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Control of Airborne Respirable Dust in the Face Area With Water Sprays Using a Full-Scale Laboratory Model

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CONTENTS

ILLUSTRATIONS

TABLES

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cfm	cubic foot per minute	mg	milligram
ft	foot	mg/m^3	milligram per cubic meter
ft/min	foot per minute	min	minute
gpm	gallon per minute	mm	millimeter
g/cm^3	gram per cubic centimeter	pct	percent
in	inch	psig	pound per square inch, gauge
L/min	liter per minute	qt	quart
μm	micrometer	rpm	revolution per minute

CONTROL OF AIRBORNE RESPIRABLE DUST IN THE FACE AREA WITH WATER SPRAYS USING A FULL-SCALE LABORATORY MODEL

By Lung Cheng[1] and Welby G. Courtney[2]

ABSTRACT

This report presents the results of a Bureau of Mines laboratory investigation of the effect of water sprays in reducing respirable dust that escaped the face area of a full-scale wooden model of a mine entry containing a wooden model of a ripper-type continuous mining machine and exhaust brattice. Areas examined were (a) the general effectiveness of a low-pressure water spray system mounted on top of the mining machine boom, a high-pressure spray system mounted under the boom, and the combined top- and bottom-spray systems, and (b) the effect of these three spray systems on the capture of coal dust particles of different sizes.

Dust was injected into a sump cavity at the face. Airborne respirable dust concentration was measured behind the brattice with a personal sampler and cyclone, and particle size distribution was measured with a cascade impactor. When used alone, the top-spray system captured about 55 pct of the respirable dust in the face area and the bottom-spray system captured 60 pct; the capture efficiency of each system is decreased when they are used simultaneously. From a mass-concentration viewpoint, each spray system preferentially captures larger dust particles.

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INTRODUCTION

The coal dust that is generated during mining operations at the face can become entrained by the ventilation airstream and be discharged into the return. The respirable component of the airborne dust (particles less than 10-μm nominal diameter) that escapes the face area increases the health hazard for downstream personnel and also increases the safety hazards. Coal dust deposited in the return can be reentrained during a methane explosion and initiate a coal-dust explosion.

The main dust-control technique used with ripper-type continuous mining machines is water sprays (*1*).[3] However, the location, type, and operating pressure of the spray nozzles often are selected in a rather arbitrary manner, such as merely adding more spray nozzles in the hope greater dust reduction will be achieved.

An early Bureau field study with a ripper mining machine in an operating coal mine (*2*) indicated that conventional water sprays mounted on the top of the cutting boom, operated at 80 psig and directed toward the face, reduced the respirable dust that escaped from the face area into the return by 20 pct when compared to dry operation sprays mounted under the boom, and also operated at 80 psig, reduced dust by 50 pct. The effectiveness of the boom sprays was not increased by operating them at 140 psig and with a 50-pct increase in water flow rate. The orientation of the bottom sprays, whether directed forward toward the face or downward, did not appear to be important.

Later laboratory tests (*3*) used a full-scale model mine entry containing a full-scale model of a Joy 12CM. The entry used exhaust ventilation with brattice. Dust was added to the face. The dust-capture efficiency of two boom-mounted spray systems was investigated by measuring the concentration of respirable dust behind the exhaust brattice during wet and dry operation. One spray system used 20 conventional spray nozzles directed toward the face and operated at 100 psig. The other spray system used three venturi-shrouded spray nozzles operated at 800 psig. Each spray system delivered a total of 16 gpm. The low-pressure spray system gave a 52 pct reduction in respirable dust in the return behind the brattice compared to dry operation, while the high-pressure spray system gave a 64 pct reduction.

Recent field tests have been conducted (*4*) with several novel spray systems designed to reduce the rollback of face dust over the machine operator. Results indicated a wide variation in the effectiveness of the systems in reducing the dust that was discharged into the return.

This report presents the results of a laboratory reinvestigation of dust reduction at the face with water sprays in order to examine (a) the general effectiveness of a low-pressure top-spray system, a high-pressure bottom-spray system, and the combined top- and bottom-spray systems in reducing the respirable dust concentration escaping the face area, and (b) the effect of these three spray systems on the capture of coal dust particles of different sizes.

ACKNOWLEDGMENTS

The authors would like to acknowledge Natesa Jayaraman, mining engineer, Pittsburgh Research Center, for the initial development and testing of the experimental system.

EXPERIMENTAL[4]

MODEL OF MINE ENTRY

Tests were conducted in the full-scale wooden entry containing a wooden model of a Joy 12CM (fig. 1) as noted in reference 3. The 14-ft-wide, 6-ft-high entry was ventilated with 5,000 cfm exhaust ventilation using a roof-to-floor brattice 20 in from the right rib. Tests were conducted with the front end of the brattice located 10 and 15 ft from the face.

Twenty Spraying Systems[5] BD-3 water spray nozzles were located along the continuous miner boom, 10 on the top and 10 on the bottom of the boom. The nozzles were directed toward the face. These 20 nozzles, which were always operated at 100 psig and delivered a total of 17 gpm, are top-spray system. Four Spraying System 1100067-TC nozzles were located on the gathering pan and directed upward toward the bottom of the boom. These nozzles, which were always operated at 2,500 psig and delivered a total of 4 gpm, are the bottom-spray system. The two spray systems could be operated separately or simultaneously.

