CONTROL OF DUST FROM CONTINUOUS COAL MINING MACHINES *

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Considerable effort has been expended in a search for an efficient means of controlling the dust generated by continuous mining machines. The methods studied fall into five basic categories: (1) treating the coal before it is mined to prevent dust from being generated; (2) control of fragmentation; (3) dust suppression; (4) collecting the dust at the mining face immediately after it is generated; and (5) increasing the mine ventilations to dilute the respirable dust to an acceptable level.

Pretreating the coal would be an attractive solution to the problem, but no consistent and economical technique has yet been set forth for doing so. Control of fragmentation would also be an attractive solution, but although there has been a great deal of effort in this direction, a satisfactory method has not yet been developed. Neither increasing mine ventilation nor providing protective equipment for mine operators really solves the dust problem. Considering the wide variety of high-efficiency dust removal equipment available, however, it seems probable that a satisfactory dust collection system could be developed.

The objectives of this investigation were to determine the size distribution and loading of respirable coal mine dust, conduct performance tests on various commercially available scrubbers, and determine the applicability of these collectors to the coal mine dust problem. Basic dust collection mechanisms were reviewed, including gravitational, inertial, diffusional, electrostatic, porous filtration, radiation and thermal gradient, magnetic, diffusophoretic, agglomeration, and particle buildup. Based on this review, it was decided that inertial collectors would be most likely to satisfy both the constraints on design and the requirements for performance in controlling respirable coal mine dust.

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. The performances of several common inertial collectors are tabulated in Table 1. The efficiencies of these collectors are typically direct functions of the inertial impaction parameter:

$$K = \frac{\rho U D_p^2}{9 \mu D_c} \tag{1}$$

(See Table 2.) Since pressure drop across the collector is a direct function of

* This study was supported by a contract from the Bureau of Mines, Department of the Interior.

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the air velocity, U, increased efficiencies require increased pressure drops. Several collectors in this general category are described below.

Cyclones

Cyclone separators are devices that employ a rotary motion of the entire gas stream to spin out dust particles under the influence of centrifugal force. The rotation is caused when the air enters the collector either through a tangential opening or through propeller-like guide vanes that 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 clean air leaves through a centrally located opening.

TABLE 1

EFFICIENCY OF DUST COLLECTORS * [1]

Dust Collector	Efficiency at 5μ* (7.07)† %	Efficiency at 2μ* (2.83)† %	Efficiency at 1μ* (1.41)† %
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
Spray tower	94	87	55
Wet impingement scrubber	97	92	80
Self-induced spray deduster	93	75	40
Venturi scrubber	99.6	99	97

* For dust of density 2.7 g/cm³.

† Multiply diameters by $\sqrt{2}$ for coal density = 1.35.

Cyclones with small diameters are more efficient than those with large ones; because of this superiority, a variety of multiple small-diameter cyclones operated in parallel have been developed. For the particular case of a cyclone with an axial inlet or "hub" at the center,[2] the efficiency is given by:

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

Curved Passages

A variety of dust collectors utilize curved passages of some sort to turn the gas stream and cause the dust particle to impact on an obstacle. Examples of this type of collector are louvered or deflector collectors, zigzag or corrugated

TABLE 2

EXPERIMENTAL RESULTS

Scrubber	Test Dust Size		Test Dust Penetration (%)				Estimated Penetration (%)	
Liquid Rate, gal/mcf; Throat or Impaction Velocity, ft/sec; Pressure Drop, in H_2O	Mean Diameter (Microns)	Standard Deviation	0–1 Microns	1–2 Microns	2–3.3 Microns	Total	Test Dust	Respirable Dust
Multiple cyclone								
0; 50; 6	1.50	1.70	89–100	70–89	50–83	76	79	53
Packed bed								
0; —; 8	1.82	1.68	100	36–53	8–25	39	41	25
2; —; 8	1.44	1.74	35–100	20–42	8–30	33	50	25
Impingement scrubber								
8 top, 8 bottom; 61; 6	1.44	1.70	65–77	43–50	6–14	41	48	27
8 top, 0 bottom; 61; 6	1.44	1.70	56–76	44–56	10–15	44	48	27
Wetted screen								
0.72; 58; —	1.50	1.80	72–100	40–51	12–34	54	56	35
Venturi with rods in throat								
6; 370; 39	1.42	1.64	23–30	5–8	0–6	9.4	3	3
10; 370; 40	1.42	1.64	12–21	0–6	0–6	5.5	3	1
Venturi with marble bed entrainment separator								
16.7; 310; 43	1.44	1.70	0–8	0–1	0	1.2	2	<1
5.0; 410; 39	1.44	1.70	7–10	0–2	0–1	2.9	5	3

passages, and beds packed with massive shapes (as distinguished from fibers). In the packed beds, collection is caused essentially by the flow of the air through a multitude of tortuous, curved passages. As the air turns through these passages, the dust particles are impacted on the solid or liquid collection surfaces by the inertial action.

The penetration (the additive complement of efficiency) as a function of particle diameter for a packed bed can be described [3] by the equation

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

Impingement of Air Jets on Liquid or Solid Surfaces

When a jet impinges on a surface, it changes direction. The particles present in the air are spun out of the air stream and 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 1. 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.

