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COST-EFFECTIVENESS OF DUST CONTROLS USED ON UNPAVED HAUL ROADS

Volume I -- Results, Analysis, and Conclusions

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16. Abstract (Limit: 200 words) The basic objective of this project was to determine the cost-effectiveness of dust controls used on unpaved mine haul roads. Field testing was conducted at three surface coal mines (two in Wyoming, one in southern Illinois) for a total of 20 weeks. The highest control efficiency measured for a chemical dust suppressant, 82 pct, was for calcium chloride 2 weeks after application. Generally, however, the control efficiencies hovered in the 40 to 60 pct range over the first 2 weeks after application, and then decreased with time. After the fifth week, the limited number of data points suggest a control efficiency of less that 20 pct. Composite watering data were fairly uniform. Watering once per hour resulted in a total suspended particulate control efficiency of approximately 40 pct. Doubling that application rate increased the control effectiveness by about 15 pct to 55 pct. Chemical dust suppressants (primarily salts and lignons) can be shown to be more cost-effective than watering under some conditions. Data summaries and the analysis of data are contained in volume I. Volume II contains basic data.

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FOREWORD

This report was prepared by PEDCo Environmental, Inc., Golden, CO under USBM Contract number J0218021. It was administered under the technical direction of U.S. Bureau of Mines with H. William Zeller acting as technical Project Officer. David J. Askin was the contract administrator for the Bureau of Mines. This report is a summary of the work recently completed as a part of this contract during the period September 1981 to December 1983. This report was submitted by the authors in December 1983.

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SECTION 1

EXECUTIVE SUMMARY

1.1 STUDY DESCRIPTION

1.1.1 Objectives

The basic objective of this project is to determine the cost-effectiveness of dust controls used on unpaved haul roads. The major technical questions are:

1. What control methods (different chemicals and water) are suitable for dust control on unpaved mine roads?
2. How does control effectiveness vary over time, by application method (mixed in place or topical), and by application rate?
3. How does control effectiveness vary with the type of vehicle using the road (light-duty versus haul trucks), road surface characteristics (silt content, abrasiveness of surface, load bearing strength), and meteorological variables?

1.1.2 Products Available

A comprehensive questionnaire survey indicated that 40 manufacturers marketed various products for unpaved road dust suppression. Available products were divided into five categories based on their method of dust control and chemical similarity. These categories are:

Salts--Hygroscopic compounds that extract moisture from the atmosphere and dampen the road surface, e.g., calcium chloride, magnesium chloride, hydrated lime, sodium silicates, etc.

Surfactants--Substances capable of reducing the surface tension of the transport liquid, thereby allowing available moisture to wet more dirt particles per unit volume, e.g., soaps, detergents, Dust-set, Monawet, etc.

Adhesives--Compounds that are mixed with native soils to form a new surface, e.g., calcium lignon sulfonate, sodium lignon sulfonate, ammonium lignon sulfonate, etc.

Bitumens--Compounds derived from coal or petroleum, that are mixed with native soils to form a new surface, e.g., Coherex, Peneprime, asphalt, oils, etc.

Films--Polymers that form discrete tissues, layers, or membranes, e.g., vinyls, fabrics, etc.

Although these categories are not mutually exclusive, most products exhibit a predominant characteristic that allow them to be classified.

Salts, adhesives, and bitumens can be applied topically (sprayed on the road surface) or mixed in place (blade mixed with the top 4 to 6 inches of the roadbed) at intervals of weeks or months. Surfactants are routinely added to the water in water wagons and applied at intervals of hours. Most films require major road reconstruction.

All chemicals can be applied with water wagons except some bitumens (which require an asphalt distributor). Although not required, a better application method for chemicals than a water wagon is sometimes a calibrated spray bar because the material can be more evenly applied in known amounts.

Empirical data were not adequate to rank the effectiveness of each category of suppressant or to rank the chemicals within each category. Therefore, a representative chemical from each category except films was selected for testing (films are being tested under an EPA contract). Water was also tested. This approach was designed to answer the first major technical question guiding the study.

To determine how control effectiveness varied over time, by application method, and by application rate (major technical question 2), the testing scheme shown in Table 1 was adopted. Each dust suppressant was tested twice each day for six weeks, weather permitting. This schedule theoretically allowed for 12 tests of each control treatment at each mine, thereby meeting the statistical requirement.

To determine how control effectiveness varied by vehicle, road surface characteristics, and meteorological conditions (major technical question 3), tests were run at three mines exhibiting diverse conditions with regard to the variables in questions. The mine areas chosen are also shown in Table 1.

The basic design feature of the sampling configuration was simultaneous sampling on three contiguous test sections (Figure 1). The major advantage of this design is that it permits a direct comparison of uncontrolled and controlled emission rates under identical test conditions (vehicle type, road surface

TABLE 1. DUST SUPPRESSANTS TESTED

Category	Mine 1--southern Illinois			Mine 2--southwest Wyoming			Mine 3--northeast Wyoming		
	Chemical name	Application 1	Application 2	Chemical name	Application 1	Application 2	Chemical name	Application 1	Application 2
Salt	Liquidow ($CaCl_2$)	Mixed in place, 0.6 gal/yd^2 of 38%	Topically, 0.27 gal/yd^2 of 38%		Same as Mine 1		Liquidow ($CaCl_2$)	Mixed in place, 0.6 gal/yd^2 of 35%	Topically, 0.27 gal/yd^2 of 35%
Surfactant	Soil-Sement (acrylic)	Topically, 3.0 gal/yd^2 of 11%	Topically, 1.9 gal/yd^2 of 14.5%	Soil-Sement (acrylic)	Topically, 1.0 gal/yd^2 of 13.5% Reapplied in 2 weeks	Topically, 1.0 gal/yd^2 of 13.5% Reapplied in 2 weeks	Biocat (enzyme)	Mixed in place, 2.0 gal/yd^2 of 0.005%	None
Adhesives	Flambinder (lignon)	Mixed in place, 2.1 gal/yd^2 of 18%	Topically, 0.5 gal/yd^2 of 18%		Same as Mine 1		Flambinder (lignon)	Mixed in place, 1.8 gal/yd^2 of 18%	None
Bitumen	Petrotac (emulsified asphalt)	Mixed in place, 1.0 gal/yd^2 of 18%	Mixed in place, 0.7 gal/yd^2 of 18%	Arco 2200 (emulsified asphalt)	Mixed in place, 2.8 gal/yd^2 12.5%	Topically, 0.9 gal/yd^2 of 12.5%	Arco 2200 (emulsified asphalt)	Mixed in place, 2.3 gal/yd^2 of 14%	Topically, 1.1 gal/yd^2 of 14%
Water		Twice/hour, unknown quantity	Once/hour, unknown quantity		Same as Mine 1			Once/hour, unknown quantity	Once/2 hours unknown quantity

Reference to specific brands, equipment, or trade names in this report is made to facilitate understanding by the Bureau of Mines.

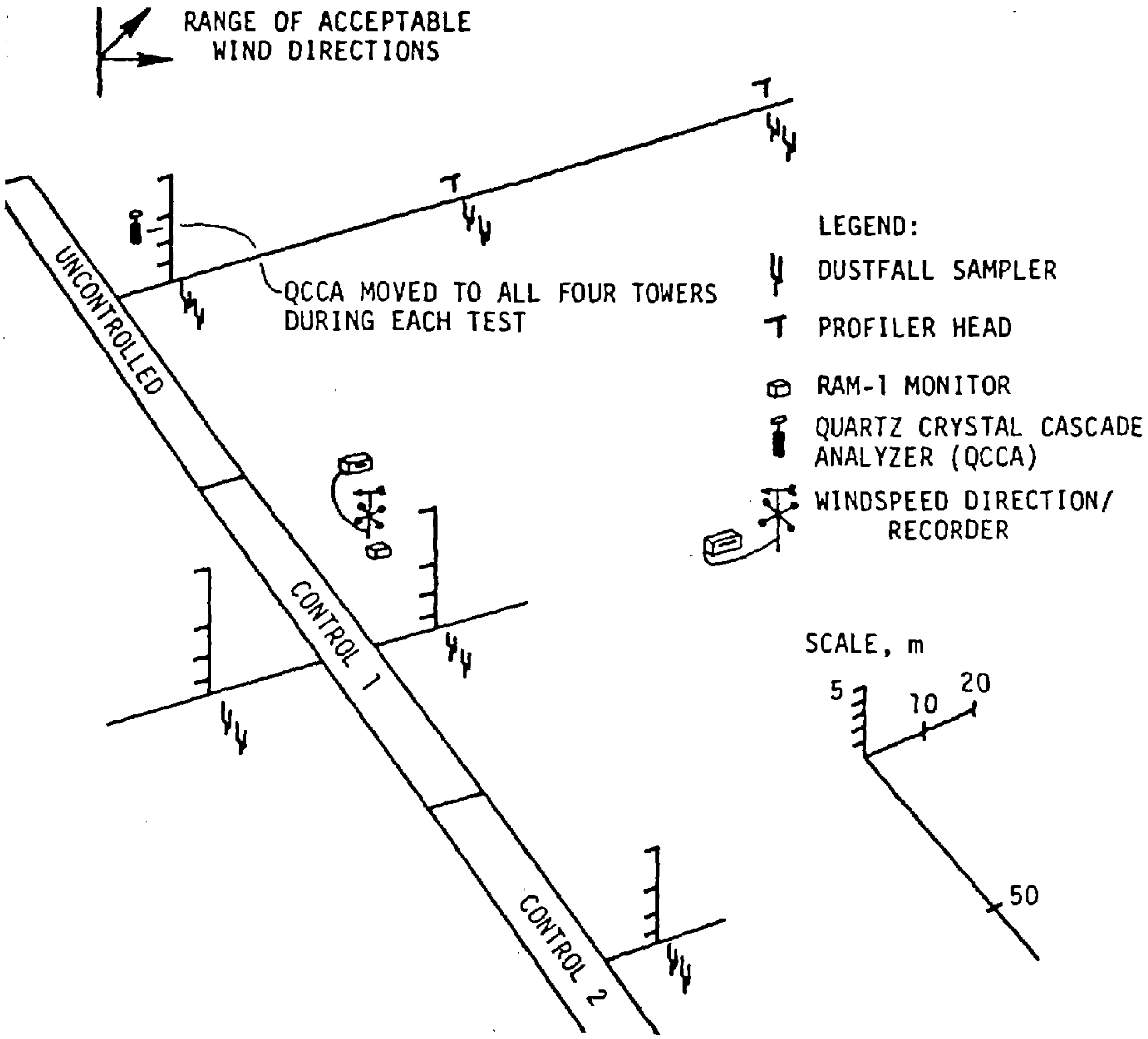


Figure 1. Sampling configuration.

properties, and meteorology). This design eliminates the need to adjust measurements to account for the varying effects of these independent variables between sequential tests. Every set of three simultaneous tests provides two specific control efficiency values. A second advantage of this design is that it reduces the total number of samples required to produce statistically valid results by permitting the use of a single upwind profile for three downwind profiles.

The primary sampling instrument for the study was the vertical exposure profiler, which samples isokinetically at four heights (1 to 9 meters) in the plume. The profiling head design is based on the stacked filter concept investigated by Stevens and Dzubay (1978) and Cahill et. al. (1979). The profiling heads consisted of a one-inch orifice inlet, a fine mesh screen to remove particles larger than 30 μm (larger than TSP), an 8-μm pore size Nuclepore filter corresponding to a 2.5-μm cut size, and a backup filter to catch particles smaller than 2.5 μm.

1.1.4 Test Locations

Chemicals were applied at Mine 1 in southern Illinois from June 9 to 11, 1982. Vendors were on site to supervise all applications. Soil tests for the poorly constructed roadway resulted in a classification of lean clay. The roadway contained a very high percentage of fines (50 to 74 percent) and had a very low estimated bearing capacity (2000-6000 psf). The testing period was plagued with rain, with a total of 7.28 inches falling in 12 storm events spread over 38 days. This greatly hindered testing and depressed emission levels. Sixty-three tests were performed.

Chemicals were applied at Mine 2 in southwestern Wyoming on July 31, 1982. Vendors again supervised application. Road construction was excellent. Test conditions were hot and dry, and personnel at the mine were very cooperative. A total of 123 tests were performed.

Chemicals were applied at Mine 3 in northeastern Wyoming on October 16, 1982. The test period was deliberately scheduled late in the year to meet a project objective of testing dust suppressants when freeze/thaw cycles were prevalent. The roadway surface material was scoria, with a silt content of 24 percent. Similarly to Mine 1, the high percentage of fines resulted in a very low bearing capacity. When wet, the road became very muddy and rutted badly. The test period was plagued with snow and high winds, and was cancelled after three weeks due to heavy snow and a subsequent complete reworking of the road by mine personnel. A total of 44 tests were performed in moist conditions at or below freezing.

1.2 RESULTS

1.2.1 Control Efficiencies

Control efficiencies for chemical dust suppressants are shown in Table 2. The data are presented by mine, chemical, application method, and time since application.

