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Deposition of Respirable Coal Dust in an Airway

By Welby G. Courtney, Lung Cheng, and Edward F. Divers

UNITED STATES DEPARTMENT OF THE INTERIOR

Report of Investigations 9041

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°F	degree Fahrenheit	L/min	liter per minute
ft	foot	$mg/(ft^2 \cdot min)$	milligram per square foot per minute
ft^2	square foot	mg/ft^3	milligram per cubic foot
ft/min	foot per minute	mg/m^3	milligram per cubic meter
ft^3/min	cubic foot per minute	min	minute
g/cm^3	gram per cubic centimeter	mm	millimeter
in	inch	µm	micrometer
lb	pound	pct	percent

SYMBOLS USED IN THIS REPORT

A = cross-sectional area of airway (ft^2)

c = local dust concentration (mg/ft^3)

D = particle diameter

dm/dt = rate of dust deposition per unit area along airway [$mg/(ft^2 \cdot min)$]

g = acceleration of gravity

k = dust deposition rate constant (ft/min)

K = slope

k_{exp} = "mean" value corresponding to the particle size distribution in the respirable size range.

L = deposition surface across airway (ft)

η = air viscosity

ρ = particle density

σ = air density

R_s = side rate

R_f = floor rate

R_r = roof rate

v = air velocity (ft/min)

x = distance along airway (ft)

DEPOSITION OF RESPIRABLE COAL DUST IN AN AIRWAY

By Welby G. Courtney,[1] Lung Cheng,[2] and Edward F. Divers[3]

ABSTRACT

Because of the inherent safety problem associated with the deposition of airborne respirable dust onto the floor and other airway surfaces, the Bureau of Mines investigated the rate of reduction of airborne respirable dust in an airway due to deposition of the particles onto the surfaces of the airway. The effects of relative humidity and air velocity on the deposition rate were examined. It was found that the deposition rate was comparable in magnitude with the Stokes sedimentation rate and that it was independent of relative humidity. However, near the dust source the deposition rate depended significantly upon the air velocity, with such dependence decreasing with increasing distance from the dust source. In addition, the size distribution of the airborne particles was approximately constant along the first 300 ft of the airway, indicating that it was not merely the larger (heavier) particles that were being deposited. These results suggest that deposition, though comparable with the Stokes sedimentation rate in magnitude, does not follow a simple Stokes-type process, and that the process of deposition remains to be explained.

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INTRODUCTION

The coal dust that is inevitably formed during mining operations and becomes entrained by the ventilation airstream tends to deposit onto the floor and other surfaces of the mine airway. Deposition of the respirable component of the airborne dust (particles less than 10 µm nominal diameter) decreases the health hazard of downstream personnel but increases the safety hazard in that a coal-dust deposit can be reentrained during a methane explosion and initiate a violent coal-dust explosion.

The extent of the health or safety problem depends upon the rate of deposition of the airborne dust particles onto surfaces of the mine airway. Consider a monodisperse dust cloud being passed along a rectangular airway by an airstream. Mass balance in a control volume along the airway (fig. 1) requires that the rate of decrease of the airborne dust concentration be equal to the rate of deposition of the airborne particles onto surfaces of the airway,[4] and

$$vAc - \left[vAc + \frac{d(vAc)}{dx} dx \right] = \frac{dm}{dt} L \, dx$$

or

$$-vA \frac{dc}{dx} = L \frac{dm}{dt} \qquad (1)$$

where v = air velocity (ft/min),

A = cross-sectional area of airway (ft^2),

c = local dust concentration (mg/ft^3),

x = distance along airway (ft),

dm/dt = rate of dust deposition per unit area along airway [mg/(ft^2·min)],

and L = deposition surface across airway (ft).

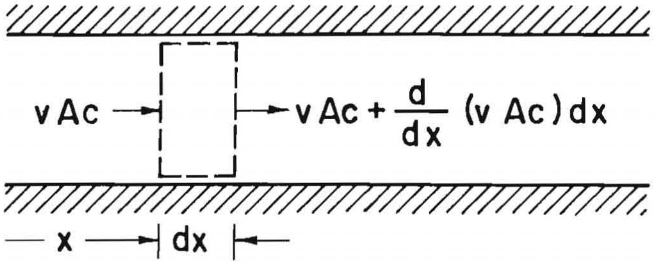

FIGURE 1.—Control volume in airway.