In the case of impingement on liquid, there may be additional factors to consider, as in the case of sieve plates, in which 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 that 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.[4] Other types of plate or tray equipment, such as bubble caps, ballast trays, marble beds, and others, also involve this mechanism.

Impaction on Obstacles

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 inertia 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 that 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, defined by Equation 1. A further refinement in this parameter is the inclusion of the Cunningham slip correction factor, omitted here for simplicity. It causes an increase in K of about 15% for one-micron diameter particles and increases for smaller particles also, but it causes decreases for larger ones.

The two right-hand curves in FIGURE 1 show 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 1 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

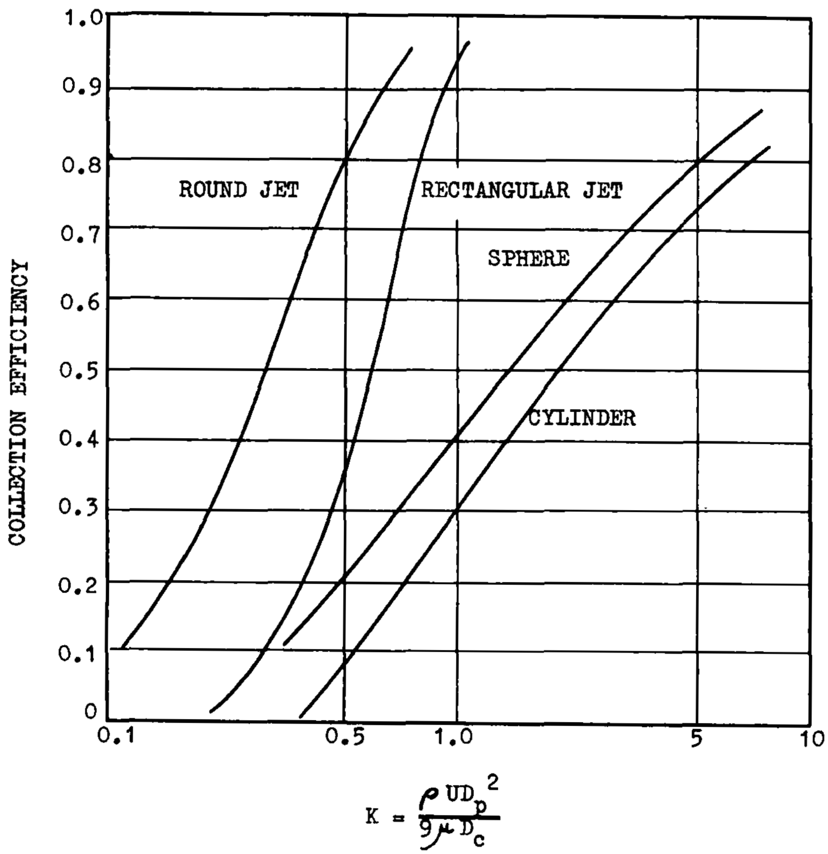

FIGURE 1. Particle collection efficiency versus impaction parameter for jets and bodies.

velocity to collector diameter would have to be at least 5×10^4 sec^{-1} in order to obtain 50% efficiency in an encounter with a cylindrical collector. Thus, if the air velocity were 100 feet per second (fps), the cylinder diameter would have to be 0.024 inches.

Impaction on liquid drops as furnished by sprays or by the atomizing action of a high velocity air stream impinging on a liquid surface is 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 1, 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.

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 fps. 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 Equations 5 and 6.

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

In order to calculate the impaction parameter, it is necessary to know the diameter of the spherical collector, in this case, the water droplet. Drop diameter has been correlated previously by Nukiyama and Tanasawa [9] as a function of gas velocity and liquid rate. This correlation for air and water at standard conditions is:

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

for velocities in the 200–600 fps range.

The final term needed to solve Equation 5 is f_a', the velocity ratio for atomization. This is the ratio between the drop velocity, relative to the air velocity, and the air velocity; it seems to be about 0.4, based on collection data in typical operating ranges. 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. The velocity ratio for atomization can vary significantly, however, depending upon air velocity, liquid rate, and the method of water injection.

COLLECTION EFFICIENCY REQUIREMENTS

In order to determine the applicability to the coal mine dust problem of a collector based on one of the mechanisms described above, it is necessary to know the size distribution, $f(D_p)$, and the total concentration of the dust to be collected. If these factors are known, the total dust penetrating the collector can be calculated from the integral:

$$P = \int_0^\infty P_t(D_p)\, f(D_p)\, dD_p \qquad (7)$$

Based on data provided by the Bureau of Mines and other sources,[7] the total float dust would appear to have the distribution shown in FIGURE 2. By multiplying this size distribution by the penetration function for an AEC type personal sampler (as shown in FIGURE 3) and evaluating Equation 7 over discrete size ranges, one can generate an estimated cumulative size distribution for respirable dust as shown in FIGURE 2. Available data indicate that the AEC respirable dust loading might be 10 milligrams per cubic meter of air (mg/m^3), or 16 mg/m^3 on the basis of the MRE type sampler. Thus, the overall penetration must be 0.125 in order to achieve an outlet concentration of 2 mg/m^3. It is assumed that if this efficiency were achieved on the respirable fraction, all of the larger dust particles would also be captured.