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[3] Italic numbers in parentheses refer to items in the list of references preceding the appendixes.

[4] Tests were conducted by Jack A. Ward, Jr., electronics technician, and Eugene M. Bazala, physical science technician, with assistance by Frank Nagy, physical science technician, and Thomas J. Ozanich, mining engineering technician, Pittsburgh Research Center.

[5] Reference to specific products does not imply endorsement by the Bureau of Mines.

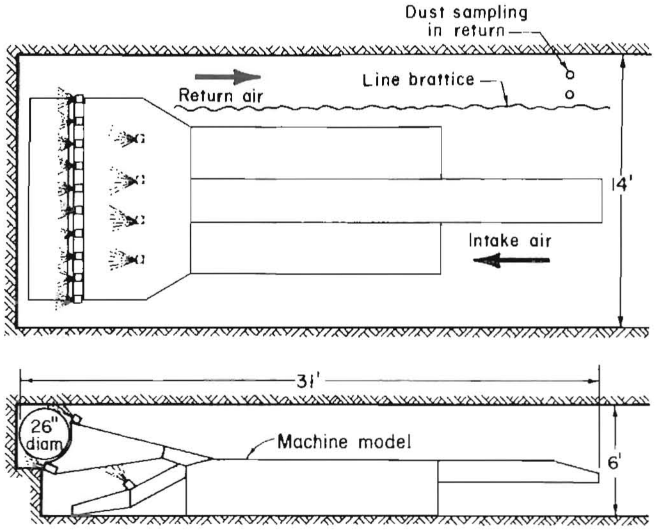

Figure 1.—Model of mine entry.

The face was constructed to simulate sumping at the roof. Minus 200-mesh Pittsburgh-seam coal dust was screw fed from a vibrated hopper with nominal constant dust input rate into a duct containing a 200-cfm airstream. This dusty airstream was discharged into the sump cavity through 16 ports while the cutter drum was being rotated at 60 rpm in the cavity. The dust-generation system was run for 10 min to reach a steady-state operation before dust sampling was started. Separate runs were made for dry and wet runs; i.e., the dust system was shut down at the end of a dry run and restarted for the wet run.

PARTICLE SAMPLERS

Airborne dust was sampled behind the brattice during dry and wet operation. Conventional MSA personal samplers with cyclones were used to measure respirable dust concentration by sampling at 2 L/min. Size distribution of the airborne particles was measured with Andersen (model 2000 20-830) cascade impactors.

Two sampler packages were located behind the brattice, 20 ft from the face. Each package contained two MSA personal samplers with 10-mm cyclones and filter cassettes to measure respirable dust and one Andersen impactor. One package was located 2 ft below the roof and the other 2 ft above the floor. The personal-sampler cyclones of the package were horizontally located 10 in apart. Cyclone inlets were pointed into the airstream.[6]

The Andersen impactors were operated at 11.8 L/min (0.42 cfm) and used a sampling probe having a 0.40-in-diam sharp-edged circular entrance inlet with the probe axis parallel to the airstream to isokinetically sample the 500-ft/min dusty airstream behind the brattice. The inlet was joined to a 1-in-diam tube that was bent 90° with a 7-in radius of curvature and connected to the 3/8-in-diam entrance to the Andersen impactor. Tapered joints were used to minimize dust deposition in the probes. Equivalent aerodynamic median particle sizes collected on the various impactor stages as reported by the manufacturer but modified to include particle density (1.3 g/cm^3) and also to reflect the change in sampling air flow rate are given in table 1. The manufacturer sizes for unit-density spheres and a sampling flow rate of 1 cfm were divided by $(1.3)^{0.5}$ and $(0.42)^{0.5}$.

TABLE 1. - Effective cut points for each stage of Andersen sampler, corrected for particle density and flow rate

	Particle diameter, µm
Preseparator	>13.5
Stage 0	12.2
Stage 1	7.8
Stage 2	6.3
Stage 3	4.5
Stage 4	2.8
Stage 5	1.5
Stage 6	1.0
Stage 7	.7
Filter	.3

EXPERIMENTAL RUNS

A test involved dust sampling during a dry run and then, after installing fresh packages of cassettes and impactors, dust sampling during a wet run. Each wet run thus had a dry run for comparison. Cassette sampling duration was 45 and 90 min for dry and wet runs, respectively. Impactor sampling was simultaneous but for only 15- and 30-min durations during dry and wet runs, respectively, to avoid overloading the Andersen impactors.

The initial four tests compared size distributions measured with the Andersen impactors in dry and wet runs. Particle loss in the impactor due to deposition onto the impactor wall was negligible. Several wet runs were made using a 1-qt mason jar as a plenum chamber between the probe inlet and the impactor to scavenge most of the water drops. The mason jar had no effect on the measured particle size distribution and was not used in subsequent tests. Tests 5 and 6 results were discarded because of malfunction of the water pump.