The highest control efficiency measured, 82 percent, was for calcium chloride two weeks after application. Generally, however, the control efficiencies hovered in the 40 to 60 percent range over the first two weeks since application, and then decreased with time. After the fifth week, the limited number of data points suggest a control efficiency of less than 20 percent. It could be argued that the moist conditions at Mines 1 and 3 decreased measured control efficiencies because of the dampness of the uncontrolled sections and resulting comparatively lower no-control emission rates. However, testing at Mine 2, where conditions were hot and dry, was ideal for evaluating chemical dust suppressants.

Composite watering data are shown in Table 3. A total of 36 data points are represented. The data were fairly uniform. Watering once per hour resulted in a TSP control efficiency of approximately 40 percent. Doubling that application rate increased the control effectiveness by about 15 percent to 55 percent.

1.2.2 Cost Effectiveness Analysis

The benefits to a mine operator using a dust suppressant include the following:

1. Maximum haul truck speed can be attained because of increased driver visibility and better road surface conditions, thereby decreasing the coal haul cycle time and cost (labor and equipment).
2. Haul road and vehicle maintenance expense is decreased.
3. Air quality is improved, resulting in fewer worker days lost and a cleaner environment.

These three benefits must be completely characterized to fully dimension the benefits of dust suppressants. Portions of the first two benefits can be costed, but the air quality benefit is difficult or impossible to cost. The next problem is whether to compare chemical dust suppression and watering cost with each other, or with no control at all. Comparison with no control is illogical since all mines have dust control programs in the summer to aid driver visibility.

TABLE 2. AVERAGE DAILY CONTROL EFFICIENCY

Control	Weeks Since Application													
	1		2		3		4		5		6		7	
	M[a]	T[b]	M	T	M	T	M	T	M	T	M	T	M	T
	Salt (LiquiDow, $CaCl_2$)													
Mine 1														
TSP[c], %			82	76									14	18
FP[d], %			50	50									56	64
Vehicle passes			4,608										17,581	
Mine 2														
TSP, %	24	51	59	64	50	55	42	41						
FP, %	45	49	46	52	31	27	50	36						
Vehicle passes	4,476		10,188		16,518		24,084							
Mine 3														
TSP, %			20	26	0	16								
FP, %			42	16	6	0								
Vehicle passes			4,449		8,119									
	Surfactant													
Mine 1 (Soil Sement)[e]														
TSP, %					30	34	59	81	37	52	4	14		
FP, %					58	79	50	74	35	36	0	22		
Vehicle passes					6,161		9,567		12,422		14,726			

(continued)

Table 2 (continued)

Control	Weeks Since Application													
	1		2		3		4		5		6		7	
	M[a]	T[b]	M	T	M	T	M	T	M	T	M	T	M	T
Mine 2 (Soil Sement)														
TSP, %		71				24				3				
FP, %		53				21				0				
Vehicle passes	2,622				14,046				26,706					
Mine 3 (Biocat-Enzyme)														
TSP, %	38		0											
FP, %	20		46											
Vehicle passes	2,891		6,561											
Adhesives (Flambinder, lignon)														
Mine 1														
TSP, %			59	55										
FP, %				31										
Vehicle passes			4,608											
Mine 2														
TSP, %	63	25	52	39	50	32	52	42						
FP, %	46	21	22	27	28	22	53	50						
Vehicle passes	1,386		8,952		15,282		25,320							
Mine 3														
TSP, %	45		38		31									
FP, %	44		49		46									
Vehicle passes		729	4,801		8,823									

(continued)

Table 2 (continued)

Control	Weeks Since Application													
	1		2		3		4		5		6		7	
	M[a]	T[b]	M	T	M	T	M	T	M	T	M	T	M	T
	Bitumen (Arco 2200, Emulsified Asphalt)													
Mine 2														
TSP, %	30	38	0	25	28	29	20	4						
FP, %	42	41	0	17	36	28	25	26						
Vehicle passes	7,716		12,660		18,990		22,848							
Mine 3														
TSP, %	44	56												
FP, %	33	73												
Vehicle passes	2,187													

[a] Mixed in place application.
[b] Topical application.
[c] Total suspended particulate.
[d] Fine particulate.
[e] Both are topical applications. The "M" section represents Section 1 in Table 6-2.

TABLE 3. COMPOSITE CONTROL EFFECTIVENESS OF WATER

	Watering Frequency, minutes		
	120	60	30
Mine 1			
TSP, %	16	37	51
FP, %	29	40	43
Vehicles/hr	32	24	28
Mine 2			
TSP, %		41	59
FP, %		26	47
Vehicles/hr		65	78

Many of the analysis problems can be eliminated if the comparison is based on the cost to achieve a specified level of control efficiency. In this instance, many of the costs associated with chemicals and watering become equal or do not apply. For example, the comparative dollar benefits from air quality (cleaner environment, fewer worker days lost) become equal. Therefore, chemicals and water were compared for a specific control level. The control level used for this analysis is 50 percent. Based on measured control efficiencies, no higher control level could be sustained over a period of weeks.

Table 4 shows the assumptions used in the analysis. They were derived from data supplied by specific mines, and values could vary from mine to mine. Table 5 presents the cost-effectiveness analysis. The analysis of chemical dust suppressants had to be limited to the products shown, since testing data for the other product/application combinations did not allow an accurate estimation of the required reapplication interval to maintain an average 50 percent control efficiency. Table 5 indicates that the topically applied salt or mixed-in-place adhesive (east) is more cost-effective than watering. However, the decision to use chemicals or water should also include the observations given in Section 1.4.

Reapplications of the chemicals would probably result in higher control efficiencies than the initial application because of residual traces of the material. Therefore, this analysis based on initial applications may overestimate the cost of a long-term chemical program. Conversely, watering displays no such cumulative control effects. Mixed-in-place application is usually only recommended once/year or at the time of initial application. Therefore, costs for topical application are more indicative of long-term chemical suppressant program costs.

1.3 COMPARISON WITH OTHER STUDIES

Tests for the effectiveness of watering are fairly consistent. Taken in total, the data suggest that the 50 percent control effectiveness commonly credited for watering is realistic with once/hour or greater watering frequency.

The majority of the previous testing of chemical dust suppressants shares a common failing: the data were collected within two days of application. These data are highly misleading for two reasons:

1. Cost of chemical dust suppressants is $1,000 to $15,000/-mile-application. Therefore, application is usually feasible on a monthly or less-frequent basis.

TABLE 4. ASSUMPTIONS FOR COST-EFFECTIVENESS ANALYSIS

Benefit/cost differential indices	$/h	Hours/mile			Frequency
		Chemicals			
		Mixed	Topical	Water	
Application					
Surface prep	75	16	8	0	1/application
Material cost	--	--	--	--	1/application
Application	45	8	2	0.15	1/application
Grading cost	75	0	0	4	Water, 1/wk Chemicals, 1/ application
Remaining watering	95	0.15	0.15	0.15	Water, 1.5/h Chemicals, 1/ shift

TABLE 5. PRELIMINARY COST-EFFECTIVENESS COMPARISON TO ACHIEVE 50 PERCENT CONTROL

Control[b]	Cost of chemical application/ mile, $[a]		Cost of grading, watering/week, $		Applications required to average 50% control	Cost per week	
	East	West	Grading	Water		East	West
Salt							
Mixed	7240	11,263	0	143	1/4 weeks	1953	2959
Topical	3260	5,058	0	143	1/4 weeks	958	1408
Adhesive							
Mixed	4813	7,644	0	143	1/4 weeks	1346	2054
Water			300	1710	120/week	2010	2010

[a] Includes surface preparation, material cost, and application. Material cost is delivered cost in East (southern Illinois) and West (Rock Springs). Material cost is: Liquidow, $0.36/gallon East, $0.47/gallon West; Flambinder $0.33/gallon East, $0.47/gallon West. Assumes 50-foot and 60-foot-wide road in East and West.

[b] Required application intervals could not be estimated for adhesive--topical, surfactant, or bitumens. Comparative costs could not be calculated.

2. Chemical dusts suppressants are typically applied at application rates of 0.3 to 3.0 gallons per square yard. At these rates, the roadway is likely still wet or moist for 24 to 48 hours depending on humidity and solar intensity. Therefore, testing during this "wet-road" period is really testing moisture (water), not the effectiveness of the dust suppressant over the long term in a dry state.

Testing of dust suppressant in coal mines at time-since-application of greater than 7 days is limited. The only other coal mine long-term testing results are ARCO tests (4 data points) which showed a control efficiency of 35 percent after 3.5 weeks. Long-term testing at iron and steel facilities shows higher control efficiencies. This is probably due to the smaller vehicles involved, lower average vehicle speeds, eastern testing locations, and perhaps due to better overall road construction.

The results for long-term ($\geq$ 1 month) testing taken in total seem to suggest that the 85 percent control value commonly credited for chemical dust suppressant effectiveness in coal mines is probably optimistic considering the common mine practice of applying at once a month or less intervals. Further testing is required to determine if application at more frequent intervals, or the cumulative impact of multiple applications, would markedly increase control effectiveness.

1.4 CHEMICALS VERSUS WATER

The control efficiency data presented in Section 1.2.1 indicates that initial chemical applications cannot be expected to yield greater than 50 to 60 percent control averaged over one month. Additional data are necessary to determine if repeated applications would yield significantly greater control efficiencies because of the residual buildup of material. However, the cost analysis in Section 1.2.2 indicates that applications at frequencies greater than once every four weeks will make all but the least cost chemicals (lignons/salts) less cost effective than water. Control efficiencies of 50 to 60 percent can also be achieved by watering programs with applications of greater than once per hour, sometimes at a similar cost. Therefore the choice of using chemicals or water is not clear and will depend on mine specific variables including availability of equipment, union restrictions, the type of road surface, and other factors. Except for union restrictions, these factors are discussed below.

1.3.1 Equipment Availability

Equipment already in inventory could impact on the decision to use chemicals or water. A chemical program (topical application) will require about 50 and 90 percent less grader and water truck capacity even when these same pieces of equipment are used for chemical application. If the chemical application is contracted, water truck capacity is reduced 94 percent as compared to a watering program (watering of about once per shift is still required with chemicals). Unless other uses can be found for grading and watering capacity, idle equipment must also be considered a cost.

1.3.2 Control Type Versus Road Surface Aggregate

Although sufficient test data is not yet available to conclusively prove the factor, it is apparent that certain types of dust suppressants work better in certain types of road aggregate. Recommendations appear in Table 6.

TABLE 6. CONTROL TYPE VERSUS PROPER ROAD AGGREGATE SIZE GRADATION

Road Surface	Suppressant With Best Potential for Control
>Gravel	Water
>Sand	Bitumens
Good Gradation	Any
>Silt	Rebuild Road

The recommendations in Table 6 are based on the following:

1. In road surfaces with too much gravel, only watering will be effective. Chemical dust suppressants can neither compact the surface because of the poor size gradation, or form a new surface, and water soluble suppressants will leach.

2. In compact sandy soils, bitumens, which are not water soluble, will be the most effective. Water soluble suppressants such as salts, lignons, and acrylics will leach from the upper road surface. However, in loose medium and fine sands, bearing capacity will not be adequate for the bitumen to maintain a new surface.

3. In road surfaces with a good surface gradation, all chemical suppressant types offer potential for equal control.

4. In road surfaces with too much silt (greater than about 20 to 25 percent as determined from a scoop sample, not a vacuum or swept sample) no dust suppression program will be effective and the road should be rebuilt. In high silt locations, the chemical suppressants will

tend to make the road slippery, will not be able to compact the surface, or maintain a new road surface because of poor bearing capacity. Further, rutting under high moisture conditions will require that the road be regraded, which almost completely destroys chemical dust suppressant effectiveness. If the road cannot be rebuilt, watering is the best program.

1.3.3 Other Factors

All chemical dust suppressants (with infrequent watering) share one common failing as compared with frequent watering. Material spillage on roadways is extremely common in mines, particularly if ash haulers are also using haul roads. Material spilled is subject to reentrainment. With frequent watering, the spilled material is moistened at approximately hourly intervals. With chemicals, the spilled material could go 8 to 24 hours before being moistened, and the material would again redry. Therefore, in mines where spillage cannot be effectively controlled, watering will probably be more effective for dust control.

In both Mines 1 and 3, mine operators claimed that the chemically treated road sections were more slippery than the water-treated sections. Both mines had road surfaces high in silt and clay content, which leads to slippery conditions when moisture is present. Chemical suppressants probably do aggravate this problem because the hygroscopic salts and the surfactants keep the road surface wetter longer and the adhesives and bitumens can act as a lubricant between the fine particles. In Mine 2, no slippery problems were experienced. This mine had a coarser (better-drained) road surface with a silt percentage of less than 10 percent.

In locations where trackout from an unpaved road to a paved road is a problem, chemical suppressants will generally be a better choice. Watering aggravates the trackout problem with moisture and mud, whereas a chemical suppressant (particularly bitumens and adhesives) leaves the road dry.

Some mines have a dust problem in winter when temperatures are subfreezing but little moisture is present. The case for chemical suppressants over water in this case is clear.