If dust particles deposit onto the roof, ribs, and floor at equal rates, then L is the perimeter of the airway. When deposition occurs only on the floor, then L is the width of the airway.

If the rate of dust deposition depends upon the local dust concentration, then

$$dm/dt = kc$$

where k = dust deposition rate constant (ft/min).

Equation 1 then becomes

$$-Av \frac{dc}{dx} = Lkc$$

and $$c/c_o = \exp \{-L/Av) kx\}, \qquad (2)$$

where c_o is the dust concentration at the dust source.

The numerical value of k (the deposition rate constant) will depend upon sedimentation, diffusion, thermal, electrostatic, and other phenomena. For respirable-size particles (and larger particles), diffusion, thermal, and electrostatic effects probably are negligible and the deposition rate will probably depend only on a sedimentation type of process.

Dawes and Slack (1)[5] investigated the rate of decrease of respirable-size (and larger) coal dust particles from a turbulent airstream in a laboratory smooth-walled wind tunnel and observed the

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[4] Dust reentrainment is assumed to be negligible.

[5] Underlined numbers in parentheses refer to items in the list of references at the end of this report.

exponential decrease of concentration with distance noted in equation 2. They assumed that deposition involved deposition in the laminary boundary layer adjacent to the "well-mixed" turbulent airstream and took k as the Stokes terminal sedimentation velocity

$$k_{St} = \{(\rho-\sigma)g/18\eta\}D^2, \qquad (3)$$

where ρ = particle density,

σ = air density,

g = acceleration of gravity,

η = air viscosity,

and D = particle diameter.

They concluded that their experimental dust deposition rates agreed with equation 3 for particles between 1.4 and 10 µm diam, and that the experimental deposition rate was larger than equation 3 for smaller and larger particles because particle diffusion becomes important for smaller particles and their thermal-precipitator dust-measurement technique undersampled the larger particles. They further concluded that the experimental deposition rates onto the side (R_s) and roof (R_r) were less than the floor rate (R_f) and depended on particle size,

$$R_s/R_f = 2D^{-1.35}$$

$$R_r/R_f = 5.3D^{-3.3}$$

For $D \sim 2$ µm, R_s and R_r were comparable to R_f, i.e., L in equation 2 is the perimeter of the wind tunnel. For $D \sim 5$ µm, R_s was ~ 25 pct of R_f and R_r was ~ 2.5 pct of R_f. Field tests in a coal mine roadway basically agreed with the wind-tunnel results in that:

1. R_f decreased 10 pct for 5-µm-diam particles and 75 pct for 30-µm-diam particles along a ~ 300-ft length because of the corresponding decreases in the airborne concentrations; and

2. For the respirable component (0.5-5 µm), $R_s/R_f \sim 0.85$ and $R_r/R_f \sim 0.60$.

A survey of dust deposits in U.S. coal mines (2), which involved respirable and also larger particles, indicated that the R_s/R_f ratio was 0.30 and the R_r/R_f ratio was 0.07.

Pereles (3) developed a theoretical model for dust deposition onto a smooth wall from a turbulent airstream which was based on the dust particles being "flung" by turbulent eddies directly to the deposition surface; i.e., the boundary layer was assumed negligible. He concluded that (1) R_f was equal to the Stokes terminal velocity for particles greater than ~ 5 µm diam, (2) the theoretical values of R_s/R_f and R_r/R_f agreed with the data of Dawes and Slack for 0.5- to 5-µm particles, but (3) R_f and also R_s and R_r increased with increasing air velocity. Owen (4) extended the theoretical model to include eddy transport in the boundary layer. The particle trajectory then depends upon gravity and the viscous resistance and decreasing turbulent velocity in the boundary layer. Results were similar to those of Pereles.

However, several investigators [e.g., Browne (5) and El-Shoboksky and Ismail (6)] have found that the rate of deposition of respirable particles is much greater for even slightly-rough surfaces than for smooth surfaces, and the rate increases as the roughness increases. This sensitivity to roughness is especially acute for particles less than ~ 5 µm diam. Although roughness apparently has a negligible effect on the deposition rate of particles larger than ~ 10 µm diam, prediction of the deposition rate of respirable-size particles is difficult because of the problem of obtaining an accurate value of equivalent wall roughness.