Tests 7 through 12 compared respirable dust concentrations and size distributions measured during dry and wet operation when the top-spray system, the bottom-spray system, and both spray systems were used. Thus, with nominal constant dust input conditions into the sump cavity of the face, a total of six dry runs were made, and one wet run was made for each of the six spray-brattice conditions. This program was ended before replicate wet runs could be made.

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[6] Cyclone sampling the present 500-ft/min airstream should not cause oversampling due to nonisokinetic sampling (*5*).

RESULTS

The average coefficient of variation (CV)[7] of the simultaneous measurements of respirable dust concentration behind the brattice was an excellent 7.8 pct (29 cases, 3 outliers) despite the 10-in horizontal distance between the two cyclones. This value is to be compared with the 10-pct CV value reported in another study (*6*).

With the 10-ft-distance brattice, the respirable dust concentration measured behind the brattice near the roof during dry and wet operation was about 15 pct greater than measured near the floor. However, with the 15-ft-distance brattice, the roof concentration was 15 pct less than the floor concentration. The numerical average of the roof and floor concentrations is used in the following discussion.

DUST COLLECTION EFFICIENCY OF WATER SPRAYS

The average respirable dust concentrations measured with cyclones and cassettes in the return for each of the six dry runs and for their corresponding wet runs are given in table 2. The resulting collection efficiencies are included in table 2. Collection efficiencies for respirable dust with the 10-ft-distance brattice were 54 pct for the top-spray system, 58 pct for the bottom-spray system, and 71 pct for the combined spray system. With the 15-ft-distance brattice, the collection efficiencies were 57 and 63 pct for the top- and bottom-spray systems, respectively, and 75 pct for the combined spray system. The values of 54 and 57 pct for the top-spray system agree closely with the 52-pct value noted in reference 3 for the top-spray system (the brattice distance was not reported).

Table 2 also shows that reproducibility of the dust feed technique was good; i.e., the CV of the respirable dust concentration measured behind the brattice in the six dry runs was only 17 pct.

TABLE 2. - Respirable dust collection efficiencies for wet versus dry runs

	Respirable dust conc, mg/m^3		Collection efficiency,
	Dry	Wet	pct
10-ft-distance brattice:			
Top sprays	46.64	21.66	53.5
Bottom sprays	36.60	15.29	58.2
Top and bottom sprays	35.50	10.20	71.2
15-ft-distance brattice:			
Top sprays	31.54	13.68	56.6
Bottom sprays	29.98	11.25	62.5
Top and bottom sprays	35.18	8.80	74.9

PARTICLE SIZE

The dust that entered the sampling probe of the impactor partly deposited on the probe wall, partly on the preseparator and 0th stage, and partly on the lower respirable stages. Table 3 gives the average values of the mass fractions of the total dust that entered the probe and deposited at the various locations and includes the CV's of these average values. The various values for top and bottom locations and both brattice distances were combined to obtain the values given in table 3. Sixty percent of the total dust that entered the Andersen probe during a dry run was in the respirable size range; during a wet run 83 pct of the dust was in the respirable size range.

Size distributions measured at the floor and roof with the Andersen samplers during dry and wet runs and calculated on the basis of the total mass of dust collected on the preseparator and the various impactor stages are shown in figures 2 and 3 for the floor and roof locations during dry and wet runs with 10- and 15-ft brattice distances. Raw data are given in appendixes A and B. Size distributions were reasonably linear. The mass median diameters of total dust taken from figures 2 and 3 are summarized in table 4. Results were somewhat scattered[8] but suggested that the mass median diameter for a wet run was about one-half of the corresponding dry run.

The collection of dust in the respirable size range (<10-μm nominal diameter) was of principle interest. Size distributions in the respirable range were calculated from the

TABLE 3. - Average values of mass fractions of total dust deposited in impactor sampling, percent

	Dry	CV	Wet	CV
Probe	17	20	0	NAp
Preseparator and 0th stage	23	42	17	28
Respirable stages	60	15	83	6

NAp Not applicable.

TABLE 4. - Mass median diameters of total dust measured by Andersen sampler, micrometers

	Dry		Wet	
	Floor	Roof	Floor	Roof
10-ft-distance brattice:				
Top sprays	5.4	7.0	2.8	3.3
Bottom sprays	8.0	8.0	5.2	3.7
Top and bottom sprays	3.7	7.0	2.5	4.2
15-ft-distance brattice:				
Top sprays	7.2	7.2	2.0	3.5
Bottom sprays	6.8	10.0	2.5	2.5
Top and bottom sprays	5.7	5.0	3.2	2.8

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[7] $CV = (2)^{1/2}(|c - \bar{c}|)/\bar{c}$ when two samples are being compared, where c is a measured concentration and $\bar{c}$ is the average of the two measured values.

[8] The standard deviation of the mass median diameters deduced from figures 2 and 3 was 3.

