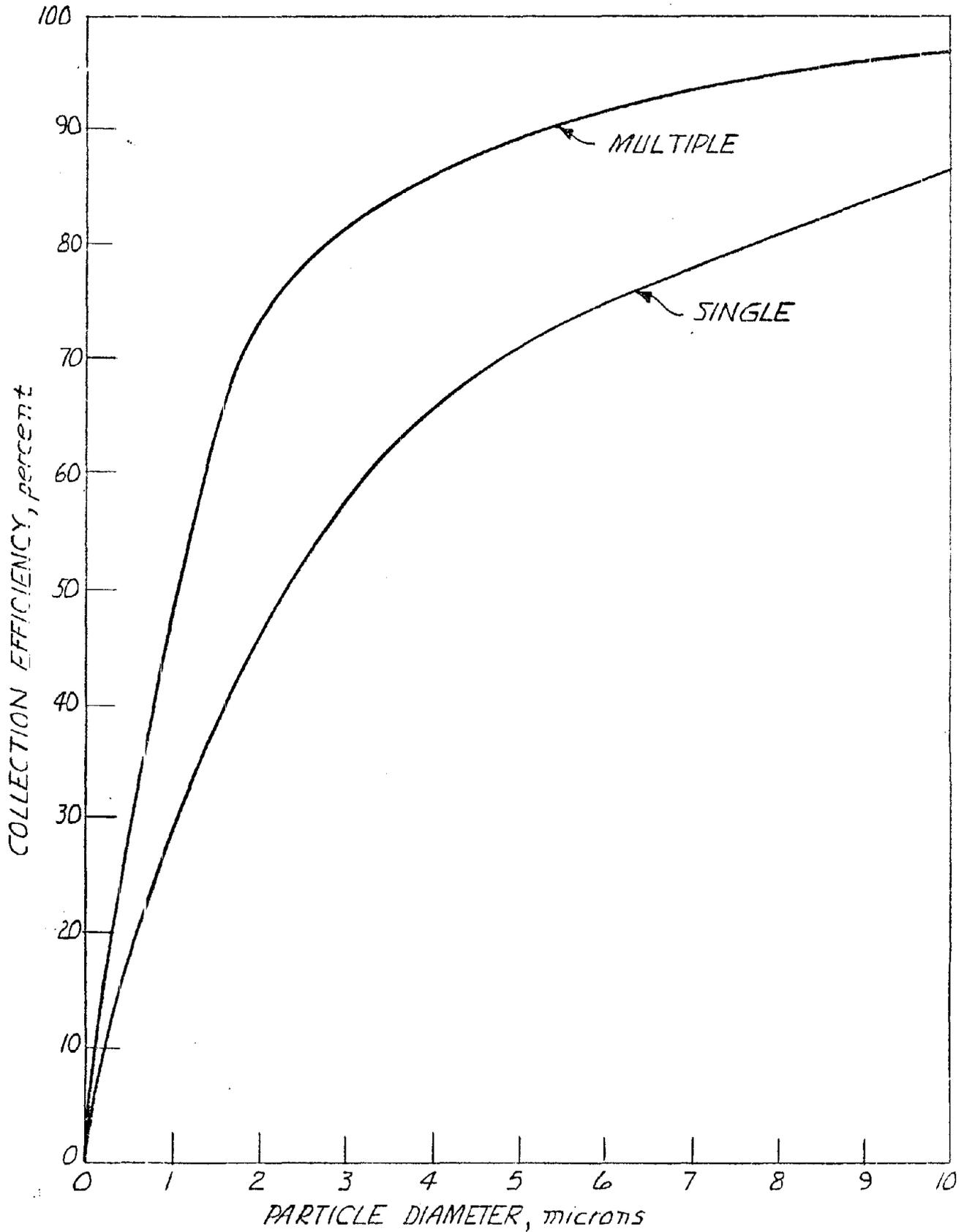


TABLE 1

Efficiency of Dust Collectors \* (2)

<u>Dust Collector</u>	<u>Efficiency at 5 <math>\mu</math> * (7.07 <math>\mu</math>)** %</u>	<u>Efficiency at 2 <math>\mu</math> * (2.83<math>\mu</math>)** %</u>	<u>Efficiency at 1 <math>\mu</math> * (1.41 <math>\mu</math>)** %</u>
Medium-efficiency cyclone	27	14	8
High-efficiency cyclone	73	46	27
Low pressure-drop cellular cyclone	42	21	13
Tubular cyclone	89	77	40
Irrigated cyclone (high efficiency)	87	60	42
Electrostatic precipitator	92	85	70
Irregated electrostatic precipitator	98	97	92
Fabric filter	> 99.9	99.9	99
Spray tower	94	87	55
Wet impingement scrubber	97	92	80
Self-induced spray deduster	93	75	40
Disintegrator	98	95	91
Venturi scrubber	99.6	99	97

\* For dust of density 2.7 g/cm<sup>3</sup>

\*\* Multiply diameters by  $\sqrt{2}$  for coal density  $\approx$  1.35.

air through a multitude of tortuous curved passages. As the air turns through these passages, the dust particles are spun out against the solid or liquid collection surfaces by the action of centrifugal, inertial forces.

The penetration as a function of particle diameter for a packed bed can be described (4) by the equation :

$$P_t = \exp (- 10 (Z/D_c) K) \quad (3)$$

where:

$P_t$  = Fraction of particles penetrating the column.

$Z$  = Packed height (ft. or cm).

$D_c$  = Packing size (ft. or cm - must be same units as  $Z$ )

$K$  = Inertial impaction parameter (dimensionless)

$$= \frac{U \rho D_p^2}{9 \mu D_c}$$

$U$  = Air velocity (cm/sec. or ft./sec.)

$\rho$  = Particle density ( $\text{gm/cm}^3$ ) = 1.35 for coal

$D_p$  = Particle diameter (cm = micron  $\times 10^{+4}$ )

$\mu$  = Air viscosity (poises) = about  $1.8 \times 10^{-4}$  for standard air.

#### Impaction on Obstacles

Inertial forces can also come into play when the air stream is forced to pass around obstacles within the air stream. These obstacles or collection elements can be of a variety of sizes, shapes and materials. They may also be stationary or moving.

Cylindrical objects such as rods, wires and fibers are used in a large number of collection devices. The dust particles are moved out of the air stream toward the impaction element under the influence of inertial forces as the air turns to pass around the element. The efficiency of dust collection by this mechanism can be extremely high. High-efficiency paper filters owe much of their efficiency to this mechanism which generally acts in concert with other mechanisms of particle collection.

The factors influencing collection efficiency are the air velocity relative to the collection objective, the diameter of the collection object, the viscosity of the air, the number of collection objects which the air must pass and the dust particle diameter and density. All of these factors except the number of collection stages are included in the inertial impaction parameter, which has been defined by equation 3. A further refinement in this parameter is the inclusion of the Cunningham slip correction factor, which has been omitted here for simplicity. It causes an increase in K of about 15% for one micron diameter particles and increases for smaller particles, while decreasing for larger ones.

Figure 2 is a plot of collection efficiency as a function of impaction parameter for impaction on spheres and cylinders. The curves are approximate representations of experimental data for these two situations. These curves can also be represented quite well by the correlation:

$$E = \frac{K^2}{(K+0.7)^2} \quad (4)$$

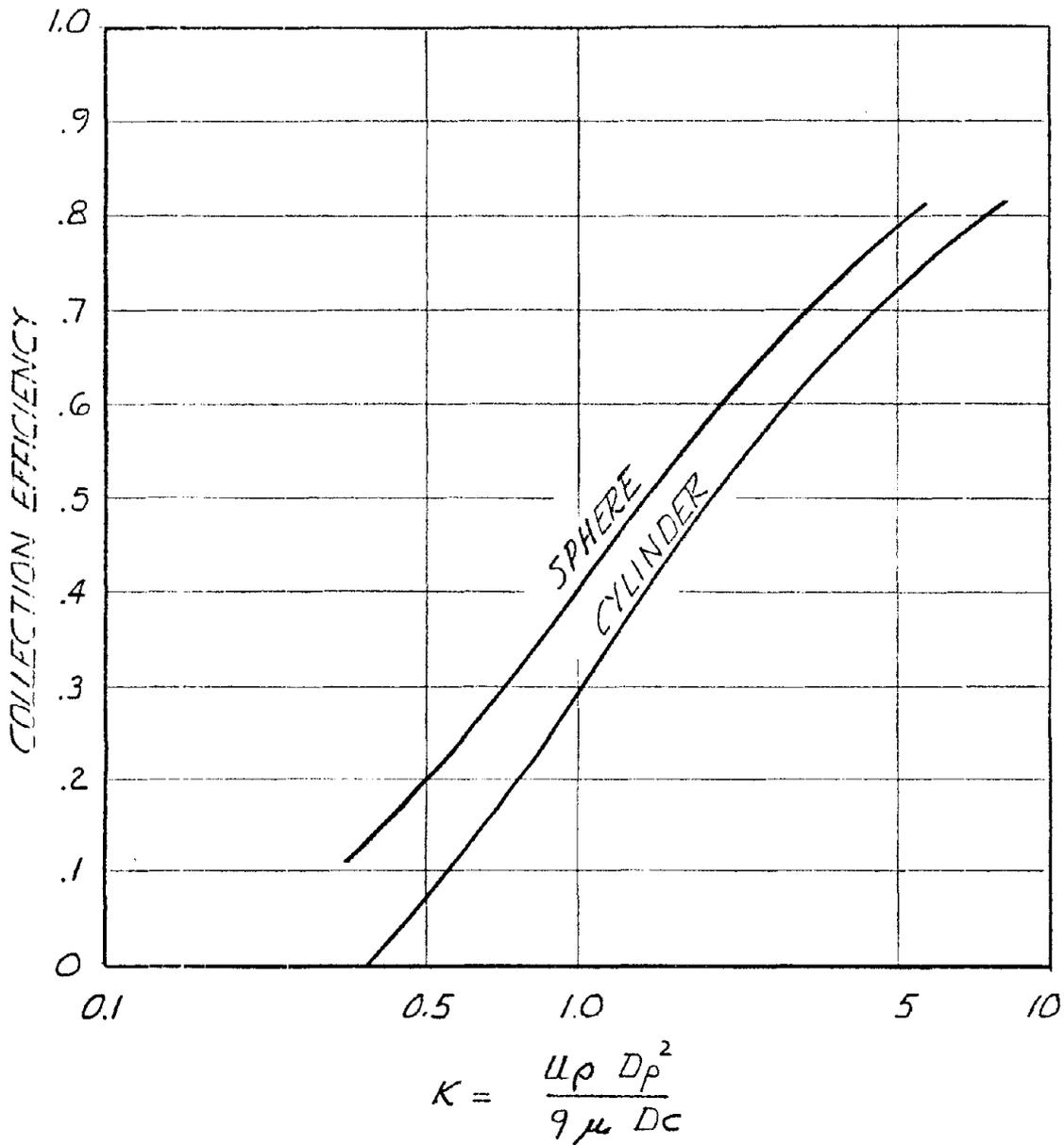
One can observe from Figure 2 that a value of at least 0.5 for K is necessary in order to obtain some collection efficiency on a single cylinder. To illustrate, for a two micron diameter coal particle with density 1.35, the ratio of air velocity to collector diameter would have to be at least  $5 \times 10^4 \text{ sec}^{-1}$  in order to obtain 50% efficiency in an encounter with a cylindrical collector. Thus, if the air velocity were 3,000 cm/sec., the cylinder diameter would have to be 0.06 cm.

Liquid drops as furnished by sprays or by the atomizing action of a high velocity air stream impinging on a liquid surface or jet are also used in a variety of particle collectors. Examples of this type of collector chamber are sprays directed into the air, venturi and orifice type scrubbers, ejector venturi scrubbers, and numerous wet collection devices in which the air impinges upon a liquid surface and causes atomization.

The collection efficiency of the liquid drops is approximately the same as for solid spheres of the same size. As indicated by Figure 2 the collection efficiency of a sphere is approximately 10% higher than that of a cylindrical element at the same value of the inertial impaction parameter.

FIGURE 2

PARTICLE COLLECTION EFFICIENCY  
VS IMPACTION PARAMETER  
FOR IMPACTION ON OBSTACLES



Approximate efficiency relationships are shown in Figure 3 and Table 1 for spray towers, impingement scrubbers, orifice scrubbers and venturi scrubbers collecting particles with a density of 2.7 gm/cm<sup>3</sup>.

### Venturi Scrubbers

Orifice and venturi scrubbers are devices in which the air is forced through a narrow opening at velocities usually on the order of 200 to 400 ft./sec. Liquid, usually water, is introduced either at the throat of the venturi or orifice or somewhat upstream. The water is atomized by the high velocity air stream and dust particles are collected on the resulting droplets.

The penetration for a venturi throat can be estimated from the equation:

$$P_t = \exp \left( - (13500 L + 1.2 L^{2.5} U) E_a' \left( \frac{fa'}{2} \right) 10^{-4} \right) \quad (5)$$

where L is the liquid rate in gal./mcf and U is the air velocity at the throat (5, 6).  $E_a'$  is the efficiency for impaction on spheres and can be estimated from Figure 2 or calculated from equation 4.

In order to calculate the impaction parameter, it is necessary to know the diameter of the spherical collector, which in this case is the water droplet. Drop diameter has been correlated previously by Nukiyama and Tanasawa as a function of gas velocity and liquid rate. This correlation for air and water at standard conditions is:

$$D_c = \frac{16,400}{U} + 1.45 L^{1.5} \quad (6)$$

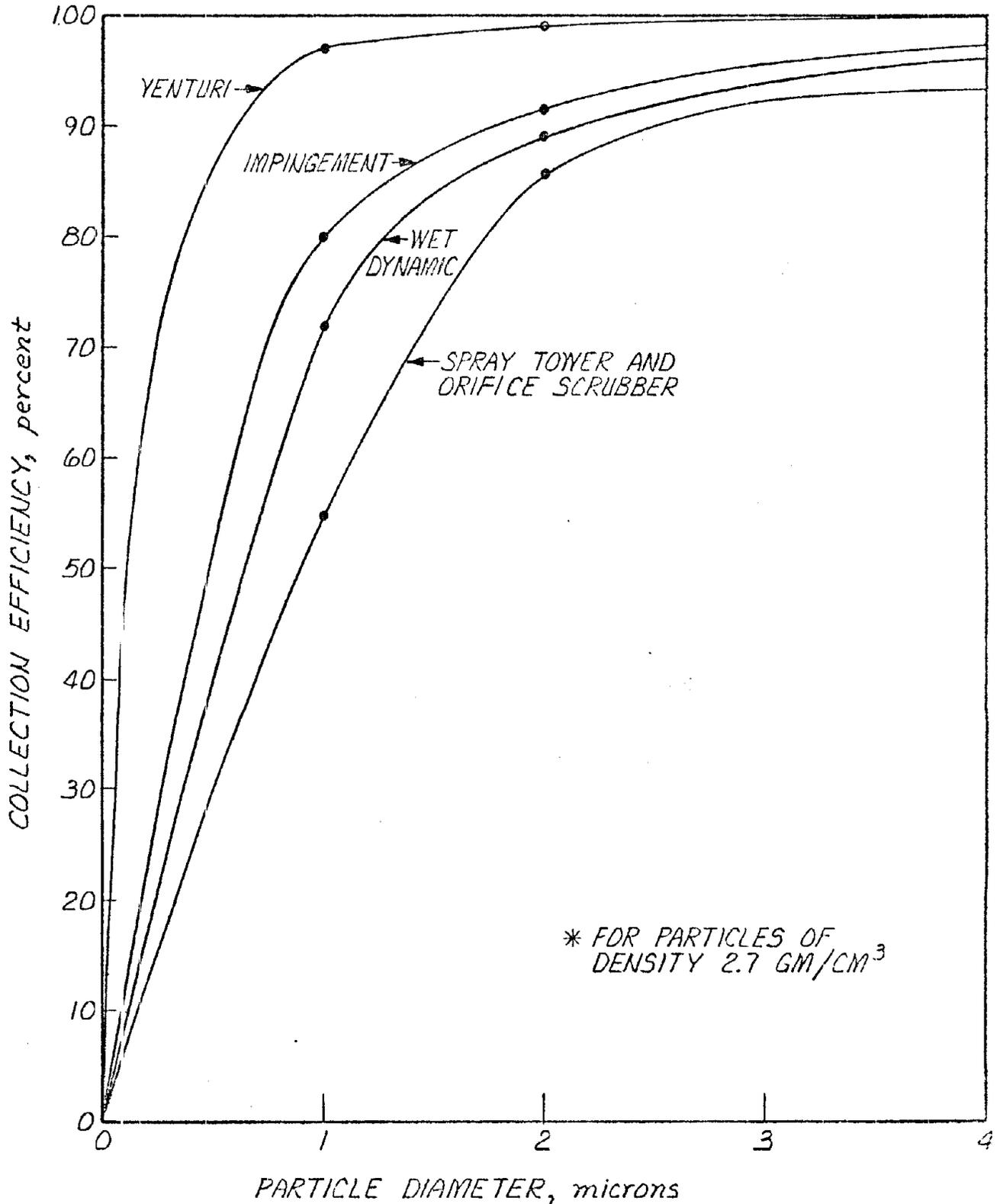
for velocities in the 200 to 600 ft./sec. range. Below this velocity range, the drop diameter can be calculated from the critical Weber number (7):

$$We = \frac{\rho_g U^2 r}{\sigma} \quad (7)$$

where the critical value of the Weber number,  $We$ , is estimated at five for water,  $r$  is the drop radius, and  $\sigma$  is the surface tension.

FIGURE 3

TYPICAL EFFICIENCY CURVES  
FOR SEVERAL  
WET SCRUBBER MECHANISMS \*





The final term needed to solve equation 5 is  $f_a'$ , the velocity ratio for atomization. This ratio is the ratio between the drop velocity and the air velocity, and seems to be about 0.4 based on collection data. In other words, the liquid seems to be accelerated to about one-half the gas velocity before it shatters to final size, and this adjustment to the effective impaction velocity is assumed to have a linear effect on efficiency.

Figure 4 represents the solution of equation 5 for the case of particle radius squared times density equal to 1.0. In the case of coal dust, with a density of 1.35, this would correspond to a particle radius of 0.86 microns or a diameter of about 1.72 microns. It can be seen that the effects of air velocity and water to air ratio may be used interchangeably to obtain variations in collection efficiency and pressure drop.

### Sprays

The use of open sprays to suppress coal dust has been investigated and found to be of marginal value on respirable dust. Walton and Woolcock (8) determined that high pressure sprays could remove dust particles from the air with efficiencies as high as 55% for two micron diameter dust and 28% for one micron diameter dust. The water requirement would be on the order of 5 to 10 gal./mcf (gallons per 1,000 cubic feet) of dust cloud. A major disadvantage is that several feet of distance for spray travel are required, depending on the spray drop size. Their conclusion was that under normal conditions high velocity sprays might be a practical way of air cleaning near the source of production or in duct downstream from the source. Brewer (9) is in general agreement with this finding.

Ejector type spray scrubbers can provide high collection efficiency and are technically feasible from that standpoint. They operate by means of spraying water at high velocity into a pipe or venturi section in the axial direction. The water drops exert drag on the air and cause it to move through the device. Following the collection zone there is some form of entrainment separator for removing the water drops.

Based on the data published on this type of ejector venturi scrubber, it appears that the water requirement would be 50 to 100 gal./mcf of gas scrubbed. The water pressure would have to be 100 psi or higher.

PREDICTED PENETRATION AND PRESSURE DROP VS AIR VELOCITY WITH WATER RATE, L, AS PARAMETER

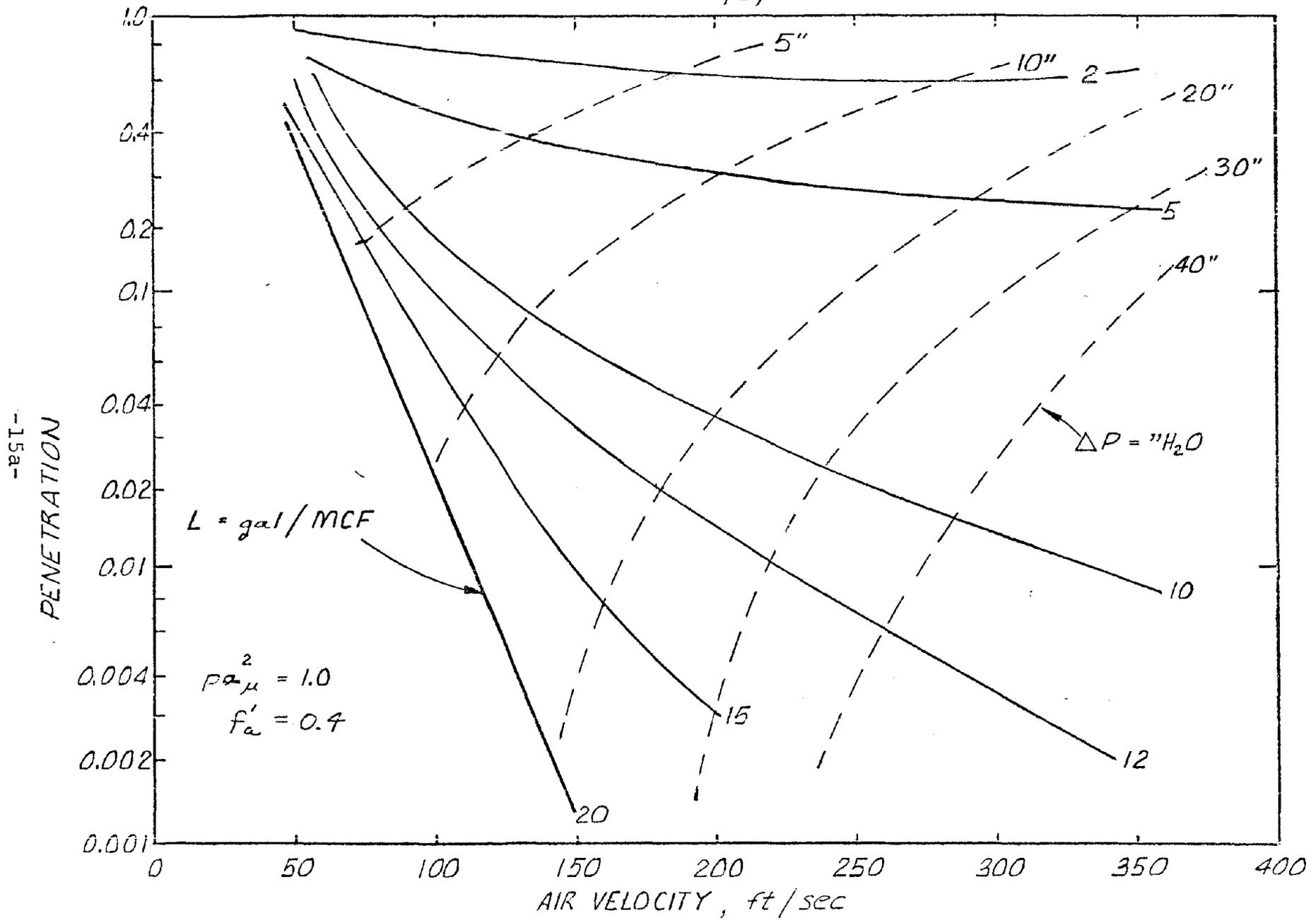


FIGURE 4

## Impingement of Air Jets on Liquid or Solid Surfaces

Banks of cylindrical, streamlined struts, and various channel forms have been used for particle collection. The spacing of these elements is generally on the order of the diameter of the element or less. Because the spacing is close, the flow characteristics are no longer the same as for air flow around immersed bodies such as single cylinders. Therefore the collection is defined by the impingement of air jets against a solid surface.

When a jet impinges on a surface, it changes direction and there is a region of curved flow where this occurs. The particles present in the air are spun out of the air stream and will collide with the surface, depending on their inertia, the air velocity, the dimensions of the jet and the air viscosity.

Experimentally determined collection efficiencies for the impaction of round and rectangular jets are presented in Figure 5. As can be seen, the inertial impaction parameter is the most important determinant of the collection efficiency. In the case of rectangular jets, the significant dimension,  $D_C$ , is the width of the jet. It is presumed that the jet length is long enough so that it is not a factor.

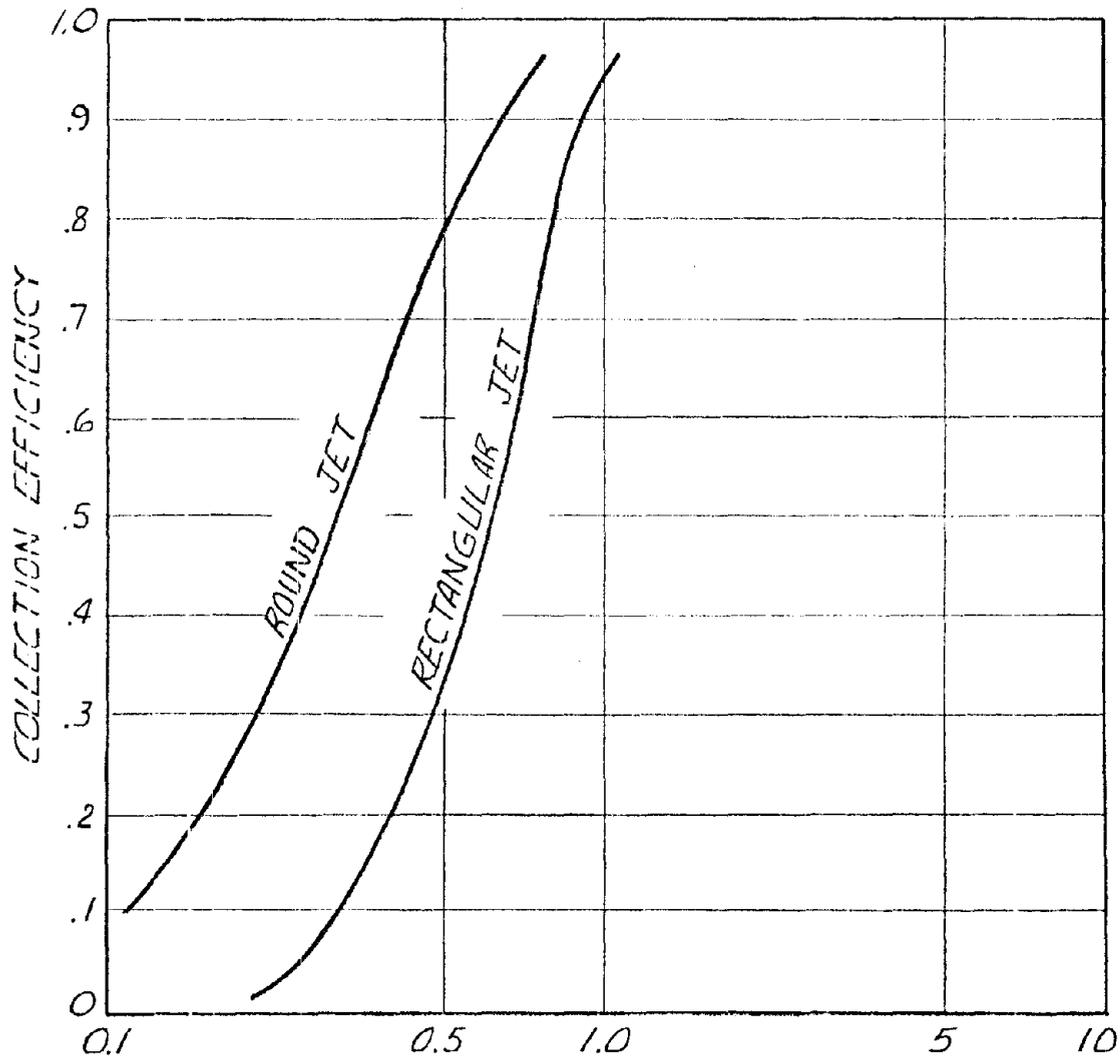
Equipment which involves the impingement of jets as the major collection mechanism include the Peabody scrubber, the Doyle scrubber (note that in cases where liquid is present there can also be the atomization of liquid and subsequent collection of particles on the drops), perforated plates, or so-called foam plates.

In the case of impingement on liquid, there may be additional factors to consider, as in the case of sieve plates where the air enters through the perforations in the plates and the resulting jets pass upward into a pool of liquid. Because the liquid is free to move, it forms a froth or foam layer which is in violent agitation. The calculated efficiency, based on jets of the size emerging from the perforations must be corrected for the foam density which defines the movement of the liquid away from the jets (10). Other types of plate or tray equipment, such as bubble caps, ballast trays, marble beds, and others, also involve this mechanism.

FIGURE 5

PARTICLE COLLECTION EFFICIENCY  
VS IMPACTION PARAMETER

FOR IMPINGEMENT OF JETS ON  
LIQUID OR SOLID SURFACES



$$K = \frac{U_p D_p^2}{9 \mu D_c}$$

## Porous Filters

Porous filters (or fabric filters) are capable of providing very high dust collection efficiency so that the major considerations are equipment size and cost, pressure drop, and maintenance requirement. Size is probably a major deterrent insofar as underground use is concerned. Taking an air face velocity in the range of 1 to 10 ft./min. and assuming 1/3 ft.<sup>3</sup> of filter assembly for each ft.<sup>2</sup> of filter area, one can estimate the size of a filter for 3,000 CFM as 100 to 1,000 ft.<sup>3</sup>. This is high for use on a mining machine but not inconceivable for use on return airways and other locations remote from the coal face.

## EQUIPMENT COSTS

Equipment and operating costs for a variety of particle collection systems have been presented by Stairmand (2), Sargent based on Stairmand (1), and NAPCA (9). These data are for the cases of air pollution control in above-ground industrial applications. Operating and installation costs may differ somewhat from those which would be encountered underground but they will indicate the approximate magnitude and relative costs for various collectors.

Table 2 is taken from the NAPCA report on "Control Techniques for Particulate Air Pollutants" (9) and illustrates some basic collector costs and their variation with size. Table 3 is a summary of data from NAPCA (9) and Sargent based on Stairmand's data (1). It illustrates the purchase costs for dust collectors only and the annualized costs for several types of systems for 5,000 CFM. Costs for other system air capacities (say, 2,000 to 10,000 CFM) may be roughly estimated on a constant cost/CFM basis. Note that materials of construction are a very important factor.

## COLLECTION EFFICIENCY REQUIREMENT

In order to design dust collection equipment for coal mine dust, i.e., to determine whether the characteristics of the equipment are suitable, it is necessary to know the size distribution of the dust in the respirable range. From this, one can compute the performance requirement in some standardized form which will allow rapid and accurate comparisons of various types of collection equipment. To determine this performance requirement one must:

TABLE 2

Approximate Cost of Wet Collectors in 1965

<u>Type of Collector<sup>a</sup></u>	<u>Cost, dollars/cfm capacity, cfm</u>			
	<u>1,000</u>	<u>5,000</u>	<u>20,000</u>	<u>40,000</u>
Cyclonic: <sup>b,c</sup>				
Small diameter multiples	0.50	0.30	0.20	0.20
Single chamber, constant water level	1.40	0.45	0.35	0.25
Single chamber, multiple stage, overhead line pressure water feed	0.95	0.40	0.25	0.20
Single chamber, internal nozzle spray	3.00	1.50	1.00	0.75
Self-induced spray <sup>b,c,d</sup>	0.80	0.40	0.25	0.25
Wet impingement <sup>b,c</sup>	1.00	0.50	0.25	0.25
Venturi <sup>c,d</sup>	3.00	1.50	1.20	0.50
Variable pressure drop inertial <sup>c,d</sup>	1.00	--	--	0.30
Mechanical <sup>c,d</sup>	1.75	0.75	0.35	--

<sup>a</sup>Basic designs, mild steel construction.

<sup>b</sup>Add 30 to 40 percent to base price for fan, drive, and motor (standard construction materials).