This Bureau of Mines report presents the results of an investigation of the effect of air velocity and relative humidity on the reduction of airborne respirable dust in an airway having rough surfaces that simulate the roughness of coal mine airways.

EXPERIMENTAL WORK[6]

Tests were done in a limestone mine in Drift D of the Bureau of Mines' Lake Lynn Laboratory. Drift D consists of a straight 1,664-ft-long entry with a constant rectangular cross section of 7 ft height and 18 ft width. The floor had a limestone flat surface and the bottom half of the ribs had a conventional concrete surface, both with an average physical roughness of ~ 1 mm. The limestone surfaces of the top half of the ribs and the roof (fig. 2) had an average roughness of ~ 1 in.

Between tests, the ventilation airstream was varied from 80 to 500 ft/min by adjusting a ventilation blower and a movable bulkhead located 20 ft downstream from the right-angle entrance to the entry. The ventilation air velocity was maintained nominally constant during each test, but actually varied by 5 pct during a test due to a variation in the speed of the blower.

Pulverized coal dust was dispersed into the ventilation airstream by a trickle duster (MSA,[7] No. 92916) located 50 ft downstream from the bulkhead. Test duration was 20 to 40 min, during which 100 to 200 lb of the pulverized dust was dispersed into the airstream. The discharge hose of the trickle duster (fig. 2) was moved in a circular manner by hand during the test to disperse the dust cloud across the airstream. The size distribution of the pulverized coal dust, measured by a Coulter counter, is given in figure 3. The mass median diameter of the pulverized dust was 34 µm with 5 pct of the mass in the respirable range

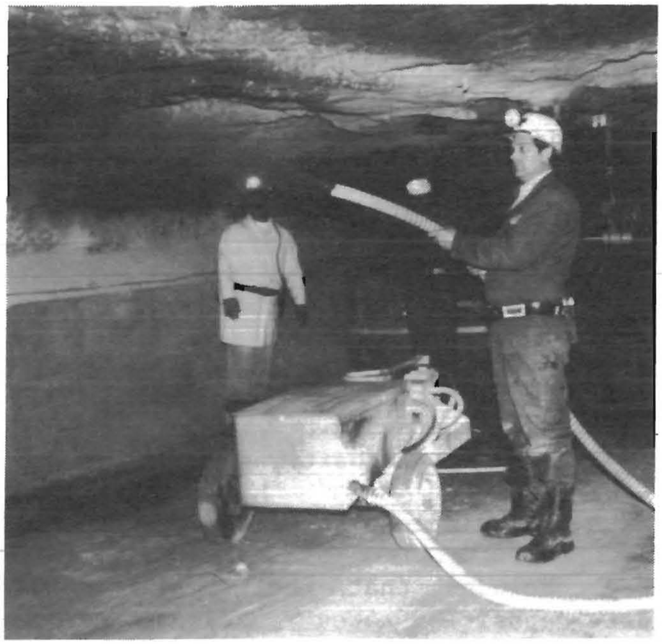

FIGURE 2.—Wall roughness and trickle duster.

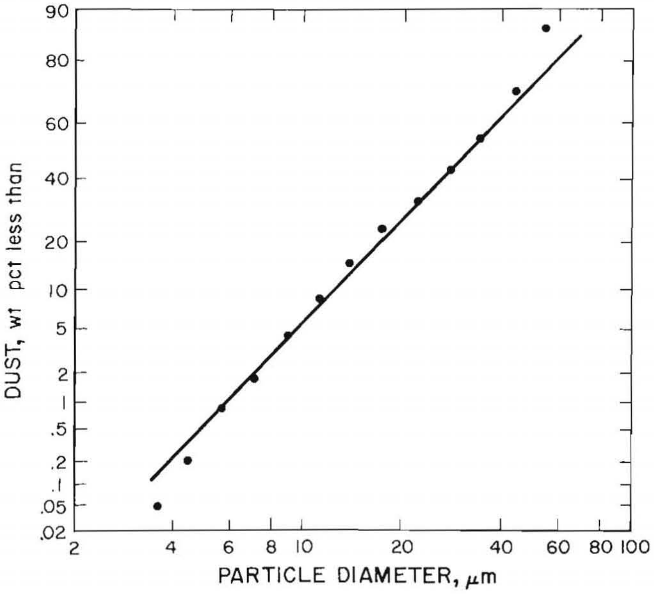

FIGURE 3.—Size distribution of pulverized dust measured by Coulter counter.