SECTION 2

CONTROLS TO BE TESTED

2.1 PRODUCTS AVAILABLE

A literature search was completed and questionnaires were sent to 83 manufacturers. Survey results indicated that 23 of the manufacturers referenced in the literature as producers of dust suppressants are no longer in business or no longer manufactured dust suppressants; 40 manufacturers of dust suppressants specifically market their product(s) as suitable for road application. Table 7 identifies the products marketed as suitable for road application.

The dust suppressant manufacturing industry has not developed a standardized procedure for classifying their products. Previous investigators have utilized numerous classification schemes. The following classification scheme is used throughout this report:

Salts - Hygroscopic compounds, i.e., calcium chloride, magnesium chloride, hydrated lime, sodium silicates, etc.

Surfactants - Substances capable of reducing the surface tension of the transport liquid, i.e., soaps, detergents, dust-set, monawet, etc.

Soil cements - Compounds that are mixed with the native soils to form a new surface, i.e., calcium lignon sulphonate, sodium lignon sulfonate, ammonium lignon sulphonate, portland cement, etc.

Bitumens - Compounds derived from coal or petroleum, i.e., coherex, peneprime, asphalt, oils, etc.

Films - Polymers which form discrete tissues, layers, or membranes, i.e., latexes, acrylics, vinyls, fabrics, etc.

Salts increase roadway surface moisture by hygroscopically extracting moisture from the atmosphere. Surfactants decrease the surface tension of water, which allows the available moisture to wet more particles per unit volume. Soil cements, bitumens, and films generally form coherent surface layers that seal the road surface and thereby reduce the quantity of dust generated.

TABLE 7. HAUL ROAD APPLICATION AND PURCHASE PRICE INFORMATION

Products	Application rate for dust control and road stabilization per sq yd of road	Application rate for dust control per sq yd of road	Topically applied	Mixed in place	FOB purchase price,[a] dollars
Bitumens					
Arco 2200	0.5 gal of 4:1	0.5 gal of 10:1	X	X	1.75/gal
Arco 2300	0.75 gal of 10:1	0.25 gal of 10:1	X	X	1.85/gal
Coherex	0.5 gal of 4:1	0.5 gal of 10:1	X	X	1.25/gal
Docal 1002	1 gal	0.5 gal	X	X	0.67/gal
Dustex-petroleum-resin-emulsion	1.5-3 gal	1 gal	X	X	1.75/gal
Foramine 21-194	Not available	Not available	X	X	0.27/gal
Peneprime	1 gal	0.5 gal	X	X	1.25/gal
Petro-Tact 60	Not available	Not available	X	X	1.45/gal
Resonex	Not available	Not available	X	X	-
Retain	0.5 gal of 4:1	0.5 gal of 10:1	X	X	5.55/gal
Films					
Bidim	1 sq yd	Not applicable		X	1.00/sq yd
Curasol AK	Not applicable	0.2-0.5 gal	X		5.95/gal
Latex 3011	Not applicable	0.1 lb	X		4.16/gal
Mirafi	1 sq yd	Not applicable		X	-
Suferm	0.5 gal	0.2 gal	X	X	1.88/gal
Supac	1 sq yd	Not applicable		X	0.60/sq yd
Typar	1 sq yd	Not applicable		X	-
Salts					
Dowflake	2.5-4.2 lb	0.8-1.3 lb	X	X	153.00/ton
Liquidow	0.6-1.0 gal of 30%	0.2-0.3 gal of 30%	X	X	0.50/gal
Nalco 8806	Not applicable	0.25 gal	X		0.45/gal
Peladow	2.1-3.4 lb	0.7-1.0 lb	X	X	214.00/ton
Pentron-21	0.5 gal	0.25 gal	X	X	0.35/gal
Sodium silicate (N)	Not available	Not available		X	0.61/gal
Sodium silicate (O)	Not available	Not available		X	0.61/gal

(continued)

TABLE 7. (continued)

Products	Application rate for dust control and road stabilization per sq yd of road	Application rate for dust control per sq yd of road	Topically applied	Mixed in place	FOB purchase price,[a] dollars
Soil cements					
Dust/bond 100	1.0-1.5 gal	0.4-0.6 gal	X	X	0.40/gal
Flambinder N	1.4-2.8 gal	0.9 gal	X	X	0.15/gal
Flambinder NX	1.4-2.8 gal	0.9 gal	X	X	0.17/gal
Foramine 21-94	Not available	Not available			0.27/gal
Lignosite	10 gal of 25% sol	0.5 gal of 25%	X	X	152.00/ton
Lignosite 50% neutralize	1.0 gal of 50% sol	0.5 gal of 25%	X	X	0.17/gal
Norlig A	0.6-1.2 gal of 20%	0.3-0.5 gal of 20%	X	X	0.185/gal
Orzan AL-50	2.0-5.0 gal	1.6-2.3 gal	X	X	0.20/gal
Orzan DSL	2.0-5.0 gal	1.6-2.3 gal	X	X	0.20/gal
Orzan GL-50	2.0-5.0 gal	1.6-2.3 gal	X	X	0.20/gal
Soil sement	0.2 gal	0.12 gal	X	X	1.83/gal
Soiltex	2.0-5.0 gal	0.8-1.6 gal	X	X	0.33/gal
Vinol 540	Not available	Not available	X	X	1.39/gal
Woodchem LS	3.0 gal	1.5 gal	X	X	0.17/gal
Surfactants					
Aerospray 70	Not applicable	Not available	X		5.00/gal
Compound MR	Not applicable	Not available	X		4.00/gal
Compound MR 20/40	Not applicable	Not available	X		5.25/gal
Dustbinder concentrate	Not applicable	Not available	X		4.50/gal
Dustex	Not applicable	Not available	X		6.98/gal
Dust-set	1.4 lb 1:50 dilution	1.4 lb 1:500 dilution	X	X	8.00/gal
Haul road dust control	Not applicable	Not available	X		3.75/gal
MO 70E	Not applicable	Not available	X		6.30/gal
Sterox DF	Not applicable	Not available	X		6.35/gal
Sterox ND	Not applicable	Not available	X		6.35/gal
Sterox NJ	Not applicable	Not available	X		6.35/gal

[a] FOB purchase price as reported to PEDCo by manufacturer's sales representative. December 1981-January 1982. Volume discounts are generally available from the vendors and/or manufacturer.

The cost of using a dust suppressant is very site specific. Factors such as the soil type, the dust suppressant's longevity, frequency of rain, labor costs, material transportation costs, available equipment, miles of road, average daily traffic counts, severity of the dust problems, and level of control desired, are all site specific. Shipping costs to the mine are a major part of the product cost and may exceed product cost.

Dust suppressants are applied either topically or mixed in place. The type of suppressant and the stability of the roadbed prior to dust suppressant application generally dictate the type and rate of application. Some of the products are capable of reducing dust quantities and increasing the load bearing capacity of the roadbed if they are mixed in place. However, if the road bed has sufficient load bearing capacity, some of the products may also be applied topically with the primary benefit being dust control. Table 7 also indicates the dust suppressant manufacturers recommended application rates and whether the dust suppressant is mixed in place or topically applied.

2.2 SELECTION OF CHEMICALS FOR TESTING

It was desirable to rank order the products to focus the available project resources in the most meaningful way. Unfortunately, no adequate empirical data existed to rank the effectiveness of each category of suppressant, or to rank the chemicals within each category. Actual field measurements of dust suppression effectiveness are limited to less than 30 field tests within 48 hours of application (other interested parties are conducting additional tests at this time). Therefore, it was decided to test a representative chemical from each category except films. The effectiveness of films in reducing dust is being tested as part of another study (EPA 1980).

Criteria were developed for selecting the representative chemical from each category (Table 8). Based on these criteria, four dust suppressants were selected and final arrangements were made with vendors (Table 9). It was necessary to use different bitumens and surfactants at some mines because of product availability.

2.3 USE OF TEST SECTIONS

The basic design feature of the sampling configuration is simultaneous sampling on three contiguous test sections (Subsection 4.1). The major advantage of this design is that it permits a direct comparison of uncontrolled and controlled emission rates under identical test conditions (vehicle type, road surface properties, and meteorology).

TABLE 8. CRITERIA FOR SELECTION OF CHEMICALS

Item	Requirement
Existing use in coal mines	Be currently widely used in surface coal mines
Representative of category	Be a typical product for the applicable category
Vendor cooperation	ID suggested application Method Rate Decay time Watering schedule Be present during application and beginning of testing Supply chemical delivered to test site

TABLE 9. DUST SUPPRESSANTS TESTED[a]

Category	Product name	Product type	Mine usage
Bitumen	Petrotac	Emulsified asphalt	Southern Illinois
	Arco 2200	Emulsified asphalt	Southwest Wyoming
			Northeast Wyoming
Salts	Liquidow	Calcium chloride	All mines
Soil cements	Flambinder	Calcium lignon sulfonate	All mines
Surfactant	Soil Sement	Surfactant/acrylic polymar	Southern Illinois Southwest Wyoming
	Biocat	Surfactant/enzyme	Northeast Wyoming

[a] Selection of a particular product does not constitute an endorsement. The comparitive value of other products is not known.

Referring back to the objectives of the study (Subsection 1.1) it was desirable to test each suppressant for control effectiveness over time, by application method (mixed in place or topical), and by application rate. Control effectiveness over time was evaluated by testing at periodic time intervals since application. The second and third segments were used to evaluate control effectiveness by application rate and/or method.

Two criteria were used to determine how the second and third segments would be used:

1. Practicality - the application method or rate must be presently in use at some mines or be feasible from a cost and operational standpoint.

2. Manufacturers recommendations - the application method or rate must conform to the manufacturers recommended procedures.

The two criteria were applied through discussions with mine owners and the dust suppressant vendors participating in the study. With the exception of the surfactants, it was decided to use one control segment with the material mixed in place (representing a maximum treatment), and the other control segment with the material topically applied, both at manufacturers suggested rates. Soil Sement was applied topically on both sections, but at different application rates. The Biocat product had only one control section which was mixed in place. Detailed application rates and methods are described in Section 6.

SECTION 3

NUMBER OF TESTS REQUIRED AND SELECTION OF TEST CONDITIONS

3.1 REQUIRED SAMPLE SIZE

Statistical evaluations were performed to determine the number of mines where testing should desirably occur, and to determine the number of tests required of each control measure at each mine. The recommended precision and confidence levels are ±20 percent of the relative emission rates (1 - control efficiency) and 90 percent confidence, respectively. These levels correspond to those specified in a recent EPA-sponsored emission factor development study (EPA 1981).

A control efficiency value is actually composed of two simultaneous tests, one on a controlled section and the other on an uncontrolled section of haul road. Precision and confidence levels for uncontrolled emission rates will be much greater than those for control efficiencies because of the basic testing design (see Subsection 5.1). Fully one-third of the tests will be on uncontrolled sections, with the remaining tests distributed among five controls and different application rates and methods.

Time since application was not considered as a variable in determining required sample size. The length of a mine visit, which constitutes the total range of time since application over which testing can occur, was expected to be less than the effective life of all controls except watering.

Since uncontrolled emission rates for haul roads are not normally distributed (EPA 1981), controlled emission rates and control efficiencies are probably not either. Therefore, Stein's relatively simple two-stage method for estimating required sample sizes cannot properly be applied. A similar method for estimating sample size, based on the assumption that uncontrolled and controlled emission rates are each lognormally distributed, has been derived in Appendix B of the Long-Range Test Plan. In addition to the assumption of lognormality, the derivation also assumes that the relative standard deviations of the controlled and uncontrolled emission data sets (untransformed) are equal. With the latter assumption, the standard deviation from the EPA-sponsored study (EPA 1981) can be used to estimate expected variance in BOM test data.

The equation derived for estimating sample size is:

$$\sqrt{n} = \frac{2\sqrt{2}\ ts}{\ln K}\text{ , where}$$

n = number of control efficiency (CE) values, equal to number of tests for a control option

t = tabled t-value for specified confidence level and n-1 degrees of freedom

s = estimate of population standard deviation, obtained from previous haul road testing

K = ratio of upper limit value to lower limit value for confidence interval around (1 - CE)

The estimates of standard deviation (of ln-transformed values) obtained from the EPA-sponsored mining study are 0.25 for haul road samples from a single mine and 0.55 for samples from all mines. The value of K equivalent to an error (precision) level of ±20 percent is 1.5, as demonstrated by the confidence intervals calculated below:

		Confidence limits		
Mean CE	1 - CE	-20%	+20%	K, ratio of upper to lower limit
0.90	0.10	0.08	0.12	1.5
0.80	0.20	0.16	0.24	1.5
0.70	0.30	0.24	0.36	1.5
0.60	0.40	0.32	0.48	1.5
0.50	0.50	0.40	0.60	1.5

Using Equation 1 and trial substitutions of t-values with n-1 degrees of freedom and 90 percent confidence, the required number of samples of a control option (specific application rate and method) at one mine can be calculated to be 10:

$$\sqrt{n} = \frac{2.828(1.833)(0.25)}{\ln 1.5}$$

$$n = 10.2$$

Similarly, the minimum number of samples from all mines can be determined to be 42:

$$\sqrt{n} = \frac{2.828(1.684)(0.55)}{\ln 1.5}$$

$$n = 41.7$$

As a first estimate of the number of mines where testing should be done, the total number of required samples can be divided by the number required per mine (41.7 ÷ 10.2 = 4.1).