<sup>c</sup>Special materials construction costs for 1,000 to 40,000 cfm range units are approximately as follows:

  Rubber lining. base increase of 65 to 115 percent  
  Type 304 stainless steel. base increase of 30 to 60 percent  
  Type 316 stainless steel. base increase of 45 to 100 percent

<sup>d</sup>Add from 10 to 40 percent to base price per additional stage as in some cyclonic and wet impingement designs.

TABLE 3

Control Equipment Costs for 5,000 CFM

<u>Equipment</u>	<u>Cost Only (Purchased) (\$)</u>	<u>Installed Cost (\$)</u>	<u>¢/Yr-CFM Based On 60,000 CFM (Sargent)</u>	<u>¢/yr-CFM (NAPCA)</u>	<u>Annual Costs (\$)</u>
Filter, Intermittent Cleaning	4,000		47	38	1,900
Filter, continuous cleaning	6,000		50	26	1,300
Venturi - #316 SS	6,000		71-91	48-106	2,400-10" 5,300-40"
Venturi - #304 SS & Concrete lined Sep.	5,800		71-91	48-106	2,400-10" 5,300-40"
Venturi - #304 SS mild Steel	3,700		71-91	48-106	2,400-10" 5,300-40"
Packed Tower	5,700			30	1,500
Wet collectors, Low efficiency (75%)	2,00	4,00		30	1,500
Wet collectors, Med efficiency (90%)	3,500	7,000		50	2,500
Wet collectors, Hi-efficiency (99%)	3,500	12,000		160	8,000
Dry centrifugal, low efficiency (50%)	1,000	1,600	9	11	550
Dry centrifugal, Med efficiency (70%)	1,900	2,600	10	14	700
Dry centrifugal, Hi-efficiency (95%)	2,700	4,200	16	17	850



1. Define a representative size distribution for dust generated by continuous mining machines.
2. Relate number (or count) size distribution to mass distribution if available data on number distribution are to be used.
3. Compute the size distribution of the respirable fraction which would be sampled by a personal (AEC) type sampler, given the collection efficiency of the pre-classifier and the size distribution of the total dust population entering the pre-classifier.
4. Compute the "50% cut diameter" required by dust collectors operating on the inertial impaction principle.

The three main sources of data on dust from continuous coal mining operations were the Bureau of Mines (11), publications of E.J. Baier (12), and samples taken by the authors as part of this investigation. The data provided by the Bureau of Mines show mass concentrations of respirable and total (gross) dust fractions and were used to check against Baier's data, which are on a count basis. One can convert size by count to size by mass for a logarithmic normal size distribution by use of the relationship:

$$\ln X_g = \ln X'_g - 3 \ln^2 \sigma_g \quad (8)$$

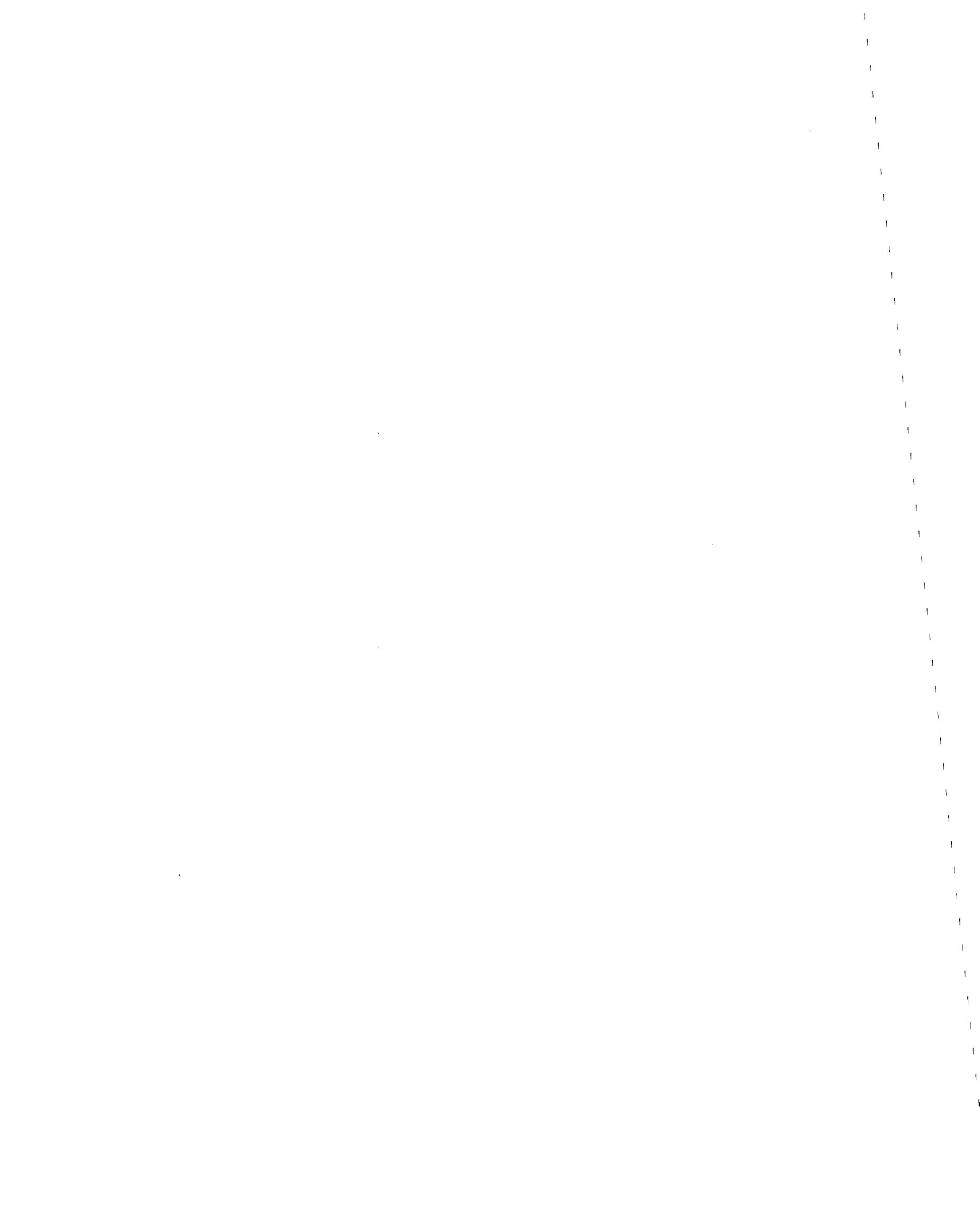
where:

$X_g$  = count mean diameter

$X'_g$  = mass mean diameter

$\sigma_g$  = geometric standard deviation

If one takes Baier's median size of 1.6 micron and standard deviation of 3.3, the resulting mass mean diameter would be 115 microns. This would indicate that the fraction smaller than three microns should be about .01% of the total. The calculated mass mean diameter is very sensitive to  $\sigma_g$  and would be 16 microns if  $\sigma_g$  were 2.4 instead of 3.3. Because other investigators (11) have indicated  $\sigma_g$  around 2.6, one suspects the value of 3.3 is too high. Also, the Bureau of Mines data show that 2 to 50% of the gross dust is in the respirable range, and data taken by the authors suggest that 5 to 10% of the gross dust is in the respirable range.



For purposes of estimation, it was therefore decided to use  $\sigma_g = 3.0$  and to place more confidence in the mass fraction data. Thus, a mass mean diameter of 15 microns was used since, as shown in Figure 6, this gives a fraction below three microns of seven percent of the gross, which is in accord with the Bureau of Mines data. This is also a conservative approach since the particle size is taken to be smaller than indicated by converted number distribution.

Taking the AEC collection efficiency data (Figure 7) for the cyclone pre-classifier as correct, one can compute the size distribution of dust in the respirable range (i.e., on the after filter). The size distribution of the respirable fraction, as computed (see Tables 4 and 5) and shown in Figure 6, may be approximately described as  $X'_g = 2.55$  micron,  $\sigma_g = 1.7$ .

Now that the approximate size distribution of the respirable fraction is known, it is possible to compute the overall collection efficiency (or penetration) of this fraction, given the performance characteristics of a dust collector. It would be more convenient, however, if one could, in a simple way, specify the required performance in order to get a desired reduction in respirable dust. This can be done by characterizing the penetration functions for the various types of collectors by their functional groups as follows:

	<u>Collector Mechanism</u>	<u>Equation Based On</u>	<u>Characteristic Functional Group</u>
1.	Impingement scrubbers and impaction on cylinders.	4	$(\frac{D_p^2}{D_p^2 - C_1})^2$
2.	Packed beds.	3	$\exp(-C_2 D_p^2)$
3.	Cyclones	1	$(1 - (D_p/C_3)^2)^{1/2}$
4.	Venturi scrubbers	5	$\exp(-C_4 (\frac{D_p^2}{D_p^2 - C'_4})^2)$

where:

$D_p$  is the particle diameter, and the C's are characteristic constants. For each of these mechanisms it is possible to determine the total penetration of a dust of known distribution by calculating the integral:

$$P = \int_0^{\infty} P_t(D_p) f(D_p) dD_p \quad (9)$$

FIGURE 6

SIZE DISTRIBUTIONS OF GROSS DUST AND RESPIRABLE FRACTION

$X_g$  = COUNT MEAN DIAMETER  
 $X_g'$  = MASS MEAN DIAMETER  
 $\sigma_g$  = GEOMETRIC STANDARD DEVIATION

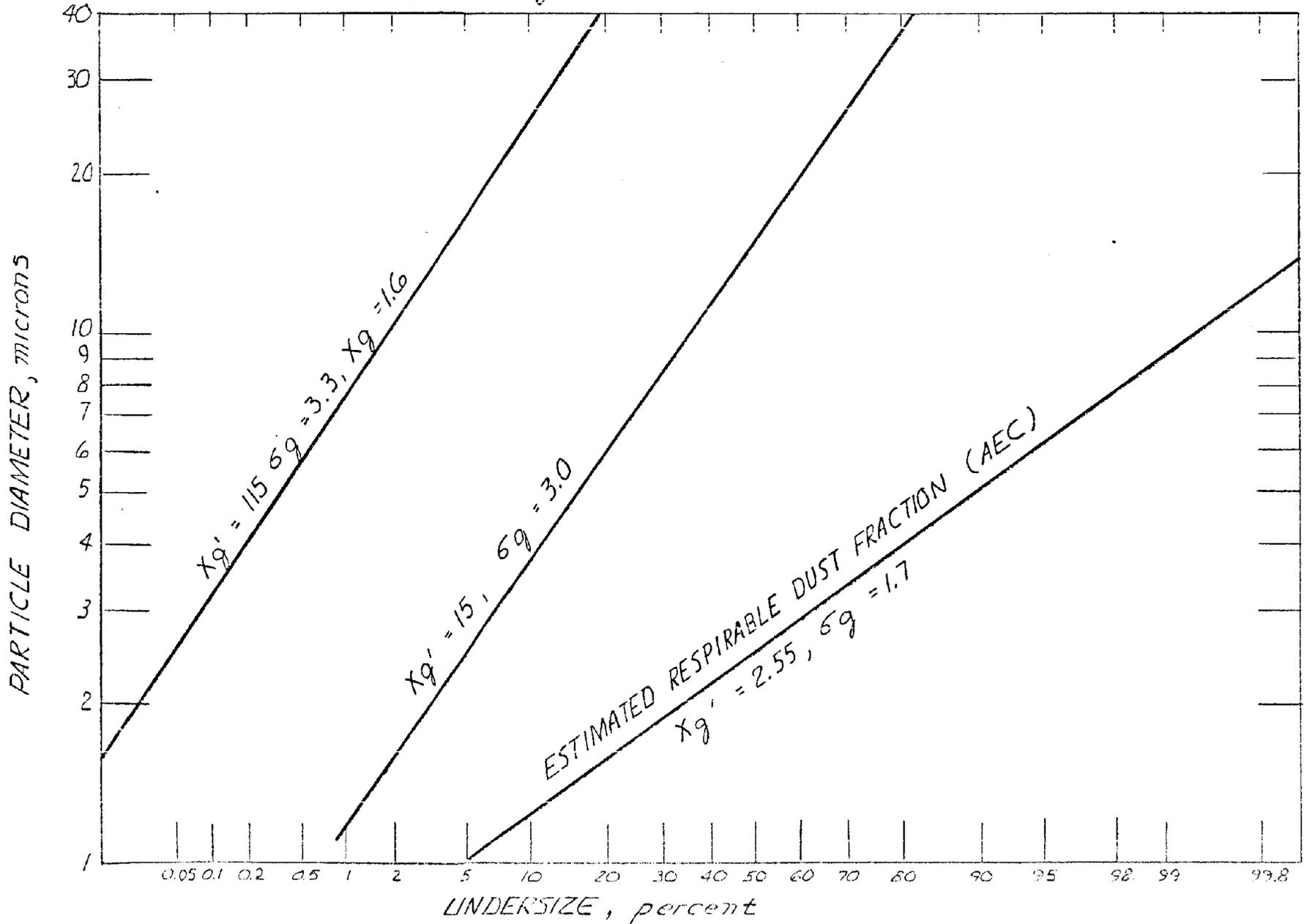


FIGURE 7  
COMPARISON OF RECOMMENDED RESPIRABLE SIZE CRITERIA WITH PULMONARY DEPOSITION CURVE

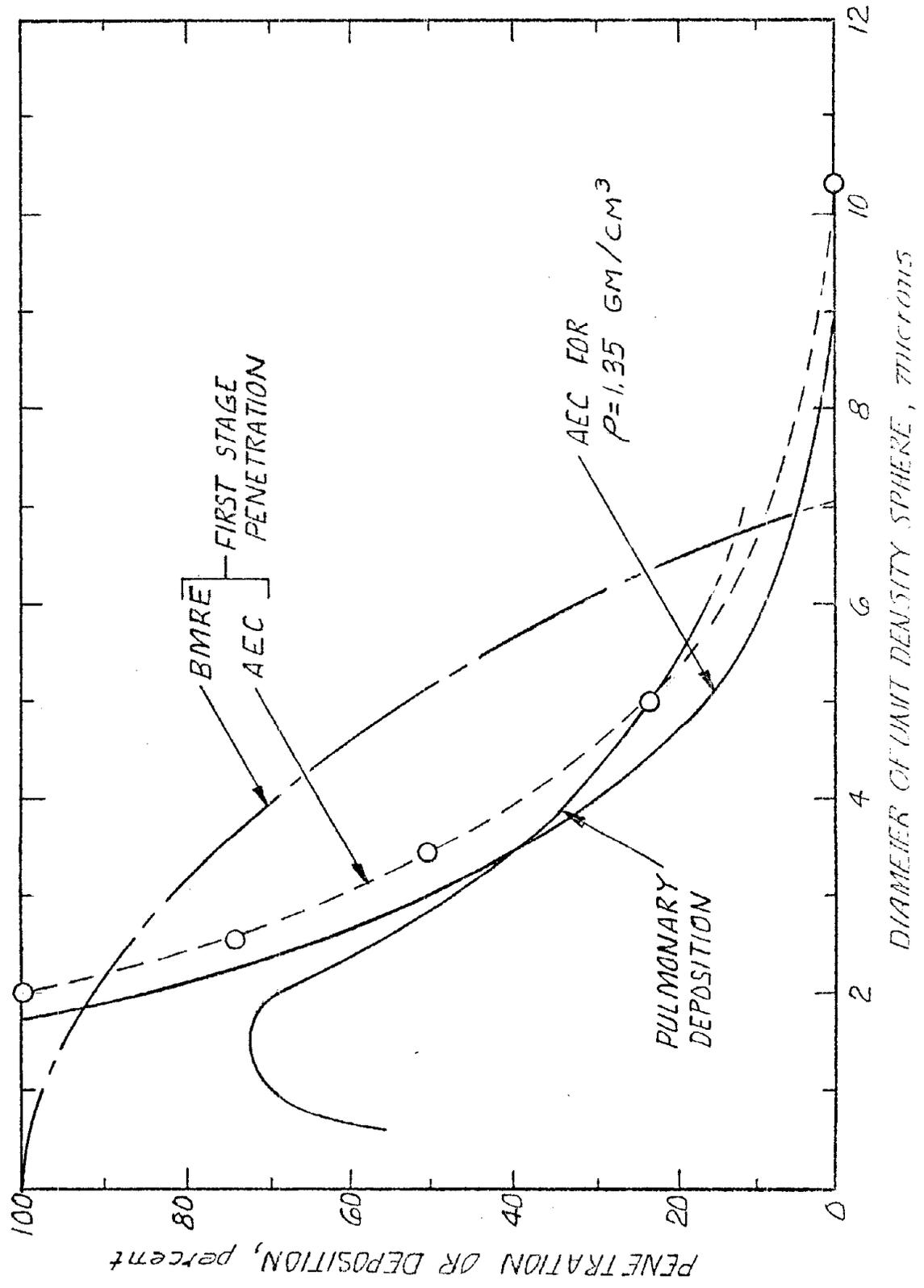


TABLE 4

AEC Cyclone Efficiency

<u>D<sub>p</sub></u> <u>(microns)</u>	<u>Penetration</u> <u>(%)</u>
1.8	100
3.0	52
4.0	30
6.0	9
9.0	0

TABLE 5

Size Distribution of Respirable Dust Fraction (AEC)

<u>D<sub>p</sub></u> <u>(Microns)</u>	<u>Undersize</u> <u>(%)</u>
2.0	31.8
3.7	75.5
4.9	88.5
6.1	94.5
7.3	97.2
10.0	100.0

where  $P(D_c)$  is the penetration function for the collector and  $f(D_c^t)$  is the dust size distribution. In this case it is of interest to determine the penetration of the estimated respirable dust as a function of the "cut diameter",  $d_c$ , or the diameter for which the penetration is 50%. The integral in equation 9 was calculated for the first three mechanisms shown above for values of  $d_c$  from 0 to 2.5 microns, and the results are plotted in Figure 8.

For venturi scrubbers the situation is somewhat more complicated because the venturi mechanism is dependent upon two constants:  $C_4$ , which reflects the liquid rate, and  $C_4'$ , which reflects the throat velocity. Thus, equation 9 was evaluated for several combinations of throat velocity and liquid rate, and the results are plotted in Figure 9.

The AEC respirable dust loading has been estimated at from 5 to 10 mg/m<sup>3</sup>. Respirable dust control legislation, however, is based on the MRE sampler, which has been shown to measure a respirable dust loading different than the AEC determination (13, 14). The relationship between the AEC and MRE samples is:

$$\text{MRE} = 1.63 \times \text{AEC} + .67 \quad (10)$$

Thus, the MRE limit of 3 mg/m<sup>3</sup> would translate to a concentration of 1.43 mg/m<sup>3</sup> as measured by the AEC, and will soon become 0.81 mg/m<sup>3</sup> when the MRE limit is reduced to 2 mg/m<sup>3</sup>. If the maximum AEC respirable loading in air from the coal face is estimated conservatively at 10 mg/m<sup>3</sup>, then the respirable dust penetration must be 8% or less. As can be seen from Figure 8, the cut diameters for this penetration range from 0.65 to 1.35 microns, and the venturi scrubber operating conditions vary from 12 gal./mcf at a throat velocity of 140 ft./sec. to 7 gal./mcf at a throat velocity of 350 ft./sec.

Thus, it is possible to rapidly determine the applicability of a given collector to the coal mine dust problem by comparing its cut diameter to the cut diameter in Figure 8, or, in the case of the venturi scrubber, by comparing its operating conditions to those shown in Figure 9.

#### SELECTION OF TEST EQUIPMENT

It was not possible or necessary to test all of the potentially available dust collection equipment within the time and budget limitations of this investigation. The philosophy of the experimental program was to investigate and characterize

FIGURE 8

AEC RESPIRABLE DUST PENETRATION  
VS CUT DIAMETER

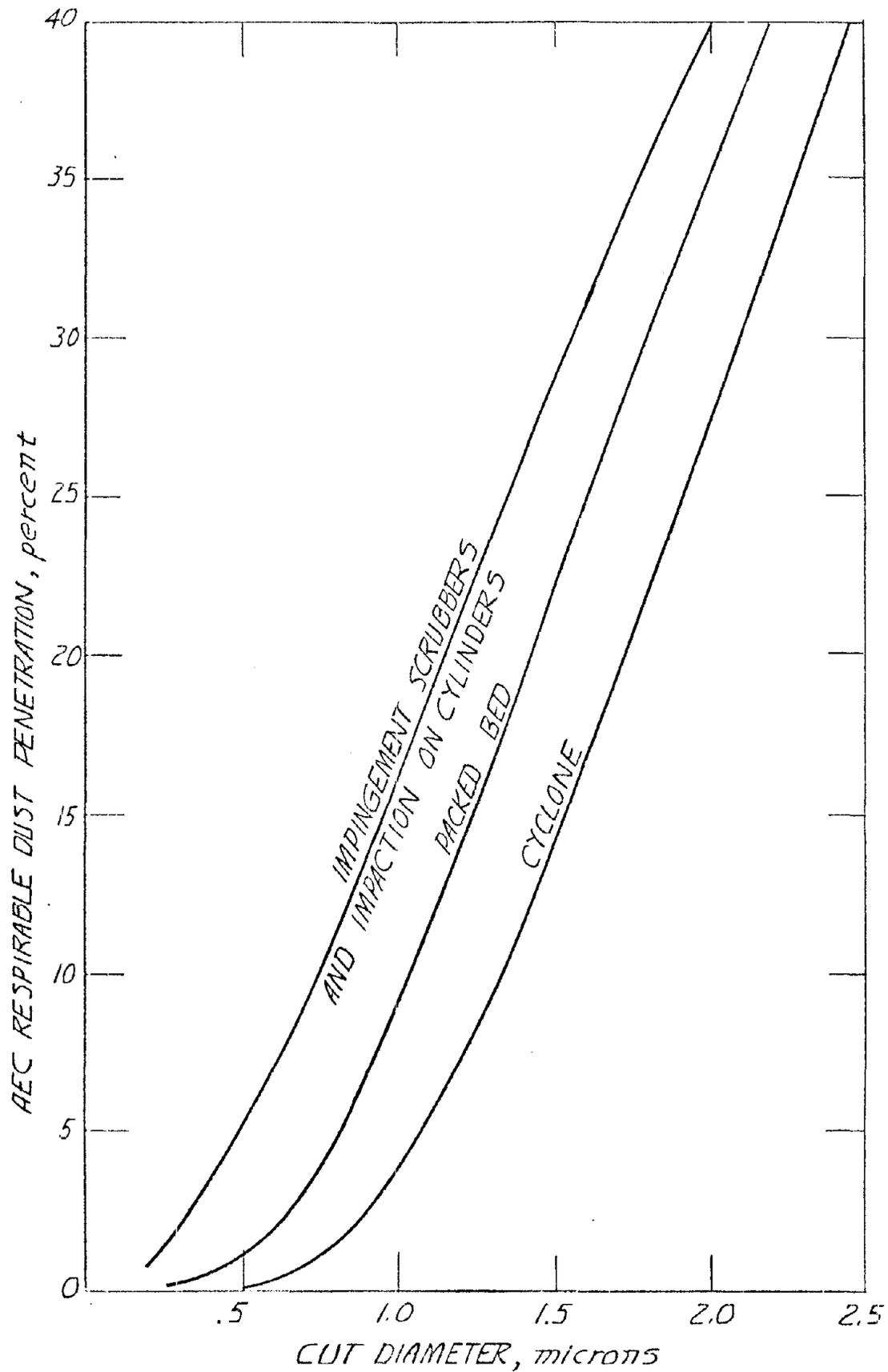
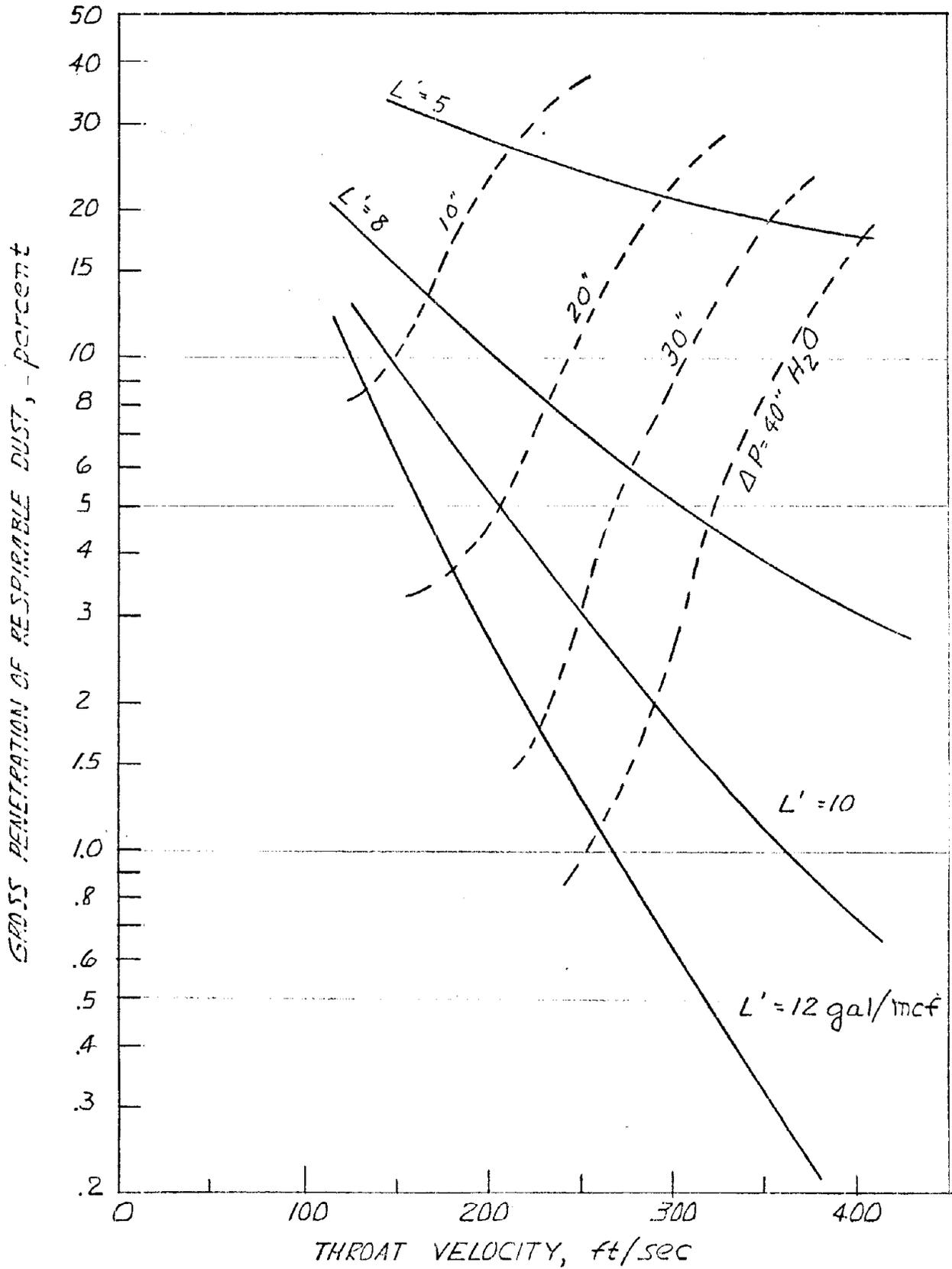


FIGURE 9

TOTAL PENETRATION OF ESTIMATED  
RESPIRABLE DUST FOR COMBINATIONS OF  
AIR VELOCITY AND LIQUID RATE





the basic dust collection mechanisms that might be applicable to the coal mine dust problem. This philosophy was, however, manifested in two ways. Tests were conducted on units for which the mechanisms were not immediately obvious in order to determine what the mechanisms were or, where this was not possible, to characterize them empirically. In other cases, tests were conducted on units operating according to known mechanisms in order to confirm that conventional theory could explain the experimentally determined results.

In all cases the objective was to characterize the unit or mechanism quickly with a minimum number of experiments. Thus, a unit was tested several times at the manufacturer's recommended operating conditions. If the results were reproducible and consistent with generally accepted theory, the collector was considered to be sufficiently understood for the purposes of this investigation.

In the first week of the program, letters were written to essentially all major manufacturers of dust collection equipment. These letters explained the nature of the investigation and requested that the manufacturer reply if he felt that he had a collector that would be applicable to the respirable coal mine dust problem.

Of 35 companies contacted, 12 expressed no interest immediately or did not reply. Follow-up letters were written to those that did not reply, but these letters did not generate any significant responses. Of the 23 positive replies received, there were nine offers of low energy wet dynamic scrubbers, seven offers of high energy venturi or ejector scrubbers, five offers of fabric filters and two offers of cyclones. It should be noted at this point that electrostatic precipitators were considered independently of this survey. It was felt in general that electrostatic precipitators would be unsafe in the coal mine environment, and this opinion was reinforced by contacts with manufacturers.

Of the nine wet dynamic types offered, five were considered to be essentially spray and baffle arrangements. These units were not considered further because they did not appear to provide a large enough impaction parameter for a cut diameter of about one micron or less. The remaining four units were a "wetted screen" scrubber, an "Air Tumbler", an impingement scrubber and a packed bed. Arrangements were made to test the first three of these units: the "wetted screen" because of its compact physical arrangement and interesting mechanism, the "Air Tumbler" because its mechanism was not immediately apparent from inspection of the literature, and the impingement scrubber because it represented a classical

configuration. It was decided to fabricate a packed bed in-house rather than rent the unit offered. The homemade unit was inexpensive and increased the flexibility of the testing schedule since it was available for use as a fill-in when other units were not available.

Of the seven high energy venturi and ejector scrubbers offered, arrangements were made to test two - the "Ventri-Rod" and "Ventri-Sphere" scrubbers because the effects of the rod and sphere parts of the respective mechanisms were not immediately apparent. A third venturi was fabricated inhouse to demonstrate the basic venturi mechanism. The other venturis offered were not considered to have substantially unique features worthy of experimental evaluation. The two ejector scrubbers offered were not tested because they are described by the same mechanism as the venturi, they require a very high water pressure, and one manufacturer felt that they were unsuitable for this application.

None of the five fabric filters offered were tested. First, it was felt that there was no doubt that fabric filters could achieve the desired level of efficiency. Second, it was felt that filters would require too much space to be applicable in the confined environment near a continuous miner. A 3,000 cfm air filter would require a volume of approximately 240 cubic feet, which is more space than could reasonably be made available. Third, the important questions about cloth filter operation concern cloth cleanability and life and the determination of these and related factors will require very extensive tests.

In general, it was felt that a dry cyclone could probably not achieve a high enough level of efficiency, but arrangements were made to test one multiple cyclone in order to confirm this opinion.

## PROCEDURES

### Description of Test Apparatus

To test the selected types of dust collection equipment described in the preceding section, a pilot plant scale test apparatus was designed and constructed. The pilot plant consisted of a dust feeder section, an air intake and mixing section, an upstream duct section, a downstream duct section, and a blower. An overhead schematic of the pilot plant area is shown in Figure 10. The pilot plant is shown in operation in Plates 1 and 2.