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[6] Tests were conducted by F. Nagy, physical science technician, Pittsburgh Research Center.

[7] Reference to specific equipment does not imply endorsement by the Bureau of Mines.

(<10 µm diam). The respirable fraction had a mass median diameter of 8.0 µm.

Dust sampling stations were established 100, 300, 500, and 700 ft downstream from the trickle duster. At each station, two MSA personal samplers operated at 2 L/min with nylon cyclones were mounted with the inlet ports to the cyclones within 6 in of each other and facing into the ventilation airstream. Each sampler package was located 2 ft 10 in above the floor in the middle part of the entry.

In several tests, personal samplers were also mounted 1 ft below the roof at a station to measure the vertical gradient in respirable dust concentration. Also, one Andersen cascade impactor (model 20-831) was mounted 2 ft 10 in up from the floor at a station and another Andersen impactor was mounted 1 ft down from the roof to simultaneously measure roof and floor size distributions of the airborne particles at that station. The eight-stage impactors also contained the commercial preseparators and were operated at 0.42 ft^3/min by a Staplex pump (TFIA) with individual inlet ports throttled with needle valves and in monitored with vacuum gauges. Circular, sharp-edged sampling orifices pointed directly into the airstream were used to isokinetically sample the airborne dust cloud. An orifice was connected to its impactor with a 9-in-long sampling probe having a 1-in ID and a 90° bend with a 7-in radius of curvature. The orifice-probe juncture was conically tapered to minimize particle deposition at the juncture. The probe-impactor juncture similarly was tapered to the 3/8-in-diam entrance to the impactor.

Relative humidity (RH) and temperature of the ventilation air were measured at each sampling station with a sling psychrometer. Results did not depend upon location. An attempt to increase the RH of the airstream with a bank of water sprays at the trickle duster was largely unsuccessful in that the RH was increased only 5 pct. The effect of RH, therefore, was examined by comparing tests performed winter and summer months when the natural RH in the mine was ~ 65 and ~ 95 pct, respectively.

A total of nine tests were performed to measure the airborne respirable dust concentration along the entry. Test conditions are summarized in table 1. Several other tests were conducted shortly after test 9 to measure size distributions along the airway.

TABLE 1. - Test conditions

Test	Date	v, ft/min	RH, pct	Temp, °F
1........	2/28/84	160	64	46
2........	3/14/84	250	70	47
3........	3/21/84	500	72	42
5........	4/03/84	80	61	51
6........	4/26/84	110	70	53
8........	7/17/84	100	91	59
9........	8/09/84	240	95	68

RH Relative humidity.

RESULTS

SIZE DISTRIBUTION

Figure 4 is a photomicrograph of coal dust particles that deposited onto a glass slide on the floor at the 100-ft station. There were a considerable number of ~ 50-µm-diam and larger particles and considerable agglomeration between particles. Mean aerodynamic particle sizes collected on the Andersen stages, given in table 2, were calculated by dividing the manufacturer's values for unit density spheres at a sampling flow rate of 1 ft^3/min by $\sqrt{1.3}$ and by $\sqrt{0.42}$. Size distributions measured with the Andersen impactors may be affected by preferential deposition of large particles in the probe along with deagglomeration in the probe, etc. Table 3 gives the percent of the mass of dust that entered the sampling orifice of the probe which was deposited on the probe walls or the preseparator, or accumulated at the other impactor stages. At the 100-ft station, 20 pct of the mass of the dust sampled near the floor deposited onto the probe walls, 70 pct deposited on the preseparator, and only 10 pct passed the

TABLE 2. - Mean aerodynamic particle diameter for Andersen impactor stages, micrometers

Preseparator	>13.5	3	4.5
0	12.2	4	2.8
1	7.8	5	1.5
2	6.3	6	1.0

TABLE 3. - Separation of sampled dust particles in impactor sampling

(Percent of sampled dust)

Location	100-ft station		300-ft station	
	Floor	Roof	Floor	Roof
In probe	20	5	0	0
On preseparator	70	65	95	80
On other impactor stages	10	30	5	20