However, due to limited resources in Phase I, it is recommended that testing be planned for three mines with provision for an additional mine (or mines) in Phase III if indicated by the Phase I results. At each mine, at least 10 tests are to be taken for each control option. A summary of the test plan is shown in Table 10.

3.2 TEST CONDITIONS

3.2.1 Mines Selected for Testing

Mining regions in which sampling occurred in Phase I were selected according to the following criteria:

1. The greatest amount of travel on unpaved mine roads.

2. The greatest need for dust control due to proximity to population centers or Class I lands.

3. Values for independent variables which permit a characterization of the impact of each variable.

Based on these three criteria, it was recommended that Phase I testing be performed in the southeast Montana/northeast Wyoming region, the Illinois/Indiana/western Kentucky region, and the southern Wyoming/northwest Colorado region.

Criteria were developed to select a mine for testing within each of the three desired mining regions (Table 11). Approximately ten mine owners in each of the three mining regions were contacted by mail in late March 1982 to solicit cooperation.

Mines in each region that wished to cooperate and that appeared to meet the requirements for testing were visited by PEDCo personnel to make a final determination of suitability and make final plans for testing. Based on the presurvey visits, a mine was selected in each mining region. The mines selected were in southern Illinois, southwest Wyoming (near Rock Springs), and northeast Wyoming (near Gillette).

The schedule for testing at each mine was configured using the following considerations:

- Seasons - An objective of the study is to test the suppressants under a wide range of climatic conditions. The Illinois/Indiana mine will be the wettest of the three areas in May/June, the southeast Montana/northeast Wyoming mine will be the hottest and driest of the three areas in July/August, and the southern Wyoming/northwest Colorado mine will be the coldest of the three areas in October/November.

TABLE 10. SUMMARY OF TEST PLAN

Treatment on test section	No. of tests Mine 1	Mine 2	Mine 3
Chemical A Sections			
- Application A1[a]	10	10	10
- Application A2	10	10	10
- Uncontrolled	10	10	10
Chemical B Sections			
- Application B1	10	10	10
- Application B2	10	10	10
- Uncontrolled	10	10	10
Chemical C Sections			
- Application C1	10	10	10
- Application C2	10	10	10
- Uncontrolled	10	10	10
Chemical D Sections			
- Application D1	10	10	10
- Application D2	10	10	10
- Uncontrolled	10	10	10
Watering Sections			
- Application W1	10	10	10
- Application W2	10	10	10
- Uncontrolled	10	10	10
Total tests required to meet statistical goals	150	150	150

[a] A1 and A2 represent 2 distinct application methods or rates.

TABLE 11. CRITERIA FOR MINE SELECTION

Item	Requirement
Mine cooperation	° Access to mine for a 1-day presurvey visit and for one 6-week test period ° Apply dust suppressant or make available manpower and equipment at reasonable cost (chemicals supplied by BOM) ° Alter watering schedule on test sections
Roadway characteristics of test sections	° Adequate length of permanent haul road for five test sections, 300 meters each in length ° At least two different directional orientations to the test sections ° Flat or gently rolling terrain adjacent to test sections ° Average haul road traffic of >20 haul trucks/hour ° $\geq$1/4 mile away from other major dust sources ° Test sections not previously treated with chemicals within previous two years

- ° Proximity to equipment repair locations - The Illinois/Indiana location is closest to population centers and to Cincinnati (PEDCo main office). In the event of equipment failure or malfunction during the first testing period, the equipment will be the easiest to repair from the Illinois/Indiana location.

- ° Mine availability - Final arrangements could be made with an Illinois/Indiana mine before the other regions.

Based on these considerations, the order of testing suggested by the seasons was desired. Based on other practical considerations, the southern Wyoming/northwest Colorado mine was tested second.

There are several types of unpaved roads associated with surface coal mines. They can be classified as:

1. Mine Access Roads - Roadways usually outside the mine used predominately by employees with light-duty vehicles. Where coal is not shipped by train, the roads may also be used by heavy-duty trucks for coal transport.

2. Permanent Haul Roads - Roadways in the mine from the pit area to the processing plant. The road is used predominately by haul trucks but also may be used by light-duty vehicles. The road is relatively permanent over the life of the mine.

3. Temporary Haul Roads - Roadways in the pit area to provide access to the exact location in the pit where work is being performed. The road is used predominately by haul trucks but is also used by light-duty vehicles. The road exists for days to months.

4. In-Mine Service Roads - Roadways within the mine to provide access to specific service areas in the mine. The roads are used primarily by light-duty vehicles and can be temporary or permanent.

Mine access roads can be a major source of particulate emissions, particularly around large mines with 300 to 500 employees. However, Best Available Control Technology (BACT) for access roads in EPA Region VIII is paving, or chip and seal. Therefore, this emission source will be of less importance for new mines, and also in some existing mines that choose to use BACT on their access roads. In addition, while a significant quantity of emissions may be produced, the impact on particulate concentrations is often minimal because of the isolated location of most access roads.

Permanent haul road particulate emissions represent from 20 to 85 percent of all particulate emissions from a mine (EPA 1981). Because permanent haul roads are such a major source, and because the roads are permanent over the life of the mine, this category of road has been the primary focus of control effectiveness investigation.

Temporary haul roads are less appropriate for testing for several reasons. First, because they are temporary, any control except watering is probably not economically feasible. Second, truck speed on these roads is usually very low, resulting in a lower emission rate. Third, many of these roads are down in the pit and a portion of the emissions does not escape the pit. Fourth, some of the roads are only used for days, making long-term testing impossible. Fifth, testing would be hampered by the proximity to several other dust producing activities.

Mine service roads are usually not a significant emissions source because they are used relatively infrequently and predominately by light-duty vehicles.

In light of the above, permanent haul roads were selected for Phase I testing. The next most likely category, access roads, will be of less importance as an emissions source in the future and should be tested as part of Phase III, if at all.

3.2.2 Testing Schedule within the Mine

As noted in Subsection 3.2.1, ten tests are required of each chemical in each mine to obtain the desired statistically determined confidence level.

The main parameters for determining the schedule of testing within a mine are shown in Table 12. The parameters dictate the idealized testing scheme shown in Figure 2. Each of the five test sections will be tested twice on one day each week over a five week period. This will ideally facilitate achieving the ten tests over a five week period. Experience with previous mine sampling, however, indicates that the idealized testing scheme may have to be compromised chiefly because of wind conditions (sample abort criteria are discussed in Section 5).

TABLE 12. PARAMETERS DETERMINING THE TESTING SCHEDULE WITHIN A MINE

Parameter	Rationale
Mine related	Days when coal haul trucks are operating
Roadway related	Winds must be ±35 degrees perpendicular to the roadway segment to be tested
Effectiveness of suppressant over time	Desirable to test each segment periodically over the greatest period of time to evaluate control decay over time
Testing equipment related	Time required to erect sampling array makes it desirable to test in only one location per day
Test period length	Project resources limit field testing to 6-week periods in each of three mines

	MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY	SATURDAY
WEEK 1	BITUMEN	SALTS	SOIL CEMENTS	SURFACTANT	WATER	MAKEUP
WEEK 2	BITUMEN	SALTS	SOIL CEMENTS	SURFACTANT	WATER	MAKEUP
WEEK 3	BITUMEN	SALTS	SOIL CEMENTS	SURFACTANT	WATER	MAKEUP
WEEK 4	BITUMEN	SALTS	SOIL CEMENTS	SURFACTANT	WATER	MAKEUP
WEEK 5	BITUMEN	SALTS	SOIL CEMENTS	SURFACTANT	WATER	MAKEUP
WEEK 6	MAKEUP MISSED DAYS					

Figure 2. Idealized testing scheme, each mine.

SECTION 4

TEST PROCEDURES

4.1 BASIC DESIGN FEATURE

The basic design feature of the sampling configuration was simultaneous sampling on three contiguous test sections (Figure 3). The major advantage of this design is that it permits a direct comparison of uncontrolled and controlled emission rates under identical test conditions (vehicle type, road surface properties, and meteorology). This design eliminates the need to adjust measurements to account for the varying effects of these independent variables between sequential tests. Every set of three simultaneous tests provides two specific control efficiency values. A second advantage of this design is that it reduces the total number of samples required to produce statistically valid results by permitting use of a single upwind profile for three downwind profiles, and by separating the control efficiency calculations from the analysis of factors affecting emission rates.

4.2 SAMPLING CONFIGURATION--SOUTHERN ILLINOIS MINE

4.2.1 Test Section Layout

The sampling configuration with profiling towers downwind of each test section is shown in Figure 3. A complete list of sampling equipment used in the southern Illinois mine is presented in Table 13.

The profiling towers were located 10 m downwind from the edge of the haul road. This distance has been found to be far enough to eliminate interferences from large, mechanically entrained particles but close enough so that deposition has not yet reduced the initial emission rate. The tower height of 9 m is very near the top of any plume from a haul truck at this downwind distance, even under conditions of light winds and an unstable atmosphere. The upwind tower was located 20 m from the upwind edge of the road so that the mixing cell over the road does not diffuse far enough to impact the upwind samplers during periods of light variable wind. This distance has also been determined to be appropriate based on previous testing of mining haul roads. The upwind site was placed adjacent to a controlled test section to further reduce impact during any wind reversal. Dustfall collectors were placed at the 20 m upwind site and at

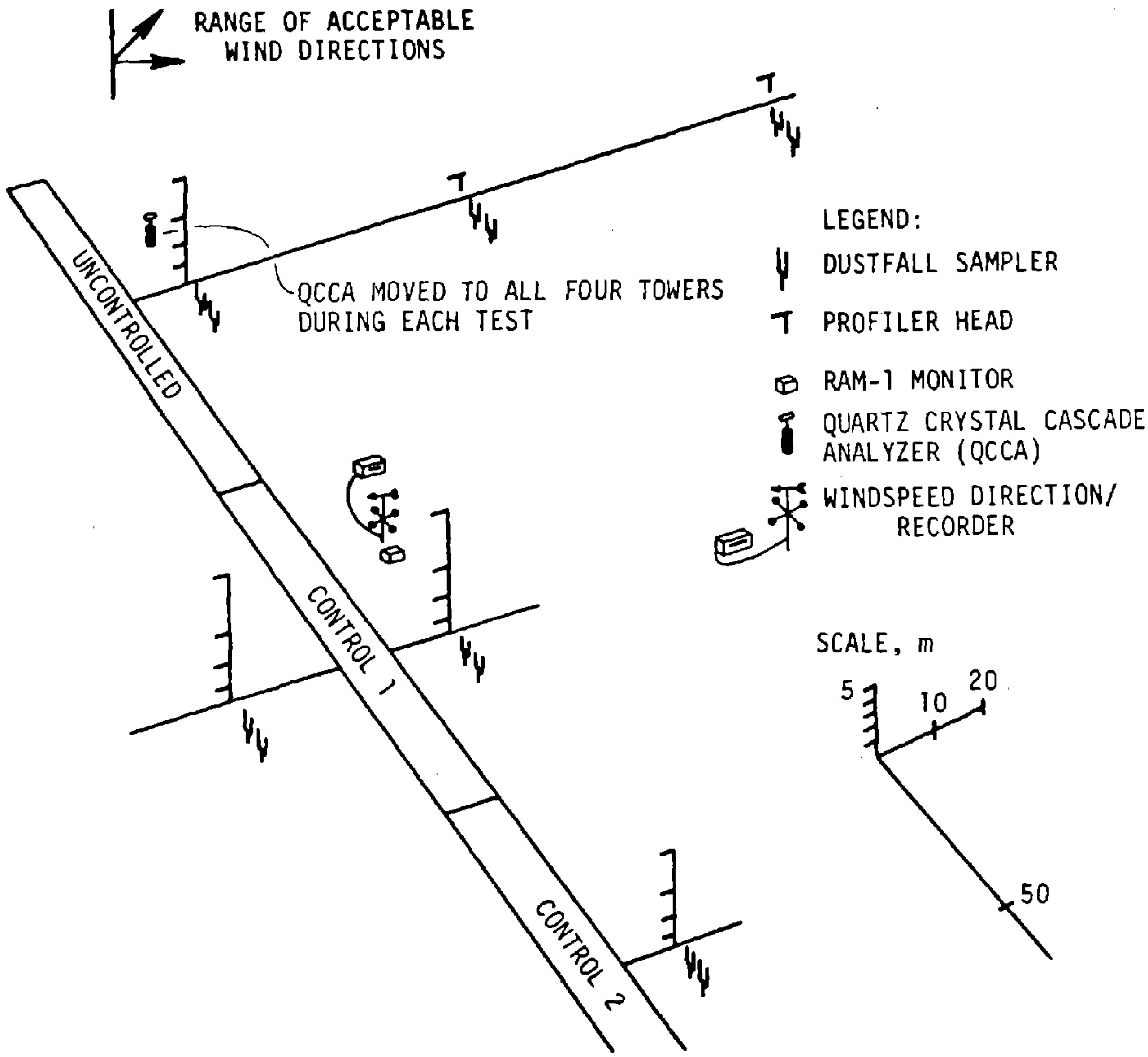


Figure 3. Sampling configuration.