FIGURE 10  
OVERHEAD SCHEMATIC OF TEST AREA

(1/4 in. = 1 ft)

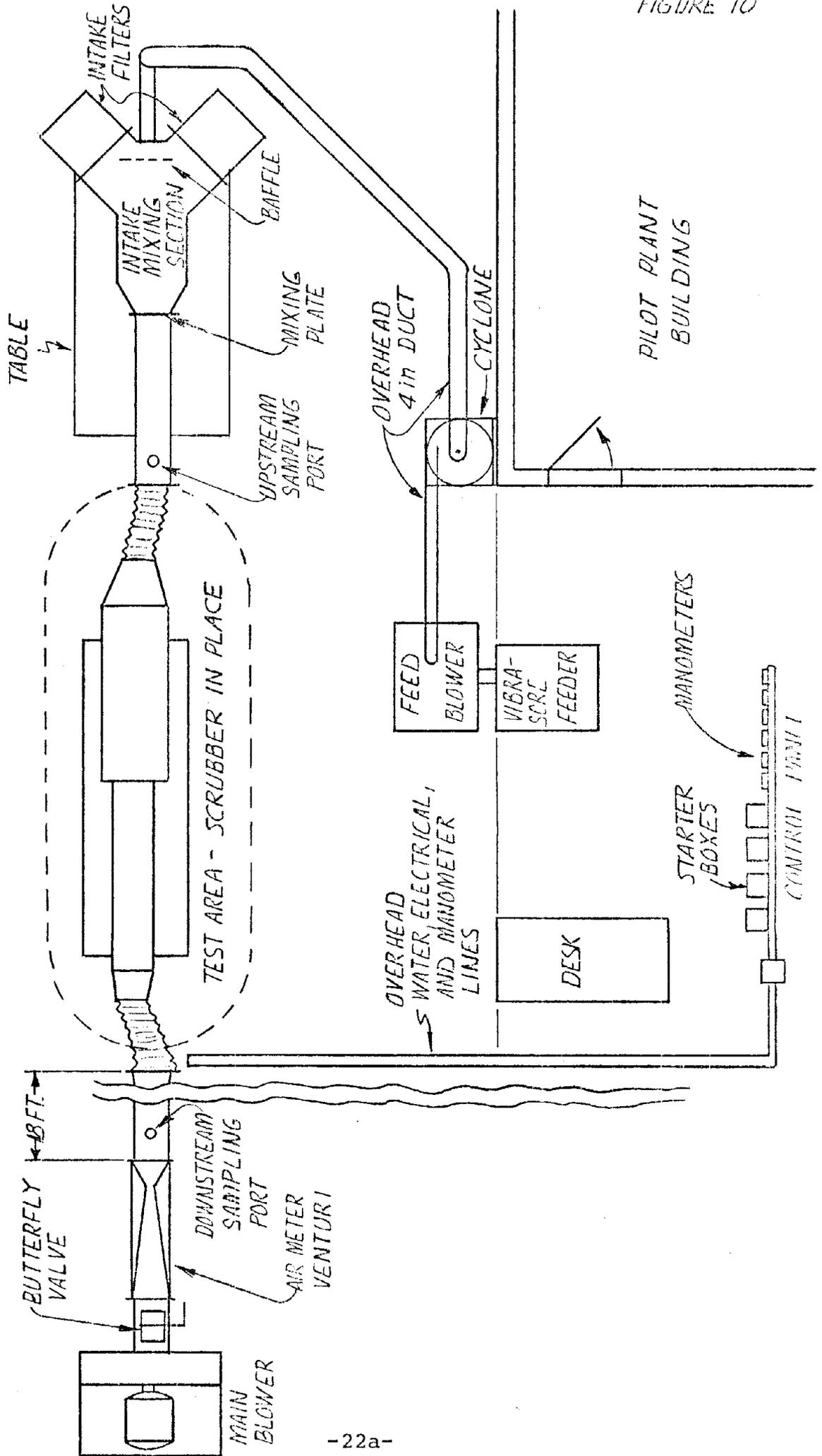
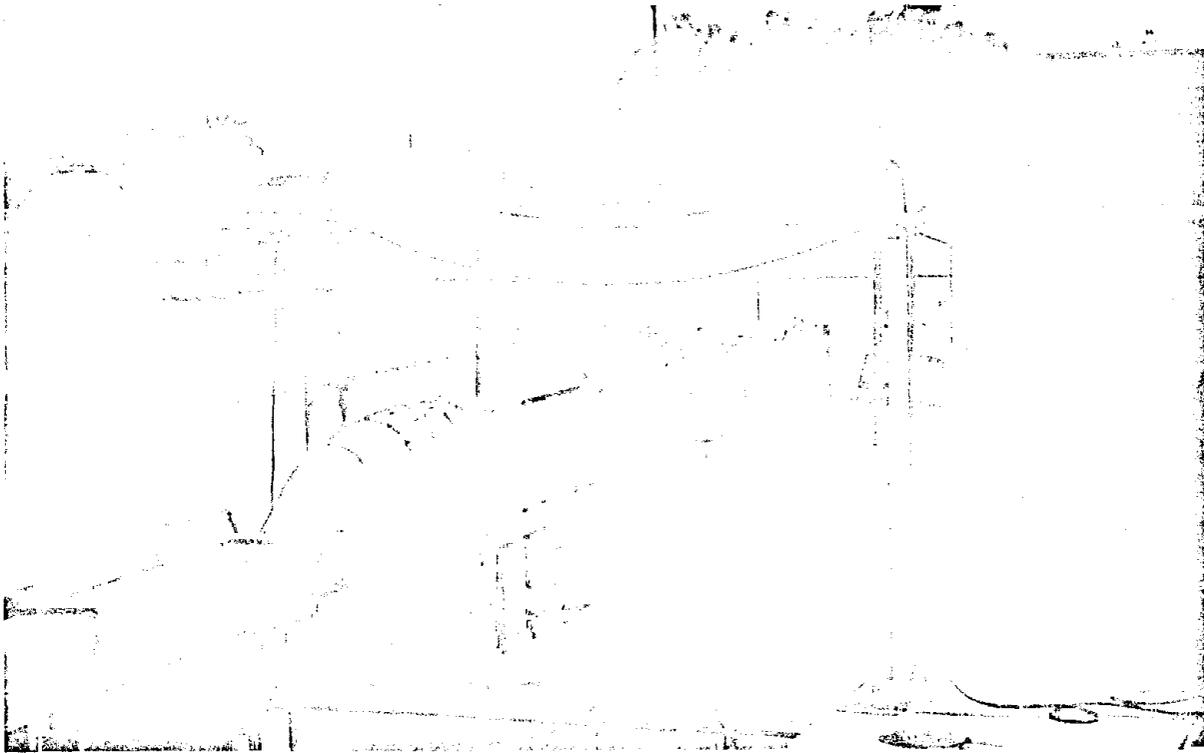
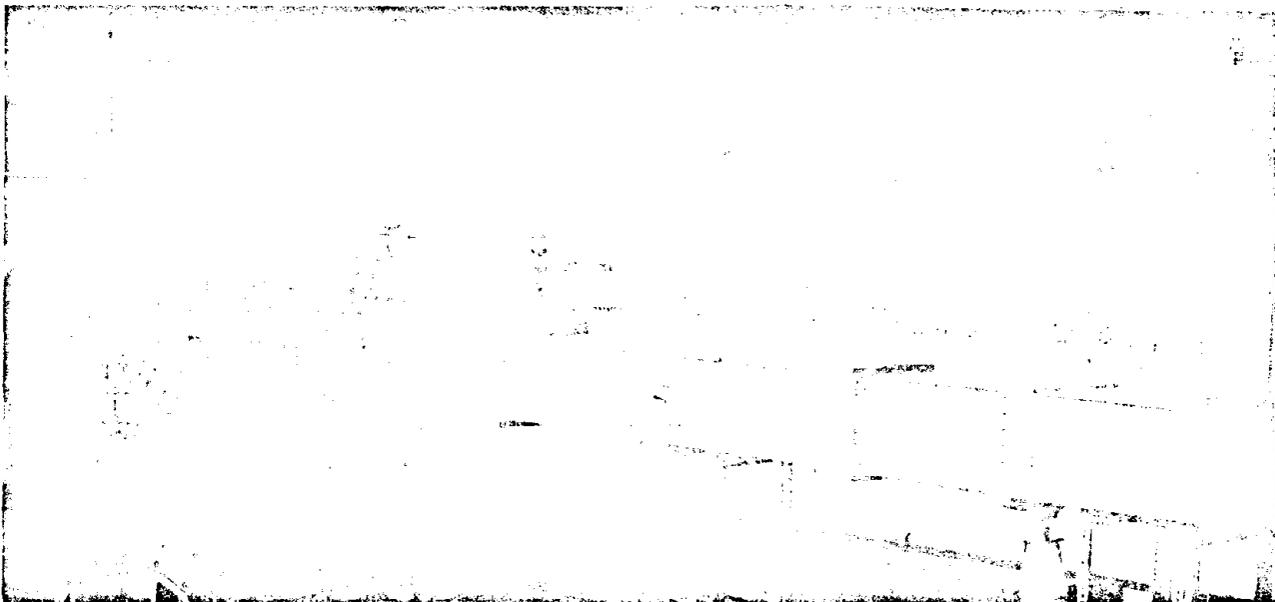


FIGURE 10

PLATE 1

Coal dust passes from the Vibrascrew feeder (right center) to the small blower (behind table) which blows it through the cyclone. The dust passes through the 4 in. overhead line to the air intake section (center). The "wetted screen" scrubber is shown during testing. The packed bed scrubber stands at the left.

PLATE 2

Downstream duct section during testing. The multiple cyclone is mounted inline at right center. The sampling pump and meter at the center are connected to a filter sample circuit, while the other pump and meter (center left) take a Andersen sample simultaneously from beneath the duct. The 3,000 cfm blower is shown at far left.

A schematic of the dust feeder section is shown in Figure 11. A standard Vibrascrew live bin feeder with a one-inch diameter screw, a three cubic foot hopper, and a one-third horsepower motor with a variable speed transmission and a 10:1 turndown ratio, was used to meter the coal into the dust feeder system. The feeder has a capacity of 100 to 1,000 grams per minute of coal. The dust was fed into the inlet of a five horsepower 700 cfm blower and the blower exhaust conveyed to a cyclone by a four inch diameter galvanized steel duct. The duct contained a two inch diameter venturi throat, and a water manometer was connected at the throat so that the flow rate could be determined. The flow rate could be regulated by means of a damper immediately upstream from the blower.

The cyclone was designed to eliminate all dust larger than 10 microns so that the equipment tests could be conducted on dust in the respirable range. The undersize from the cyclone typically proved to be 98% less than five microns. A schematic of this cyclone is shown in Figure 12. The oversize dust was collected in a 20 gallon drum mounted below the cyclone, and the undersize dust was conveyed out of the top of the cyclone by a four inch diameter galvanized duct section.

This concentrated dust stream was diluted into air intake section as shown in Figure 10. The dust stream itself was approximately 150 cfm, while the overall air intake stream ranged from 1,500 to 3,000 cfm. The intake section consisted of two foot square Cambridge Aerosolve filters, which had a 97% efficiency on atmospheric dust and an 85% efficiency on 0.3 micron smoke. These filters were mounted at a 45° angle to the center line of the duct on either side of the four inch dust inlet duct. The mixing section itself was two foot square, and a one foot square baffle was mounted inside the section perpendicular to and six inches out from the dust inlet. This baffle served to mix the dust stream into the overall air stream.

The two-foot square mixing section was reduced to a one-foot square section and adapted to the one-foot square upstream duct by means of a one-inch angle iron flange. A mixing plate, consisting of 1.25 in. holes on 1.5 in. centers, was mounted between the intake mixing section and the upstream duct. All of the duct sections were constructed of 1/16 in. galvanized steel and connected by one-inch angle iron flanges. One four-foot, one five-foot, and three six-foot duct sections were fabricated with interchangeable flanges.

FIGURE II

COAL DUST FEEDER SYSTEM

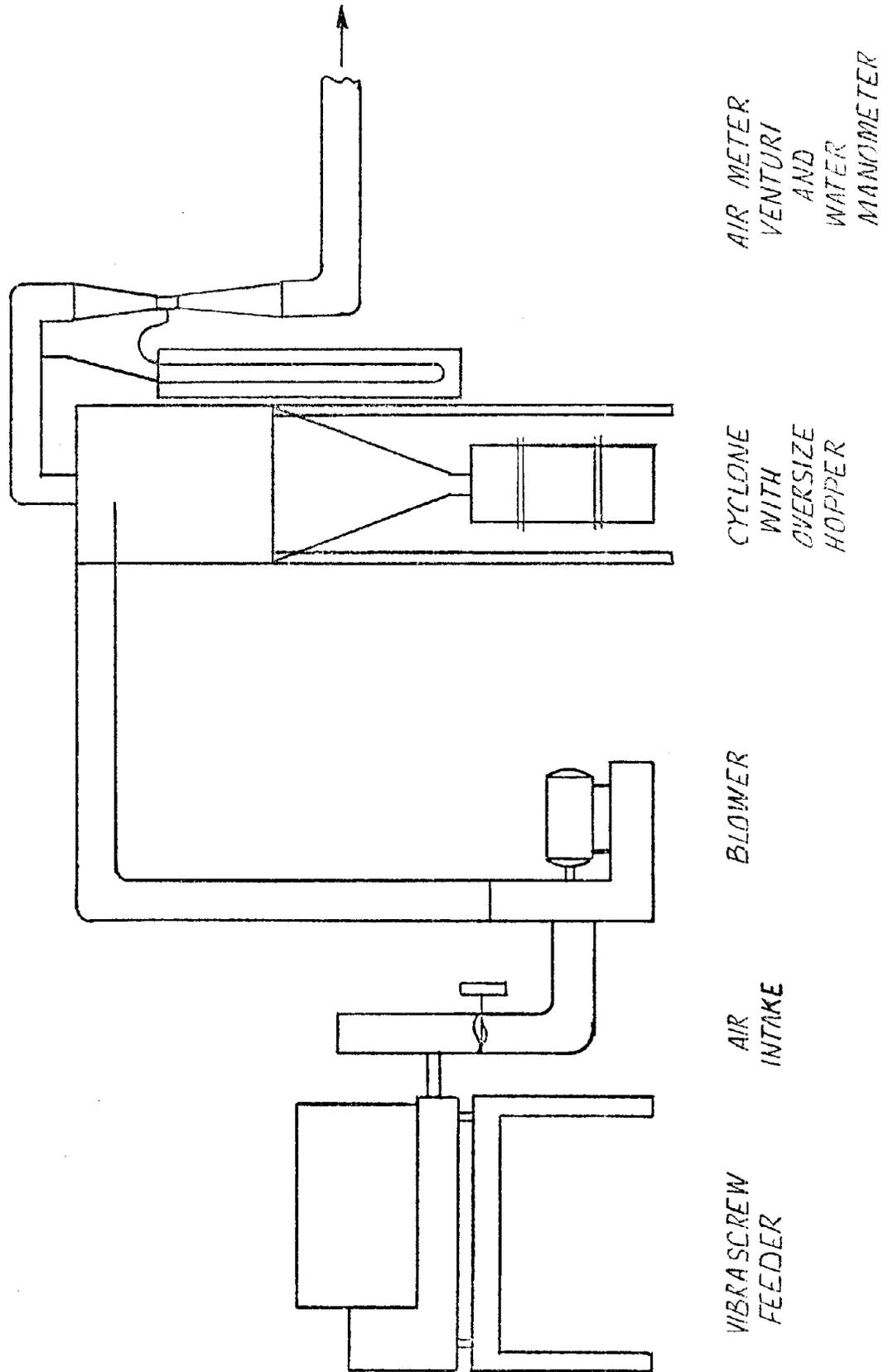
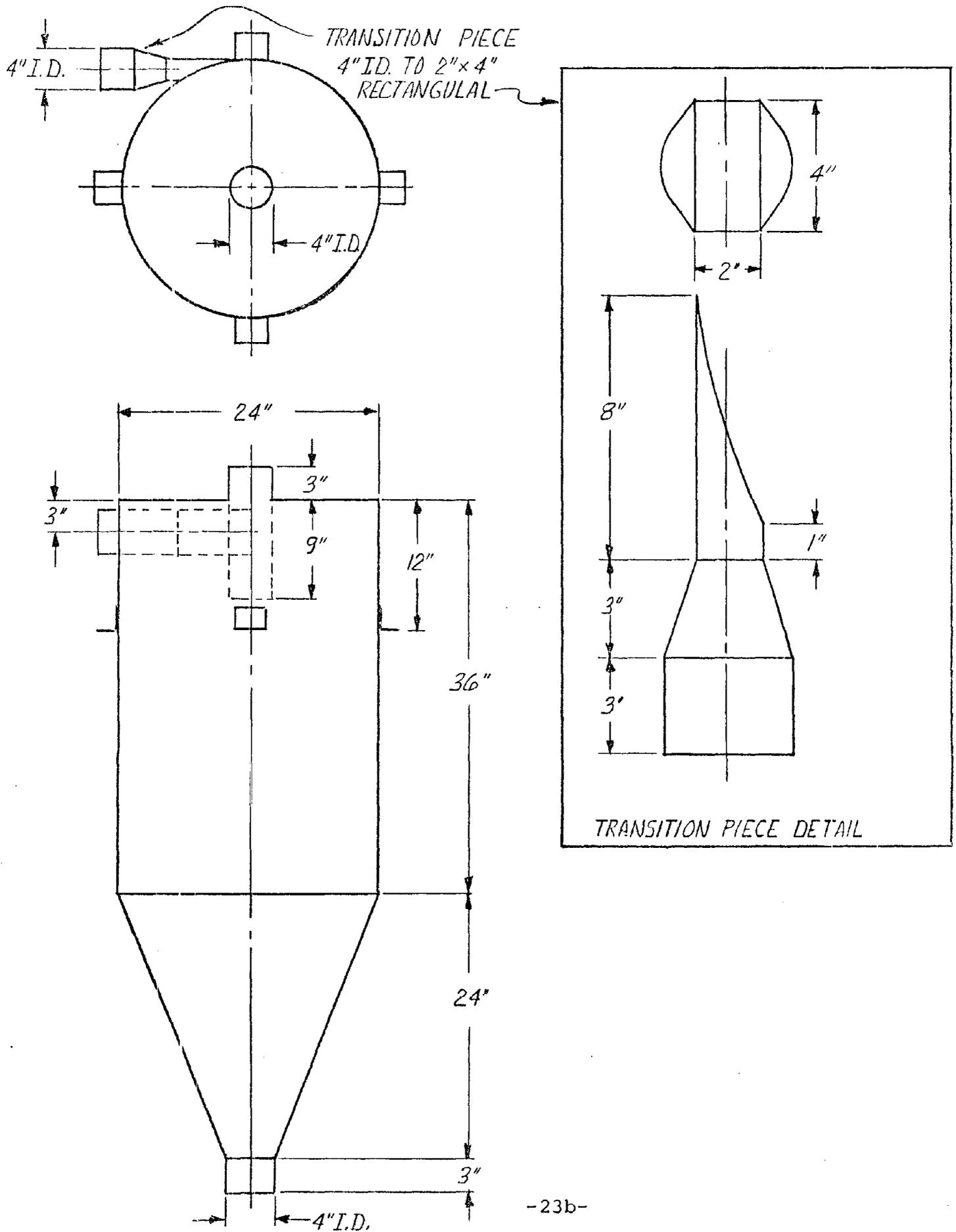


FIGURE 12  
DUST FEEDER CYCLONE



It was thus possible to rapidly rearrange the pilot plant configuration in any manner necessary to accommodate particular pieces of equipment. The rigid ducts were connected to each individual scrubber with sections of 12 in. diameter galvanized duct, 12 in. diameter flexible air hose, and 12 in. diameter galvanized adjustable elbows. The 12 in. diameter duct was adapted to each individual scrubber with adapters constructed of 1/16 in. galvanized steel, which were especially fabricated for each scrubber tested.

The main blower had a throughput of 3,000 cfm at -54 in. water gauge, and was driven by a 40 hp, 3,500 rpm motor. A damper immediately in front of the blower allowed regulation of the air rate, and a venturi section immediately in front of the blower allowed the operator to observe the pressure drop across the venturi section and subsequently adjust the system to the desired air rate.

A 50 gpm water supply was provided at the test site and a direct readout water rotameter was used to determine the water flow to the scrubber being tested.

The electrical controls and the water rotameter were mounted on a 4 ft. x 8 ft. plywood panel, which was supported by an angle iron frame. Six water manometers were also mounted on this panel, and lines from them were run overhead on stanchions to the test equipment as required.

### Analytical Techniques

The objective of the experimental investigation was to determine what types of dust collection equipment might be applicable to respirable coal mine dust. In other words, it was necessary to determine whether or not a given collector could reduce the concentration of respirable dust, previously estimated as having a mean diameter of 2.55 microns and a standard deviation of 1.7, to below the prescribed maximum concentration of two milligrams per cubic meter (MRE).

It has already been shown that, in order to reduce the concentration to this level, it is necessary for the total, or gross, penetration of the respirable dust on the collector to be 8%. The gross penetration can be expressed as:

$$P = \int_0^{\infty} P(D_p) f(D_p) dD_p$$

where  $P(D_p)$  is the fractional penetration as a function of particle  $D_p$  diameter,  $D_p$ , and  $f(D_p)$  is the logarithmic normal size distribution frequency of the respirable dust. Thus, if

the penetration function is known for a given collector or collector mechanism, it is possible to calculate the total penetration of a dust of known distribution.

Since this integral is rather cumbersome, a numerical integration computer program was written so that the effect of any given penetration function on any given size distribution of dust could be rapidly calculated. The actual size distribution of respirable mine dust is not well known at this time, and it would be difficult to reproduce this distribution in the laboratory even if it were well known. Therefore, this program proved to be extremely valuable for interpreting the relationship between experimental results and potential mine conditions.

### Coal Dust Source

At the beginning of this investigation, there was a great deal of concern that the collection efficiency of a given scrubber on coal dust might be dependent upon surface properties of the dust and that a given scrubber might therefore have a significantly different level of performance on different coal dusts. To determine the significance of this possibility, coal samples were obtained from several different sources so that different types of coal could be tried on each collector.

Coal samples were obtained from mines of the Island Creek Coal Company in Holden, West Virginia, Grundy, Virginia, and Madisonville, Ky. and from the U.S. Bureau of Mines in Bruceton, Pennsylvania. During the course of the investigation, each of these different coals was used in the pilot plant operation. Different coals generate different amounts of respirable dust and will therefore require different collector performances in order to meet the same output criteria. However, the only knowledge of a given dust necessary to determine the performance of a given collector on that dust is the loading and size distribution of the dust. As the experimental results will show, the collector performance is in all cases dependent only upon inertial factors and is independent of such variables as surface properties and composition of the coal. Therefore, from this point forward, no distinction will be made between the various types of coal tested.

The coal supply was stored in 55 gallon drums and was prepared for the coal dust feeder system in batches of approximately one-half barrel. The coal was first ground to -8 mesh in a model 250 Holmes mill and then ground to -60 mesh in a model 500 Holmes mill. The previously described coal dust feeder system was designed on the assumption that the

dust would be fed into the 700 cfm blower where the fan would reduce the dust even further in size, and that by regulating the blower air rate, the cut point of the cyclone could be regulated in a manner that would allow the operator to produce any desired coal dust distribution and loading.

A wide variety of operating conditions were tested in an effort to characterize the dust generation system, but no quantitative relationships were established. Different coals produced slightly different loadings and size distributions, but the loading and size distribution for a given coal proved to be reproducible from day to day. When operated at 150 cfm with 100 grams per minute of feed, anywhere from one to five grams per minute of coal was introduced into the main air system with the remainder of the coal being collected in the oversize hopper beneath the cyclone. At these operating conditions, the mean diameter of the coal dust coming into the system ranged from 1.3 to 1.7 microns and the standard deviation ranged from approximately 1.7 to 2.0. When the main air system was operated at 2,500 cfm, this concentration of dust from the feeder system produced a total concentration of from 10 to 70 milligrams per cubic meter of respirable dust.

Attempts were made to increase the mean diameter of the inlet dust by increasing the coal feed rate and decreasing the air rate to the cyclone in an effort to raise the cut point of the cyclone. In this manner the mean diameter was raised to approximately three microns, but the total rate of consumption of the coal supply was too high to make operating at these conditions practicable. Therefore, in all of the runs noted in the experimental results, the dust feed rate was 100 grams per minute and the air rate of the dust feeder system was 150 cfm.

#### Size Distribution Determination

Size distribution determinations were conducted with an Andersen sampler, a schematic of which is shown in Figure 13. The Andersen sampler works by impinging the air stream on a succession (cascade) of six stainless steel plates followed by a total filter. When operated at one cfm, the stages of the Andersen sampler have cut points as shown in Figure 13.

To take a sample with the Andersen sampler, the sampler was placed beneath the duct and the probe inserted into a port at the bottom of the duct as shown in Figure 14. A one inch diameter probe was used as suggested by the manufacturer, and a series of interchangeable tips were used with various inside diameters so that isokinetic samples could be taken at one cfm at various different overall duct air rates. A water

FIGURE 13

*SCHEMATIC OF THE ANDERSEN SAMPLER*

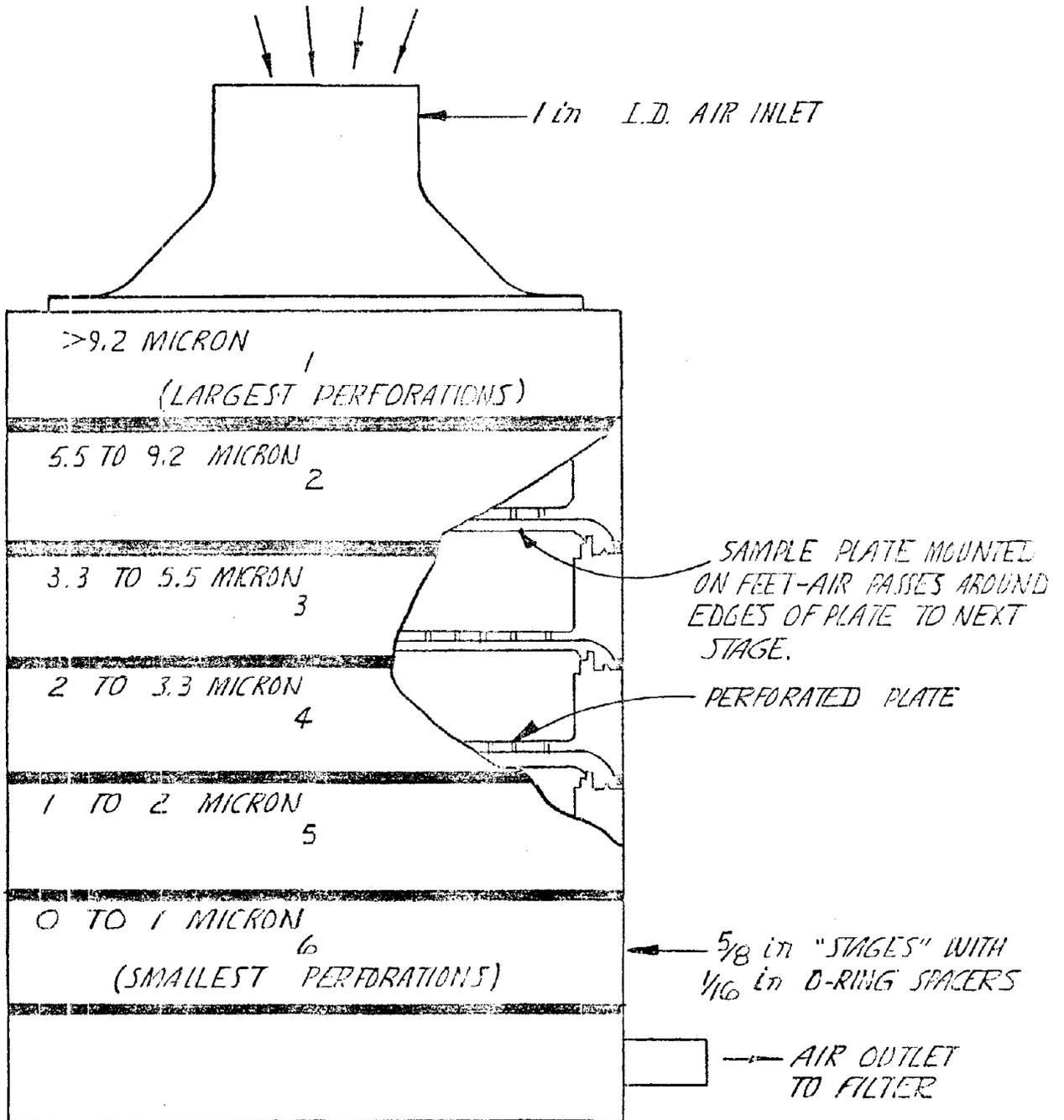
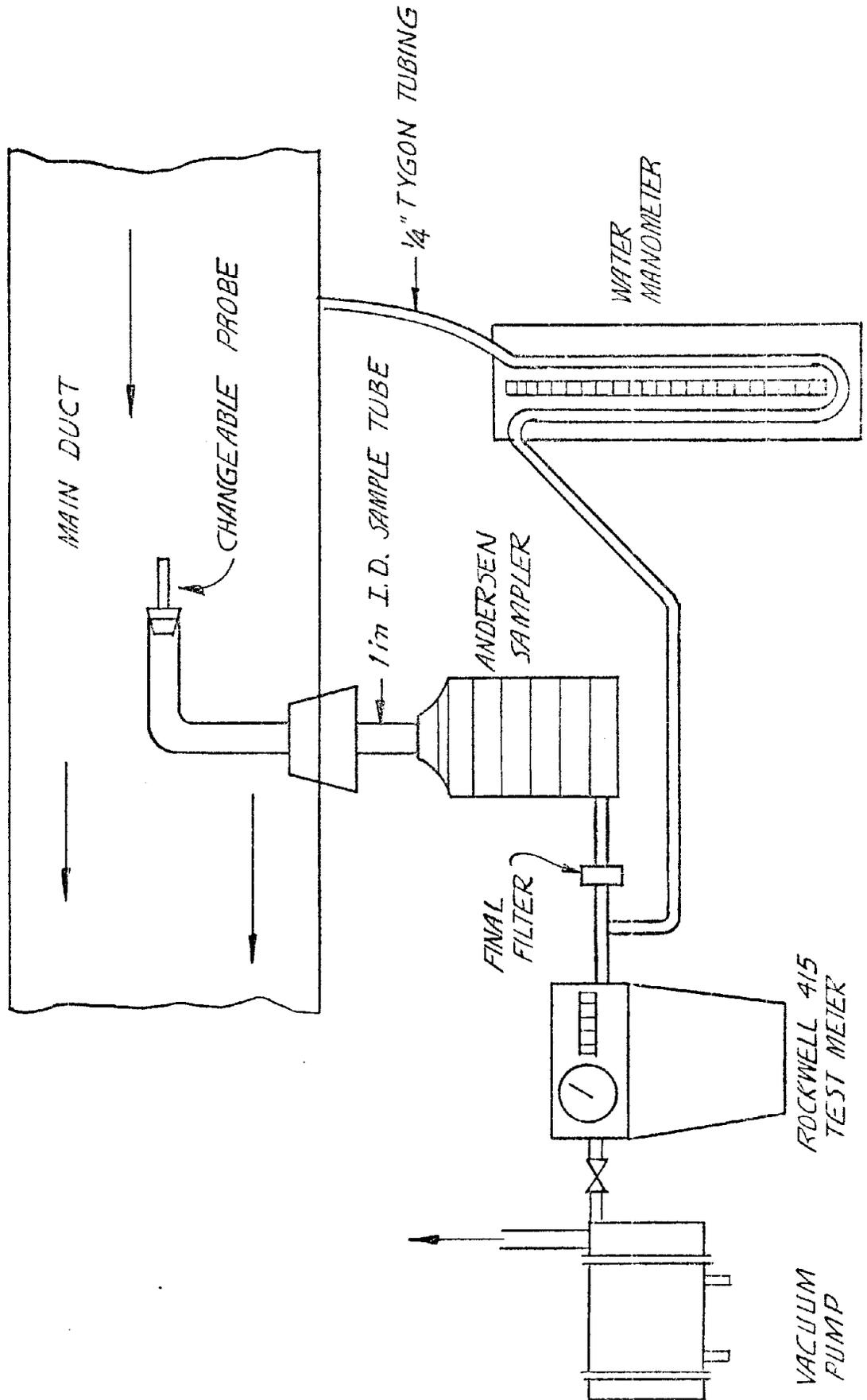


FIGURE 14  
ANDERSEN SAMPLER MOUNTED BELOW DUCT



manometer was connected between the main duct and the sample line at a point between the final filter and the air meter.

Before each sample was taken the velocity at the center line of the duct was measured with a pitot tube and recorded. After the sample was taken, the effective air rate at the meter was calculated and then corrected for the pressure drop across the Andersen sampler and the filter to the actual duct conditions. In all cases, the air rate was within plus or minus 10% of one cfm and the actual sampling velocity was within plus or minus 10% of the isokinetic velocity. The sampling bias for velocity ratios in this range and for particle diameters in this size range is less than three percent.