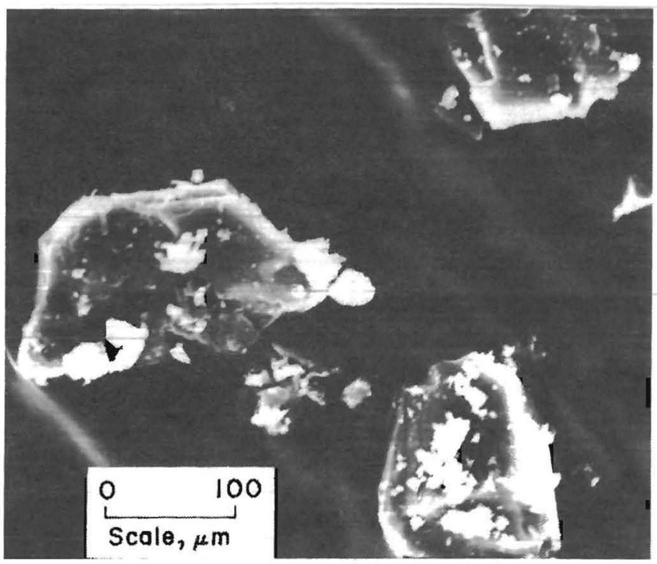

FIGURE 4.—Dust deposit at 100-ft station.

preseparator and deposited on the other stages. Near the roof, 5 pct deposited in the probe, 65 pct on the preseparator, and 30 pct on the other stages. Such results imply a large number of airborne particles of >13.5 μm diam and an appreciable vertical gradient of such large particles. For comparison, at the 300-ft station, negligible dust deposited in the probe, and the fraction of the mass of the sampled dust which passed the preseparator similarly increased near the roof, implying a lesser concentration of very large particles and a similar vertical gradient in large particles at the 300-ft station.

A much smaller vertical gradient occurred with the respirable fraction of the dust cloud, with the roof concentration of respirable dust being 92 pct of the floor concentration at the 100-ft station and 97 pct of the floor concentration at the 300-ft station.

Figure 5 plots the size distributions[8] of the dusts that entered the Andersen impactors near the floor and roof at the various stations along the airway. Impactor data at the different stations were obtained in the different tests since only two Andersens were available, and figure 5 should be viewed with caution since the size distribution may change between tests. A median particle size in the respirable range was obtained by taking the "wt pct less than" of particles less than 10 μm and deducing the particle size of the dust mass fraction having one-half of the 10 μm mass fraction. For example, for the roof sample at the 100-ft station, 20 pct of the sampled dust had a particle size less than 10 μm. Since 10 pct of the dust had a size about 4.7 μm, 4.7 μm is taken as the median size in the respirable range. At the 100- and 300-ft stations, the

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[8] It should be noted that "wt pct less than" is based on the total weight of dust that entered the sampling orifice of the probe; i.e., the sum of the weights collected in the probe, on the preseparator, and on the other impactor stages.