TABLE 13. REQUIRED SAMPLING EQUIPMENT FOR EACH TEST PERIOD

Location	Dist. from edge of road, m	Equipment	Intake ht, m
Upwind	20	4 profiler heads w/flow controls	1, 2.5, 5, 9
		4 windspeed sensors	1, 2.5, 5, 9
		1 control system for flow rates	
		2 dustfall collectors	1
		1 generator	
Downwind (each of 3 sections)	10	4 profiler heads w/flow controls	1, 2.5, 5, 9
		4 windspeed sensors	1, 2.5, 5, 9
		1 control system for flow rates	
		2 dustfall collectors	1
		1 windspeed/direction recorder[a]	2.5
		1 generator	
		1 Berkeley Instruments quartz crystal cascade analyzer (QCCA)[a]	Varies
		1 GCA RAM-1 monitor w/recorder[a]	
Downwind of uncontrolled section	50	2 dustfall collectors	1
		1 profiler head (flow controlled by controller at 10 m)	1
	100	2 dustfall collectors	1
		1 profiler head (flow controlled by controller at 10 m)	1

[a] Only on one downwind section.

each of the downwind profilers. In addition, collocated single profiling heads and duplicate dustfall collectors were placed at 50 and 100 m distances downwind of the uncontrolled section. Each test road section was at least 100 m long in order to avoid interference during periods with oblique winds.

This sampling configuration and the sampling equipment designs described later in this section represent substantial advances in the application of exposure profiling to determine emission rates from fugitive dust sources. Some of these advances are:

1. Every measurement of a controlled emission rate had a corresponding measurement of uncontrolled emission rate taken under the same conditions so that external variables do not enter into the estimation of control efficiencies.

2. For the first time, upwind profile measurements were taken for determination of upwind flux rate at each sampling height.

3. The single upwind profiler for each set of three downwind profiling tests reduces overall sample requirements.

4. The tower was higher than previous profiling towers; this provided more complete coverage of the plume. The vertical placement of samplers on the tower was optimized to reduce interpolation/extrapolation errors.

5. Improvements in the tower structure reduced setup and sample changing times.

6. The downwind towers were located 10 m from the edge of the road, thereby improving measurement precision by reducing the effects of turbulence and plume nonuniformity.

7. The sampling heads were easily shifted during sampling to keep them pointed directly into the wind.

8. Particle sizing was performed by fractionation of a single sample rather than from complex calculations using partial data from several samples with assumptions.

9. Elimination of the settling chamber wash samples from the profilers greatly simplified sample analysis and calculations. These samples were primarily of particles larger than 30 μm diameter and therefore of little direct interest, but usually constituted more than half of the initial weight from which sub-30 μm emission rates were calculated.

4.2.2 Tower Design

Based on previous experience and sampling requirements for the exposure profiler in the present study, the following eight design criteria were specified:

- Minimum height, 9 m
- Tower constructed of interlocking or telescoping sections for easier transportation
- Rapid erection and disassembly: maximum of 20 minutes per tower for two persons
- Quick, safe filter loading and removal procedures (no climbing of tower)
- Secondary safety mechanism to prevent collapse of tower
- Sturdy construction, easy to maintain and repair in the field
- Wiring permanently attached to tower
- Able to rotate heads or tower at least 35 degrees in either direction while in operation

The tower design is shown in Figure 4.

Three of the four sampling heads were mounted on the lower section of the frame. Wiring for these samplers was attached to the frame. However, wires to the top sampler were kept loose so they could move as the upper section of the frame was extended.

4.2.3 Design of Sampling Heads

While the concept of isokinetic sampling at several points over a plume cross-section is appealing and has many basic advantages, all previous sampler designs have suffered from practical problems that have biased results. The major problems are identified below:

1. With the MRI design, the sampling rate is set at the beginning of the test based on windspeed at that time. There is no provision for varying flow rates during the test. The previous PEDCo version could vary rates by a cumbersome procedure involving 20- to 30-second windspeed readings with directionally sensitive hot-wire anemometers, followed by manual adjustment of flow rates based on individual calibration curves.

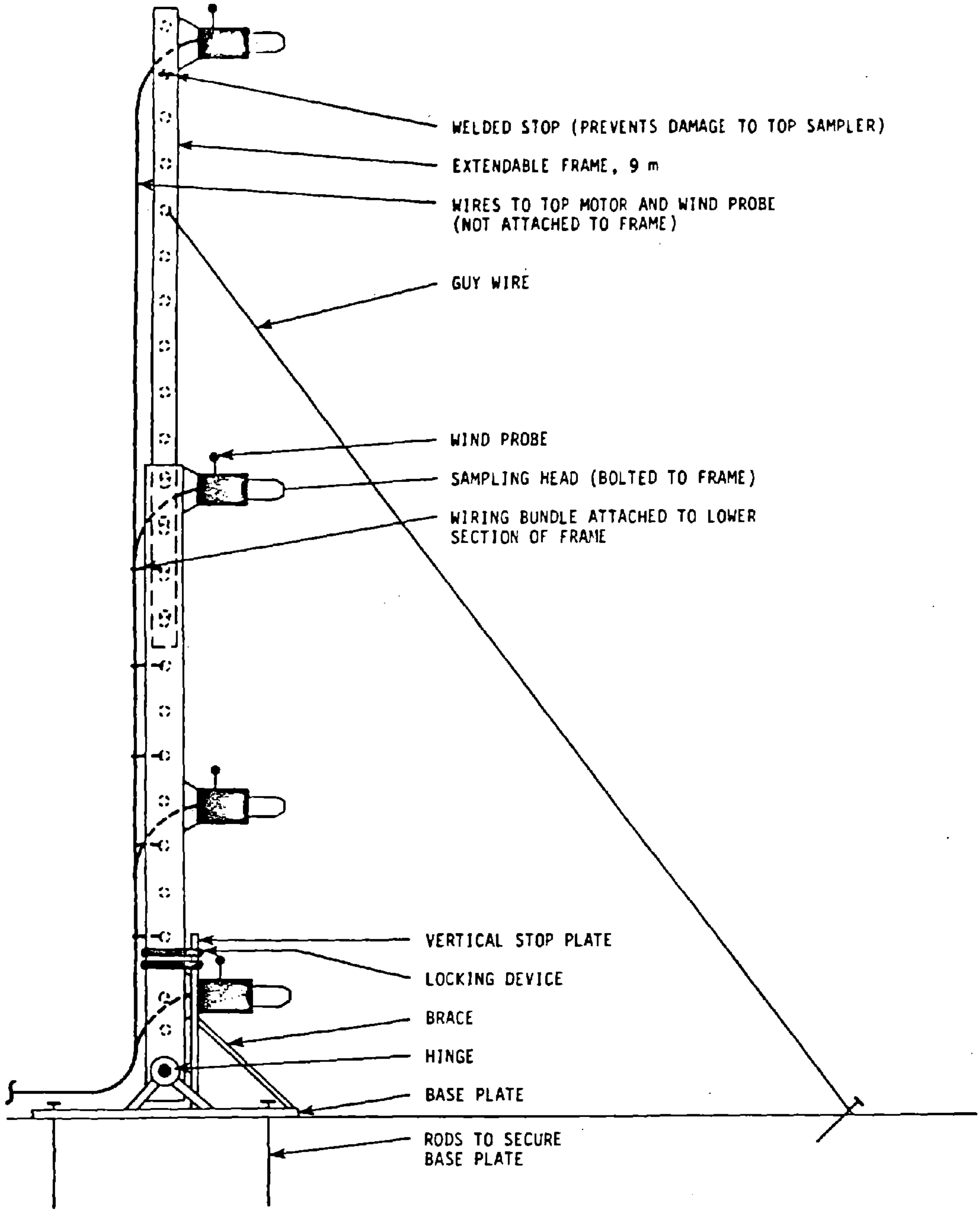


Figure 4. Tower design.

2. The profiler samplers provide no particle sizing; size distribution of the total particulate catch is estimated from separate samplers (that are not located at all profiler head heights) that measure concentration, not particulate flux rate, non-isokinetically. All of the instruments used to measure size fractions have serious measurement errors.

3. Two separate samples are generated by each head, but neither one is a specific size fraction. The wash sample is difficult to handle and labor-intensive to analyze.

4. Particles larger than 30 μm collected in the samples are extraneous to the determination of suspended particulate, even though they normally constitute 50 to 80 percent of the sample weight.

5. The estimate of TSP fraction requires two critical assumptions--that TSP has a 50 percent upper cut point of 30 μm (aerodynamic) and that the percent of the sample less than 30 μm can be determined by linear extrapolation of the percent less than 2.5 μm and the percent less than 15 μm on log probability graph paper. Neither of these assumptions was verified as part of the procedure development.

6. Measurements of the 2.5 and 15 μm fractions with the dichotomous sampler both have their own problems. The sub-2.5 μm fraction is negligible in many cases, resulting in no bottom point for extrapolation to 30 μm. The inlet device with a nominal 15 μm cut point is windspeed sensitive, so the measured values must be adjusted based on average windspeed during the sample.

These problems were addressed in the new profiler head design described in this section.

With the recent change in proposed IP standard from 15 μm to 10 μm, the three size fractions of interest are now 2.5 μm, 10 μm, and TSP (estimated at 30 μm). The ideal profiler head would sample at a rate that maintains isokinetic flow and then internally fractionates this sample into three sub-samples: <2.5, 2.5-10, and 10-30 μm. The use of inertial particle separation devices such as impactors or cyclones does not appear feasible if the sampler is to have variable flow and thereby be isokinetic.

The concept of stacked filters has been proposed in the literature for size fractionation of particulate samples (Stevens and Dzubay 1978; Cahill et al. 1979). Filters of known, uniform pore size can be placed in series to sequentially remove smaller sizes of particles. The cut points (sizes with 50 percent removal efficiency) are relatively insensitive to changes in flow rates, so stacked filters would be compatible with the variable flow rates of an isokinetic sampler.

The filter media most widely used for particle separation is Nuclepore filters. These filters have very consistent pore diameters, created by irradiation of the polycarbonate surface with neutrons of a specific energy range. Also, the media is non-hygroscopic, has less than 5 percent variation in tare weight between filters, and has a tare weight that is only 20 to 30 percent of a similar sized Teflon or cellulose acetate filter.

Unfortunately, the largest cut point that can be obtained with a Nuclepore filter is about 3.5 μm aerodynamic diameter (using a 12 μm pore size). No filter media could be found to provide a reliable separation near 10 μm. For the 30 μm cut point, a precision stainless steel fine mesh screen can be used. Because there is no interest in the mass of particles greater than 30 μm, the material caught on the screen need not be collected as a sample.

The resulting profiler head design is shown in Figure 5. The core of the head is a hi-vol motor/blower, which is attached to the tower by a steel strap bracket. Instead of the standard rectangular face on the hi-vol, it is fitted with a commercially available 5-1/2 inch diameter threaded head. A specially fabricated adaptor section connects this head to a 102 mm (approximately 4.0 inches) diameter filter holder for the backup filter. A second identical filter holder fits directly onto the front of the first one. When changing filters between tests, this stack of two filter holders was exchanged for a set containing unexposed filters so that no handling of the Nuclepore filters was required at the test site. The holders were held in place by three bolts.

The 30 micrometer screen (approximately 400 mesh) was mounted in a filter holder or similar part so that it could be easily reached for cleaning between tests. All the parts of the profiling head that were opened had air-tight seals to ensure an accurate air volume through the unit.

The remaining component of the sampling head is the inlet orifice. This is the point at which an isokinetic velocity must be maintained. The orifice diameter needed to have an air velocity of 0 to 15 mph (22 fps) is calculated by first establishing the maximum desired face velocity across the Nuclepore filters. The value of 35 cm/s (1.15 ft/s) is reported in the literature (Cahill et. al. 1979). This required a filter to orifice cross-sectional area ratio of 22 to 1.15, or about 19. The 102 mm diameter Nuclepore filter has an effective surface area of 57 cm^2. Therefore, the cross-sectional area of the orifice was 3.0 cm^2, or 1.95 cm diameter (0.77 inch).

A prototype profiler head was extensively tested before coal mine use. This testing is described in a separate report (PEDCo 1982c).