After the sample was taken each plate was weighed, and the total weight of the dust on the plates was divided by the total amount of air pulled through the sampling system corrected to standard conditions of one atmosphere and 60°F. The total dust concentration calculated in this manner can be compared to the total concentration as determined by filter samples described in the following section. Moreover, the upstream and downstream samples can be compared on a stage by stage basis to determine the penetration as a function of particle diameter. For example, the concentration determined from the fifth plate, or the one to two micron size range, of a sample taken on the downstream side of the collector can be divided by the concentration on the same plate on the upstream side of the collector to determine the penetration of particles in the one to two micron size range.

When this method of determining penetration as a function of particle diameter was first attempted, there was some concern that there might be a possible bias in the cut point that might develop as dust accumulated on the plates. Therefore, a set of experiments were run to determine the sensitivity of the Andersen sampler efficiency to dust loading on the plates.

A particle count was made from photomicrographs of a membrane filter sampler which was dispersed in oil and photographed at 400X and 1,000X. This count distribution was converted to a mass distribution using equation 8 and compared to that obtained by the gravimetric Andersen method for a sample taken simultaneously with the filter sample. The results are shown in Figure 15. Next, a 1.5 second Andersen sample was taken and the distribution was determined by counting the particles on each plate. This count distribution was converted to a mass distribution and is compared to the distribution obtained by the Andersen method in Figure 16. Both tests confirm the gravimetric Andersen method quite well.

FIGURE 15  
 INLET COAL DUST SIZE DISTRIBUTION BY GRAVIMETRIC ANDERSEN METHOD  
 AND DIRECT PARTICLE COUNT

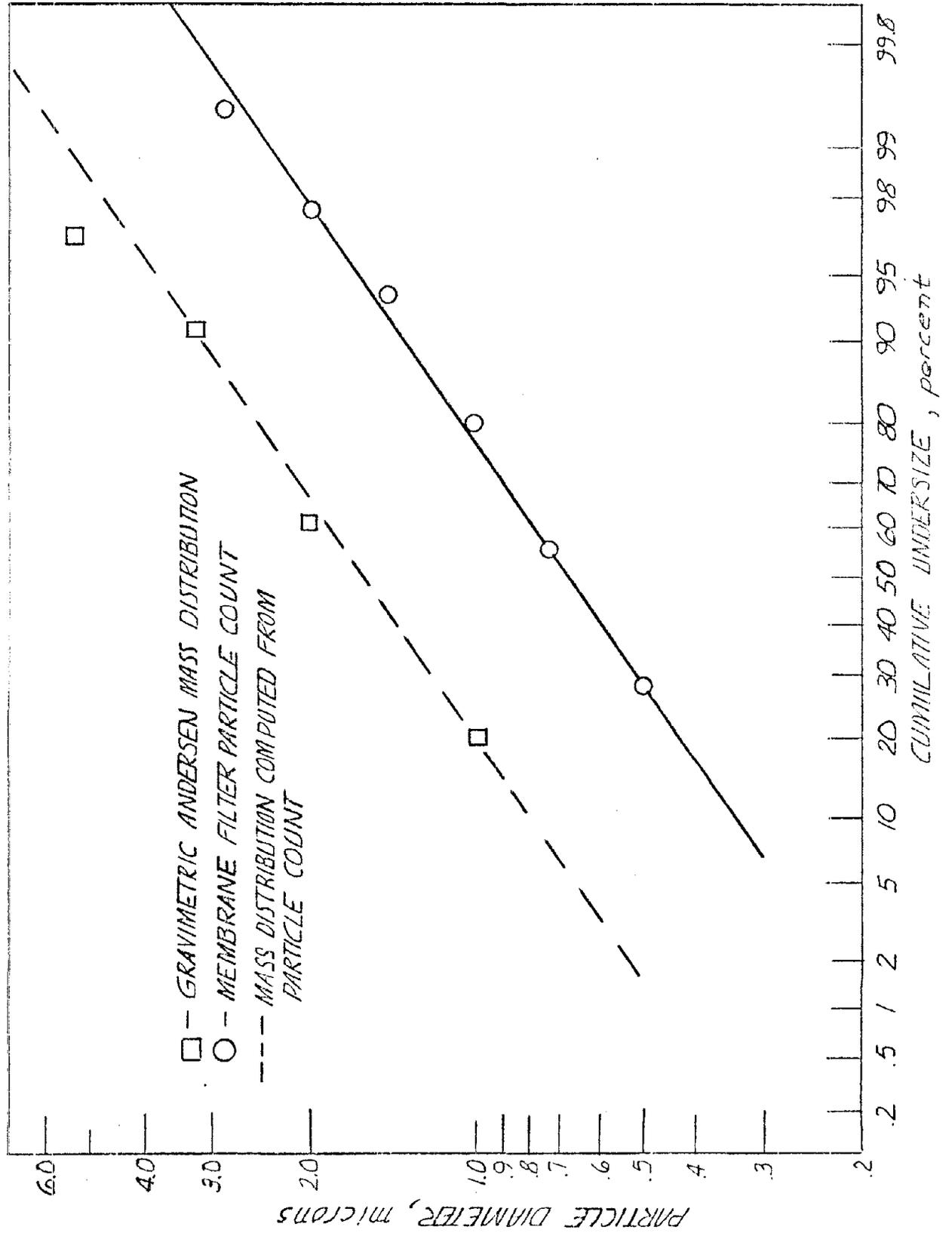
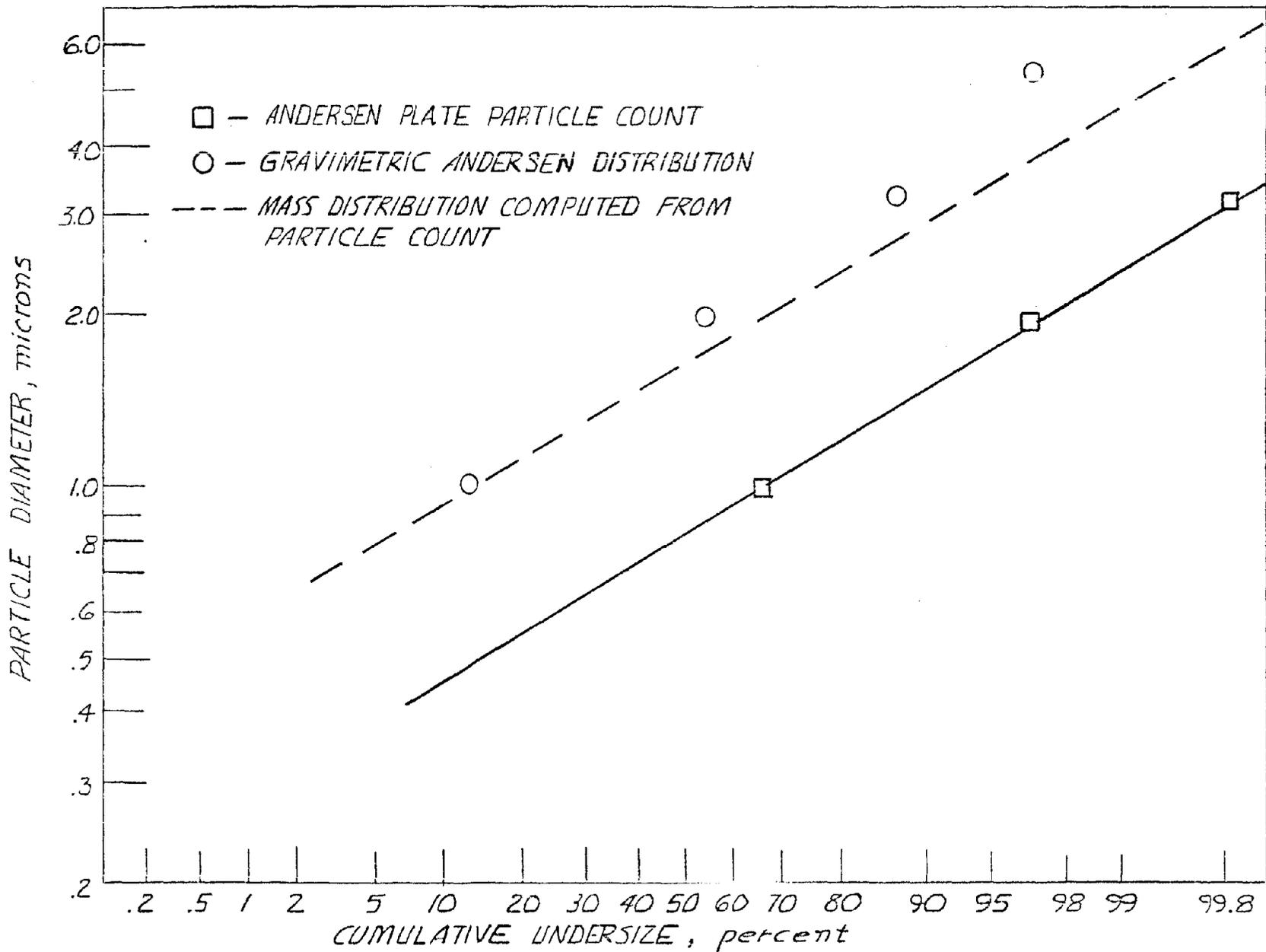


FIGURE 16

INLET COAL DUST SIZE DISTRIBUTION BY GRAVIMETRIC ANDERSEN METHOD AND  
DIRECT PARTICLE COUNT FROM ANDERSEN PLATES



-27b-

FIGURE 16

Furthermore, in retrospect, the reproducibility of the experimental results, consistency of all of the scrubber tests with conventional theory, and the correspondence of overall efficiency determined by total filters with that from the Andersen tend to further support the gravimetric Andersen method.

#### Material Balance Determination

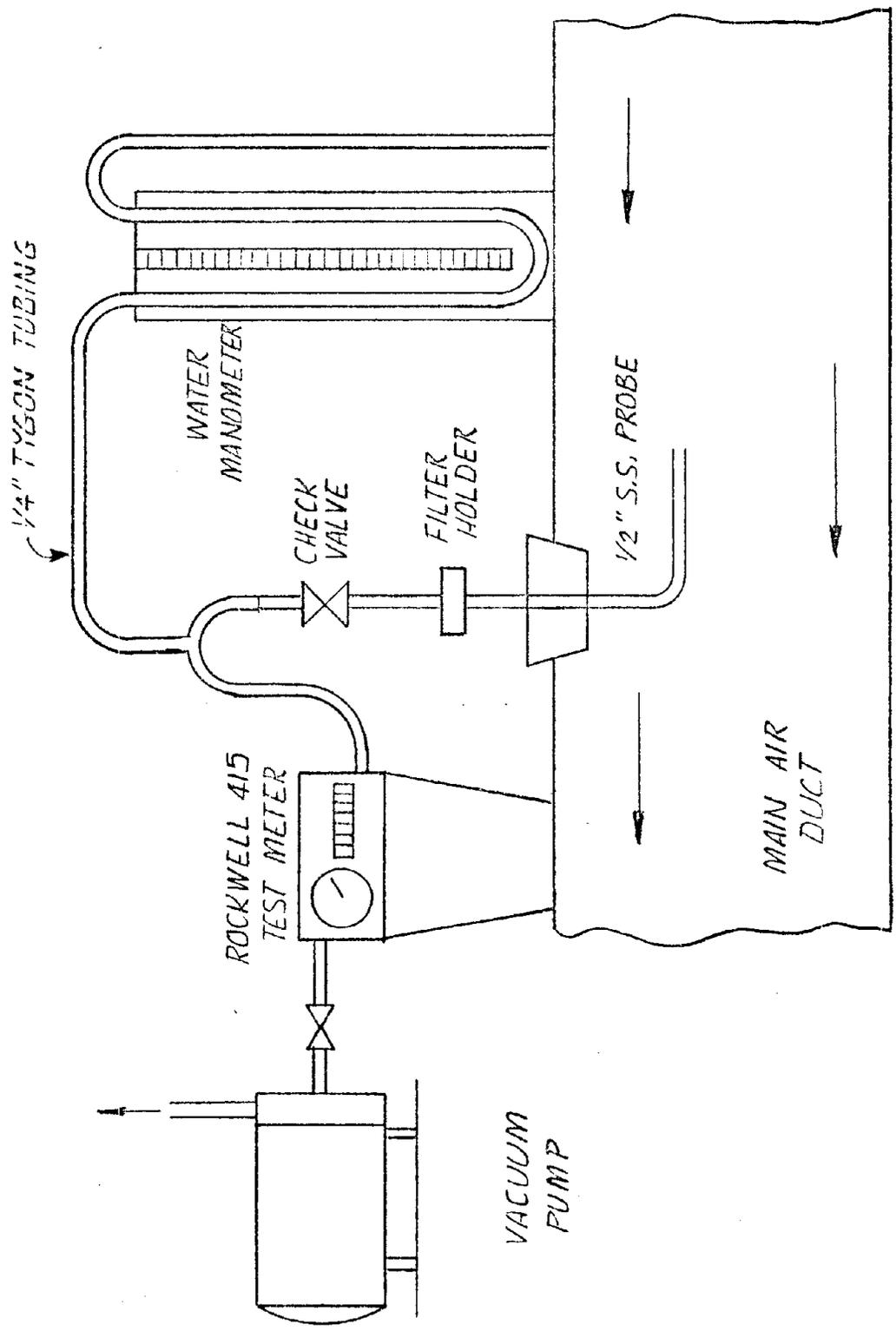
Total filter samples were taken simultaneously with the Andersen sampler in order to have a check of the total concentration determined from the Andersen and also as a method of determining the gross penetration for the total dust. The filter samples were taken in a manner analogous to the Andersen samples as shown in Figure 17 and depicted in Plates 3 and 4. The filters used were 47 mm aluminum Gelman filter holders, and the filter papers were Gelman type A glass fiber papers. Occasionally, membrane filter samples were also taken with this apparatus for visual inspection. The probe itself was 1/2 in. stainless steel tubing with a 0.028 inch wall thickness and a tapered tip.

Early in the experimental program, there were some difficulties with obtaining representative filter samples. A sampling traverse at the upstream sampling port showed that the center line concentration was approximately 50% greater than the mean concentration in the duct. This problem was eliminated by placing a baffle in front of the coal dust inlet to the mixing section as described in a previous section of this report. Subsequent sampling traverses showed that the air stream was well mixed and that within the limits of experimental error, center line dust concentration equalled the mean concentration in the duct.

In the downstream portion of the duct, sampling problems occurred due to badly skewed velocity distributions in the air stream caused by the sharp turns in the duct work that were frequently necessary when connecting the outlet of the scrubber to the stationary downstream duct. This problem was alleviated by providing a 20 foot section of straight duct before the sampling point to allow the velocity profile to even out.

After these two alterations, total filter samples proved to be consistent and reproducible throughout the entire experimental program. Furthermore, as can be seen from the experimental results, the gross penetration as determined from the total filter samples compares well with the total penetration as determined by the Andersen samples. Moreover, when the gross penetration is calculated from the integral of the product of

FIGURE 17  
FILTER SAMPLE CIRCUIT



NOT REPRODUCIBLE



PLATE 3

Technician inserts sampling probe at the upstream sampling port. The filter is held in the holder beside his right hand.

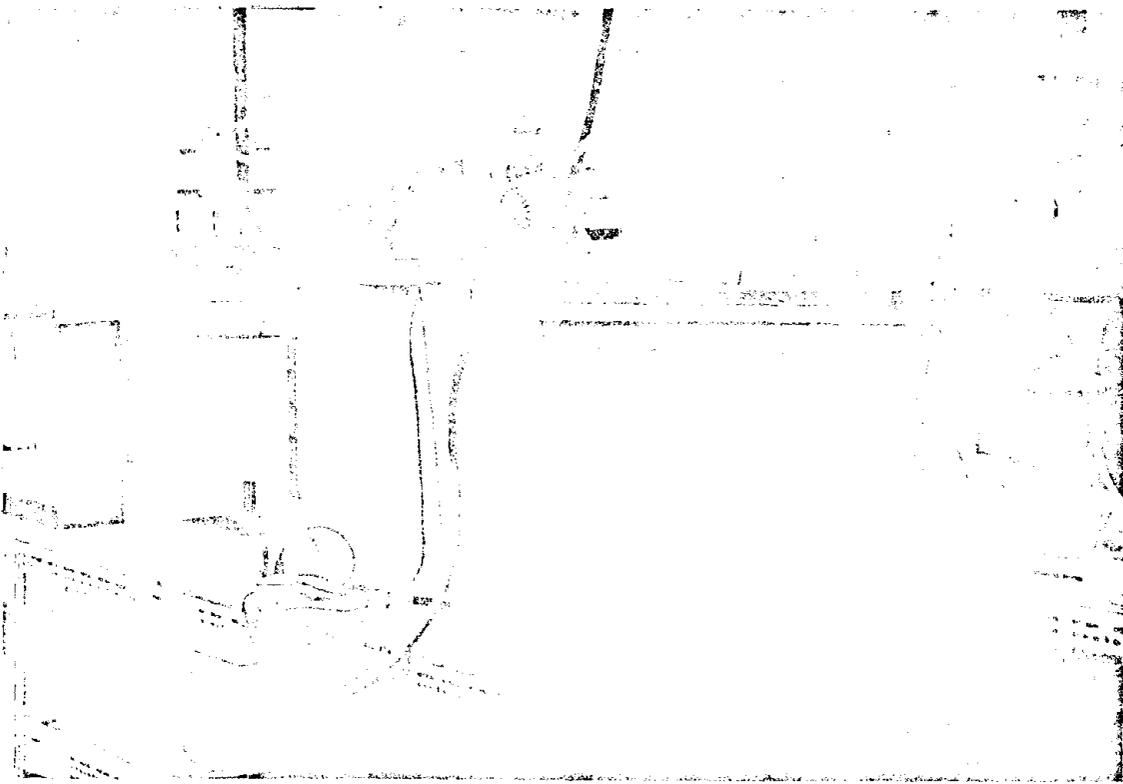


PLATE 4

Intake-Mixing section. Dust enters through the 4 in. galvanized duct (upper right). The main air supply enters through the large filters (center and right). The upstream sampling pump and meter are on top of the mixing section.

the theoretical penetration function for the scrubber and the inlet size distribution as measured by the Andersen sampler, it compares favorably with the gross penetration calculated from the total filter samples for every collector tested in this program.

#### Other Analytical Techniques

Early in the experimental program attempts were made to develop two other analytical methods, and these efforts are worthy of mention here to emphasize the care which must be taken in obtaining collection efficiency data.

The first instrument used for measuring particle size distributions was the Lundgren impactor. The Lundgren impactor is a cascade impactor with four rotating cylindrical stages and a final filter, and it works on essentially the same principle as the Andersen sampler. However, considerable experimental difficulties were encountered in the use of the Lundgren impactor that were not encountered with the Andersen sampler. First, the space between the rotating drums and the slits in front of the drums proved to be quite crucial and difficult to control. Second, the cylinders themselves weighed approximately 150 grams each and it was virtually impossible to tare them accurately and detect total dust loadings on the cylinders that were of the order of 0.1 milligrams total. Lighter weight plastic cylinders, which were obtained later, did not alleviate the difficulty. The only alternative to weighing the cylinders was to wrap them with a plastic film that could be removed and either weighed or examined under a microscope. This procedure proved to be extremely tedious and also compounded the aforementioned difficulty with the spacing between the cylinders and the slits before the cylinders. On occasion, accurate size distribution determinations were made with this impactor, but overall its performance was so erratic and the procedures for using it were so sensitive and tedious that its use was finally discontinued.

In the early stages of the experimental investigation, it was felt that generating coal dust in the respirable range with a consistent size distribution and loading would be quite difficult. Consequently, an attempt was made to use a technique involving a fluorescent aerosol of known size distribution and low standard deviation. Such an aerosol can be produced quite easily, and the concentrations upstream and downstream from the collector could be determined rapidly by measuring the fluorescence of filter samples of the aerosol.

This technique has been established by previous investigators, and in fact, little difficulty was encountered in producing a fluorescein aerosol of mean diameter 0.8 microns and standard deviation 1.8. However, further investigation of this technique showed that the fluorescein particles were sufficiently hygroscopic that they changed in size when passing through a wet collector (6). Several attempts were made to eliminate this effect by combining the fluorescein solution with slightly soluble compounds such as boric acid, but these attempts were unsuccessful. Later work showed that a sufficiently non-hygroscopic aerosol could be generated with methylene blue. Since it did prove to be possible to generate sufficient and reproducible quantities of respirable coal mine dust, the aerosol technique was no longer crucial to the experimental program, and due to the aforementioned uncertainties, its use was subsequently discontinued.

### EQUIPMENT TEST RESULTS

#### Multiple Cyclone

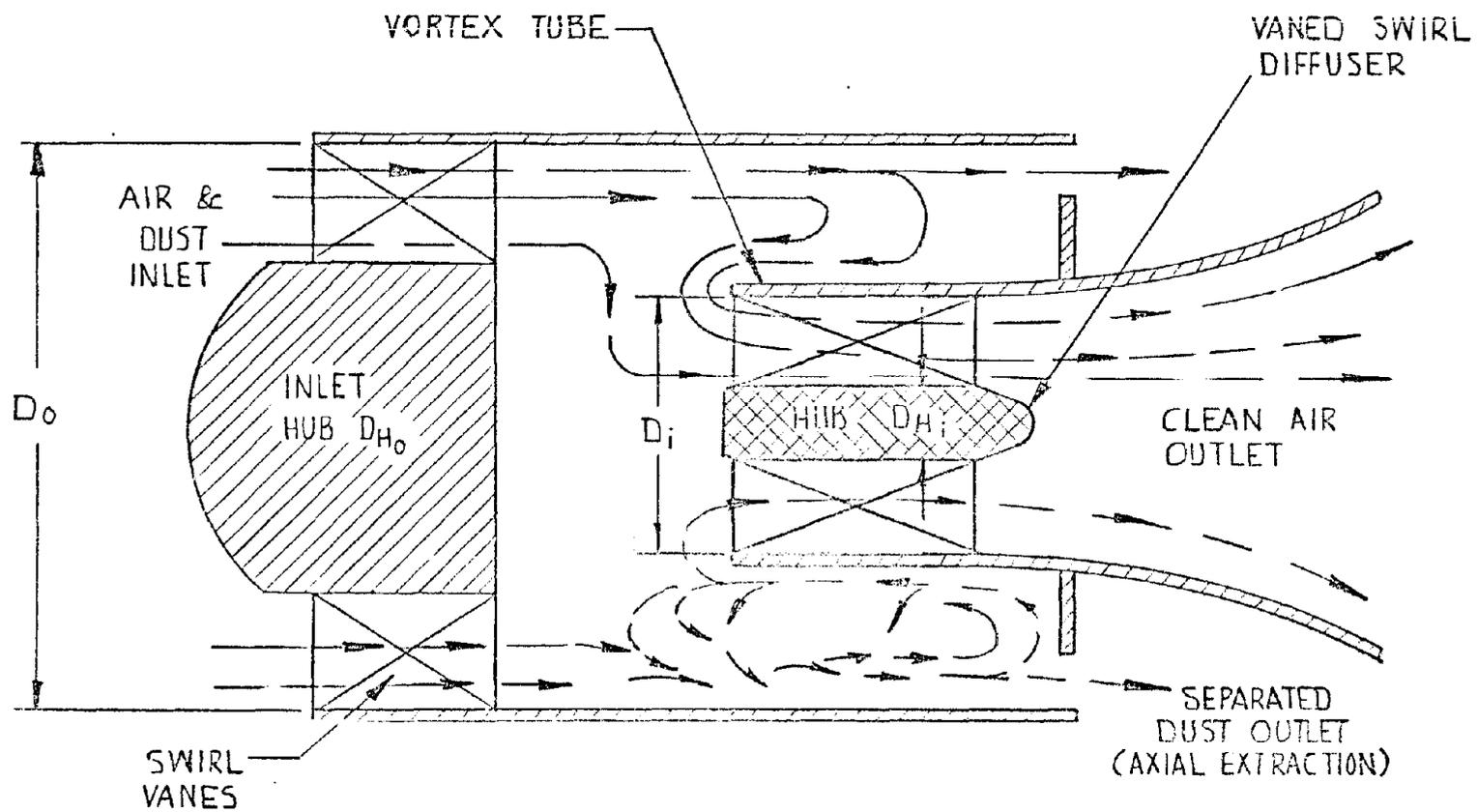
The partial reverse multiple cyclone separator consisted of a bank of 46 small cyclones. A schematic of an individual cyclone is shown in Figure 18 and a schematic of the entire cluster is shown in Figure 19. Each cyclone was 1-13/16 in. in diameter and the entire cluster was 13.25 in. x 14.75 in. The unit was designed to operate at flow rates up to approximately 1,500 cfm.

The penetration as a function of particle size for the multiple cyclone can be estimated by considering each of the 46 small cyclones to be a straight through cyclone with fixed veins. The flow reversal in each cyclone is presumed to have two effects:

1. To decrease re-entrainment of dust and hence improve the accuracy of the estimate (which makes no allowance for re-entrainment).
2. To shorten the effective length of the cyclone because of short circuiting.

Four test runs were conducted with the multiple cyclone. The gross penetration results are shown in Table 6 and the penetration as a function of diameter is shown in Figure 20. The gross penetration for the test dust was approximately 76%, and the theoretical penetration determined from equations 1 and 9 was calculated to be 79%. If this penetration function is

FIGURE 18  
PARTIAL REVERSE SEPARATOR



-30a-

FIGURE 18

FIGURE 19  
SCHEMATIC OF A 4x6 UNIT OF SWIRL VANE CYCLONE  
CYCLONE SEPARATOR SHOWING THE GENERAL FLOW PATTERNS

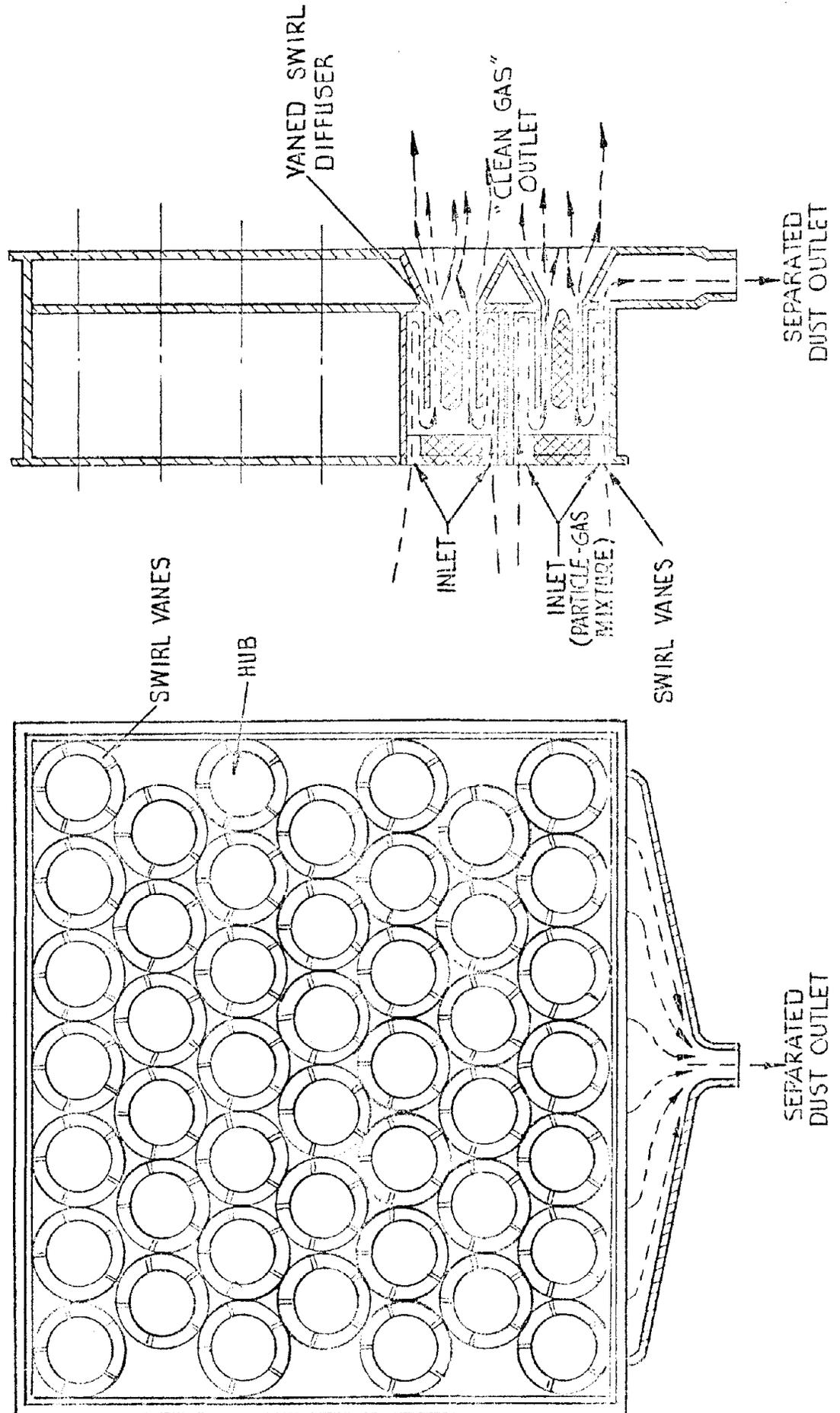


TABLE 6

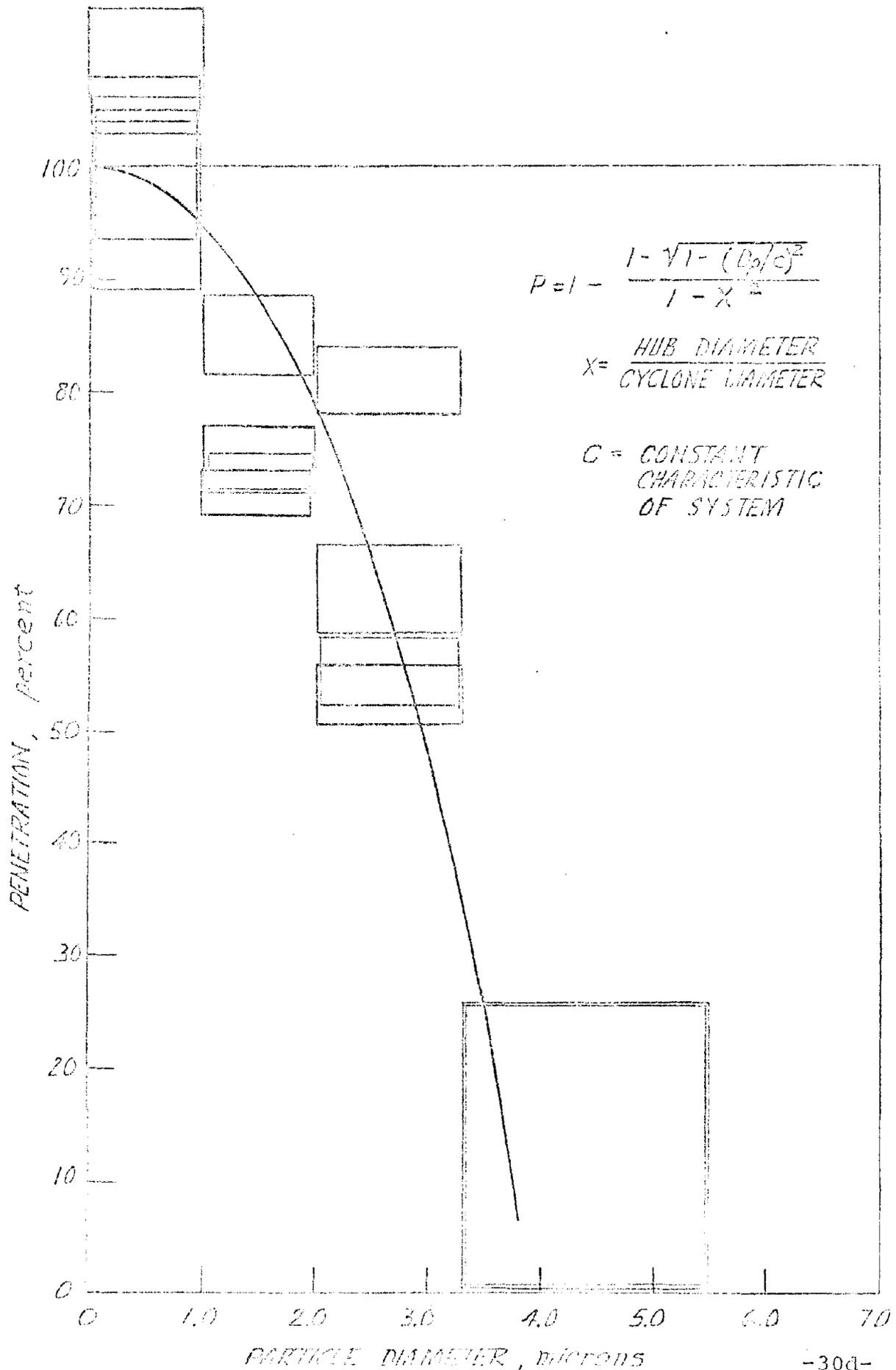
Gross Penetration For A Multiple CycloneFor An Inlet Dust Of Mean Diameter 1.5 Microns And Standard Deviation 1.7

Run	Upstream		Downstream		Penetration (%)
	Sample No. <sup>1</sup>	Concentration <sup>2</sup> (mg/scm)	Sample No.	Concentration (mg/scm)	
67	And - #1	12.6	And - #2	10.4	82.5
	348 - #1	15.3	349 - #2	11.3	73.9
	346 - #1	15.5	347 - #2	10.9	70.3
	351 - #1	14.1	352 - #2	10.2	72.3
68	355 - #1	14.9	356 - #2	11.5	77.2
	And - #1	11.6	And - #2	10.4	89.7
	357 - #1	16.4	358 - #2	12.0	73.2
69*	363 - #1	44.3	364 - #2	32.7	73.8
	And - #1	29.4	And - #2	19.6	66.7
	360 - #1	33.7	361 - #2	25.4	75.4
	365 - #1	43.7	366 - #2	35.0	80.1
70	368 - #1	54.6	369 - #2	33.1	60.6
	And - #1	39.7	And - #2	34.2	86.1
	371 - #1	56.1	372 - #2	45.1	80.4
					<u>75.8</u>

\* A new dust was used starting with Run #69

- "And" denotes total concentration calculated from Andersen sample. A number denotes a glass fiber filter sample. The number after the dash denotes the location where the sample was taken when more than one potential location was available.
- Milligrams per cubic meter of dry air at 14.7 psia and 70°F.