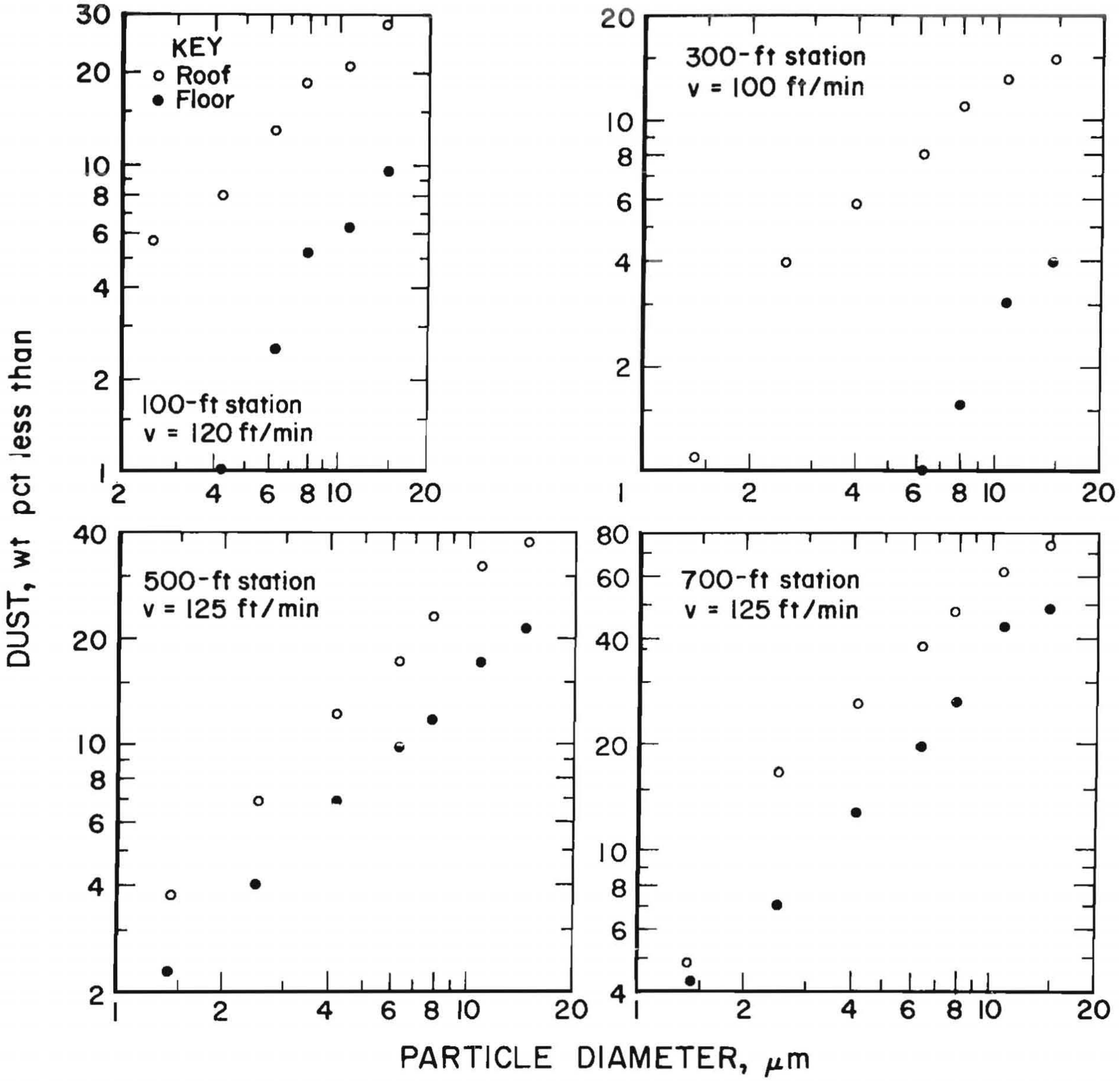

FIGURE 5.—Size distribution at roof and floor measured by Andersen cascade impactor.

median size 4.7 µm near the roof and ~ 6.5 µm near the floor. At the 500- and 700-ft stations, the median size was 4.9 µm near the roof and ~ 4.5 µm near the floor.

RESPIRABLE DUST CONCENTRATION

Table 4 gives the respirable dust concentrations measured 2 ft 10 in above the floor. Values in parentheses are considered to be questionable and were discarded. Table 4 includes average concentrations c_{av} at the locations and the coefficients of variation (CV)[9] of the measurements. The average CV was 10 pct when the questioned values were ignored. This value of CV is comparable to the 6- to 8-pct value obtained in other studies.

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[9] For two measurements, $CV = \sqrt{2}\,|(c-c_{av})/c_{av}|$ where c is a measured concentration and c_{av} is the average of the two measured concentrations.

TABLE 4. - Respirable dust concentration along airway

v, ft/min	Station, ft	Conc,[1] mg/m^3			CV,[2] pct
		First sample	Second sample	Average	
160.............	100	14.79	16.90	15.84	9.3
	300	6.77	7.94	7.36	11.1
	500	4.92	(16.33)	4.92	NAp
	700	4.37	Lost	4.37	NAp
250.............	100	(45.87)	10.14	10.14	NAp
	300	5.15	4.76	4.95	5.6
	500	3.81	3.47	3.64	6.6
	700	2.91	3.62	2.91	15.0
500.............	100	11.07	10.69	10.88	2.4
	300	3.31	3.73	3.52	8.5
	500	(2.09)	2.99	2.99	NAp
	700	2.37	2.83	2.60	12.6
80..............	100	18.94	20.88	19.91	6.9
	300	13.83	13.70	13.76	7.8
	500	8.53	8.98	8.76	3.5
	700	5.47	6.10	5.78	4.5
110.............	100	23.74	31.05	27.40	18.6
	300	17.25	18.98	18.12	6.6
	500	10.35	13.80	12.08	20.2
	700	3.80	3.80	3.80	0
100.............	100	20.70	20.91	20.80	1.0
	300	13.61	11.88	12.74	9.6
	500	7.10	9.25	8.18	18.6
	700	4.09	5.39	4.74	18.1
240.............	100	25.47	19.17	22.32	20.0
	300	7.85	6.59	7.22	12.3
	500	5.33	7.23	6.28	21.2
	700	1.89	Void	1.89	NAp