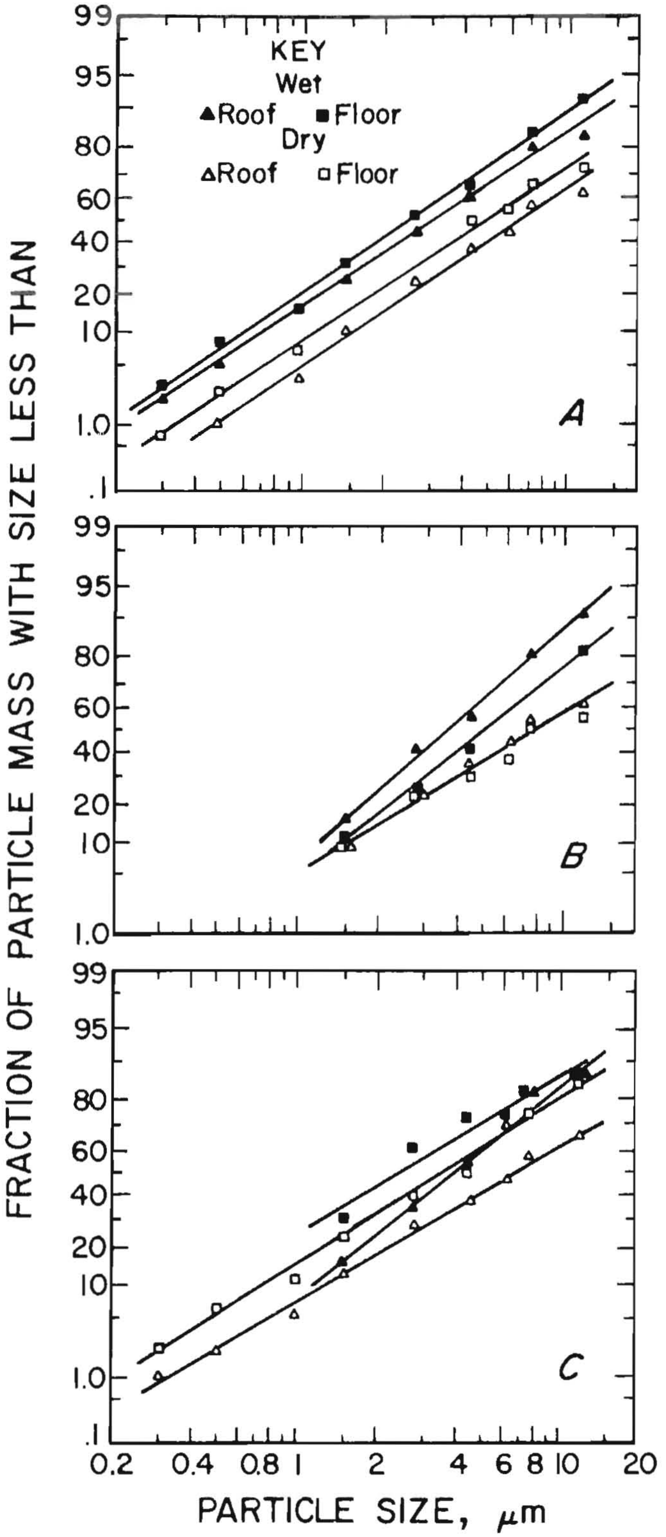

Figure 2.—Size distributions measured with 10-ft-distance brattice. *A*, Top sprays; *B*, bottom sprays; *C*, top and bottom sprays.