FIGURE 20  
MULTIPLE CYCLONE  
 PENETRATION AS A FUNCTION OF PARTICLE DIAMETER





applied to the estimated respirable dust, a penetration of 53% is calculated. The multiple cyclone does not, therefore, appear to achieve a high enough efficiency for the coal mine dust application.

### "Wetted Screen" Scrubber

The "wetted screen" scrubber was a wet dynamic scrubber. The functioning mechanism was a screen folded in a zigzag formation and wetted by a spray nozzle. The scrubber tested was designed to operate at approximately 2,500 cfm. The folded screen was 11.25 in. in diameter, had 22 "peaks", and the wires of the screen were 0.5 mm in diameter and 1.6 mm apart. It is interesting to note, as the ensuing discussion will show, that the "wire density" was almost exactly two. In other words, the total number of wires times the wire diameter was sufficiently large to cover the cross section of the scrubber two times. This wetted screen was followed by a horizontal cyclone functioning as an entrainment separator, which was in turn followed by an axial fan. A schematic of the scrubber is shown in Figure 21.

The model used for the "wetted screen" scrubber was impaction on cylinders. This mechanism has been previously described by equation 4 as follows:

$$P_t = 1 - E = 1 - \left( \frac{K}{K+1.7} \right)^2$$

where  $P_t$  is the penetration,  $E$  is the efficiency, or additive complement of penetration, and  $K$  is the inertial impaction parameter as defined in Equation 3. In this case the impaction parameter was calculated as follows:

$$K = \frac{\rho U D_p^2}{9 \mu D_c} = .2943 D_p^2$$

where:

$$\rho = 1.35 \text{ gm/cm}^3$$

$$U = 1770 \text{ cm/sec}$$

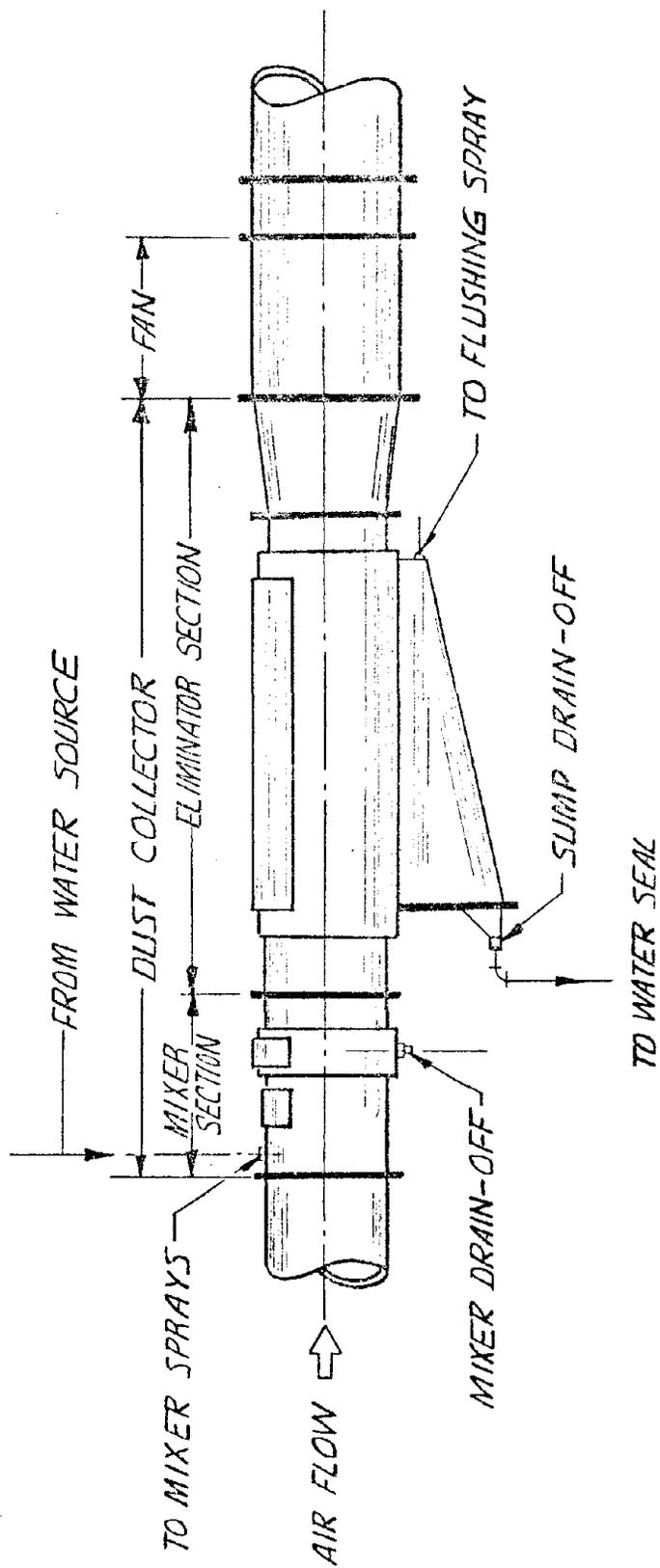
$$D_p = \text{particle diameter, microns}$$

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

$$D_c = \text{cylinder diameter} = .05 \text{ cm}$$

FIGURE 21

WETTED SCREEN "SCRAUBBER"



The scrubber was operated at 2,400 cfm with a water rate of 1.8 gpm as recommended by the manufacturer. It was considered that the "wire density" noted above might create the effect of a two-stage impaction on cylinders, which would have the effect of squaring the penetration function described above. An additional screen and spray section was provided with the pilot unit and could have been attached in series with the other unit. Tests were not performed on this configuration, but the effect of the additional screen probably would have been to square the penetration function yet again.

Three pilot plant runs were conducted with the "wetted screen" scrubber at the above operating conditions. Gross penetration data from the filter and Andersen samples are shown in Table 7, and the stage by stage Andersen data are plotted in Figure 22. Also shown in Figure 22 are the penetration function  $P$ , the square of the penetration function, which should represent the data as hypothesized above, and  $P^4$  which might approximate the effect of the additional screen and spray section.

The  $P^2$  curve appears to represent the data quite well. If the integral in equation 9 is evaluated for  $P(D_p)$  equal to  $P^2$  and  $f(D_p)$  is equal to the inlet dust distribution as determined with the Andersen sampler (mean diameter 1.5 microns and standard deviation 1.8), a gross penetration of 55% is determined. This correlates well with the 54% average penetration observed experimentally. If the same penetration function is applied to respirable coal mine dust, (mean diameter 2.55 microns and standard deviation 1.7), a gross penetration of 35% is calculated. If the additional spray and screen section were added and the  $P^4$  penetration function applied, the gross penetration for the estimated respirable dust would be 20%. Thus, this collector does not appear to meet the performance criterion established. However, it does offer several mechanical advantages such as compact physical size and low water requirement, and it is close enough to the performance requirement that it cannot be removed from consideration.

#### Packed Bed Scrubber

Packed bed scrubbers are available from a number of commercial sources, but it was found to be more convenient to fabricate one in-house rather than purchase or rent one.

TABLE 7

Cross Penetration For The "Wetted Screen" Scrubber

For An Inlet Dust of Mean Diameter 1.5 Microns

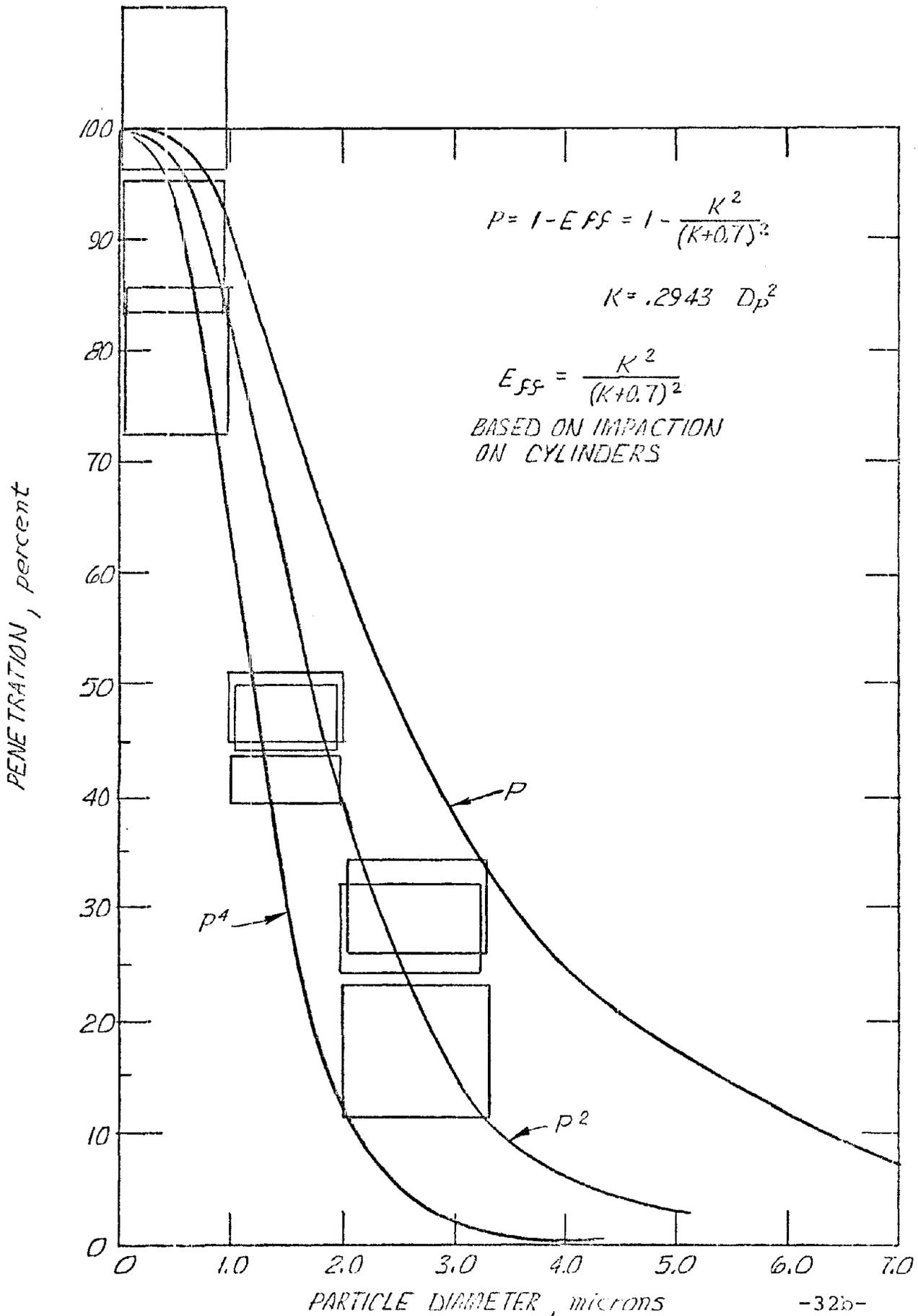
And Standard Deviation 1.8

<u>Run</u>	<u>Upstream</u>		<u>Downstream</u>		<u>Penetration (%)</u>
	<u>Sample No.</u>	<u>Concentration (mg/scm)</u>	<u>Sample No.</u>	<u>Concentration (mg/scm)</u>	
60	And - #2	10.5	And - #5	7.4	70
	297 - #2	11.9	294 - #5	6.3	53
	293 - #1	13.4	292 - #5	6.6	49
61	And - #1	16.1	And - #5	7.8	48
	304 - #1	13.9	305 - #5	6.8	49
	302 - #1	13.9	303 - #5	6.9	50
62	And - #1	11.0	And - #5	5.9	54
	308 - #1	12.5	309 - #5	7.7	62
	310 - #1	12.9	311 - #5	6.6	51
	Average	12.9		6.9	54

-32a-

Table 7

FIGURE 22  
 "WETTED SCREEN" SCRUBBER  
 PENETRATION AS A FUNCTION OF PARTICLE DIAMETER



The scrubber was constructed of 1/16 in. galvanized steel in three sections with one inch angle iron flanges and as shown in Figure 23. The unit was two feet square in cross section and 7.5 ft. tall. The air was introduced through a 12 in. diameter intake in the bottom section and passed through a three-foot deep section of 1.5 in. O.D. polypropylene Pall rings which were retained above and below by expanded metal grates. A water spray was introduced through a set of nine nozzles mounted six inches above the packing, and the water was removed through an outlet in the bottom section. Immediately above the nozzles was a three-inch deep section of the same Pall rings retained above and below by expanded metal grates. These served as an entrainment separator to remove the water droplets before the air stream passed out a 12 in. diameter exit duct.

Initial data were taken on a dry bed, for which the model had been presented previously in equation 3. Gross penetration data for these two runs are shown in Table 8, and the penetration as a function of particle diameter as calculated from the Andersen data is shown in Figure 24. The gross penetration of 39% determined from the filter samples compares very well with the gross penetration of 41% as calculated from the integral of the penetration function times the inlet distribution.

Subsequently, tests were conducted on a wet packed bed at a water rate of two gallons per thousand cubic feet. The test dust had a mean diameter of 1.44 microns and standard deviation 1.74, and showed a gross penetration of 33%. The gross penetration data are presented in Table 9, and the penetration as a function of diameter is shown in Figure 25.

According to the dry bed penetration theory, the penetration of the aforementioned test should be 50%, but this theory does not take the presence of the water into account, and the water can reasonably be expected to reduce the penetration to some extent. This difference, however, would not have a large effect on the estimated respirable coal dust which would have a penetration of 25%.

#### "Air Tumbler"

The "Air Tumbler" consisted of a horizontal wet cyclone as shown in Figure 26. The underside of the cyclone consisted of a water well, and during operation the water is distributed around the entire circumference of the cyclone. As shown in Table 10, when the "Air Tumbler" was operated in this configuration at an air rate of 2,200 cfm and a water rate of 15 gpm, a

FIGURE 23

PACKED BED SCRUBBER

2' SQUARE BY 7.5' TALL

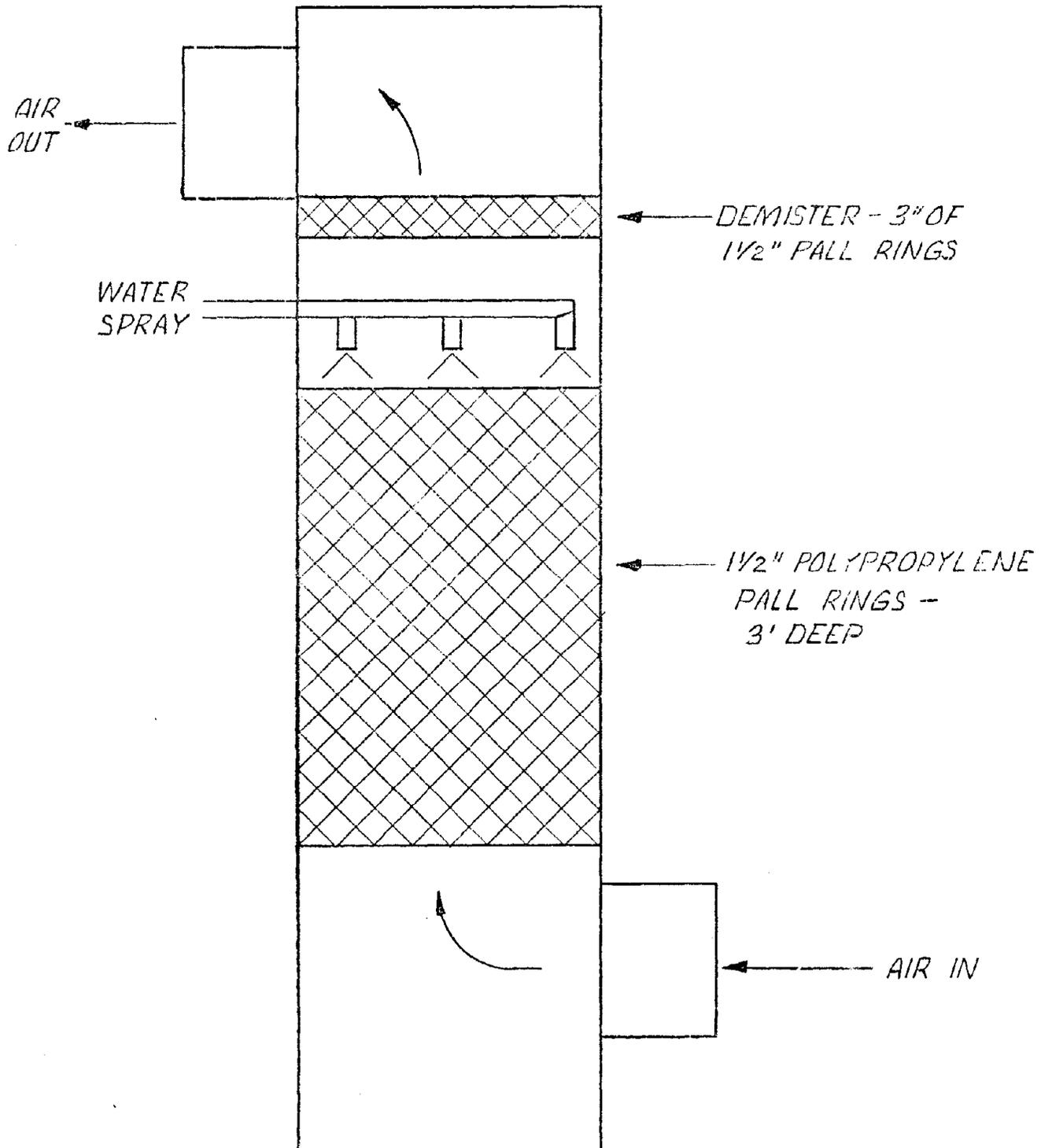


TABLE 8

Gross Penetration For A Dry Packed Bed Scrubber  
For An Inlet Dust Of Mean Diameter 1.82 Microns  
And Standard Deviation 1.63

<u>Run</u>	<u>Upstream</u>		<u>Downstream</u>		<u>Penetration (%)</u>
	<u>Sample No.</u>	<u>Concentration (mg/scm)</u>	<u>Sample No.</u>	<u>Concentration (mg/scm)</u>	
57	And - #2	11.7	And - #3	4.7	40
	269 - #2	10.7	270 - #4	3.7	30
	271 - #2	12.0	272 - #4	4.6	38
58	276 - #2	10.2	275 - #4	4.7	46
	278 - #2	13.8	277 - #4	4.8	35
	And - #2	8.8	And - #4	3.7	42
	Average	11.2		4.4	39

-33b-

FIGURE 24

PACKED BED SCRUBBER  
PENETRATION AS A FUNCTION OF PARTICLE DIAMETER

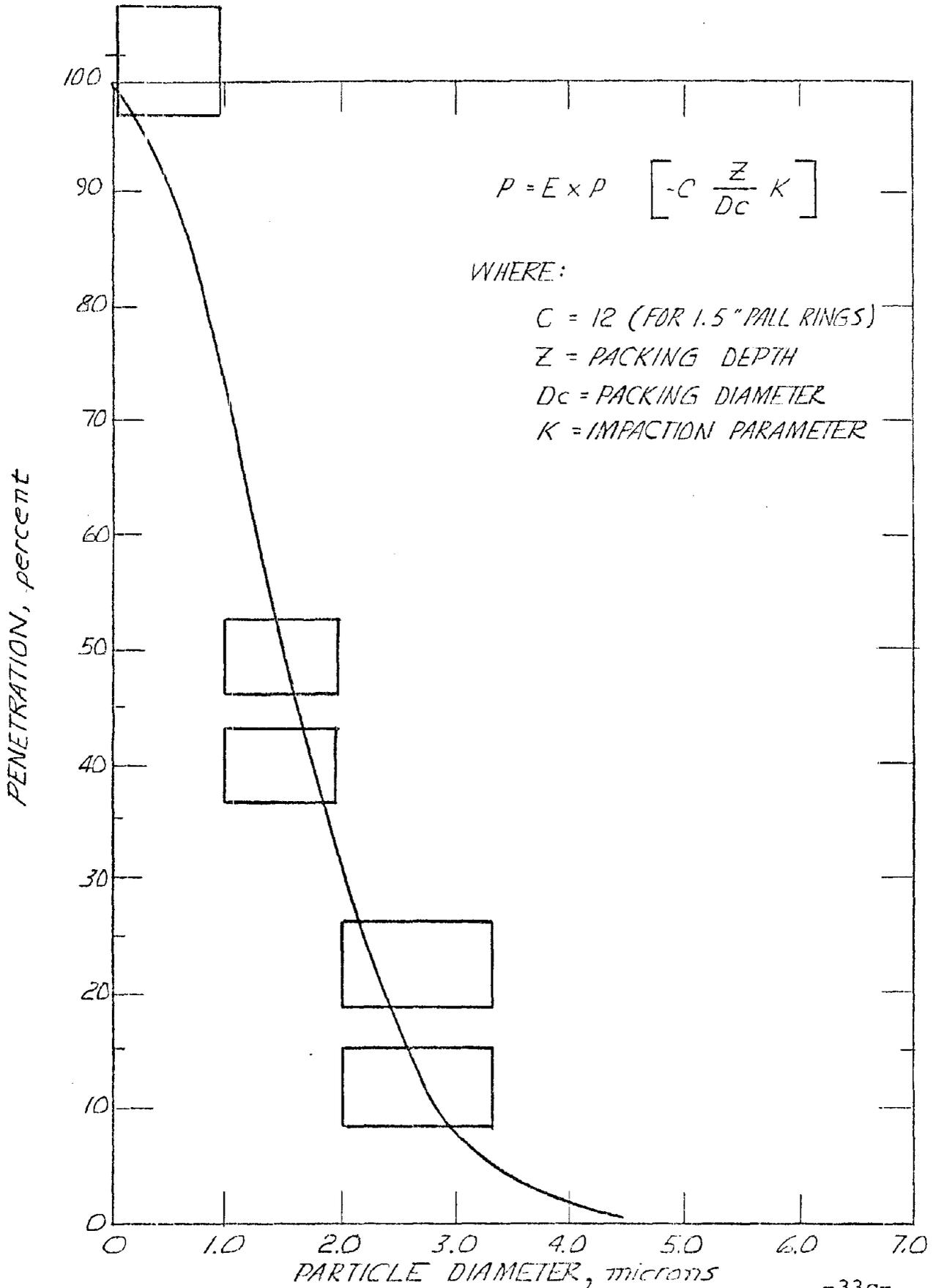


TABLE 9

Gross Penetration For A Packed Bed Scrubber\*  
For An Inlet Dust Of Mean Diameter 1.44 Microns  
And Standard Deviation 1.74

Run	Upstream		Downstream		Penetration (%)
	Sample No.	Concentration (mg/scm)	Sample No.	Concentration (mg/scm)	
63	314 - #1	13.6	315 - #4	4.0	29
	316 - #1	13.9	And - #4	6.0	43
	And - #1	12.9	317 - #4	3.3	26
64	And - #1	15.4	And - #4	5.5	36
	326 - #1	15.1	327 - #4	3.9	26
	328 - #1	15.7	329 - #4	5.6	36
65	332 - #1	13.8	333 - #4	5.7	27
	And - #1	13.2	And - #4	3.5	27
	334 - #1	15.3	335 - #4	4.8	31
66	340 - #1	14.4	341 - #4	4.8	33
	And - #1	10.9	And - #4	5.1	47
	342 - #1	15.6	343 - #4	5.9	38
	Average	14.15		4.675	33

\* Water rate = 2 gal./mcf

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FIGURE 25  
 PACKED BED SCRUBBER  
 PENETRATION AS A FUNCTION OF  
 PARTICLE DIAMETER

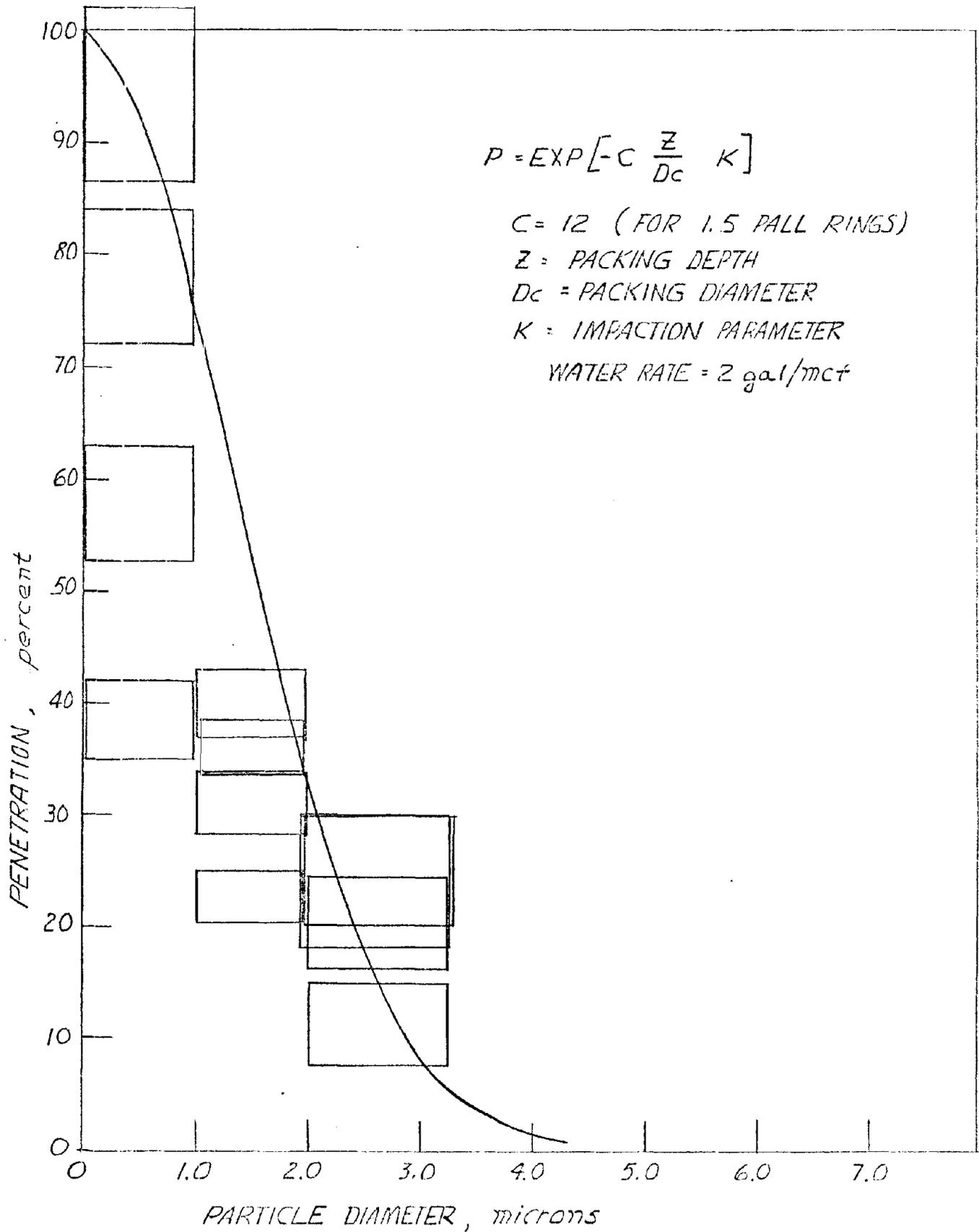
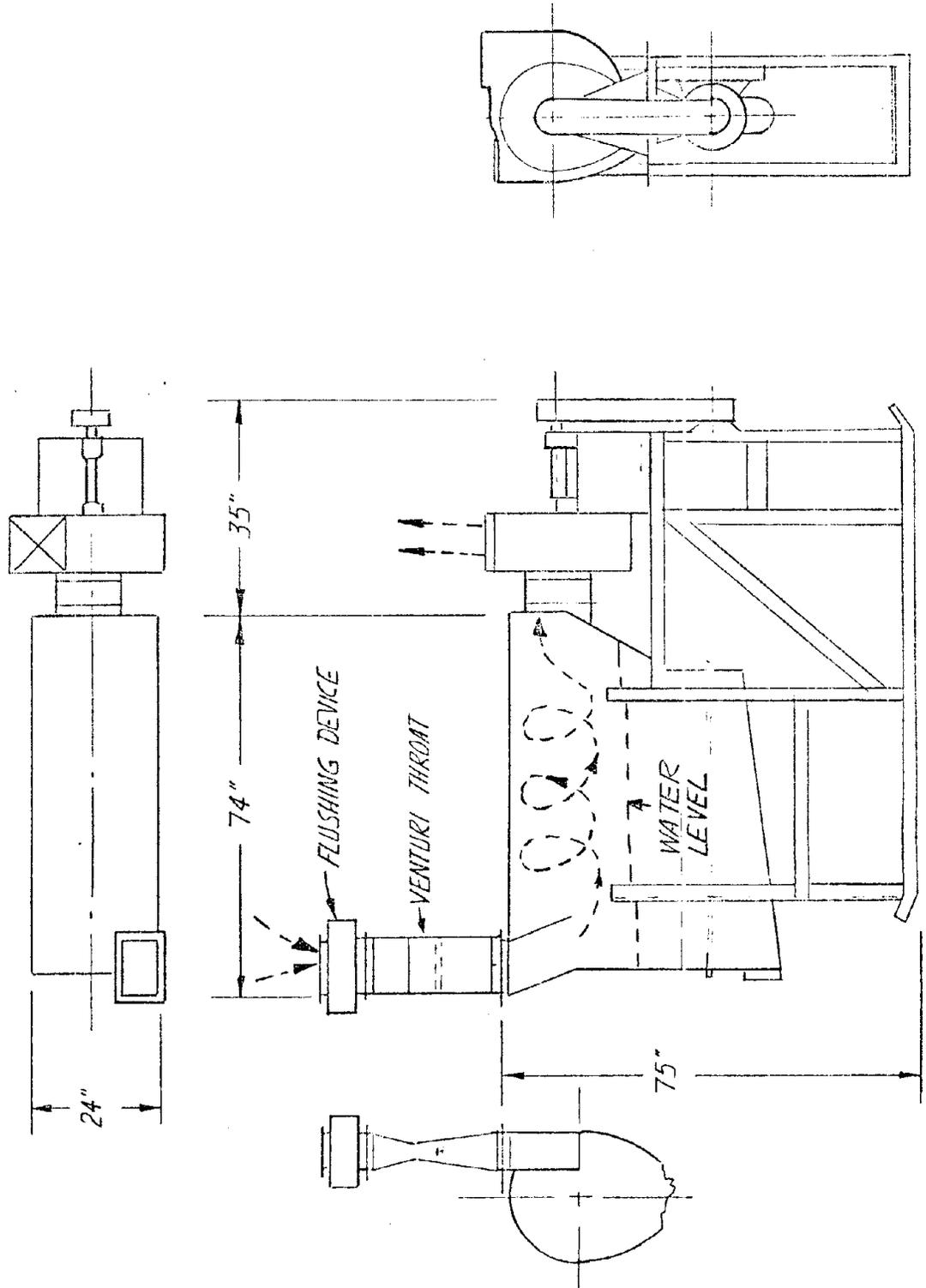


FIGURE 26  
"AIR TUMBLER"



Gross Penetration For An "Air Tumbler"  
For An Inlet Dust Of Mean Diameter 1.35 Microns  
And Standard Deviation 1.7

Run	Configuration*	Water Rate (gal/mcf)	Upstream		Downstream		Penetration (%)
			Sample No.	Concentration (mg/scm)	Sample No.	Concentration (mg/scm)	
77	1	7.5	426	38.7	427	22.5	58
71	2	2.5	374	56.4	375	18.4	33
			And	56.0	And	15.8	28
			377	44.6	378	30.7	69
			379	65.4	380	18.6	28
72	2	2.5	And	40.0	And	16.2	41
			382	54.9	383	17.9	33
			385	57.0	386	17.8	31
73	2	2.5	388	51.4	389	18.5	36
			And	38.1	And	16.7	44
			391	51.4	392	18.6	36
			393	50.2	394	18.3	36
			Average	51.4		18.9	37
74	3	2.5	And	40.4	And	20.6	51
			396	54.5	397	23.1	42
			399	55.1	400	22.5	41
			401	56.9	402	23.1	41
			Average	51.7		22.3	43
75	3	10.3	404	66.2	405	20.6	31
			407	68.7	408	20.7	30
			409	69.1	410	20.7	30
			And	60.4	And	18.4	30
76	3	10.3	413	61.2	414	19.9	33
			And	48.4	And	18.1	37
			416	65.8	417	21.0	32
			418	64.2	419	20.4	32
			Average	63.0		20.0	32

-33d-

TABLE 10 (Cont'd)

Gross Penetration For An "Air Tumbler"  
For An Inlet Dust Of Mean Diameter 1.35 Microns  
And Standard Deviation 1.7

Run	Configuration*	Water Rate (Gal/mcf)	Upstream		Downstream		Penetration (%)
			Sample No.	Concentration (mg/scm)	Sample No.	Concentration (mg/scm)	
77	2	7.5	And	43.2	And	13.4	31
			421	49.5	422	18.9	38
			424	48.3	425	18.9	39
78	2	7.5	429	68.7	430	22.2	32
			And	57.5	And	19.2	33
			432	77.8	433	23.5	30
		Average		57.5		19.4	34

\* 1 = Air Tumbler Alone.