CV Coefficient of variation.
NAp Not applicable.
[1] Items in parentheses are considered to be questionable and are discarded.

Figure 6 plots $\ln c_{av}$ versus distance along the airway.[10] The slope K (= Lk/Av in equation 2) of a plot was linear for v = 80, 100, and 110 ft/min, but K decreased with distance for higher air velocities.

Assuming that $k = k'v^n$ where k' and n are constants independent of v, equation 2 then gives K as a function of v

$$KA/L = k'v^{n-1}$$

and $$\log (KA/L) = \log k' + (n-1) \log v.$$

Further assuming that the rates of deposition on the roof, ribs, and floor are equal, $A/L = 2.5 = 18 \times 7/2(18+7)$. Mean

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[10] The concentration at the 700-ft station for V = 240 ft/min was considered to be questionable and was omitted from figure 6.

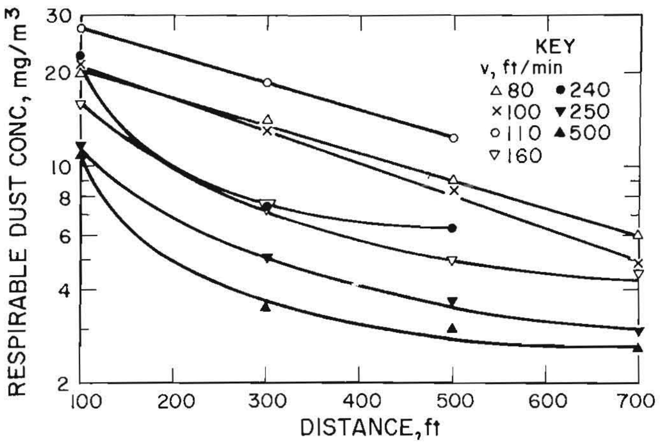

FIGURE 6.—Respirable dust concentrations along airway.