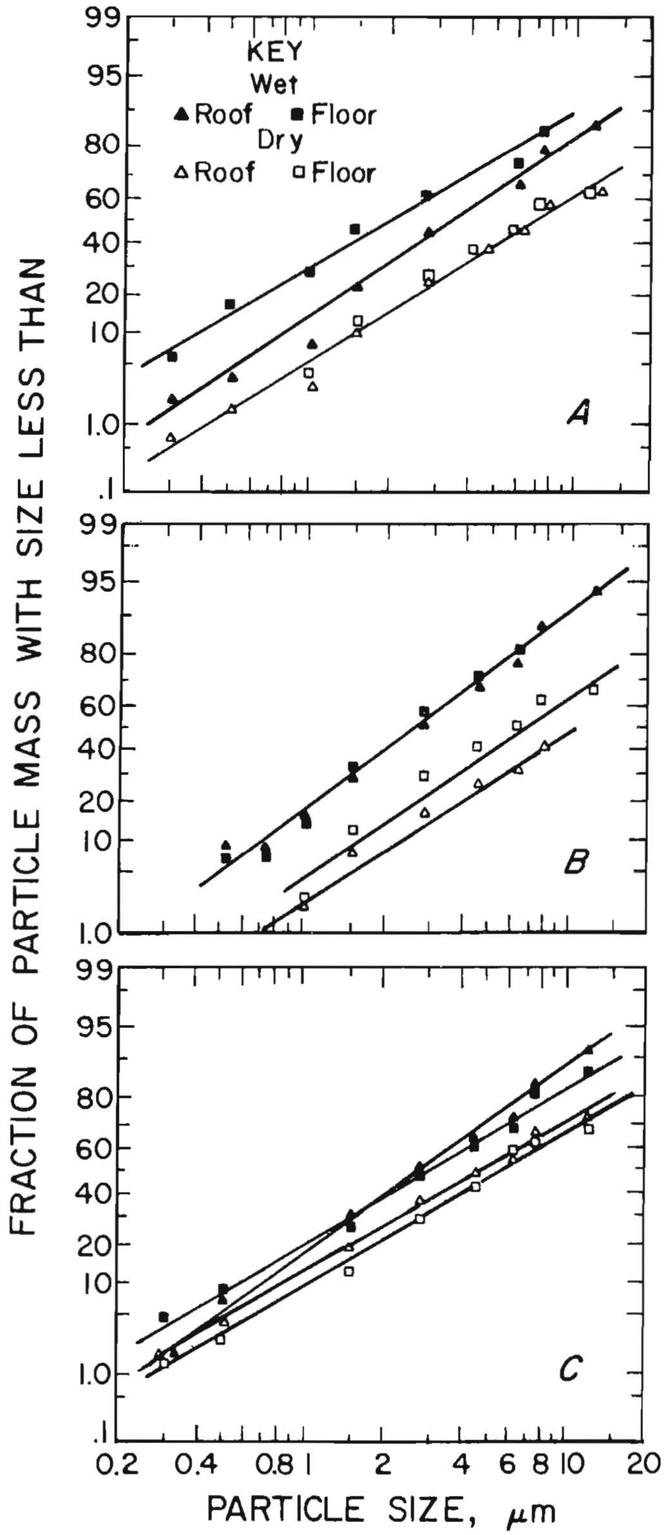

Figure 3.—Size distributions measured with 15-ft-distance brattice. *A*, Top sprays; *B*, bottom sprays; *C*, top and bottom sprays.

TABLE 5. - Mass mean diameters[1] of respirable dust(<10 μm) measured by Andersen samplers, micrometers

	Dry		Wet	
	Floor	Roof	Floor	Roof
10-ft-distance brattice:				
Top sprays	5.4	4.7	3.4	3.9
Bottom sprays	4.9	4.8	6.2	4.6
Top and bottom sprays	4.1	4.5	3.1	4.6
15-ft-distannce brattice:				
Top sprays	3.8	4.7	3.3	4.9
Bottom sprays	4.5	4.8	3.4	3.9
Top and bottom sprays	4.6	4.2	4.0	3.9

[1] Mass mean diameter = $\sum$ (mass • diameter) / $\sum$ (mass) where the summations are over the size fractions in the respirable size range.

raw data in appendixes A and B by interpolating for the mass of 10-μm dust between stage 0 (12.2 μm) and stage 1 (7.8 μm). The mass mean diameters are summarized in table 5. Results were again somewhat scattered but indicate that the mass mean diameter for a wet run usually was about 10 pct less than during dry operation.

DISCUSSION

From a mass-concentration viewpoint, the water sprays in this study appeared to preferentially capture the larger particles; i.e., the impactor results indicated that the mass of dust in the respirable size range increased from 60 pct in dry operation to 83 pct in wet operation (table 3), the mass median diameters decreased by about one-half in wet operation (table 4), and the mass of dust less than 1 μm in diameter increased from 5 pct in dry operation to about 15 pct in wet operation (figs. 2-3). While a large number of 1-μm particles could have been captured by the spray drops, the capture of a few large particles in the respirable size range would overshadow the capture of many 1-μm particles from a mass-concentration viewpoint and lead to such results.

The collection of dust particles in a dusty airstream by the injection of water drops from a spray nozzle involves the collision of the drops with the dust particles and the particle-drop agglomerate sedimenting from the airstream or impacting a surface. The dust-collection efficiency of a spray zone, discussed in reference 7 and reviewed in appendix C, depends in part upon the volume flow rate of the water in the spray zone and the volume flow rate of the dusty airstream that passes through the spray zone. Results of other Bureau laboratory studies (7) that involved the dusty airstream passing down a duct containing a single water spray indicated that optimum particle capture occurs with drops about 200 μm in diameter. This optimum drop size extended over a wide range in drop velocity and particle size. The mean drop size of the spray nozzles used in the present is uncertain but is estimated to be about 200 μm for the top-spray system and about 50 μm for the bottom-spray system. Because the bottom-spray system probably involves nonoptimum drops and a total water flow rate that was one-fourth that of the top-spray system, it was somewhat surprising that similar dust collection efficiencies were obtained with the top- and the bottom-spray systems.

However, the airflow pattern in the face area of the present system is uncertain. Smoke tests have indicated that some of the main ventilation airstream is induced below the boom by the rotation of the cutter drum, some is also induced below the boom by the top- and/or the bottom-spray system, and some is merely discharged directly into the return. The induced air mixes with the face dust and passes through the top or bottom spray system (but also may be partly recycled through a spray system) before it eventually escapes the face area and passes into the return.

The 4-pct increase in the dust-collection performance observed with all three spray systems when the brattice is moved from the 10- to the 15-ft distance (table 2) suggests that such an increase is real. The increase presumably is due to a favorable change in the airflow pattern at the face; i.e., to more of the main ventilation airstream being induced through the sprays or perhaps more recycling of the partly cleansed air.