2 = Air Tumbler With "Flushing Device"

3 = Air Tumbler With Venturi and "Flushing Device"

penetration of 58% was achieved on a dust of mean diameter 1.35 microns and standard deviation 1.7. This level of performance, while not good, is better than could be anticipated for a cyclone mechanism. It therefore must be assumed that the method of collection was atomization of the water and subsequent impaction between the water drops and dust particles. Unfortunately, the configuration of the equipment made it impossible to determine the effective liquid rate, so that any correlation of the performance must be empirical. Thus, it was assumed that the aforementioned performance could be described by an atomization mechanism, and it was subsequently clear that the "Air Tumbler" alone cannot achieve satisfactory performance on respirable mine dust.

In an effort to improve the performance of their scrubber, the manufacturers of the "Air Tumbler" recently made available two additions to their basic unit. These additions consisted of a venturi throat and a "flushing device" which the manufacturer recommended be attached to the inlet of the basic (Air Tumbler) unit to improve performance. Since the performance of the basic unit proved inadequate, tests were subsequently conducted with these additions connected to the inlet. Performance with the flushing device alone attached to the inlet is described in Table 10, and penetration as a function of diameter is presented for two sets of operating conditions in Figures 27 and 28. In an effort to arrive at a penetration function that reasonably describes these data, the aforementioned empirical correlation for the "Air Tumbler" alone was assumed to hold, while the flushing device attached to the "Air Tumbler" intake was assumed to have the same effect and mechanism as a venturi throat.

In the case of the "Air Tumbler" with the flushing device, the throat was fairly large and the throat velocity was only about 100 ft./sec, which is well below the range of applicability of the Nukiyama-Tanasawa equation for drop sizes. The drop sizes were therefore calculated from the critical Weber number, as given in equation 7. The critical Weber number gives the largest possible drop size at a given velocity, and therefore probably over estimates the mean drop diameter. Since the drop diameter appears in the denominator of the impaction parameter, over estimating the drop size has the effect of under estimating the performance of the scrubber. Nevertheless the venturi model given by equation 5, when combined with the empirical model for the "Air Tumbler" alone, gives a reasonable explanation of the data as demonstrated by the curves in Figures 27 and 28.

FIGURE 27

"AIR TUMBLER"  
PENETRATION AS A FUNCTION OF PARTICLE DIAMETER

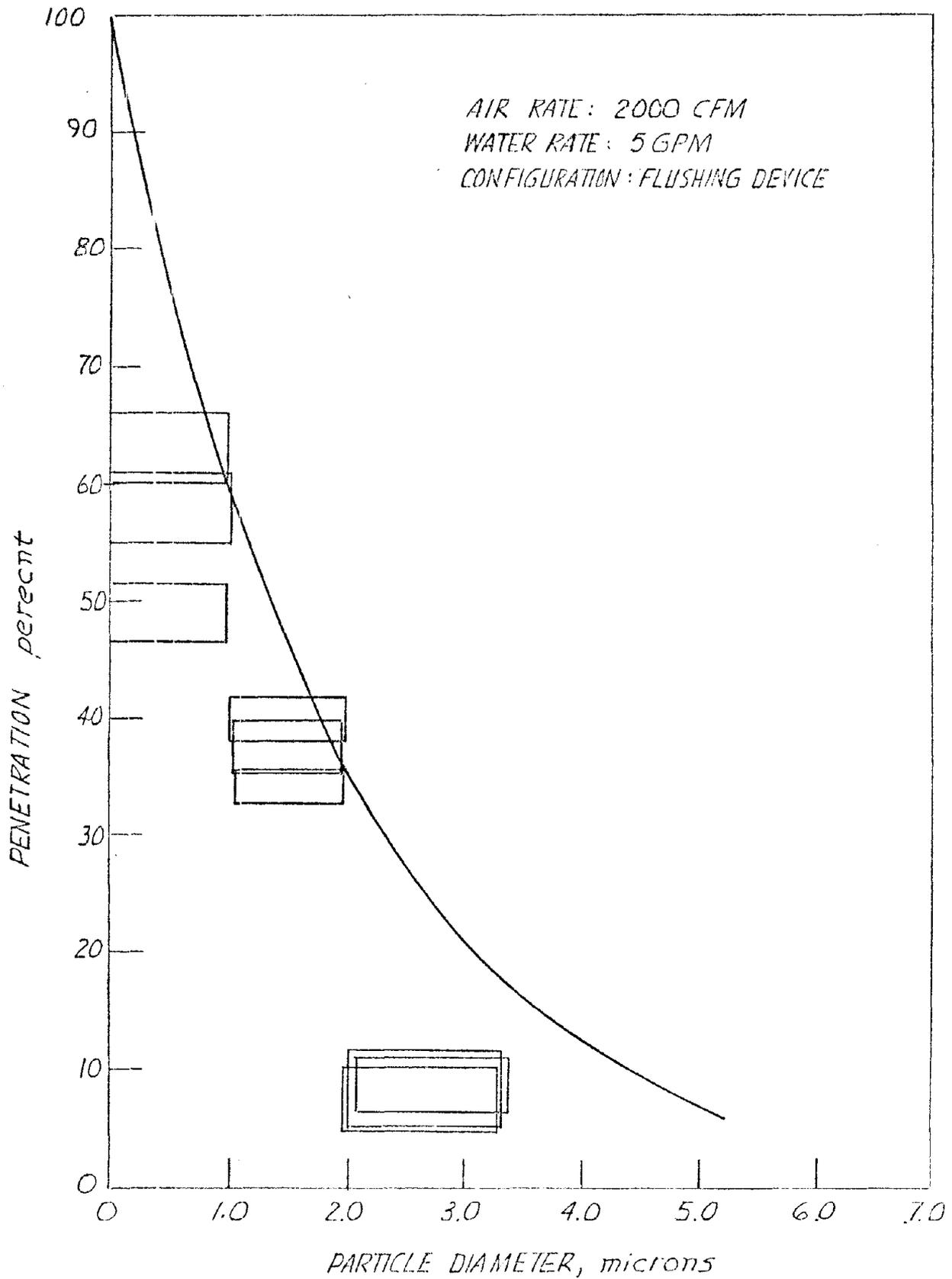
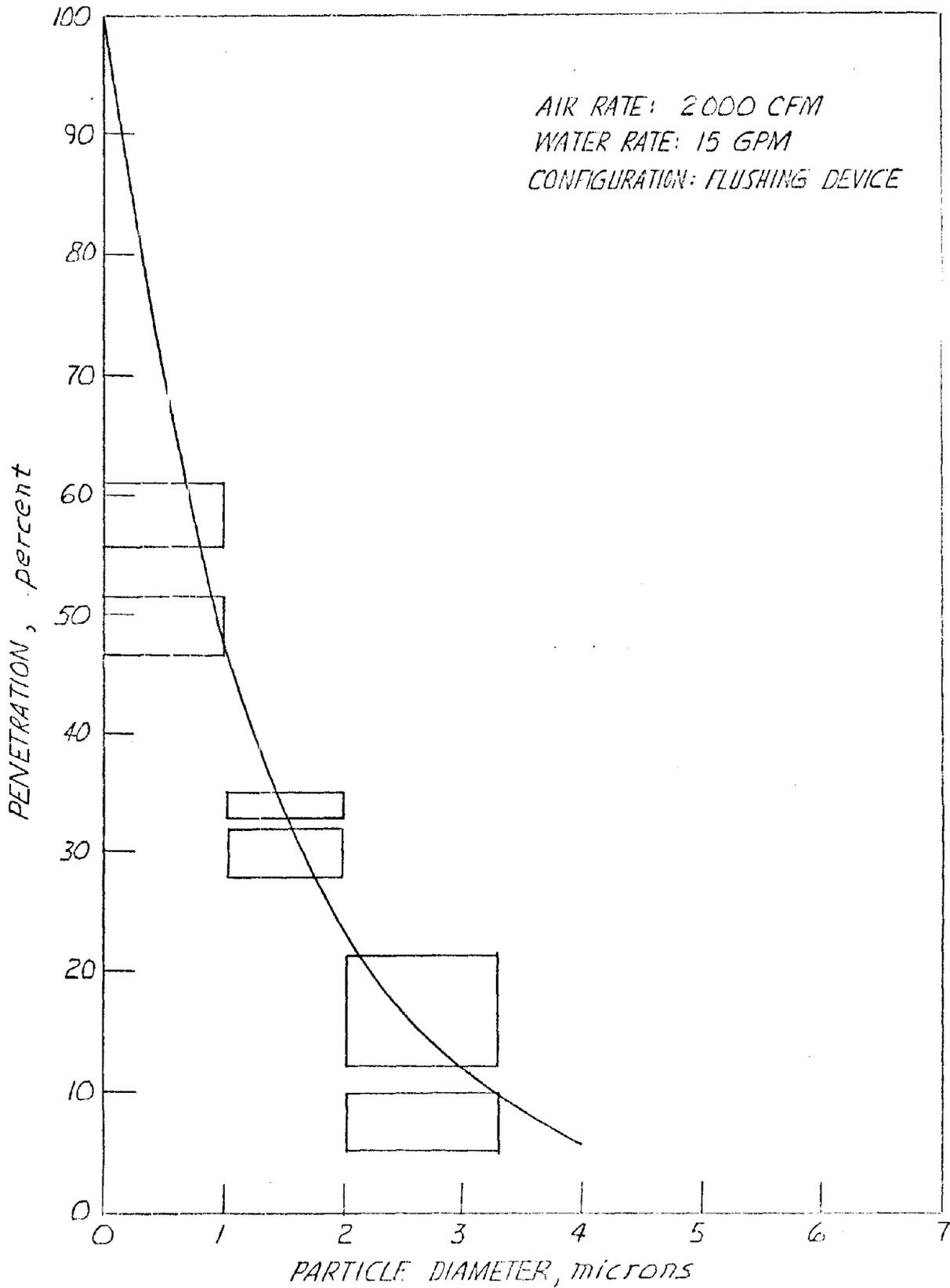


FIGURE 28

"AIR TUMBLER"

PENETRATION AS A FUNCTION OF PARTICLE DIAMETER





Next, the venturi section was attached to the air inlet of the "Air Tumbler" between the "Air Tumbler" and the flushing device. This adjustment had the net effect of further decreasing the throat area of the venturi inlet. Gross penetration for the configuration is presented in Table 10 and penetration as a function of particle diameter is presented in Figures 29 and 30. The penetration curves presented have been determined by the same method described for the flushing device. The effect of decreasing the throat area was to increase the throat velocity and thereby decrease the drop size produced at the venturi throat. The velocities at the venturi throat were approximately 200 feet per second, which is the lower end of the range of applicability of the Nukiyama-Tanasawa correlation.

In this velocity range, the Nukiyama-Tanasawa correlation will tend to predict too small a diameter for the water drops, and thereby predict too high a performance for the collector. Further, as described in the following discussion, the venturi section had three rods mounted immediately below the throat. In the venturi scrubber study, these rods were shown to have a negative effect on the performance of the scrubber. In spite of these possible corrections, however, the penetration model described offers a reasonable explanation for the improved performance obtained with the addition of the flushing device and the venturi throat.

The "Air Tumbler" with the venturi section attached to the front would appear to provide an adequate performance on the estimated respirable dust (9% penetration). However, as discussed in a later section on the venturi scrubber, the desired level of efficiency can be achieved with the venturi section alone and the "Air Tumbler" by itself is a comparatively inefficient collector.

#### Impingement Scrubber

The impingement scrubber was a classical impingement design. Air enters at the bottom of the cylindrical scrubber through a tangential intake which provides a slight cyclone effect in the bottom of the scrubber to remove very large particles. Immediately above the intake were two stages of impingement plates. The tower diameter was 2.5 ft. and the area of each impingement plate was approximately three square feet. Each plate was perforated with  $3/32$  in. diameter holes on  $3/16$  in. centers. The total open area of the plate cross-section was approximately 22% of the total area, or  $0.68 \text{ ft.}^2$ . Immediately downstream from each hole was a small tab, or plate, upon which the air jet passing through the hole impinged. The scrubber was designed

FIGURE 29

"AIR TUMBLER"

PENETRATION AS A FUNCTION OF PARTICLE DIAMETER

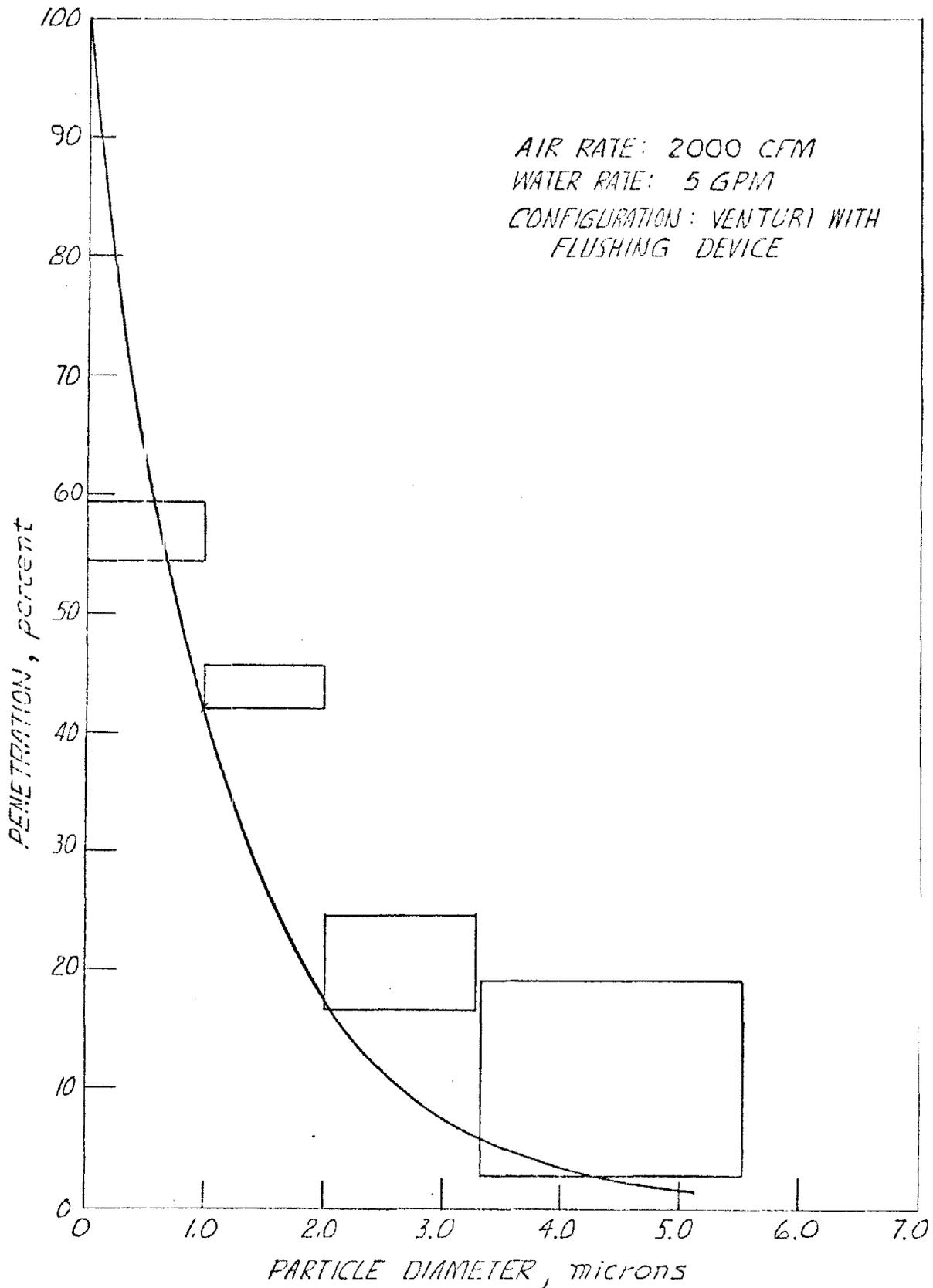
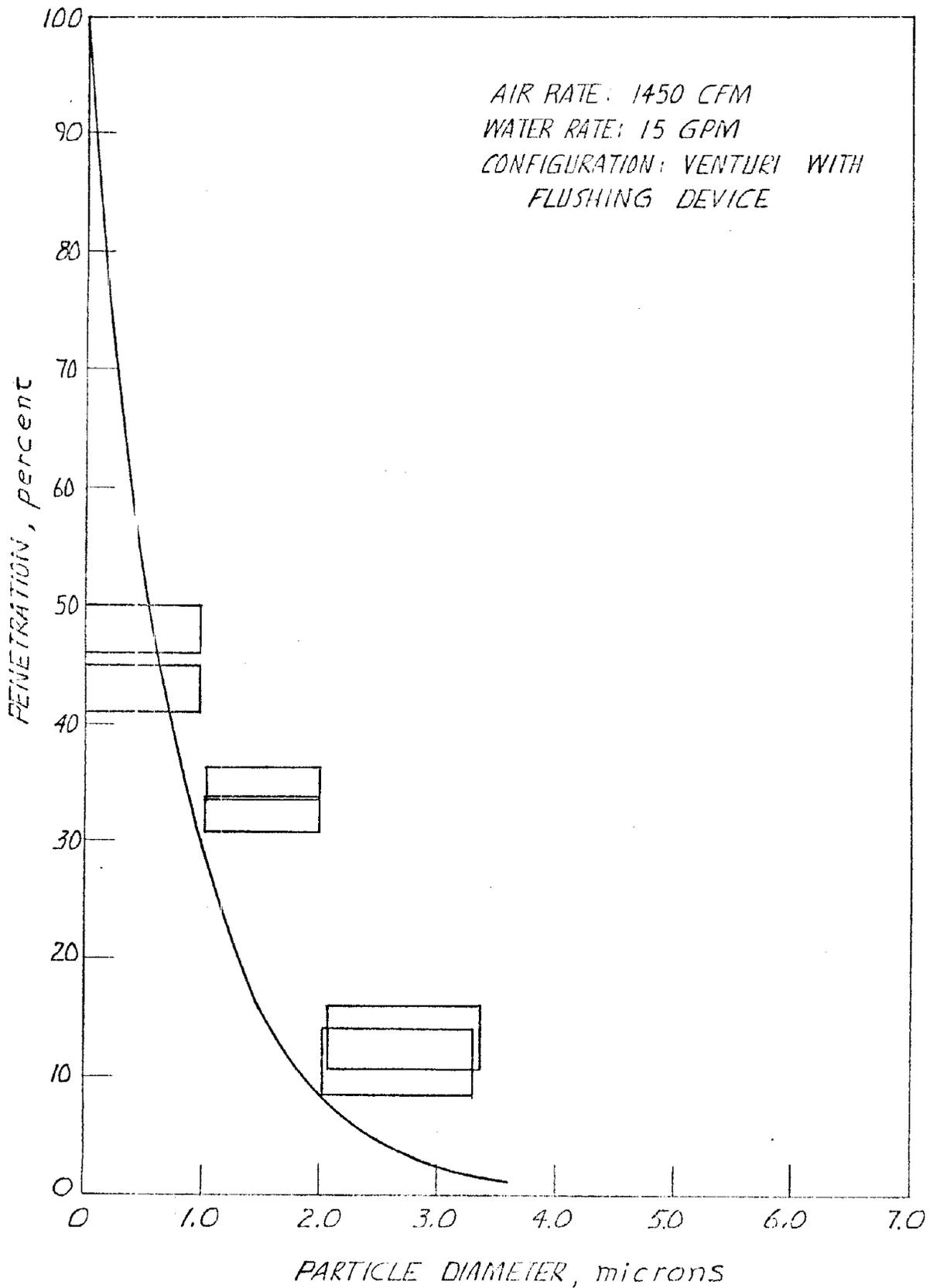


FIGURE 30

"AIR TUMBLER"

PENETRATION AS A FUNCTION OF PARTICLE DIAMETER



to operate at an air rate of 2,500 cfm with a water rate of 25 gpm flowing countercurrently over the two plates as shown in the schematic diagram in Figure 31. An additional water spray from beneath the bottom plate of 20 gpm was also recommended by the manufacturer. This spray apparently serves to keep the bottom plate from fouling under high dust loadings and to keep the walls of the scrubber wet to enhance the cyclone effect created at the air inlet. Immediately above the top plate was a set of rotating veins which served as a water eliminator. The impingement scrubber is depicted during testing in Plate 5.

The impingement scrubber was modeled as a two-stage impingement of round jets on flat plates. This mechanism has been correlated on the basis of the inertial impaction parameter, as shown in Figure 5. The impaction parameter in this case was calculated as follows:

$$U = \frac{(2500 \text{ cfm})(30.5 \text{ cm/ft.})}{(60 \text{ sec})(.68 \text{ ft}^2)} = 1870 \text{ cm/sec}$$

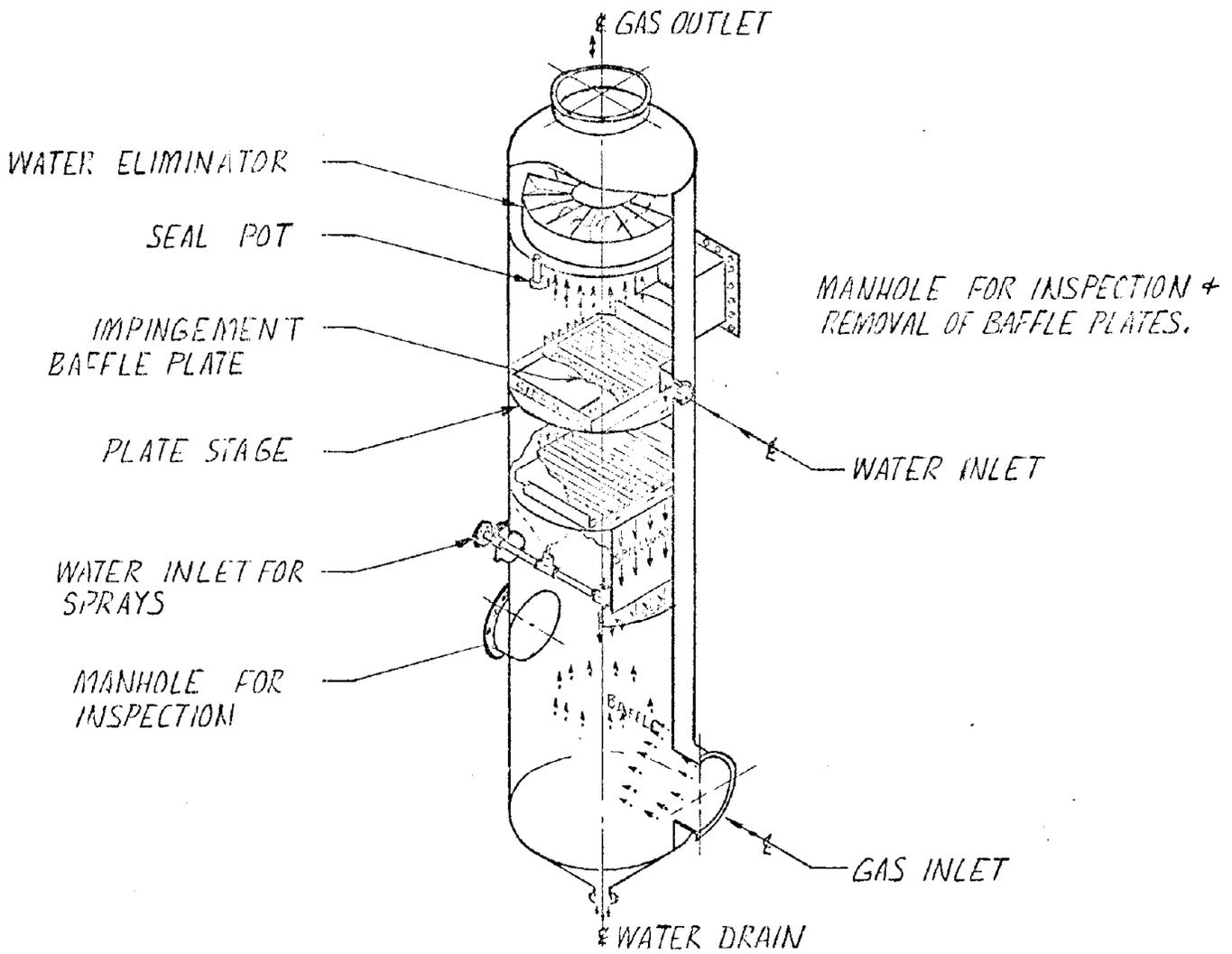
$$D_c = .09375" = .238 \text{ cm}$$

$$K = \frac{U\rho D_p^2}{9\mu D_c} = \frac{(1870 \text{ cm/sec})(1.35 \text{ gm/cm}^3)(10^{-4} \text{ cm}/\mu)^2 D_p^2}{(9)(1.8 \times 10^{-4} \text{ gm/cm-sec})(.238 \text{ cm})} = .065 D_p^2$$

Three runs were made with the impingement scrubber at 2,500 cfm with 20 gpm water rate on both the top and bottom sprays. The gross penetration data for these three runs are tabulated in Table 11 and the penetration as a function of particle diameter is shown in Figure 32. As can be seen from Figure 32, the three runs were quite reproducible and consistent with the round jet impaction mechanism that was hypothesized for this scrubber. A respirable dust penetration of 27% is calculated for this mechanism.

It has been hypothesized that the 20 gpm plate spray serves to wash the bottom plate and wet the walls of the lower portion of the scrubber, but that it is not instrumental in the collection of insoluble respirable dust particles. To test this hypothesis two additional runs were made with a 20 gpm top spray, but no plate spray from the bottom. The results of these two runs are tabulated in Table 11 and presented graphically in Figure 33. The hypothesis appears to be essentially correct; both the gross penetration and the penetration as a function of particle diameter appear to be essentially unaffected by the plate spray for this particular dust.

FIGURE 31  
IMPINGEMENT SCRUBBER



NOT REPRODUCIBLE

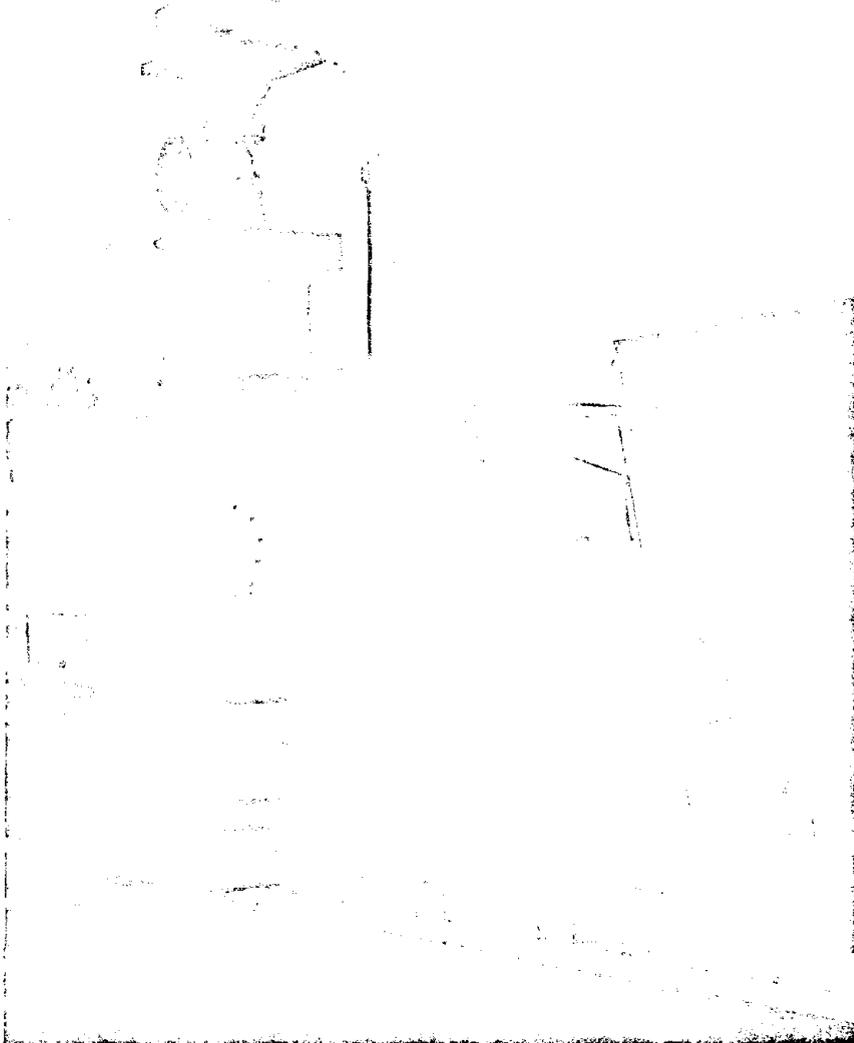


PLATE 5

The impingement scrubber is shown during testing. The "Ventri-Sphere" scrubber stands to the left. The dust feeder cyclone can be seen between the two scrubbers. The undersize dust line (center left) conveys respirable dust to the intake system.