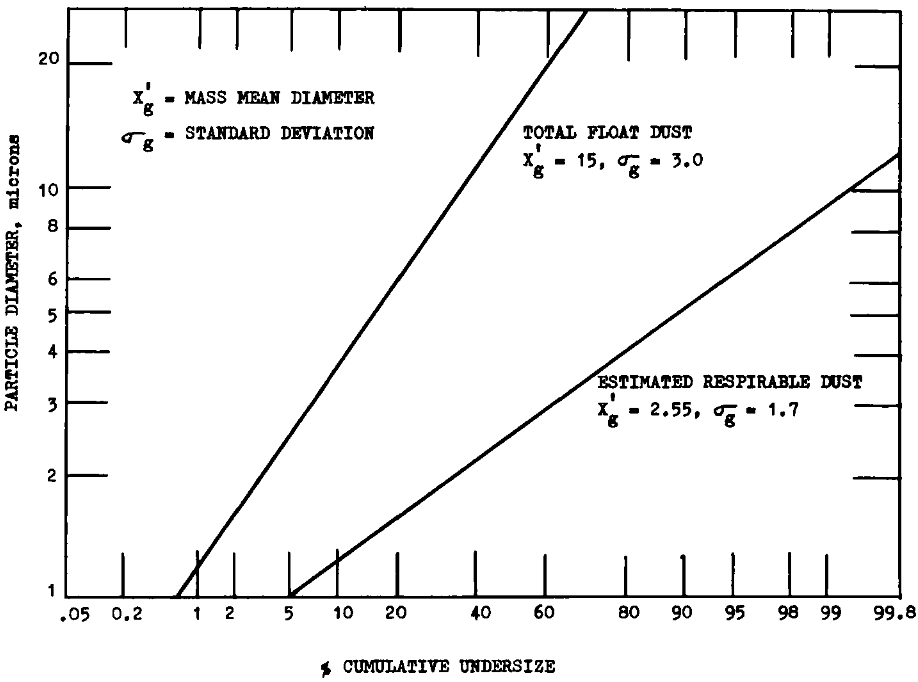

FIGURE 2. Size distributions of gross dust and respirable fraction.

It is of interest to characterize the performance of a given collector on the respirable dust as simply as possible. One notes from Equations 2, 3, and 4 that several of the collectors discussed can be described in terms of a single constant grouping that reflects operating conditions and physical properties. For one of these collectors, a knowledge of the collection efficiency at one diameter would characterize the unit completely. Thus, if, in particular, one specified the cut diameter, or diameter for which the efficiency was 50%, the collector would be specified. FIGURE 4 was generated by evaluating Equation 7 for several values of the cut diameter for the different collector characteristics. From these curves, it is clear that the collectors must have cut diameters on the

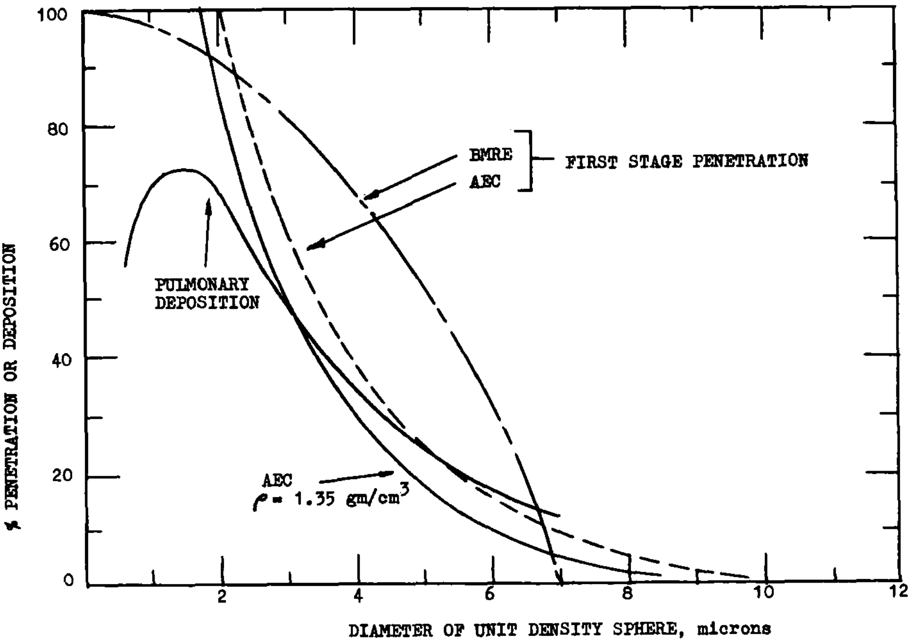

FIGURE 3. Comparison of recommended respirable size criteria with pulmonary deposition curve.

order of from 0.8–1.5 microns in order to achieve the necessary efficiency.

As can be seen from Equation 5, the venturi scrubber is somewhat more complicated, since it must be characterized by two parameters reflecting the liquid rate and throat velocity. Equation 7 was evaluated using Equation 5 and several values of liquid rate and throat velocity to generate FIGURE 5.