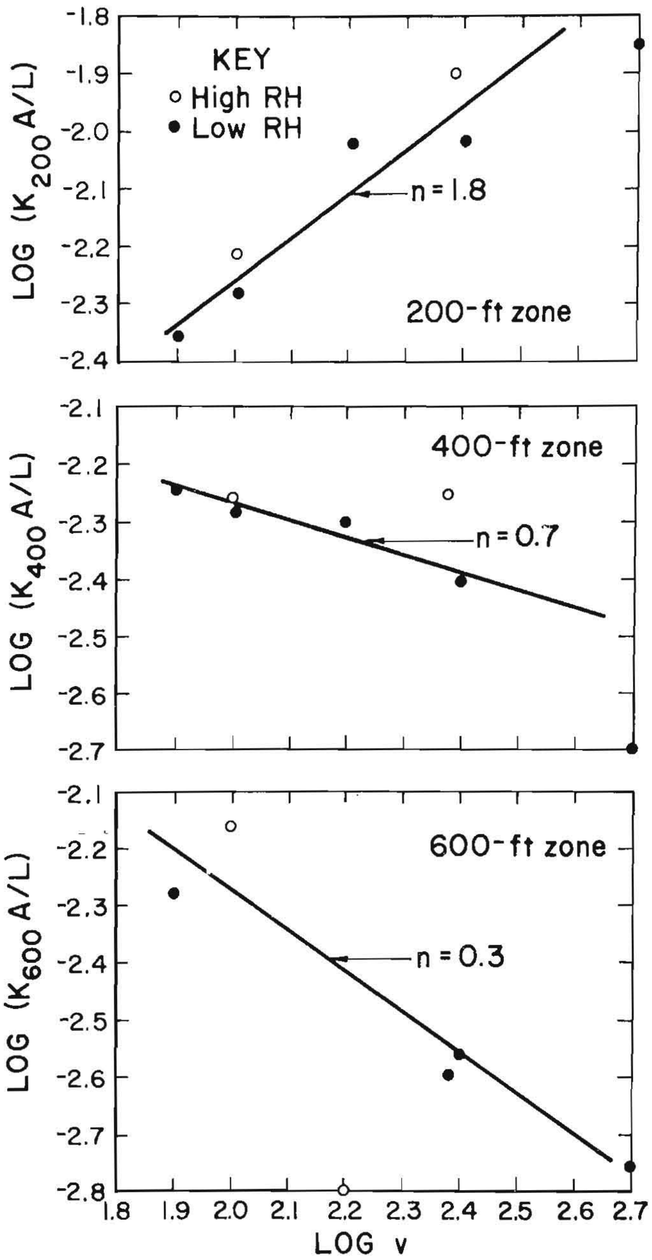

FIGURE 7.—Variation of deposition rate with air velocity and distance.

values of KA/L between sampling stations were calculated from c_{av} data given in table 4; e.g., K_{200} is the mean value between the 100- and 300-ft stations and was calculated using the c_{100} and c_{300} data.[11] Figure 7 plots $\log(K_{200}A/L)$ versus logv for the 200-ft zone. Figure 7 includes data measured in tests at high and low RH. Figure 7 also includes $\log(K_{400}A/L)$ and $\log(K_{600}A/L)$ plots using 300- and 500-ft data and 500- and 700-ft data, respectively. The plots have considerable scatter but approximately correspond to

$$k_{200} \sim 1.6\times10^{-4}v^{1.8}$$

$$k_{400} \sim 3.5\times10^{-3}v^{0.7}$$

$$k_{600} \sim 0.13\ v^{0.3} \tag{4}$$

where k_{200} is the mean experimental k value for the 100- to 300-ft zone, k_{400} is the mean value for the 300- to 500-ft zone, and k_{600} is the mean value for the 500- to 700-ft zone; k values are expressed as feet per minute. For an air velocity of 100 ft/min, $k_{200} \sim k_{400} \sim k_{600} \sim 0.5$ ft/min. Figure 7 suggests that any effect of RH is within the scatter of the plots.

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[11] The assumption of a mean K between stations is admittedly drastic for high values of v.

DISCUSSION

The dust cloud was polydisperse, and a k_{exp} value in equation 4 is a "mean" value corresponding to the particle size distribution in the respirable size range.

The values of k_{exp} in equation 4 are comparable to the simple Stokes sedimentation velocity; i.e., k_{St} = 0.2 ft/min for 5-µm particles and 0.8 ft/min for 10-µm particles while $k_{exp} \sim 0.5$ ft/min (if v = 100 ft/min).

If deposition depended only on a simple Stokes-type process, then (1) k_{exp} should not depend upon the air velocity and (2) k_{exp} should decrease along the airway because the larger particles (which should have a higher k value) should decrease in concentration along the airway.

However, k_{exp} appeared to depend upon v in the 200-ft zone per equation 4. Also, the median particle size of the airborne dust in the respirable range was approximately constant at the 100- and 300-ft stations; i.e., large and small particles deposited at similar rates along the airway for these distances. Although depletion of the larger particles appears to have occurred by the 500-ft station (the median size at the floor decreased from ~ 6.5 µm at 100 and 300 ft to 4.5 µm at 500 ft), the median sizes at 500 and 700 ft similarly remain approximately constant with distance.

The concrete and limestone surfaces of the present airway were definitely rough in texture, and the deposition rates of the smaller particles should be expected to be greater than the Stokes values. The bigger particles in the respirable range apparently have largely been deposited by the 500-ft station. Otherwise, the simplest explanation for the apparent constancy of the size distribution in the 100- to 300-ft distance and the 500- to 700-ft distance probably is that the increase in k for smaller particles due to roughness somewhat counterbalances the expected decrease in k for smaller particles due to a simple Stokes-type sedimentation process. If so, then k depends upon wall roughness and should be expected to vary between mines.

However, the dependence of k_{exp} on v in the 200-ft zone implies an actual change in the size distribution with distance and remains to be explained. Clarification of these features will be difficult and probably could best be done by laboratory-type tests using monodisperse coal aerosols. Such tests were beyond the scope of this project.

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