TABLE 11

Gross Penetration For An Impingement Scrubber  
For An Inlet Dust Of Mean Diameter 1.44 Microns  
And Standard Deviation 1.7

Run	Water Rate (gal/mcf)		Upstream		Downstream		Penetration (%)
	Top	Bottom	Sample No.	Concentration (mg/scm)	Sample No.	Concentration (mg/scm)	
90	8	8	517	35.0	518	14.8	42.3
			And	29.2	And	12.8	43.8
			520	36.2	521	14.6	40.3
91	8	8	And	25.4	And	11.7	46.1
			523	31.6	524	12.5	39.6
			526	33.5	527	12.8	38.2
92	8	8	529	33.5	530	13.7	40.9
			And	28.6	And	12.2	42.7
			532	34.9	533	14.0	40.1
			Average	32.0		13.2	41.4
93	8	0	And	31.4	536	16.4	52.2
			535	36.4	And	14.6	40.1
			538	39.0	539	17.1	43.8
94	8	0	531	36.4	542	15.4	42.3
			And	34.2	And	15.8	46.2
			544	37.1	545	15.4	41.5
			Average	35.8		15.8	44.1

FIGURE 32

IMPINGEMENT SCRUBBER  
PENETRATION AS A FUNCTION OF PARTICLE  
DIAMETER

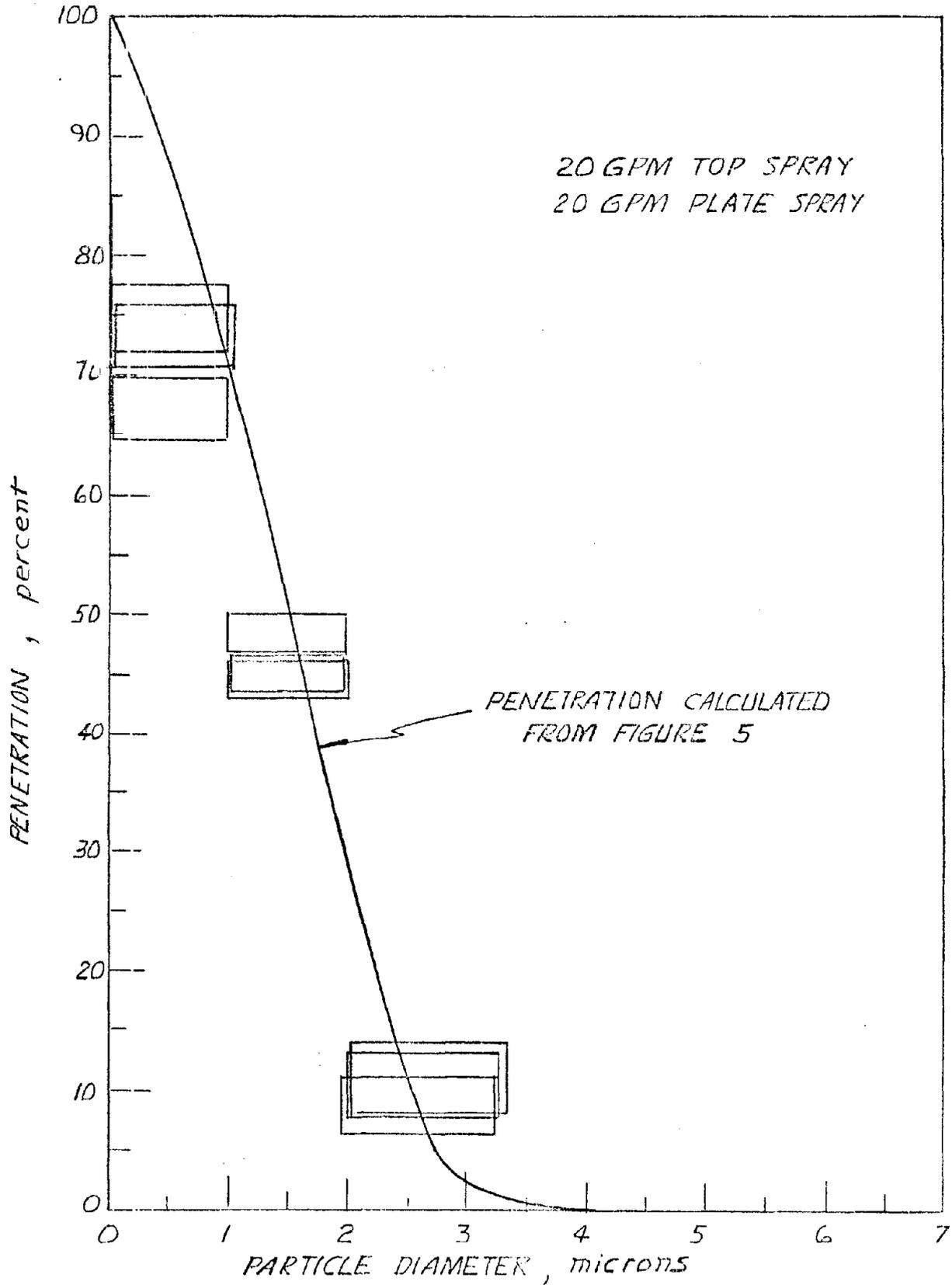
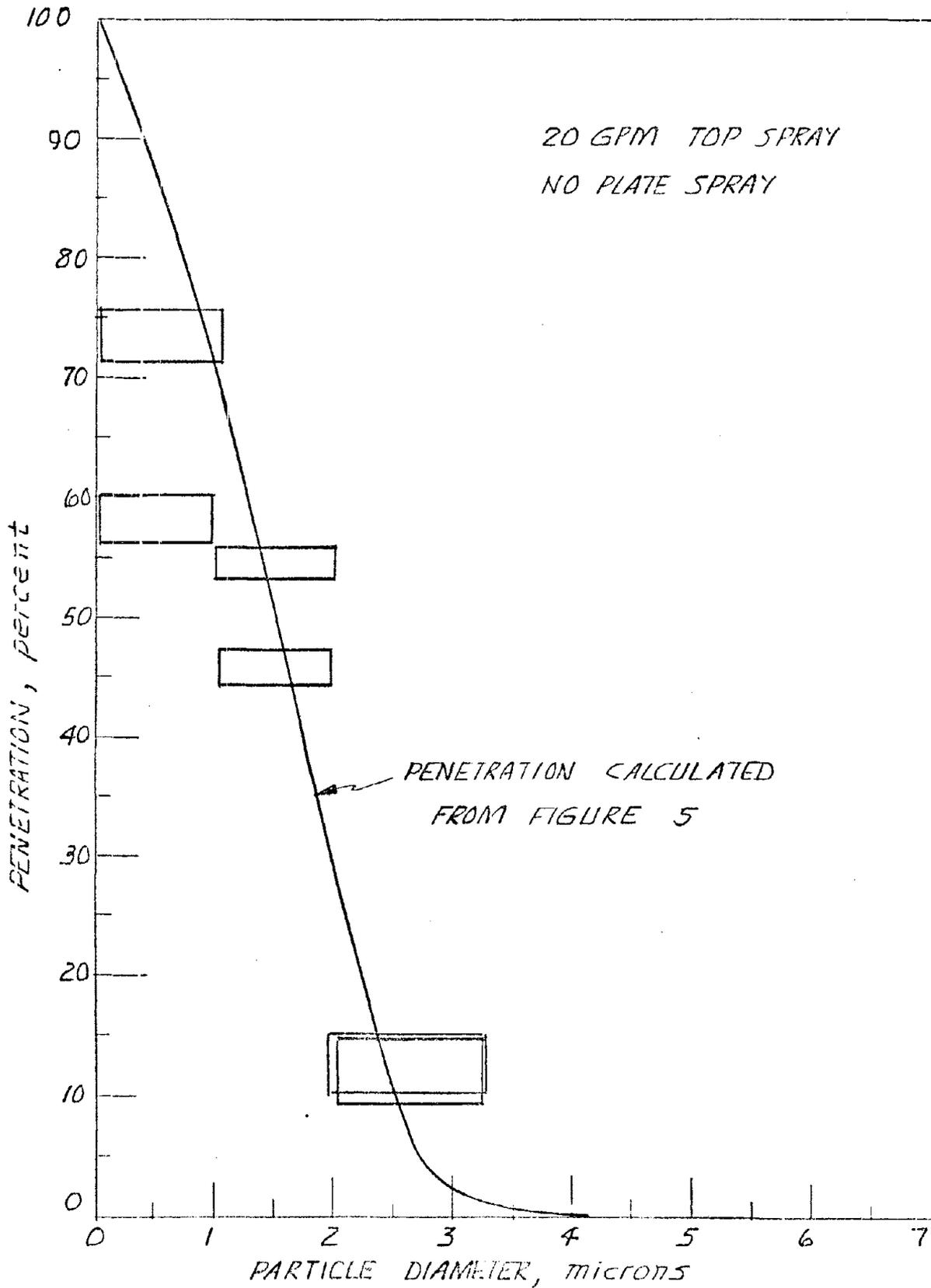


FIGURE 33

IMPINGEMENT SCRUBBER  
PENETRATION AS A FUNCTION OF PARTICLE DIAMETER





## Venturi Scrubber

A venturi scrubber was constructed in the configuration shown in Figure 34. The venturi section from the "Air Tumbler" was used for the venturi throat, and the packed bed which was previously tested was used as an entrainment separator following the venturi throat. One foot of packing was used in the packed bed instead of the previously used three foot packing depth so that the packed bed would function only as an entrainment separator, and its performance would not overlap with that of the venturi.

The venturi was first tested at a water rate of 10 gpm and an air rate of 2,000 cfm with the rods below the venturi throat removed. Two consecutive tests were quite reproducible. The gross penetration data is presented in Table 12 and the penetration as a function of particle diameter is presented in Figure 35. As can be seen from Figure 35, the performance of the venturi scrubber correlates reasonably well with venturi scrubber theory as calculated from equation 5. The next test was conducted at the same air rate but at a water rate of 20 gpm, and the results of this test are presented in Table 12 and in Figure 36. As can be seen from Figure 36, the penetration as a function of particle diameter correlates very well with the experimental data. In fact, subsequent tests with other venturi scrubbers tended to indicate that equation 5 was more representative of the experimental results at higher water rates ( $L \geq 10$  gal./mcf).

The gross penetration calculated from equation 9 was 19%. If the same penetration function is applied to respirable coal mine dust, a penetration of 6% is calculated.

Since these tests rapidly demonstrated that the venturi scrubber performed according to conventional theory when applied to coal dust, the two subsequent runs were made with the rods provided by the manufacturer mounted below the venturi throat in order to test the effect of these rods on the performance of the venturi alone, and also their effect on the performance of the "Air Tumbler". The data for these runs are presented in Table 12 and Figure 37, and it is readily apparent upon comparison of Figures 35 and 37 that, if anything, the rods below the throat have a negative effect on the venturi efficiency.

FIGURE 34

VENTURI SCRUBBER

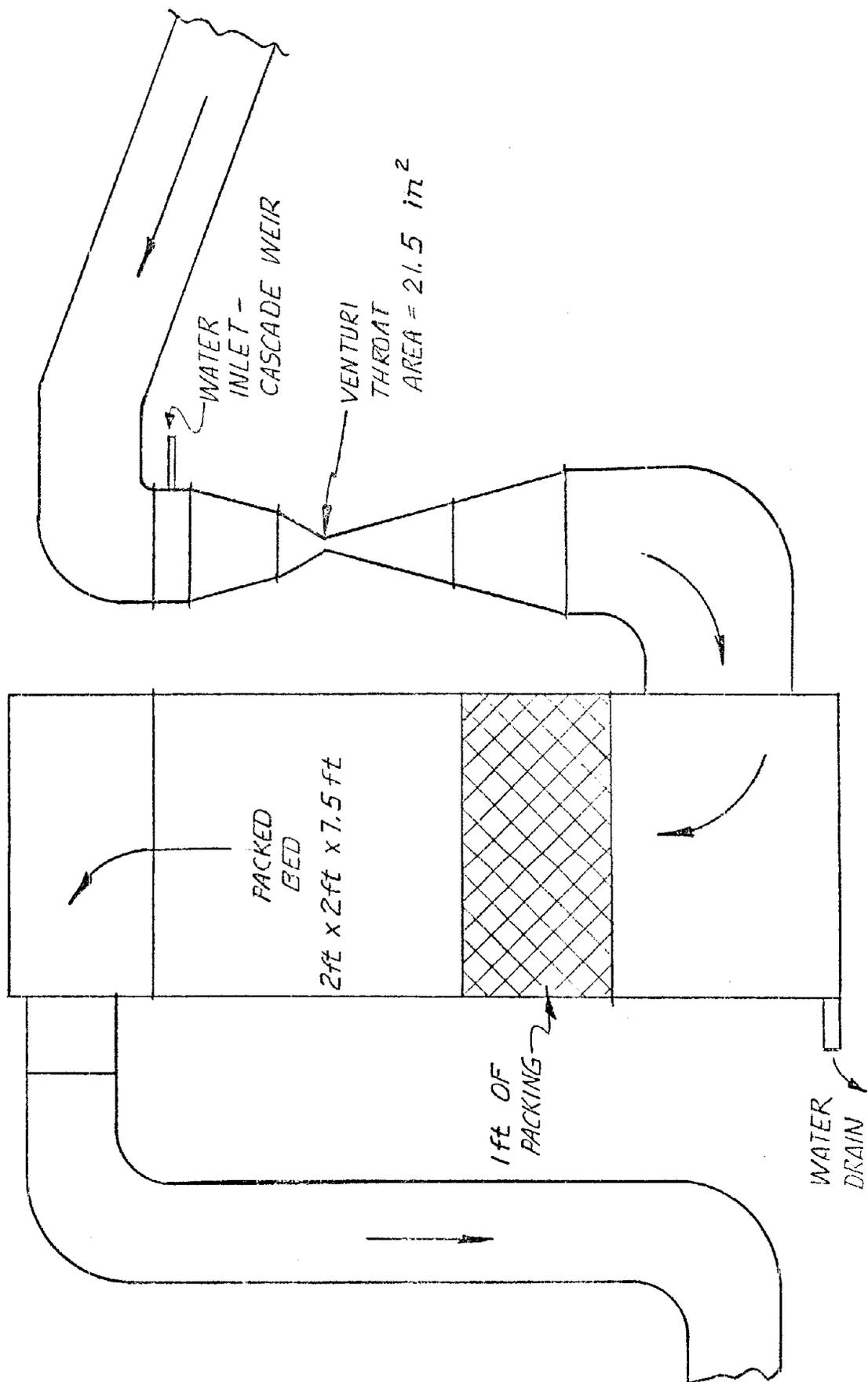


TABLE 12

Gross Penetration For A Venturi Scrubber  
For An Inlet Dust Of Mean Diameter 1.35 Microns  
And Standard Deviation 1.7

<u>Run</u>	<u>Configuration</u>	<u>Water Rate</u> <u>(gal/mcf)</u>	<u>Upstream</u>		<u>Downstream</u>		<u>Penetration</u> <u>(%)</u>
			<u>Sample No.</u>	<u>Concentration</u> <u>(mg/scm)</u>	<u>Sample No.</u>	<u>Concentration</u> <u>(mg/scm)</u>	
79	No Rods	5.0	And	40.9	And	17.0	42
			435	52.8	436	20.7	39
			438	48.8	439	18.8	39
80	No Rods	5.0	441	48.4	442	17.4	36
			And	38.1	And	16.5	43
			444	48.8	445	18.1	37
			446	52.5	447	18.5	35
			Average	47.2		18.1	38
81	No Rods	10.0	And	46.3	And	9.8	21
			449	50.2	450	10.5	21
			452	51.9	455	9.9	19
			454	52.7	457	9.0	17
			Average	50.3		9.8	19
82	Rods	5.0	459	47.4	460	21.0	44
			And	37.5	And	18.2	49
			462	44.9	463	20.5	46
			464	47.3	465	19.4	41
83	Rods	5.0	And	33.8	And	16.3	48
			467	42.4	468	17.7	42
			470	43.1	471	17.1	40
			472	43.0	473	17.1	40
			Average	42.4		18.4	43

-37b-

Table 12

FIGURE 35

VENTURI SCRUBBER

PENETRATION AS A FUNCTION OF PARTICLE DIAMETER

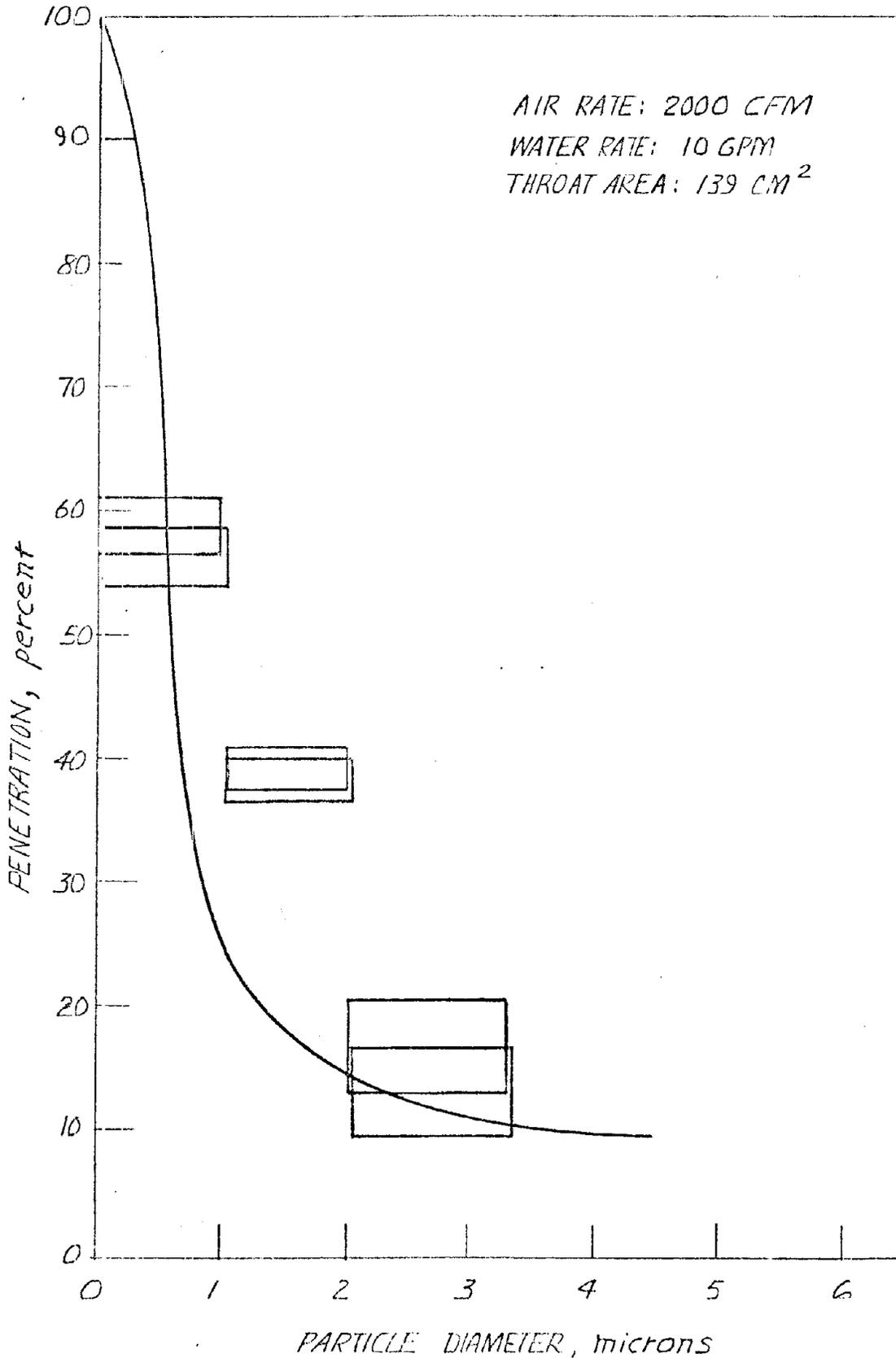


FIGURE 36

VENTURI SCRUBBER  
PENETRATION AS A FUNCTION OF PARTICLE DIAMETER

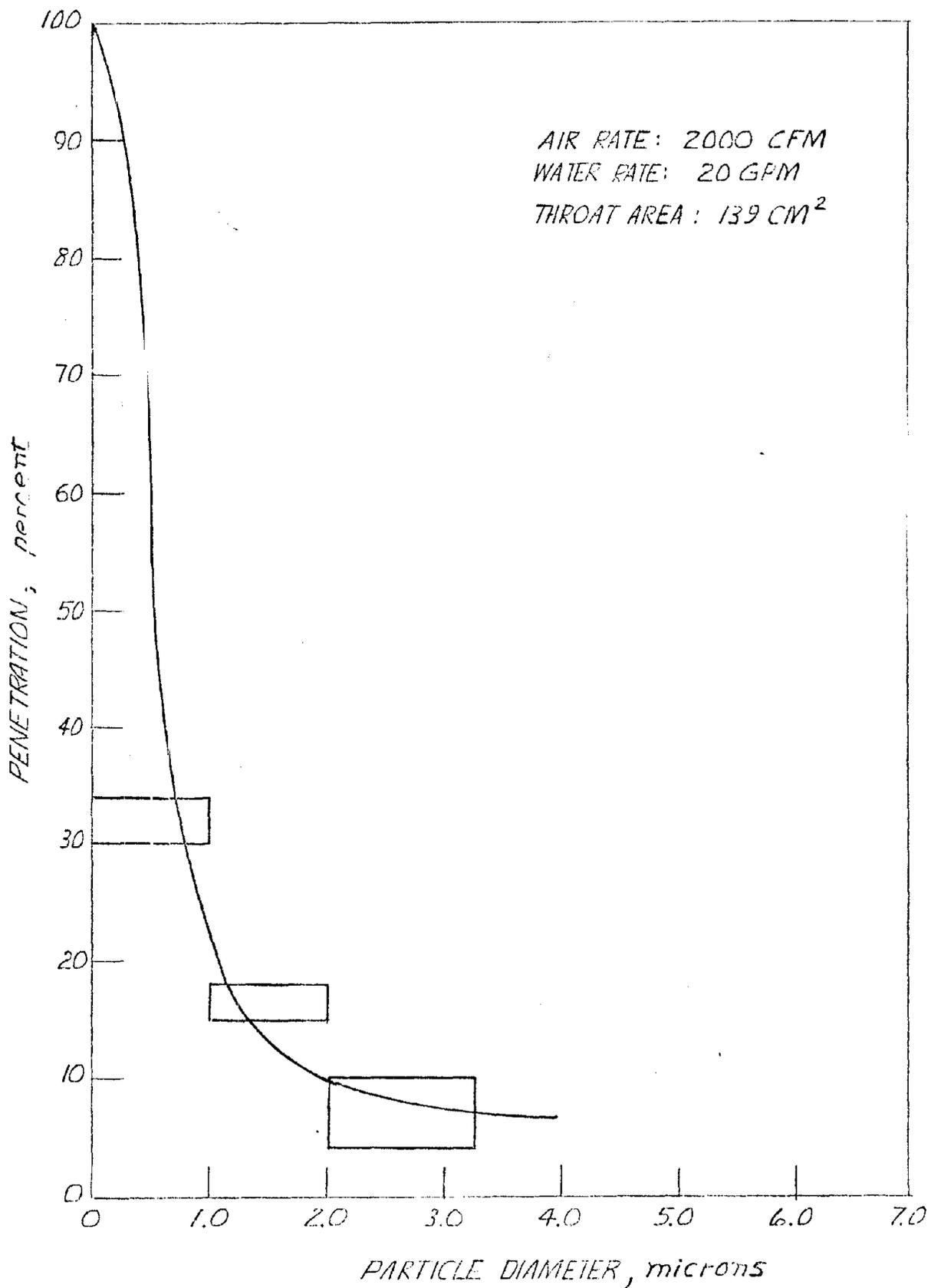
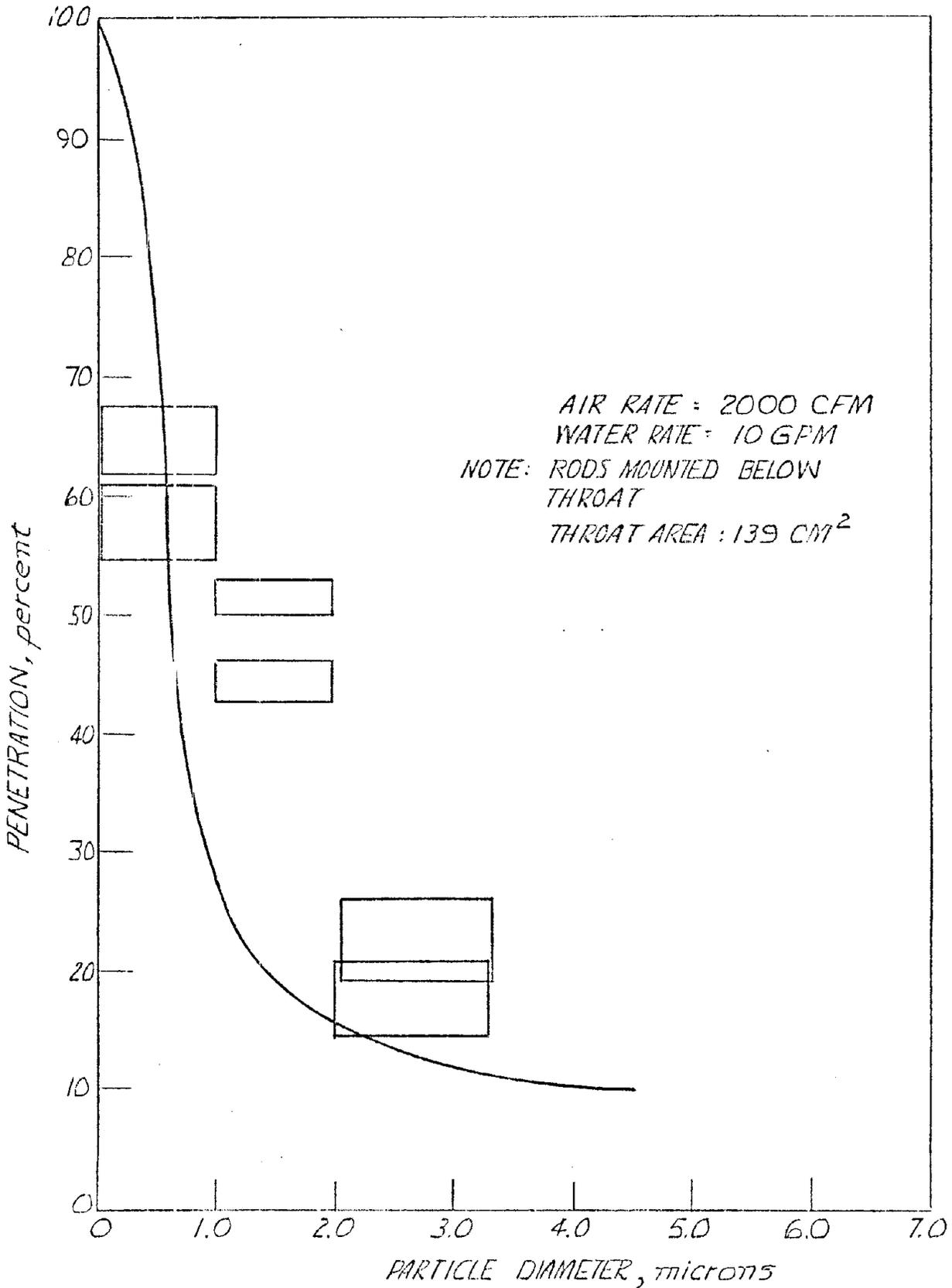


FIGURE 37

VENTURI SCRIBBER  
PENETRATION AS A FUNCTION OF PARTICLE DIAMETER



## "Ventri-Rod" Scrubber

Arrangements were originally made to test a special model of the "Ventri-Rod" scrubber. This particular unit was of interest because it was estimated to be a reasonably high efficiency venturi scrubber that was specifically designed in a low profile configuration with an overall height of approximately four feet. It was scheduled for delivery on August 15, 1970, but at the last moment the customer that was testing the unit at that time decided that he wanted to run further tests. Arrangements were therefore made to test a different unit that operated on the same mechanism but was arranged in a vertical configuration. A schematic of this unit is shown in Figure 38.

Air enters the bottom of the "Ventri-Rod" scrubber, passes through a distributor plate and then through a 7.25 in. square orifice that contains four 1.25 in. diameter horizontal rods. The net effect of these rods is to reduce the throat area to a free space 2.25 in. x 7.25 in. A nozzle is mounted immediately upstream from the "Ventri-Rod" throat. The operating conditions specified by the manufacturer for this unit are an air rate of 2,500 cfm and a water rate of 25 gpm. At these conditions the throat velocity is approximately 370 ft./sec., and the drop diameter calculated from the Nukiyama-Tanasawa equation is approximately 90 microns. Above the venturi section is a section of loose packing which functions as an entrainment separator.

The "Ventri-Rod" scrubber appeared to be an ordinary venturi scrubber and was modeled as such according to equation 5. One test was run at 2,500 cfm and 15 gpm, and three tests were run at 2,500 cfm and 25 gpm. The results of these tests are presented in Table 13 and Figures 39 and 40. As the figures show, the results correlate well with conventional venturi scrubber theory and the theoretical penetration calculated for this mechanism agrees well with the gross penetration data in Table 13. The experimental penetrations were 9.4% at 15 gpm and 5.5% at 25 gpm as compared to 8%, and 3% respectively as estimated from the integral equation. The estimated penetration of respirable dust for this scrubber is 3% at 15 gpm and 1% at 25 gpm. This is clearly a low enough penetration to make this particular scrubber technically applicable to the coal mine dust problem.