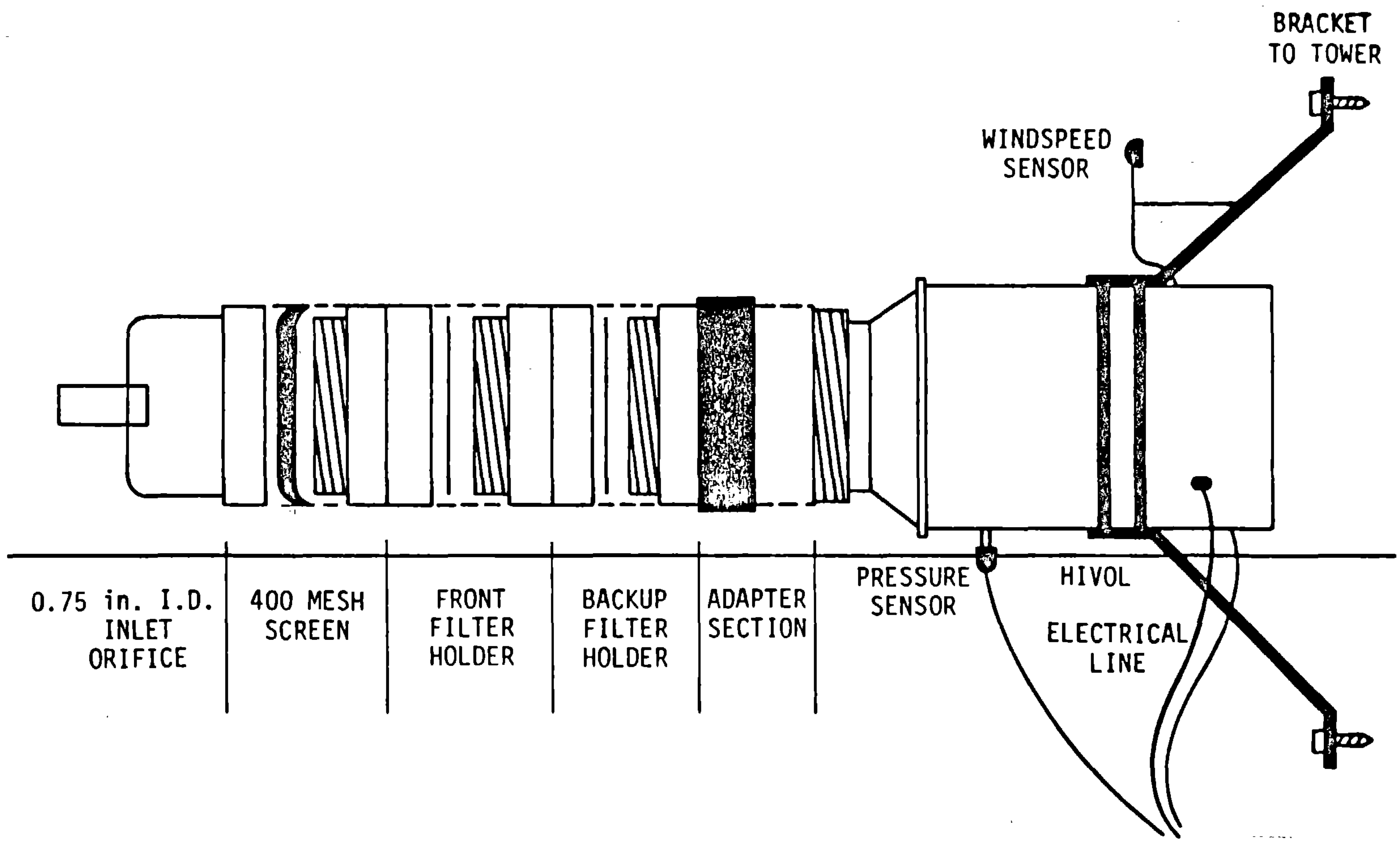


Figure 5. Proposed profiler head design.

4.2.4 Auxilary Equipment

Three pieces of auxiliary equipment were used in conjunction with the exposure profilers and dustfall collectors: the Berkeley Controls Quartz Crystal Microbalance Cascade Analyzer, the GCA RAM-1 monitor, and a windspeed/direction recorder. The purpose and operation of each of these instruments are explained in the following three subsections.

4.2.4.1 Quartz Crystal Cascade Analyzer (QCCA)--

The Berkeley Controls analyzer is a portable instrument that measures the mass concentrations in as many as 10 particle size ranges over very short averaging times. Concentrations are calculated from the change in vibrational frequencies of quartz crystal microbalances in each of the 10 stages. These frequency changes are converted into concentrations with a program on a TI-59 programmable calculator.

A picture of the quartz crystal cascade analyzer is shown in Figure 6. Each circular stage has a nozzle that impacts particles greater than a specified aerodynamic diameter onto the quartz crystal microbalance for that stage. The nominal cut points of the stages vary from 25.0 to 0.05 μm aerodynamic diameter, with each stage having a cut point half that of the preceding stage (25.0, 12.5, 6.3, 3.2, 1.6, 0.8, 0.4, 0.2, 0.1, 0.05 μm).

The redesigned exposure profiler provides direct measurements of emission rates of the 2.5 and 30 μm size fractions, but not of any intermediate sizes. The most important application of the QCCA was in providing an estimate of the 10 μm size range emissions.

The QCCA has a much shorter averaging time than the profiler (0.5 to 30 min versus 1 to 2 h) and measures concentrations rather than particulate flux. Therefore, sampling with the QCCA for direct comparison with profiling data would require an elaborate multiple sample procedure and complicated calculations, neither of which is desirable. Instead, concentrations of sub-10 μm particulate taken with the analyzer were compared with concentrations of sub-2.5 μm particulate in the same sample to develop mass ratios of these two size fractions for each sampling period. (Both concentrations would require interpolation between measured size fractions.) These ratios were then applied to the sub-2.5 μm profiling data to estimate emission rates of the sub-10 μm fraction that are specific for each test. This procedure is considerably more accurate than calculating the 10 μm emission rate by assuming a lognormal size distribution between 2.5 μm and 30 μm (this assumption was made in previous exposure profiling tests).

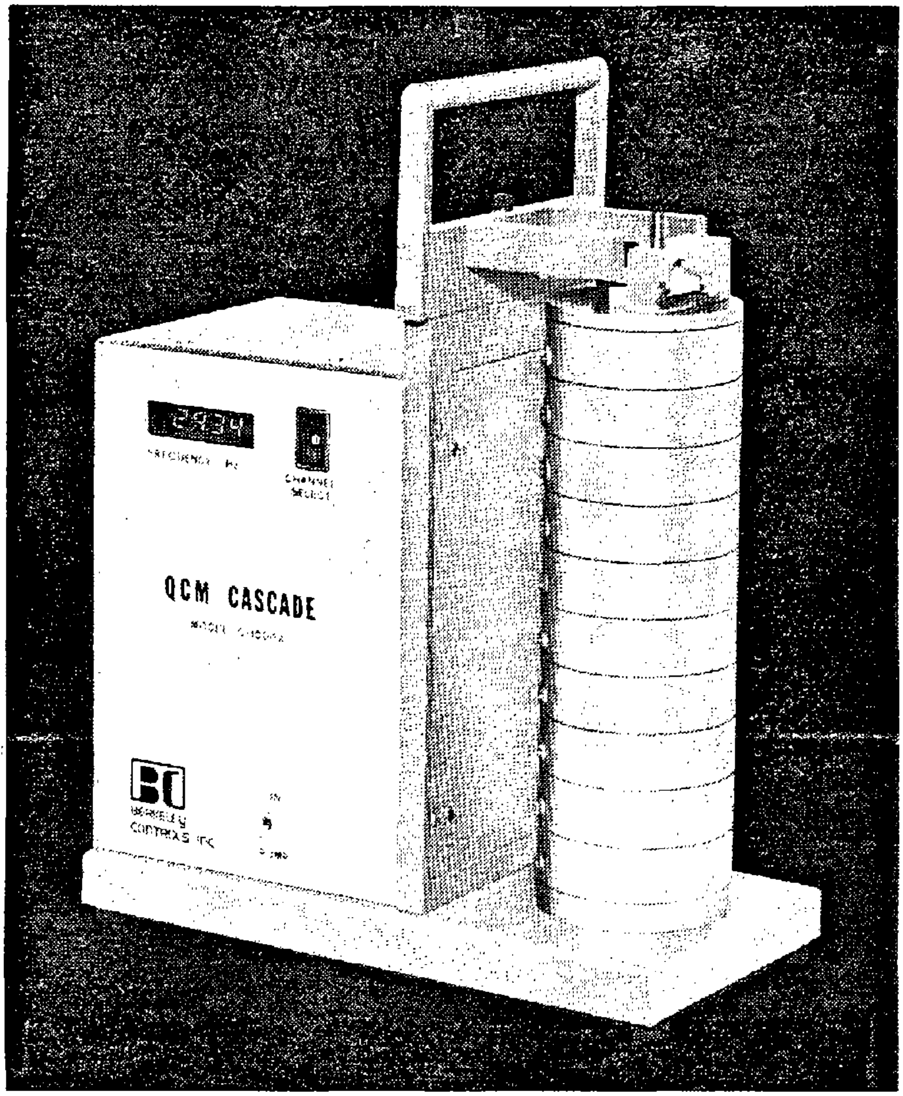


Figure 6. Berkeley Controls Quartz Crystal Cascade Analyzer.

Operation consisted of taking one or more readings at each of the bottom two heights of profiling heads (1.0 and 2.5 m) next to all four towers during each test. The readings were taken during vehicle passes, and ratios of 10 μm to 2.5 μm concentration would be developed individually for each profiler head. Ratios for the top two heights on the tower were normally assumed to be the same as the ratio at the 2.5 m height.

4.2.4.2 RAM-1 Monitor--

The RAM-1 monitor is also a portable sampler for respirable particulate, as shown in Figure 7. Its measurement is based on detection of near-forward scattered electromagnetic radiation by particles passing through the optical chamber. Airflow is maintained at a constant rate of about 2 liters/min. The sample flow is passed through a cyclone precollector to remove particles with aerodynamic diameters larger than about 3.0 μm. A pulsed semiconductor light-emitting diode generates a narrow-band signal; after passage through the sample, the radiation is detected by a silicon photovoltaic-type diode with integral preamplifier. Maximum sampling time is 32 seconds (other options are 0.5, 2, and 8 seconds).

Independent evaluation of the RAM-1 has shown reproducibility error of 3 to 5 percent and average comparisons with low volume sampler gravimetric readings of 0.90 to 1.20 (GCA Environmental Instruments 1979).

The application of the RAM-1 monitor was to provide a continuous record of downwind concentrations during the sampling period. This application was facilitated by the availability of a strip chart recorder. A continuous chart of fine particulate concentrations was valuable for several related reasons:

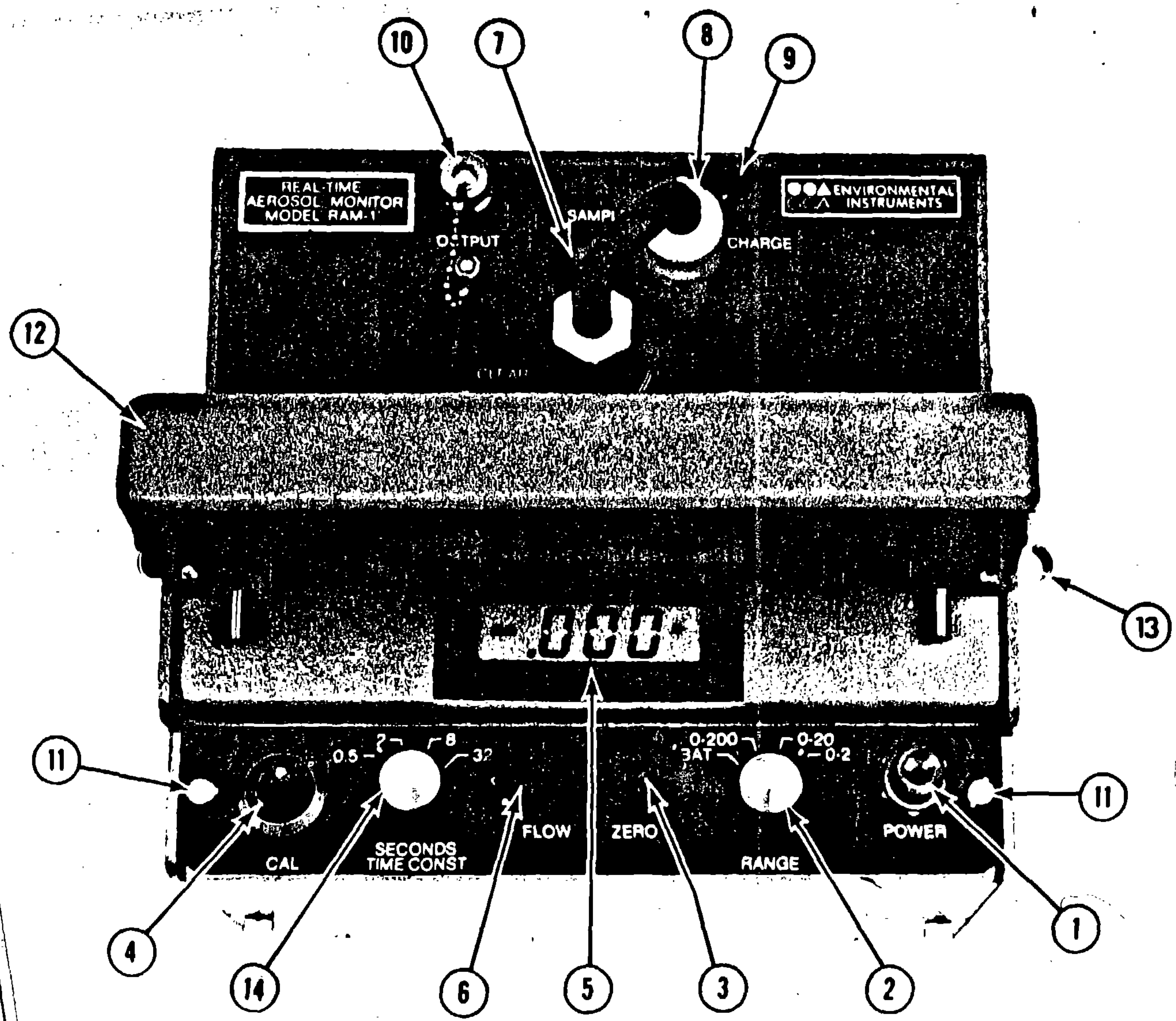
1. Peaks on the strip chart correspond to vehicle passes and provide a check of the manual counts taken during the tests.