The interactions of the top- and bottom-spray systems; i.e., the effect of the bottom spray on the dust-collection performance of the top-spray system and the effect of the top-spray system on the dust-collection performance on the bottom-spray system, are also unknown. An approximate analysis of the present results in terms of these interaction effects is presented in appendix C.

Results indicated that with the 10-ft-distance brattice the dust reduction obtained with the combined top and bottom sprays would be 80.6 pct if the top and bottom sprays both performed as effectively as they performed in their individual tests. However, only a 71.2-pct reduction was measured in the combined-spray test. Similarly, with the 15-ft-distance brattice, the dust reduction in the combined spray test would be 83.7 pct based on the individual tests but only a 74.9-pct reduction was measured. Such results imply that the dust-collection performance of the top-spray system in the combined spray system is decreased by about 37 pct (compared to the performance of only the top-spray system) by the presence of the bottom-spray system. The dust-collection performance of the bottom-spray system is simultaneously decreased by about 13 pct by the presence of the top-spray system.

The reasons for the increase in dust-collection performance when the brattice is moved from the 10- to the 15-ft distance and the decreases in the dust-collection performances of the top- and the bottom-spray systems by the presence of the other spray system are not clear. An improvement in the performance of the top-spray system can perhaps be achieved by reorientation or relocation of the top- or bottom-spray system (or both spray systems), but an experimental study is required to clarify the natures of the chaotic airflow patterns in the face area with different spray systems. Thus, while the dust collection performance of a single spray nozzle can be investigated by various techniques (7-8), the dust collection performance of a two-spray-zone system in the face area as shown in figure 1 requires using the full-scale system.

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APPENDIX A.–SIZE DISTRIBUTION DATA MEASURED WITH 10-FT-DISTANCE BRATTICE

		Floor		Roof		Floor		Roof	
	Size, µm	Mass of dust, mg	Fraction[1] less than size, pct	Mass of dust, mg	Fraction[1] less than size, pct	Mass of dust, mg	Fraction[1] less than size, pct	Mass of dust, mg	Fraction[1] less than size, pct
		Dry				Top sprays			
Preseparator	>13.5	5.83	99.99	10.63	100.00	1.49	99.98	2.96	100.00
Stage 0	12.2	1.48	71.95	1.58	61.76	1.14	90.75	.80	83.21
Stage 1	7.8	2.38	64.83	3.10	56.08	1.70	83.69	1.80	78.67
Stage 2	6.3	.98	53.38	2.20	44.93	1.26	73.16	1.47	68.46
Stage 3	4.5	2.27	48.67	3.73	37.02	2.53	65.35	2.67	60.12
Stage 4	2.8	3.88	(37.75)	3.82	23.60	3.18	49.68	3.68	44.98
Stage 5	1.5	2.45	(19.09)	1.76	9.86	2.37	29.98	2.48	24.11
Stage 6	1.0	1.00	7.31	.70	3.53	1.23	15.30	.88	(10.04)
Stage 7	.5	.38	2.50	.03	1.01	.79	7.68	.50	5.05
Filter	.3	.14	.67	.25	(.90)	.45	2.79	.39	2.21
Total	NAp	20.79	NAp	27.80	NAp	16.14	NAp	17.63	NAp
		Dry				Botttom sprays			
Preseparator	>13.5	10.40	99.98	9.63	99.98	2.00	99.99	0.51	99.99
Stage 0	12.2	1.40	55.54	1.44	60.58	1.02	83.82	.50	90.99
Stage 1	7.8	3.07	49.56	2.52	52.69	3.35	(75.58)	1.14	82.17
Stage 2	6.3	1.57	36.44	2.35	44.38	.98	48.50	.40	62.07
Stage 3	4.5	1.70	29.73	2.88	34.77	2.03	40.58	.77	55.02
Stage 4	2.8	3.23	22.47	3.48	22.99	1.81	24.17	1.50	41.44
Stage 5	1.5	1.80	8.67	1.71	8.75	1.18	9.54	.85	14.99
Stage 6	1.0	.23	(.98)	.38	(1.75)	.00	.00	.00	.00
Stage 7	.5	.00	.00	.05	(.20)	.00	.00	.00	.00
Filter	.3	.00	.00	.00	.00	.00	.00	.00	.00
Total	NAp	23.40	NAp	24.44	NAp	12.37	NAp	5.67	NAp
		Dry				Top and bottom sprays			
Preseparator	>13.5	1.91	99.99	11.72	99.98	0.75	99.99	0.90	99.99
Stage 0	12.2	1.07	83.97	2.53	65.05	.27	86.72	.35	86.64
Stage 1	7.8	2.05	74.99	3.90	57.51	.46	81.94	.80	81.45
Stage 2	6.3	.91	(57.39)	2.37	45.89	.05	73.80	1.16	69.58
Stage 3	4.5	1.32	50.16	4.14	38.83	.66	72.92	1.23	52.37
Stage 4	2.8	2.07	39.09	4.58	26.49	1.74	61.24	1.34	34.12
Stage 5	1.5	1.30	21.73	2.72	12.84	1.27	30.44	.88	14.24
Stage 6	1.0	.60	10.82	.79	4.73	.40	(7.96)	.04	(1.18)
Stage 7	.5	.43	5.79	.47	2.38	.05	(.88)	.04	(.59)
Filter	.3	.26	2.18	.33	.98	.00	.00	.00	.00
Total	NAp	11.92	NAp	33.55	NAp	5.65	NAp	6.74	NAp

NAp Not applicable.