FIGURE 5 is, to some extent, an oversimplification. Pressure drop was calculated on the basis of the energy required to accelerate the liquid to the throat velocity. In practice, the pressure drop is somewhat less than that. Also, a velocity ratio for atomization of 0.4 was used in the calculation, but it is known that well-designed venturi scrubbers have higher velocity ratios at lower liquid rates and higher throat velocities. Nevertheless, the calculation does serve to indicate the operating ranges required to satisfy the coal dust collection criterion.

TEST APPARATUS AND ANALYTICAL METHODS

A discussion of analytical methods is not a principal concern of this paper. A few of the methods used are mentioned here because they are new or instructive to individuals specifically interested in the problems of generating and measuring respirable coal dust. Persons interested in a more complete description of the test apparatus and analytical methods are referred to the Bureau of Mines state-of-the-art study.[7]

To test the selected types of dust collection equipment, 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 with a suction pressure of 54 inches of water at 3,000 cubic feet per minute (cfm).

A standard live bin feeder was used to meter the coal into the dust feeder system. The feeder had a capacity of 100–1,000 grams per minute of coal. The dust was fed into the inlet of a 700 cfm blower and the blower exhaust conveyed to a cyclone. 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. The oversize dust was collected in a drum mounted below the cyclone, and the undersize dust was conveyed out of the top of the cyclone by a duct section.

The dust stream itself was approximately 150 cfm, whereas the overall air

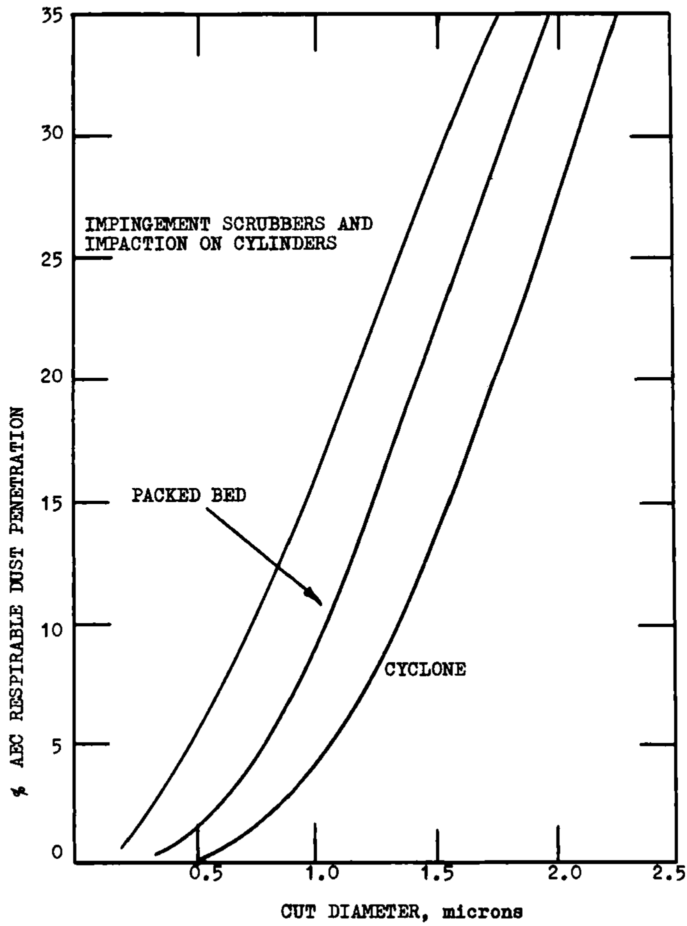

FIGURE 4. Respirable dust penetration versus cut diameter.

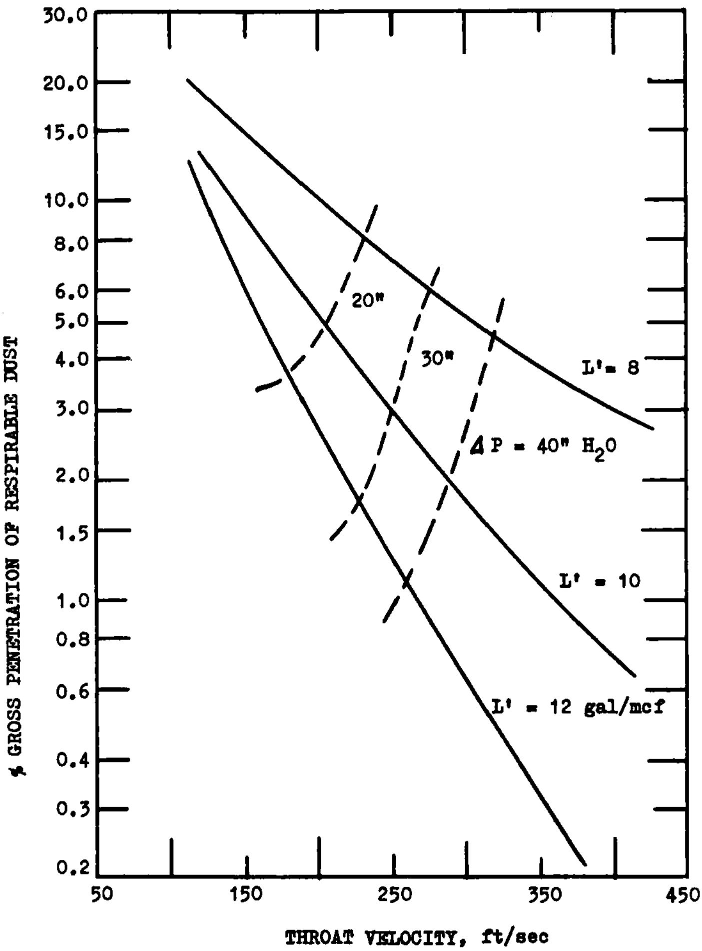

FIGURE 5. Penetration of respirable dust for a venturi scrubber.