2. Missing peaks during times when the wind direction recorder indicated parallel or reverse winds confirmed that vehicles passing the profilers at these times had no impact (except as interferences to the upwind samplers).

3. The areas under the various peaks provided the first quantitative information on the relative impacts of loaded haul trucks, empty haul trucks, and other vehicles using the haul roads (see example in Figure 8).

4.2.5 Measurement of Deposition

Most of the previous attempts to measure deposition have been directed at defining the shape of the source depletion curve with distance downwind from the source. The two methods employed



1. Power ON-OFF switch
2. Range and function selector
3. Zero or offset adjustment control
4. Calibration or gain control
5. Liquid crystal digital display
6. Pump flow-rate adjustment control
7. Inlet valve
8. Cyclone
9. Charger receptacle
10. Output connector for recorder operation
11. Four screws securing top panel
12. Protection cover
13. Detachable strap (not shown)
14. Time constant select

Figure 7. RAM-1 monitor.

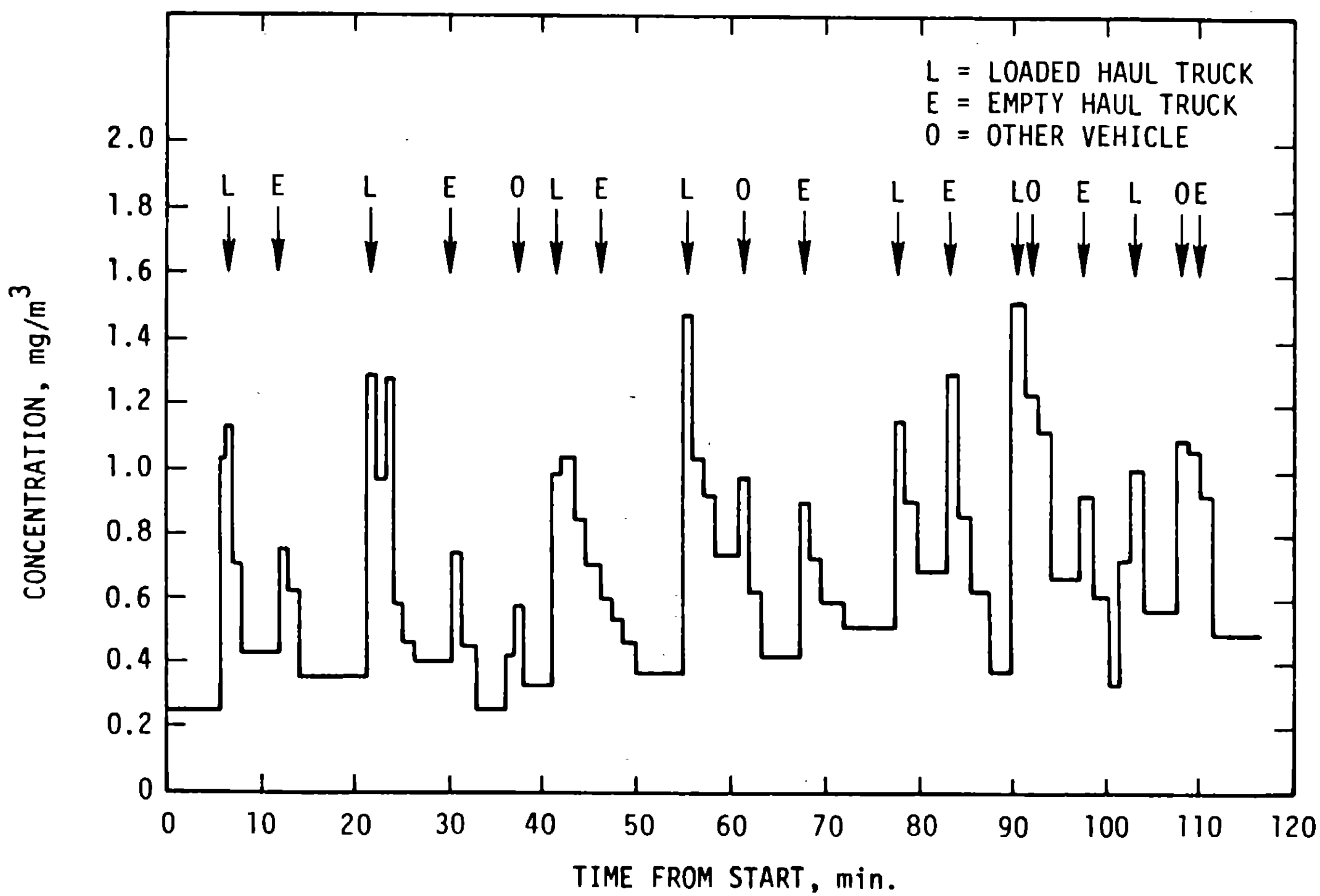


Figure 8. Example strip chart from RAM-1 monitor.

were dustfall measurements and reduction in apparent emission rates as determined from upwind-downwind sampling at various distances. None of these attempts have been successful, for several different reasons:

- The upwind-downwind measurements at typical distances from the source (50 to 100 m) had larger sampling errors than the amount of deposition occurring between sequential sampler distances.

- Neither upwind-downwind nor dustfall sampling to determine deposition rates could be done in the critical range of 200 to 1000 m downwind because detectable amounts of particulate could not be collected during 1 to 2 hour periods at these distances.

- Potential interferences from other mining sources and from reentrainment near the samplers severely limited the locations where downwind arrays could be placed.

- Dustfall measures the deposition of total particulate, which is of less interest than the deposition rates of suspended or inhalable particulate.

Even if these problems were overcome, the resulting empirical source depletion curves would have to be converted into a general equation incorporating such variables as windspeed and initial particle size distribution of the emissions.

In a recently released report, TRC undertook the task of quantifying the deposition velocity of particles in the plume at various distances from the source (TRC 1981). Although this may at first appear difficult, the deposition velocity of a polydisperse plume at any point is simply the measured deposition divided by the average concentration (Slade 1968):

$V_d = D/\bar{x}$, where

V_d = deposition velocity, m/s

D = deposition or dustfall, $\mu g/m^2$-s

$\bar{x}$ = concentration over same averaging period as dustfall measurement, $\mu g/m^3$

The overall plume V_d was found to decrease with distance from the source as the size distribution of particles remaining in suspension changed.

Deposition velocity is one of the primary variables by which the deposition function is described in available dispersion models for mines, including the ISC model. Therefore, if appropriate values for V_d can be obtained, the need for developing a complete deposition function is eliminated. The TRC analysis has some shortcomings which preclude its results from being widely applicable: the dustfall and hi-vol measurements were for different size fractions; only a single average value as a function of distance was derived from the data; the individual V_d values had so much scatter that the average value was partially based on other values reported in the literature; and the ISC model requires V_d values by particle size range rather than an average value for all particles.

The concept of calculating deposition velocities from collocated dustfall and ambient concentrations was used to evaluate deposition in the present study. So that the resulting V_d values can be applied directly in the ISC model, they will be derived by size range: <2.5 μm, 2.5-10 μm, 10-30 μm, and >30 μm. Settling velocities by size range do not vary with distance from the source, so the data can be generated by particle size sampling at a single distance. Also, the measured deposition velocities can be compared with the theoretical Stokes' terminal settling velocities.

As summarized in Table 13, collocated dustfall collectors were placed at the same 10 m distances from the road as the profiling towers. In addition, dustfall collectors were placed at the upwind tower and at 50 m and 100 m distances downwind of the uncontrolled haul road section. The mass measurements by particle size range from the 1 m height profiler were converted to concentrations by dividing by the total airflow through the sampler. The mass greater than 30 μm was determined by quantitatively collecting all the material trapped on the inlet screen and in the nozzle section of the 1 m profiler.

4.2.6 Collection of Data for Independent Variables Affecting Emission Rates

The first step in establishing test procedures for independent variables is to determine which variables are to be monitored. These were established as:

- Vehicle weight and size
- Number and size of wheels
- Vehicle speed
- Surface loading
- Silt content
- Moisture content
- Bearing strength

The test procedures to be employed to monitor these independent variables are summarized in Table 14.

TABLE 14. MONITORING PROCEDURES FOR INDEPENDENT VARIABLES

Variable	Measurement	Method	Frequency
Vehicle weight and size	Loaded and empty haul truck weights; estimated weights of other vehicles	Classify each vehicle passing samplers during the test	Get estimated wts. for vehicle fleet from mine operators, equipment vendors
Number and size of wheels	Average for all vehicles during test period	Visual observation	-
Vehicle speed	Haul truck speed past samplers	Timing over measured distance for selected vehicles	2 to 4 vehicles per test
Surface loading	Weight of loose material on haul road surface per unit area	Vacuuming	Two samples per test per section, averaged
Silt content	Percent of surface loading sample less than 75 mm in size	Dry sieving of sample with No. 200 sieve	Each combined surface loading sample (after drying)
Moisture content	Percent moisture in surface loading sample	Weigh sample before and after oven drying	Each surface loading sample
Bearing strength	Atterburg limits	ASTM Procedures	Once each visible layer on each section

The independent variables shown in Table 14 are standard variables for unpaved road emission testing, except for bearing strength. A major conclusion of a recent Bureau of Mines sponsored report (Bureau of Mines 1981) is that the effectiveness of any dust suppressant is dependent on certain roadway characteristics. This conclusion was based on deductive reasoning as opposed to field testing.

The subgrade and base strength is important because of shear stress. As a vehicle wheel passes over a section of road surface, the entire structure is put in compression. When the wheel has passed, the roadbed and surface should spring back to their initial position, due to the elastic properties of the system. However, if the road is not designed to carry the load, the design elasticity is exceeded and permanent deformation occurs. This causes surface rutting, pot hole formation, or cracking. A roadway dust suppressant agglomerates the fine particles that are easily entrained by vehicle wheel action. Therefore, any force which tends to break down these agglomerated particles after their initial formation will decrease the dust suppressant's longevity. The subgrade and base strength can be estimated with Atterburg limits.

The size gradation of the roadway surface and subgrade is also important. Besides being a determinant of the Atterburg limits, the size gradation will determine the ability of the road surface to compact and will also partially determine the residence time of the dust suppressant in the surface of the road. If the surface material is too coarse, i.e. too sandy, some dust suppressants may not remain at the surface but may percolate to a lower level. Additionally, if the road has a high percentage of fines, some dust suppressants may not have the ability to make the particles cohesive. The additional soil mechanic work being performed as part of this study is an attempt to gain additional data about these phenomena.

4.3 SAMPLING CONFIGURATION--WYOMING MINES

The sampling configuration was refined for the testing in the two Wyoming mines. The objective of the refinement was to eliminate total dependence on the profiling towers for control effectiveness determinations by adding other instrumentation common to all three test sections. The following changes were made to the sampling configuration described in Figure 3 and Table 13.

1. RAM-1 monitors were placed downwind of all three segments.
2. Size-selective hi-vols (SSI) were placed at all four sampling positions.

3. The downwind profiling head and dustfall collectors were removed from the 50 m and 100 m distances. This change was made to accommodate the increased workload caused by the first two changes, and because of poor results with the dustfall collectors (Section 7).

The positive net result of these changes was that in addition to the data collected with the towers, comparitive 3 μm data (RAM-1) and 15 μm data (SSI) were available to judge control efficiency. Negatively, the deposition data were lost.

4.4 DATA HANDLING

There are two unique aspects of the study design that greatly facilitated the data analyses. The first was the establishment of a field laboratory to perform sample analyses onsite. The second aspect was computerized onsite data analysis.