FIGURE 38

VENTRI-ROD SCRUBBER

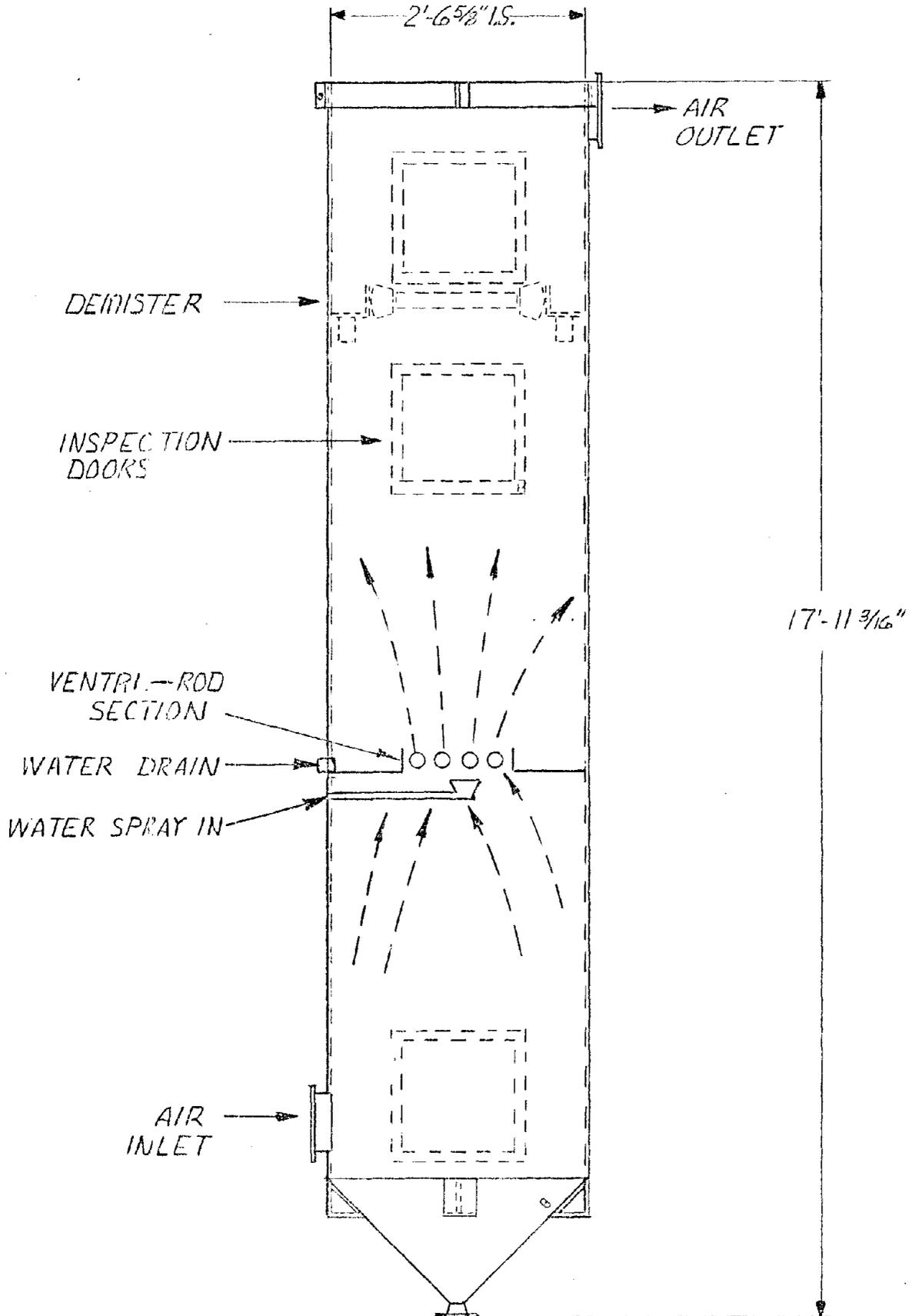


TABLE 13

Gross Penetration For A "Ventri-Rod"  
Scrubber For A Dust Of Mean Diameter 1.42 Microns  
And Standard Deviation 1.64

Run	Water Rate (Gal/mcf)	Upstream		Downstream		Penetration (%)
		Sample No.	Concentration (mg/scm)	Sample No.	Concentration (mg/scm)	
86	6	489	31.2	490	2.60	8.3
		And	23.3	And	2.70	11.6
		492	28.3	493	2.80	9.9
		494	31.0	495	2.60	8.4
		Average	28.5		2.68	9.4
87	10	And	19.5	And	1.24	6.4
		497	26.4	498	1.54	5.8
		500	31.9	501	1.74	5.5
88	10	503	34.0	504	1.76	5.2
		And	25.6	And	1.51	5.9
		506	34.3	507	1.78	5.2
89	10	And	23.4	And	1.65	7.1
		509	32.2	510	1.80	5.6
		512	35.0	513	1.75	5.0
		514	34.0	515	1.59	4.7
		Average	29.6		1.64	5.5

-38b-

FIGURE 39  
"VENTRI-ROD" SCRUBBER  
PENETRATION AS A FUNCTION OF PARTICLE DIAMETER

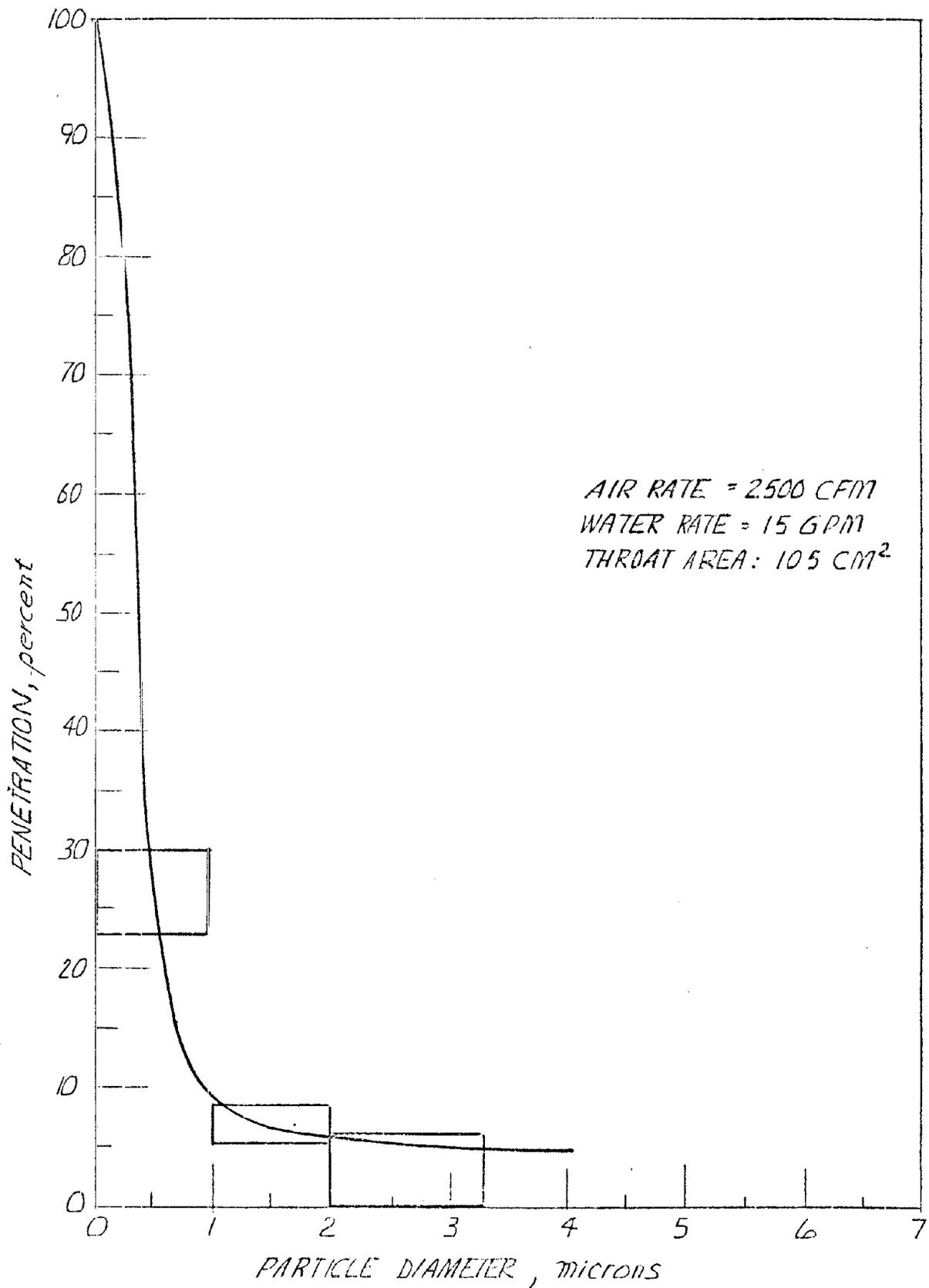
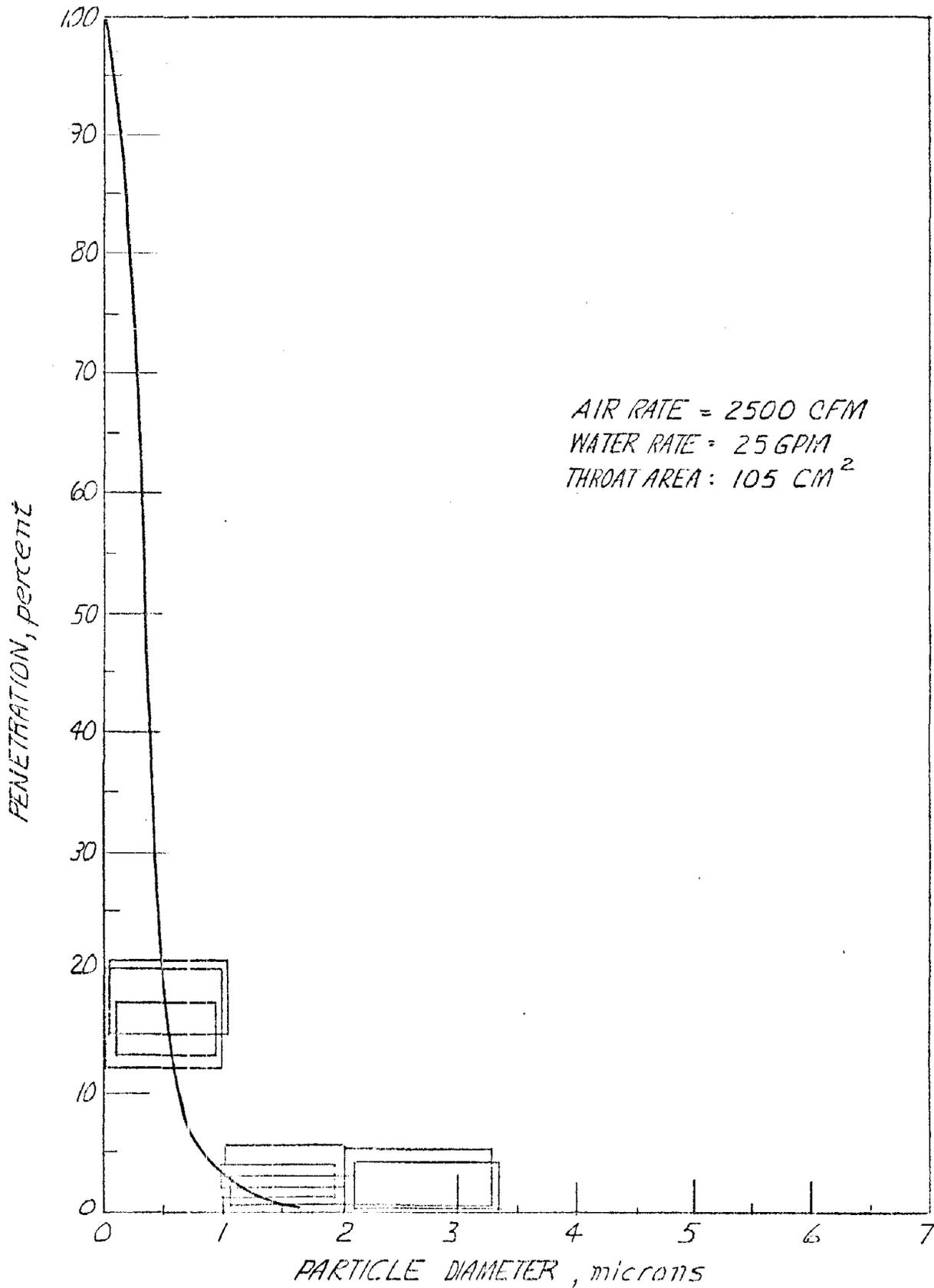


FIGURE 40  
"VENTRI-ROD" SCRUBBER  
PENETRATION AS A FUNCTION OF PARTICLE  
DIAMETER





## "Ventri-Sphere" Scrubber

The "Ventri-Sphere" scrubber was a high energy venturi scrubber. A schematic diagram of the scrubber is shown in Figure 41. Air enters the top of the unit and is accelerated through an adjustable venturi throat. Water cascades over a weir at the top and flows down the conical inlet. After the throat the air passes through a relatively long diffuser section, makes a 180° turn upward, and passes through a bed of free floating plastic spheres approximately one foot in depth.

Three tests were run on the "Ventri-Sphere" scrubber at an air rate of 1,500 cfm and a water rate of 25 gpm. The adjustable venturi throat was at the full open position and had a cross-sectional area of 11.6 square inches. The data for these tests are tabulated in Table 14 and show a gross penetration for the test dust of 1.2%. The penetration as a function of particle diameter is given in Figure 42 along with the theoretical penetration for a venturi scrubber operated at these conditions, and the theory represents the data quite well.

Two subsequent tests were conducted at 2,000 cfm and a water rate of 10 gpm. The data are presented in Table 14 and Figure 43. The gross penetration of the test dust was determined to be 2.9% experimentally, but it was necessary to use a value of  $f_a'$  equal to 0.8 in equation 8 in order to obtain the penetration function shown in Figure 43. This deviation of  $f_a'$  from 0.4 to higher values at low liquid rates was observed previously with other venturi configurations (6). It is possible that  $f_a'$  is greater than 0.4 at these low liquid rates due to the decreased probability of drop coalescence, interference and collection on the wall. It is also possible that the effect of the entrainment separator overlapped the venturi mechanism and improved the efficiency. However, the potential effect of the spheres was calculated by packed bed theory, and it did not account for the observed discrepancy.

Unfortunately, the test unit was so constructed that it was not possible to isolate the several potential mechanisms and determine which one was actually improving the performance. The distinction is, however, academic for present purposes since the respirable dust penetration according to the venturi model, is 1% for the first case (1,500 cfm, 25 gpm) and 3% for the second case (2,000 cfm, 15 gpm). Both of these penetrations are already below the desired level and the actual performance surpasses those estimated.

FIGURE 41

"VENTRI-SPHERE" SCRUBBER

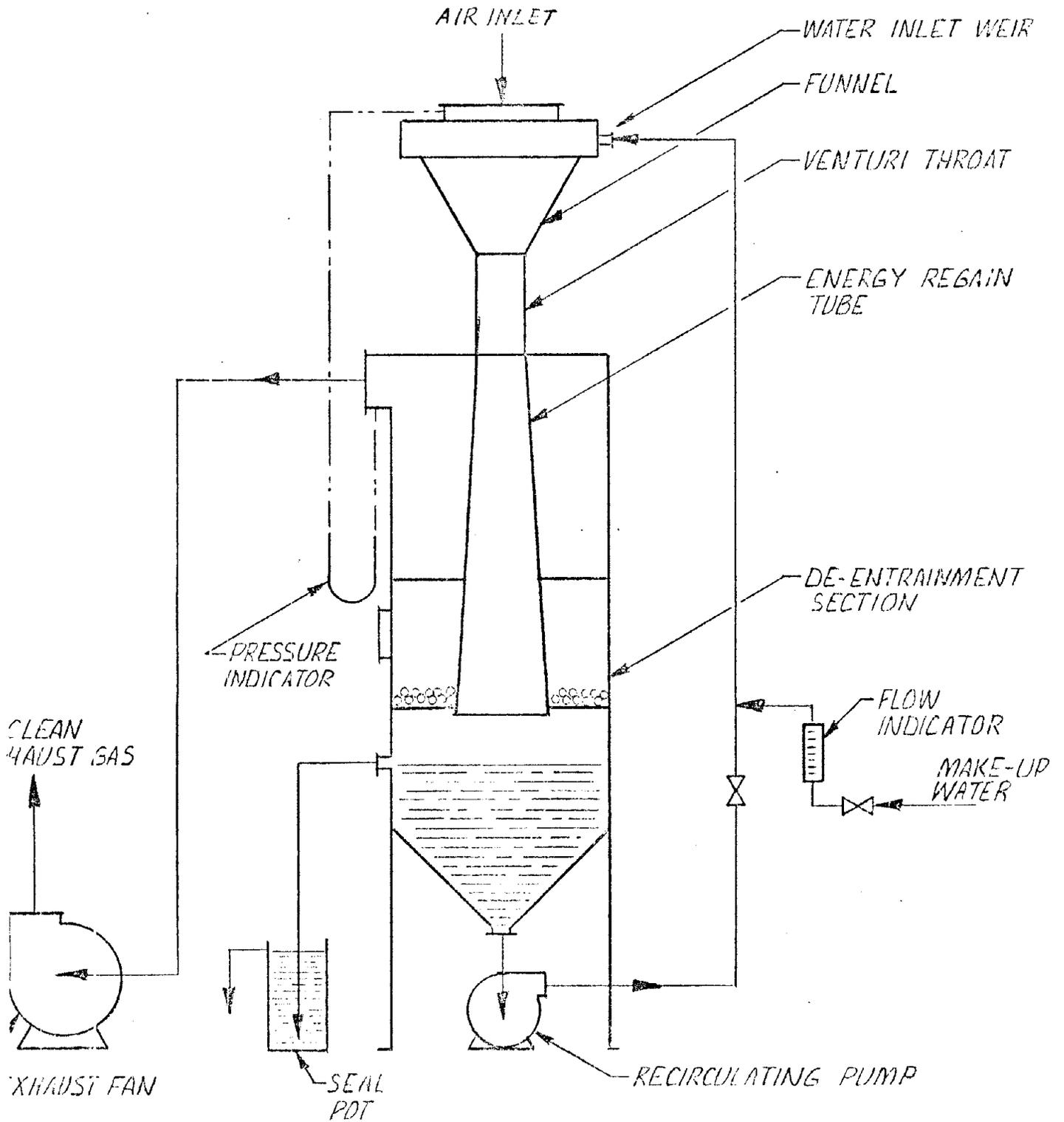


TABLE 14

Gross Penetration For A "Ventri-Sphere"  
Scrubber For An Inlet Dust of Mean Diameter  
1.44 Microns and Standard Deviation 1.7

Run	Water Rate (Gal/mcf)	Upstream		Downstream		Penetration (%)
		Sample No.	Concentration (mg/scm)	Sample No.	Concentration (mg/scm)	
95	16.7	And	48.2	And	.504	1.0
		547	58.7	548	.351	.6
		550	63.0	551	.883	1.4
96	16.7	553	59.0	554	.828	1.4
		And	52.0	And	.789	1.5
		556	64.3	557	.712	1.1
97	16.7	And	52.6	And	1.17	2.2
		559	65.9	560	.710	1.1
		562	67.6	563	.683	1.0
		Average	59.0		.737	1.2
98	5.0	565	53.1	566	1.55	2.9
		And	46.5	And	1.55	3.3
		568	56.1	569	1.45	2.6
99	5.0	And	41.0	And	1.77	4.3
		571	55.2	572	1.10	2.0
		574	56.7	575	1.48	2.6
		Average	51.4		1.48	2.9

FIGURE 42

"VENTRI - SPHERE" SCRUBBER  
PENETRATION AS A FUNCTION OF PARTICLE DIAMETER

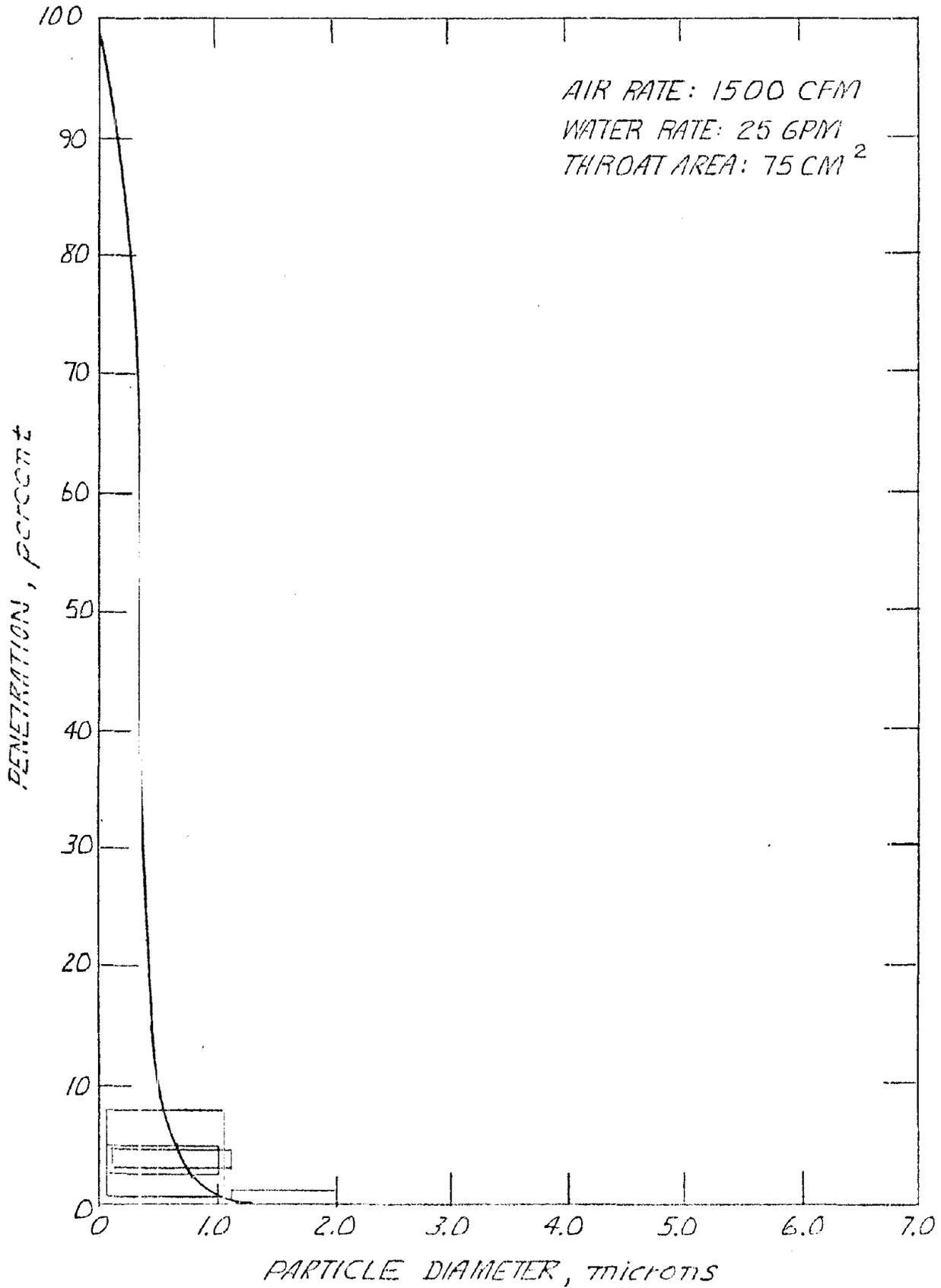
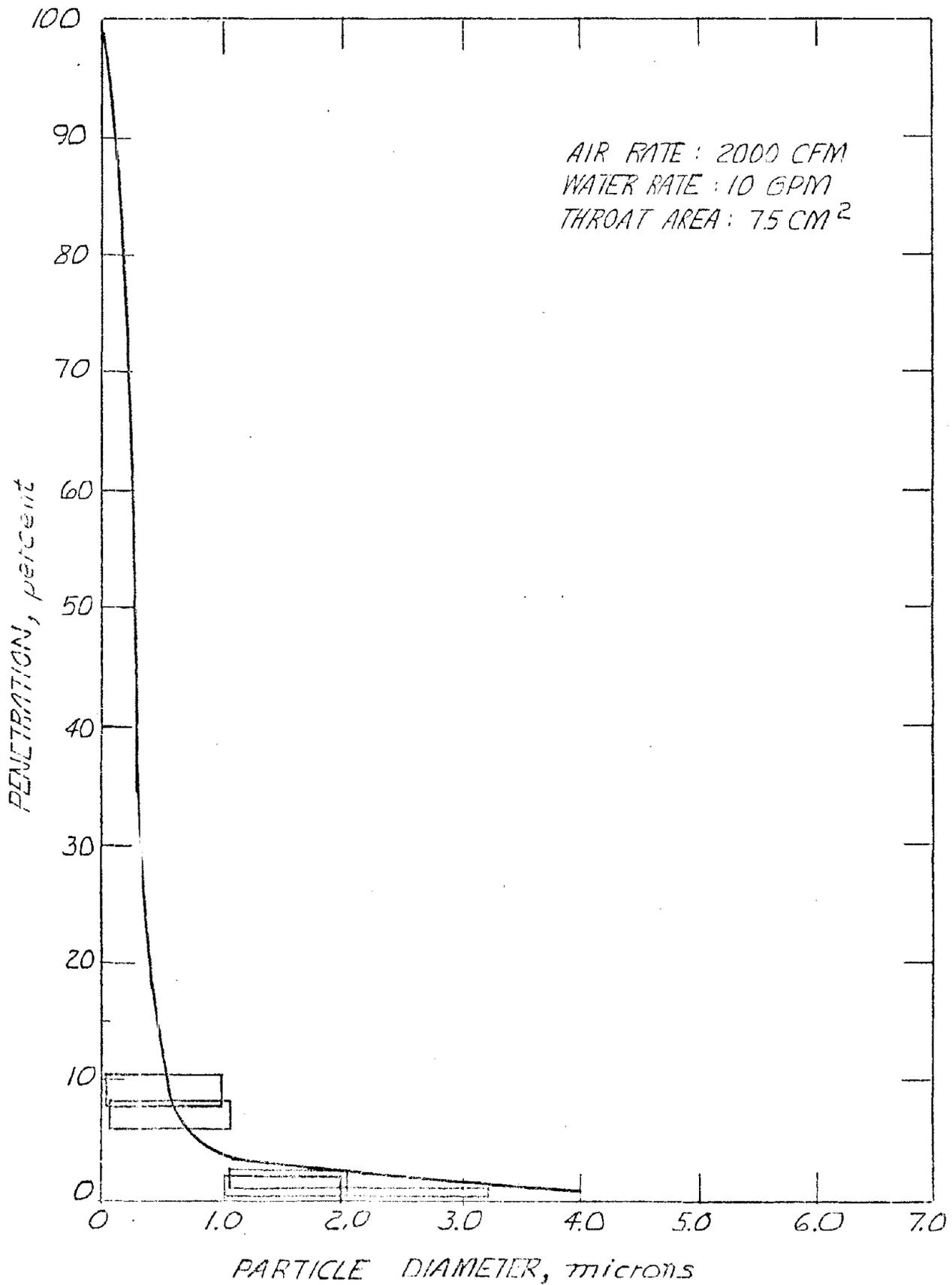


FIGURE 43

"VENTRI-SPHERE" SCRUBBER  
PENETRATION AS A FUNCTION OF PARTICLE  
DIAMETER



## EVALUATION

A reasonably conservative estimate of the respirable mine dust size distribution has indicated a mass mean diameter of 2.55 microns and a standard deviation of 1.7. It has also been estimated that it will be necessary to collect from 84 to 92% of this dust in order to achieve the required 2.0 mg/m<sup>3</sup> level.

The dust collector testing program has demonstrated that our knowledge of dust collection is adequate to both explain the performance of collection devices and to serve as a basis for their design. This knowledge leads to some general conclusions about the applicability of various types of collectors to the coal mine dust problem.

1. A dry centrifugal collector, such as the multiple cyclone, cannot achieve a performance level adequate for this application.
2. Adequate performance can certainly be achieved by porous filtration, but this method is expensive and would be difficult to implement in the constrained mine environment.
3. The elimination of the two aforementioned types of collectors leave two basic types for consideration: low energy wet dynamic collectors and the higher energy venturi scrubbers.

The wet dynamic collectors tested (packed bed, "Air Tumbler", "wetted screen", and impingement scrubber) did not demonstrate adequate performances based on the criterion established. However, design of a dust collection system for the coal mine environment may involve major revisions in the air system that would significantly alter this criterion. If a larger amount of air with a lower dust concentration were provided to the collection system, a lower performance would be required. The collectors in this general class typically have pressure drops of 10 in. H<sub>2</sub>O or less. Also, as in the case of the "wetted screen", they are often readily adaptable to the mine environment and require relatively low liquid rates (1 to 2 gal./mcf). These factors indicate that low energy wet collectors cannot be eliminated from consideration until possible revisions to the mine air system have been explored and definite performance criteria have been established.

It is apparent from the experimental results that co-current atomization, or venturi, scrubbers (the homemade venturi, "Ventri-Rod", and "Ventri-Sphere") can achieve the desired performance. As shown in Figure 9, an 8% penetration can be achieved at pressure drops as low as 10 in. H<sub>2</sub>O and water rates as low as seven gal./mcf. However, several design considerations make the use of a venturi scrubber more difficult to adapt to the mine environment than the low energy wet collectors. Venturi scrubbers typically employ higher pressure drops and higher water rates; the "Ventri-Sphere" and "Ventri-Rod" scrubbers have pressure drops of 40 in. H<sub>2</sub>O and water rates of 10 gal./mcf or more. The higher pressure drop requires an additional energy input, and the higher water rate creates an additional disposal or recirculation problem. Moreover, there is apparently no commercially available venturi scrubber that is readily adaptable to the mine environment. Venturi scrubbers are typically 15 to 20 feet tall, and redesigning for a four foot vertical space will not be a minor task. In particular, the entrainment separator must be at least as tall as the water leg required to allow the water to flow from the collector against the pressure drop.

The optimum compromise between liquid rate and pressure drop must finally be dictated by mechanical and economic consideration. However, in order to demonstrate the potential operating cost of a scrubber system operating in conjunction with a continuous miner, approximate operating costs were calculated for a 5,000 cfm system operating at 8.4 gal./mcf and 20" H<sub>2</sub>O pressure drop. Such a system would have a respirable dust penetration of 7% according to Figure 9. The estimated operating cost is itemized in Table 15 and is 3.4¢/Ton of coal produced. For a 10,000 cfm system the cost is estimated at 6.4¢/Ton.

This estimate is, of course, only an approximation. The installed cost of the system is based on typical data for above ground equipment, and the system capacity is at this point only a first order approximation. The utilities costs are based on continuous operation of the scrubber system, regardless of the operating status of the continuous miner. The cost of a self-contained liquid filtration and recirculating system has not been included in the cost of the scrubber system - cost of disposal of the liquid stream is an unknown at this time. Maintenance cost and operating life are based on typical above ground systems and could easily be different in the mine environment. All of these factors could change the operating cost, and finally, improved information on dust loading and size distribution could substantially revise the operating criteria. Nonetheless this approximate operating cost is instructive. The estimated cost is clearly neither trivial nor prohibitive in terms of the total cost of a ton of coal.

TABLE 15

ESTIMATED OPERATING COST OF A 5,000 CFM  
COAL MINE DUST COLLECTION SYSTEM

	<u>Cost \$/Year</u>
1. Straight line amortization of \$10,000 (5,000 cfm) low energy venturi scrubber system over 4 years.	\$2,500
2. Power Cost @ \$.01/kwh.	750
3. Water Cost @ \$.05/1,000 gal. and 8.4 gal./mcf.	470
4. Maintenance (at 2% of installed cost)	500
	<hr/>
Total Annual Operating Cost (480 shifts/year)	\$4,220
Total Annual Production of a Continuous Miner (480 shifts @ 250 ton/shift)	125,000 Tons
Operating Cost Per Ton	$\$4,220/125,000 = 3.4¢/\text{Ton}$

## GLOSSARY OF SYMBOLS

AEC	Concentration determined with AEC sampler, $\text{mg}/\text{m}^3$ .
C	Constant characteristic of a collector.
$d_c$	Cut diameter or diameter for which the penetration is 0.5.
$D_c$	Packing or collection unit diameter, ft. or cm.
$D_p$	Particle diameter, cm or microns ( $\mu$ ).
$D_h$	Hub diameter of a multiple cyclone, cm.
$D_o$	Outer diameter of a multiple cyclone, cm.
E	Fractional collection efficiency.
$f(D_p)$	Logarithmic normal size distribution.
K	Inertial impaction parameter, dimensionless.
L	Liquid rate, gal./mcf.
MRE	Concentration determined with MRE sample, $\text{mg}/\text{m}^3$ .
F	Total or gross penetration.
$F_t(D_p)$	Fraction of particles penetrating the collector.
r	Drop radius, cm or microns.
U	Air velocity, cm/sec. or ft./sec.
$x_g$	Count mean diameter, microns.
$x_g'$	Mass mean diameter, microns.
Z	Packing height, ft. or cm.
$\nu$	Air viscosity, poises ( $\approx 1.8 \times 10^{-4}$ for air).
$\rho$	Particle density, $\text{gm}/\text{cm}^3$ (1.35 for coal).
$\rho_g$	Air density, $\text{gm}/\text{cm}^3$ .
$c_g$	Geometric standard deviation.
c	Surface tension.



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