intake stream ranged from 1,500–3,000 cfm. The intake section consisted of two-foot-square atmospheric filters to eliminate background dust. 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 feet 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. In this manner, homogeneous respirable dust streams with concentrations ranging from 10–70 mg/m^3 were generated for the dust collector tests.

At the beginning of this investigation, there was a great deal of concern that the collection efficiency on coal dust of a given scrubber might be dependent upon surface properties of the dust and that a given scrubber might therefore perform at a significantly different level 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.

Different coals generate different amounts of respirable dust and will therefore require different collector performances in order to meet the same output criteria. According to inertial impaction theory, however, the only knowledge of a given dust necessary to determine the performance of a given collector on that dust is the loading and aerodynamic 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. From this point forward, therefore, no distinction will be made between the various types of coal tested.

Size distribution determinations were conducted with an Andersen sampler, a schematic of which is shown in FIGURE 6. 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 6.

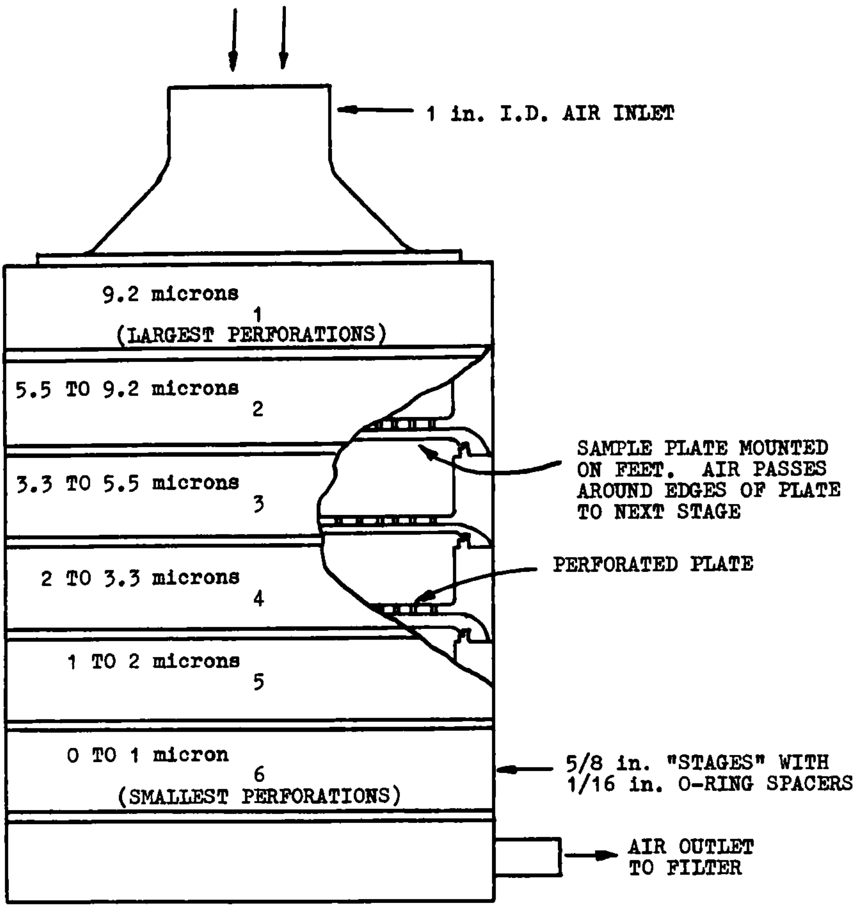

FIGURE 6. Andersen sampler.

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 7. A one-inch diameter probe was used, as suggested by the manufacturer, and a series of interchangeable tips with various inside diameters were used, so that isokinetic samples could be taken at one cfm at various overall duct air rates.

Conventional filter samples were taken simultaneously with the Andersen samples, and the total concentrations collected by the two methods were compared as a check. Moreover, the upstream and downstream Andersen samples were 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.

EXPERIMENTAL RESULTS

At the outset of the investigation, information was requested from 35 manufacturers of dust collection equipment. This information was evaluated to determine if any collectors were available that were immediately suited to the coal dust problem and to select pilot-scale units for experimental evaluation. Eight pilot units were selected for tests in order to demonstrate the predictability of the results and the possibility of achieving the desired efficiency on respirable coal dust. The results of six of these tests are summarized in TABLE 2; they indicate that the required collection efficiencies can be achieved and that the performance of a collector is reasonably predictable. The other two scrubbers tested, a wet dynamic cyclone and a conventional venturi, are not discussed here because of limitations in space, but they are discussed in the state-of-the-art study. To illustrate the results, collection efficiency data and theory for two scrubbers are presented in FIGURES 8 and 9. Following are brief physical descriptions of the collectors studied.