[1] Cumulative.

NOTE.—Numbers in parentheses were considered to be outliers and were ignored in figure 2.

APPENDIX B.–SIZE DISTRIBUTION DATA MEASURED WITH 15-FT-DISTANCE BRATTICE

		Floor		Roof		Floor		Roof	
	Size, µm	Mass of dust, mg	Fraction[1] less than size, pct	Mass of dust, mg	Fraction[1] less than size, pct	Mass of dust, mg	Fraction[1] less than size, pct	Mass of dust, mg	Fraction[1] less than size, pct
		Dry				Top sprays			
Preseparator	>13.5	8.93	99.99	8.51	99.99	0.10	99.98	1.63	99.99
Stage 0	12.2	1.51	62.25	1.45	63.15	.52	98.01	.92	86.54
Stage 1	7.8	2.65	55.87	2.81	56.87	.70	87.75	1.59	78.95
Stage 2	6.3	1.51	44.67	1.77	44.71	.40	73.94	.97	65.83
Stage 3	4.5	2.95	38.29	3.04	37.05	.35	66.05	1.73	57.83
Stage 4	2.8	3.26	25.82	3.23	23.89	.64	59.15	2.57	43.56
Stage 5	1.5	1.95	12.04	1.57	9.91	.96	46.53	1.80	22.36
Stage 6	1.0	.77	3.80	.38	3.11	.60	27.60	.47	7.51
Stage 7	.5	.13	(.55)	.19	1.47	.48	15.77	.20	3.63
Filter	.3	.00	.00	.15	.65	.32	6.31	.24	(1.98)
Total	NAp	23.66	NAp	23.10	NAp	5.07	NAp	12.12	NAp
		Dry				Bottom sprays			
Preseparator	>13.5	7.71	99.99	20.27	99.99	0.04	100.00	0.82	99.99
Stage 0	12.2	1.10	67.32	1.18	43.86	.78	99.68	.87	94.24
Stage 1	7.8	2.96	62.66	3.20	40.59	1.47	(93.34)	1.70	88.14
Stage 2	6.3	2.11	50.12	1.95	31.73	1.10	81.39	1.25	76.23
Stage 3	4.5	3.17	41.18	3.85	26.33	1.97	72.45	2.25	67.47
Stage 4	2.8	3.85	27.75	3.68	15.67	3.06	56.43	3.30	51.70
Stage 5	1.5	2.10	11.44	1.65	5.48	2.20	31.55	2.00	28.58
Stage 6	1.0	.55	2.54	.33	.91	.83	13.66	.87	14.57
Stage 7	.5	.05	(.21)	.00	.00	.55	6.91	.65	8.47
Filter	.3	.00	.00	.00	.00	.30	(2.44)	.56	(3.92)
Total	NAp	23.60	NAp	36.11	NAp	12.30	NAp	14.27	NAp
		Dry				Top and bottom sprays			
Preseparator	>13.5	9.04	99.99	4.64	99.99	1.48	100.00	0.52	99.99
Stage 0	12.2	1.60	67.33	1.15	72.40	.81	87.55	.40	90.85
Stage 1	7.8	3.22	61.55	1.78	65.56	1.48	80.75	.62	83.82
Stage 2	6.3	2.09	49.92	1.03	54.98	.94	68.30	.49	72.93
Stage 3	4.5	4.01	42.37	1.95	48.86	1.86	60.90	.81	64.32
Satge 4	2.8	4.30	27.88	3.00	37.27	2.25	44.76	1.18	50.09
Stage 5	1.5	2.05	12.35	1.75	19.44	1.41	25.84	.91	29.35
Stage 6	1.0	.62	(4.95)	.80	(9.04)	.66	(13.98)	.33	(13.35)
Stage 7	.5	.36	2.71	.41	4.28	.45	8.43	.33	7.56
Filter	.3	.39	1.41	.31	1.84	.55	4.65	.10	1.76
Total	NAp	27.68	NAp	16.82	NAp	11.89	NAp	5.69	NAp

NAp Not applicable.

[1] Cumulative.

NOTE.—Numbers in parentheses were considered to be outliers and were ignored in figure 3.