Multiple Cyclone

The partial reverse multiple cyclone separator consisted of a bank of 46 1$\frac{13}{16}$ inch-diameter cyclones. Each cyclone was considered to be a straight-through cyclone with fixed vanes. The dust was removed through a slot at the wall, and the air exited through a centrally located tube.

Packed Bed

The scrubber was constructed of $\frac{1}{16}$ inch galvanized steel in three sections with one-inch angle iron flanges. The unit was two feet square in cross section and 7.5 feet tall. The air was introduced through a 12-inch diameter intake in the bottom section and passed through a three-foot deep section of 1.5 inch O.D. polypropylene Pall rings that 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

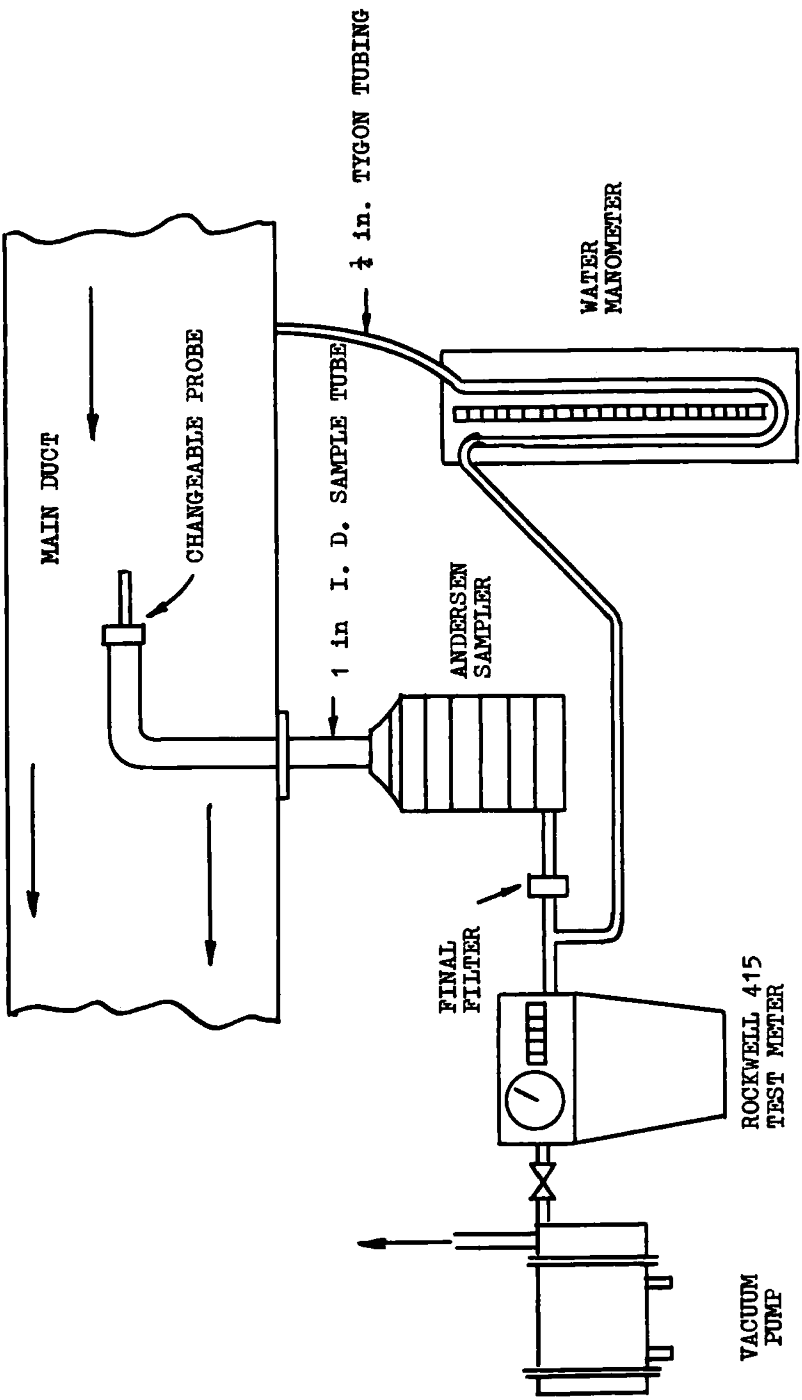

FIGURE 7. Andersen sampler in sampling position.

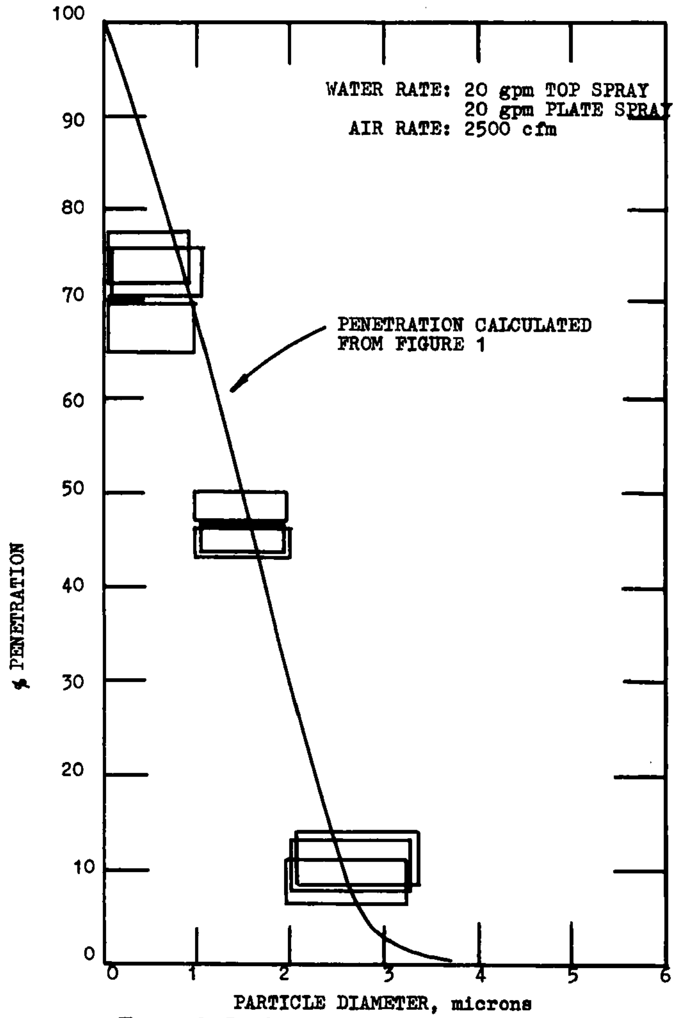

FIGURE 8. Impingement scrubber performance.

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 rings served as an entrainment separator to remove the water droplets before the air stream passed out a 12-inch diameter exit duct.

The scrubber was operated at 2000 cfm with no water and with a water rate of two gallons per thousand cubic feet of air (gal/mcf).

Impingement Scrubber

The impingement scrubber had a classical impingement design. Air enters at the bottom of the cylindrical scrubber through a tangential intake that 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 feet, and the area of each impingement plate was approximately three square feet. Each plate was perforated with 3/32-inch diameter holes on 3/16-inch centers. The total open area of the plate cross section was approximately 22% of the total area, or 0.68 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 to operate at

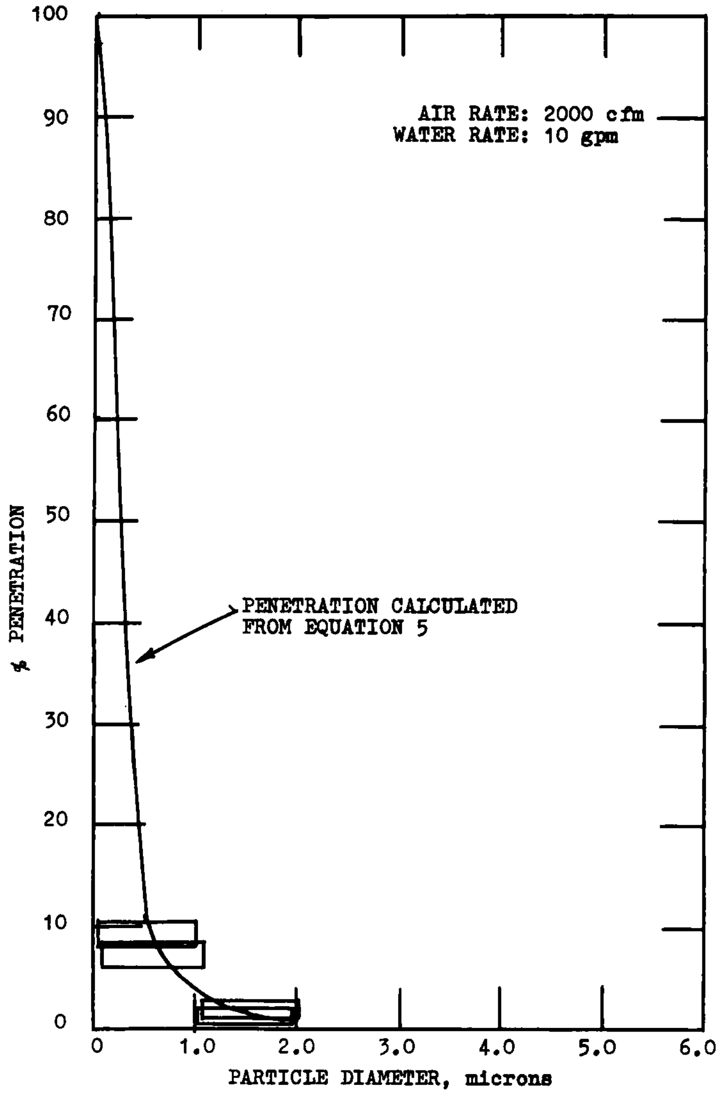

FIGURE 9. Venturi scrubber performance.

an air rate of 2,500 cfm, with a water rate of 25 gpm flowing countercurrently over the two plates. 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, enhancing the cyclone effect created at the air inlet. Immediately above the top plate was a set of rotating vanes that served as a water eliminator.

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 1. As hypothesized, the bottom plate spray does not appear to be instrumental in the collection of insoluble respirable particles. Results for one case are shown graphically in FIGURE 8.