APPENDIX C.–DUST SUPPRESSION WITH TWO SPRAY ZONES

Consider the collection of dust particles in an airstream by the injection of water drops from a water spray nozzle into the dusty airstream. The large, high-velocity water drops collide with and capture the small dust particles, and the particle-drop agglomerate then impacts onto a wall or sediments from the airstream. The overall dust collection efficiency of the spray zone can be written (*7*)[1] as

$$E_o = 1 - \exp(-K) \qquad \text{(C-1)}$$

where K is a dimensionless capture parameter of the spray zone and is given by

$$K = \frac{3}{2}\eta\gamma\frac{L\dot{Q}_w}{D\dot{Q}_g}, \qquad \text{(C-2)}$$

where η = fraction impaction of particles by drops,

γ = mass fraction of the water spray used to collect dust,

L = a characteristic length for the interaction between the water drops and the dust particles,

D = mean drop diameter,

$\dot{Q}_w$ = volume flow rate of water,

and $\dot{Q}_g$ = volume flow rate of air passing through the spray zone.

The value of γ is the effective ratio of water usage; e.g., if one-fourth of the water spray merely impacts the wall without capturing dust, then $\gamma = 3/4$.

In this study, if the top spray system in figure 1 of the main text is called 1 and the bottom spray system is called 2, with $\dot{Q}_{w_1} = 17$ gpm, and $\dot{Q}_{w_2} = 4$ gpm, and assuming $\eta_1 \approx \eta_2$, $\gamma_1 L_1 \approx \gamma_2 L_2$, $D_1 \sim 200\ \mu m$, and $D_2 \sim 50\ \mu m$, then equation C-2 gives

$$\frac{K_1}{K_2} = \frac{\dot{Q}_{g_2}}{\dot{Q}_{g_1}} \approx 1.$$

Thus, approximately equal flow rates of air pass through each spray zone in the absence of the other spray zone. Now consider a two-zone system involving spray zone 1 and 2. The overall dust-collection efficiency is given (*7, 9*) by

$$E_o' = 1 - (1 - E_1')(1 - E_2') \qquad \text{(C-3)}$$

and

$$E_o' = 1 - \exp\{-(K_1' + K_2')\} \qquad \text{(C-4)}$$

where E_1' and E_2' are the dust-collection efficiencies of each spray zone and K_1' and K_2' are the dust capture parameters of each spray zone in the two-zone system. Equations C-3 and C-4 apply whether the two zones are in series or in parallel.

If the two spray zones are in series and are independent of each other, the individual values of K_1 and K_2 separately measured with each spray zone will also apply to the two-zone system; i.e., $K_1' = K_1$ and $K_2' = K_2$.

However, if the two zones are in series and are interdependent or if the two zones are in parallel, the individual values of K_1 and K_2 separately measured in single-spray tests will not apply to the two-zone system. For example, if the airflow rate passing into zone 2 is affected by the presence of zone 1, then $\dot{Q}_{g_2}' \neq Q_{g_2}$. Similarly, if part of the water drops from zone 1 are carried into zone 2, then $\dot{Q}_{w_2}' \neq Q_{w_2}$.

The values of K_1 and K_2 can be approximately deduced from the dust-collection efficiencies given in table 2 in the main text. Assume secondary effectiveness ratios of water usage, γ_{12} and γ_{21}, which are related to the interaction of zone 2 on zone 1 and of zone 1 on zone 2 and write $K_1' = K_1\gamma_{12}$ and $K_2' = K_2\gamma_{21}$. The overall dust collection efficiency when the top and bottom spray systems are simultaneously used in a two-zone test is then

$$E_o = 1 - \exp\{-(K_1\gamma_{12} + K_2\gamma_{21})\}. \qquad \text{(C-5)}$$

Also assume that γ_{12} and γ_{21} depend upon spray-nozzle location, spray-nozzle orientation, and nozzle parameters but are independent of brattice location. The data in table 2 were used to calculate K_1 and K_2 for the individual top and bottom spray systems with the 10- and 15-ft brattice distances. Also, the data in table 2 for the combined top and bottom spray system with the 10- and 15-ft-distance brattices were then used to calculate $\gamma_{12} = 0.63$ and $\gamma_{21} = 0.87$. Results are summarized in table C-1.

TABLE C-1. - Dust capture parameters

	Single spray		Combined sprays		
	K_1	K_2	$K_1\gamma_{12}$	$K_2\gamma_{21}$	$K_1\gamma_{12} + K_2\gamma_{21}$
10-ft-distance brattice	0.77	0.87	0.48	0.76	1.24
15-ft-distance brattice	.83	.93	.52	.81	1.33

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[1] Italic numbers in parentheses refer to items in the list of references preceding appendix A.

With the combined two-zone spray system, the total dust collection parameter is greater than for either single spray system. If the top and bottom sprays in a two-zone test both performed as effectively as they performed in their individual top and bottom tests, the combined dust capture parameter would be 1.64 and a dust collection efficiency of 80.6 pct would be expected.

However, the dust-collection performance of the top spray appears to be seriously impaired by the presence of the bottom spray; i.e., since $\gamma_{12} = 0.63$, the performance of the top spray is decreased 37 pct by the presence of the bottom spray. Similarly, the performance of the bottom spray is somewhat impaired by the presence of the top spray; i.e., since $\gamma_{21} = 0.87$, the performance of the bottom spray system is decreased 13 pct by the top spray system.

This reduction in the dust-collection performance of each spray zone by the presence of the second spray zone involves a complex interaction of the basic dust-collection variables η, γ, L, D, Q_w and Q_g of each spray zone.

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