Wetted Screen

The wetted screen scrubber is a wet dynamic scrubber. The functioning mechanism is 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 is 11.25 inches in diameter and has 22 "peaks," and the wires of the screen are 0.5 mm in diameter and 1.6 mm apart. It is interesting to note that the "wire density" is almost exactly two. In other words, the total number of wires times the wire diameter is sufficiently large to cover the cross section of the scrubber two times. This wetted screen is followed by a horizontal cyclone functioning as an entrainment separator, which is followed in turn by an axial fan. The model used for the wetted screen was impaction on cylinders, and the "wire density" was considered to have the effect of squaring the penetration function. The scrubber was operated at 2400 cfm and 1.8 gpm.

Venturi Scrubbers

The first venturi scrubber tested was a high energy unit whose principal feature is a venturi "throat" consisting of a 7.25-inch-square orifice partially blocked off by four 1.25-inch-diameter rods. The scrubber body is a vertical vessel about 18 feet long. The air stream enters at the bottom and passes through the throat, which has a spray nozzle mounted immediately before it. Above the venturi section is a void section followed by a demister for water elimination.

The second venturi scrubber tested was a high energy unit. The venturi features a conical inlet with the water overflowing onto the conical wall rather than being injected through a spray nozzle. The venturi is mounted vertically, inside of and concentric to the water eliminator vessel. The air stream makes a 180° turn at the outlet of the venturi and passes upward through a bed of free-floating plastic spheres. The performance curve is shown in FIGURE 9.

CONCLUSIONS

At the outset of this investigation, the principal objective was to find an existing dust collector that would reduce the dust generated by continuous mining machines to the required level. There appears to be no dust collector available that satisfies that objective, primarily because no commercially available equipment exists that will immediately fit the physical constraints of the mine environment. The study did, however, answer several questions that point the way to a solution to the problem.

First and most important, our state-of-the-art knowledge of dust collection mechanisms is sufficient to serve as a basis for design of a dust collection system. The results further indicate that a venturi scrubber operating with a pressure drop of about 20–25 inches of water would satisfy the collection criterion if our estimate of the dust loading and size distribution is approximately correct.

Second, dust collection is, in most commercial equipment, an inertial phenomenon. Thus, the only variables that must be specified in order to design a dust collector are the dust concentration, size distribution, and particle density, as well as the air flow to be treated. Within practical limits, a knowledge of the surface properties or composition of the coal is not important. A given dust collector will, of course, achieve different efficiencies on coal dusts from different mines, but this result rests entirely on the differences in aerodynamic size distribution in the various situations.

It is now worthwhile to note that the sub-five-micron size distribution range is the region of real interest. As can be seen from the experimental results, the efficiency of inertial collectors decays exponentially in this range. Thus, data showing the dust concentration below 2 microns is essential in any attempt to design a dust collector. In designing to achieve an outlet concentration of 2 mg/m^3, knowing if the total dust concentration is 100 or 1000 mg/m^3 is relatively unimportant to the design of the collector, although it is obviously important in terms of the problem of ultimate disposal of the dust. Knowing if the dust concentration below 1 micron is 1 or 10 mg/m^3, however, is crucial.

Finally, given that the necessary data on the dust are available or can be obtained and that our knowledge of dust collection mechanisms is adequate, the problem is reduced to one of arriving at a mechanical design that can meet the physical constraints of the mine environment. If one contemplates a dust collection system that will treat the total working face air rate, say 10,000 cfm, a typical commercial collector to process this volume would displace about 200 cubic feet. If one adds to the basic collector a water handling system, an air mover and motor, and a vehicle frame and drive system to provide some degree of mobility, the total package size is not insignificant when placed in the space that might typically be available in a mine entry. Thus, the thrust of the effort to design a dust collection system to operate in conjunction with continuous mining machines should be a mechanical design for greatest economy in equipment size.

Acknowledgments

The experimental work described in this presentation was performed while the authors were associated with the Garrett Research and Development Company, La Verne, California. The authors gratefully acknowledge the cooperation of Garrett Research in the publication of the study.

Dr. Seymour Calvert, of Riverside, California, acting as a consultant to Garrett Research, was a principal collaborator in the original investigation for the Bureau. His contributions are gratefully acknowledged.

NOTATIONS

C	Constant characteristic of a collector	$P_t(D_p)$	Fraction of particles of diameter D_p penetrating the collector
D_c	Packing or collection unit diameter, ft or cm	U	Air velocity, cm/sec or ft/sec
D_p	Particle diameter, cm or microns (μ)	X	Ratio of cyclone hub diameter to cyclone outer wall diameter
E	Fractional collection efficiency		
E_a'	Collection efficiency for particles of diameter a	X_g'	Mass mean diameter, microns
		Z	Packing height, ft or cm
$f(D_p)$	Logarithmic normal size distribution	μ	Air viscosity, poises ($\cong 1.8 \times 10^{-4}$ for air)
K	Inertial impaction parameter, dimensionless	ρ	Particle density, gm/cm^3 (1.35 for coal)
L	Liquid rate, gal/mcf	σ_g	Geometric standard deviation
P	Total fractional penetration	σ	Surface tension

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