Establishment of these facilities at each mine eliminated many of the limitations identified in previous studies. Onsite laboratory analyses eliminated the need for cross-country transport for analyses and the multiple filter handlings associated with this common practice. Consequently, it was possible to maintain more strict quality assurance limits. Also, the results of the analyses were immediately available for data analysis. This eliminated the long lag time between sample generation and data analysis resulting from post-testing laboratory analysis.

The computer system was a powerful tool for data handling. With magnetic disc storage capabilities, laboratory records, raw field data, and test results can be easily retrieved and updated. In addition, the disc files further simplified the detailed statistical analyses and quality assurance checks of calculations, since all of the data already was in a computer-ready format, eliminating the need to keypunch and edit-check the data at a later date.

Figure 9 shows the basic data and sample analysis flow-chart for the study. In general, the field data sheets and test samples from each test were reviewed by the supervisor and submitted to the laboratory for analysis. The data sheets were designed to facilitate the recording of field data, laboratory results, and data entry to the computer. As the samples were weighed, the results were immediately entered on the computer terminal and field data sheets. Similarly the results of the quality assurance checks were maintained in the data files. A hard copy of each day's analyses were also generated.

Once the laboratory analyses were completed for each test, other necessary information was input to the computer and a preprogrammed alogorithm produced calculated emission rates, profiles, and control efficiency estimates for review by the

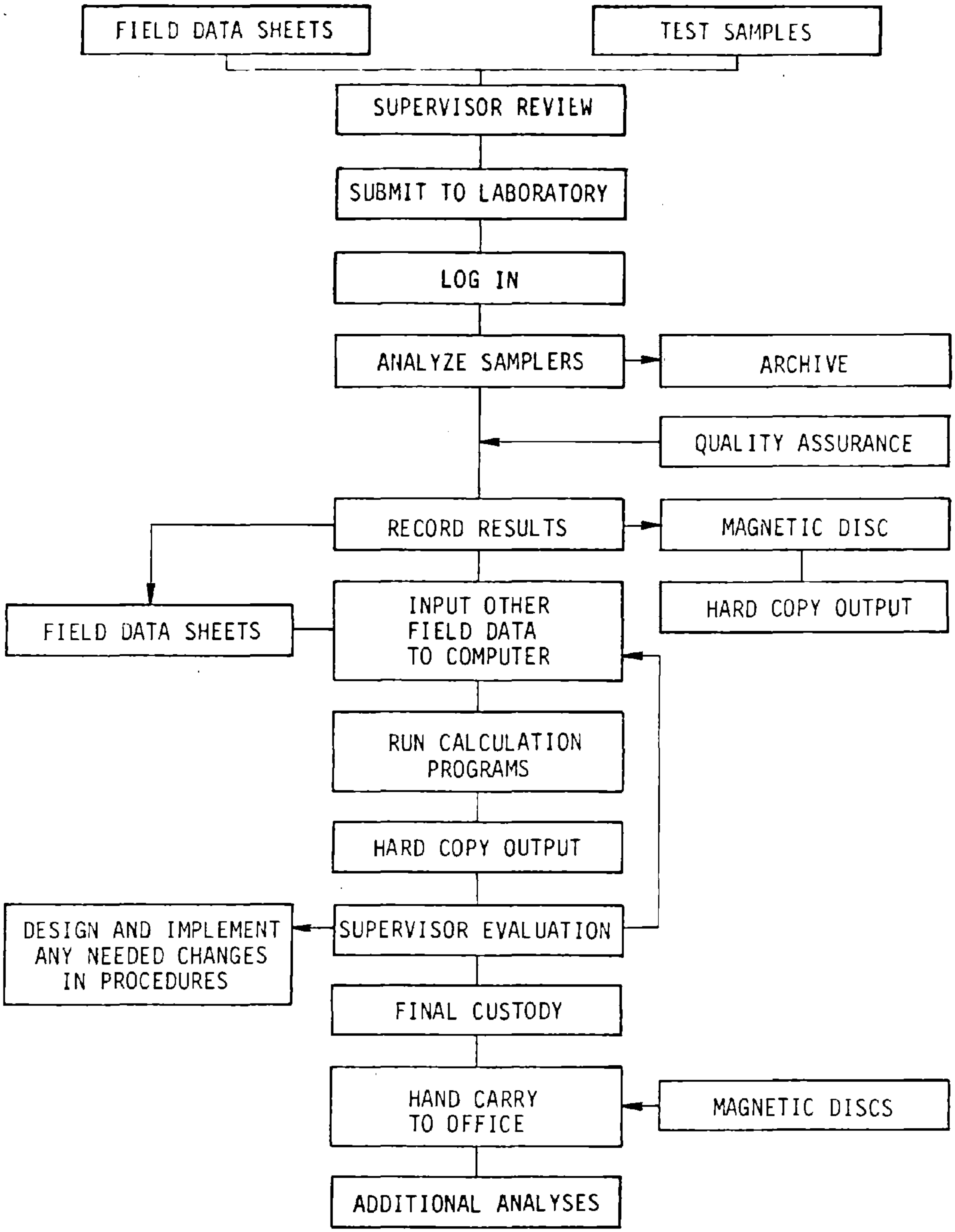


Figure 9. Flow diagram for field data.

supervisor the morning after testing. In this fashion, any problems identified with the field procedure were addressed the next sampling day. Examination of the tower exposure profile plots (drawn by the computer) allowed determination of equipment malfunction, and filter weighing errors. The equipment could be checked before the next day's sampling, and filters could be reweighed if necessary the next night. This system is far superior to laboratory analysis and calculations weeks after the entire sampling period is complete and no mid-course correction can be made. The original data sheets and program outputs remained in the supervisor's possession who hand-carried them to the office for further analyses.

SECTION 5

QUALITY ASSURANCE

The list of quality assurance procedures presented in this section covers all aspects of the study. They are subdivided into three general categories: field testing procedures, laboratory procedures, and data management. The procedures planned in each of these general areas are specified in the following subsections.

5.1 FIELD TESTING

The quality assurance procedures for field testing cover all of the activities planned for an individual test. These procedures include calibration, operation and maintenance of field equipment, sample handling, and audits.

5.1.1 Equipment Calibration and Maintenance

Each type of equipment used for the study was calibrated at the outset of sampling at each mine. In addition, several quality assurance procedures were implemented to ensure accurate results. These activities are shown in Table 15.

Several QA activities have been specified for proper operation of the equipment during the testing period at each mine. These activities include equipment maintenance checks to ensure proper operation, and operational criteria developed to obtain correct results. These activities are listed in Table 16.

5.1.2 Test Abort Protocol

During an actual test, sampling conditions had to meet certain minimum requirements. If conditions fell below the minimum, the test was stopped and no data are reported for the aborted test.

The conditions that resulted in stopping a test fall into two general categories: meteorological, and mine operations. Evaluating these conditions and making the decision to stop a test was the responsibility of the field supervisor.

TABLE 15. QUALITY ASSURANCE PROCEDURES FOR EQUIPMENT CALIBRATION

Equipment type	QA check/requirement
Calibration	
Profiler heads	Calibrate flows in operating ranges using calibration orifice. Once at each mine prior to testing. Recheck calibration every two weeks, recalibrate any units that deviate by more than 7 percent.
Quartz Crystal Cascade Analyzer (QCAA)	Calibrate on frequency specified by manufacturer.

TABLE 16. QUALITY ASSURANCE PROCEDURES FOR EQUIPMENT OPERATION AND MAINTENANCE

Activity	QA check/requirement
Maintenance	
Profiler heads	Check motors, brushes, gaskets, timers, and flow measuring devices at each mine prior to testing. Recalibrate any units requiring maintenance after initial calibration has been performed.
All other equipment	Follow manufacturer recommendations.
Operation	
Profiler heads	Adjust sampling intake orientation whenever mean wind direction changes by more than about 20 degrees.
Dustfall buckets	Cover prior to and immediately after sampling.
Windspeed/direction instrument	Setup and orient wind system prior to testing with compass.
Quartz Crystal Cascade Analyzer (QCAA)	Operate according to manufacturer's instruction. Designate one field person to perform all tests.

5.1.2.1 Meteorological--

The meteorological criteria for test abort relate to windspeed, wind direction, and precipitation. Measurements of windspeed and wind direction were recorded on a windspeed/wind direction recorder, providing a continuous record for each test. Average windspeed and direction were determined every 10 minutes to evaluate ambient sampling conditions. If average windspeeds dropped below 2 miles/hour or exceeded 15 miles/hour, the test was stopped.

The angle of the wind across the road was also important. Under ideal conditions the angle between the wind direction and the road was constant and approached 90°. Three distinct wind direction criteria have been established to address nonideal sampling conditions. These criteria relate to wind meander, angle of sampler inlet to wind direction, and minimum angle of wind direction to road.

Low windspeeds and large wind direction fluctuation (wind meander) are associated with Stability Class A (Pasquill). Testing was terminated if average wind fluctuations of more than ±35° from the mean direction was observed. The 35° value is approximately equal to 1.5 x σ_θ for A stability and should allow a conservative determination of A stability conditions.

The second wind direction criteria relates to the angle of the sampler inlet to wind direction. During a test, the sampling intake orientation was adjusted whenever the 10 minute mean wind direction changes by more than 15°.

The third wind direction criteria relates to the minimum angle between the wind direction and the road under which sampling can occur. The reason for specifying a minimum angle is to avoid possible cross-contamination between the profilers and the road sections. The minimum acceptable wind angle was ± 35° from perpendicular to the road.

The final meteorological criteria for aborting a test pertains to precipitation. A test was stopped if precipitation was encountered in sufficient quantities to change the surface conditions of the haul road.

5.1.2.2 Mine Operations--

The mine activities that resulted in an aborted test were: cessation of haul truck activity or initiation of a major dust-producing activity upwind. If it was determined, from contact with mine personnel, that the conditions were only temporary, then an attempt was made to restart when normal operations were resumed.

5.1.3 Sample Handling

Several different types of samples were collected during each test: Nuclepore filters, screen material from profiler heads (>30 μm), dustfall samples, and road surface material samples. Special handling procedures were required for each type of sample.

The Nuclepore stacked filters were contained in specially fabricated cartridges within the sampling head as explained in Section 4.0. To load filters, the entire cartridge could be inserted into the sampling heads without direct exposure to the ambient air. Similarly, the cartridges could be removed after each test without being exposed. A second set of cartridges, loaded in the lab the previous night, were inserted into the sampling heads for the second test of each day. Thus, no Nuclepore filters were directly exposed to the ambient air during filter changing within the mine.

The entire screen was lifted from the profiling head and placed in a covered dish. This procedure was accomplished within the van between the first and second test series of the day, and was accomplished in the lab after the second test series.

The pleated dustfall filters were removed from the dustfall containers at the end of each test. The filters were folded so that none of the material was lost and placed in a labeled envelope for transport to the lab.

Samples of road surface material were placed in an airtight jar, labeled, and transported to the lab.

5.2 LABORATORY

The laboratory analysis procedures and QA checks cover all aspects of sample preparation, conditioning, and gravimetric analysis. These procedures are discussed below for each type of sample. As noted in Section 4, a field laboratory was established at each mine to perform all analyses on site. The discussions include this consideration.

5.2.1 Nuclepore and Dustfall Filters

New filters were numbered, examined for defects, then equilibrated for 24 hours at 20 to 25°C and J50 percent relative humidity in a controlled room. Filters were weighed to the nearest 0.1 mg on a calibrated balance. The balance was checked against standard laboratory Class S weights prior to weighing each batch of filters.

A second analyst reweighed 10 percent of the filters as a precision check. All filters in a given batch were reweighed if any check weight varied by more than 3 mg. After weighing, the filters were packed flat, alternating with onionskin paper, for transport to the test site.

When exposed filters were returned from the site they were logged in, weighed, and checked in the manner described above. It was determined through experimentation, and supported in the literature, that no equilibration of the exposed Nuclepore filters was necessary since they were virtually non-hygroscopic. Further, in order to determine the effects of transport to and from the mine, at least one blank was handled and weighed for each 10 filters of each type.

5.2.2 Road Surface Material Samples

Samples of road dust were stored briefly in their airtight containers, then reduced with sample splitter (riffle) to about 1 kg. The final split samples were placed in a tared metal pan, weighed, and dried in an oven at 110°C for 24 hours. The dried samples were reweighed and the moisture content calculated as the weight loss divided by the original weight of the sample. The dried samples were stored in airtight containers until they were sieved.

Sieving of these samples was done with mechanical dry sieves. The portion of the material passing a 200 mesh screen is defined at the silt content (<75 μm). The nest of tared sieves was placed on a conventional shaker for 15 minutes. Each sieve was then weighed to determine the distribution of material and the silt content.

For 10 percent of the road surface samples, both halves of the final split were analyzed for moisture and silt content. This duplication allows determination of the reproducibility of the methods.

5.3 DATA MANAGEMENT

The QA procedures for data management focused primarily on maintenance of field records and data analysis.

5.3.1 Field Records

In order to assure that all necessary data were recorded for each test, data forms were designed specifically for the study. At the end of each test, all data sheets were initialed and dated by the operator. In addition, the field supervisor reviewed all of the forms on a daily basis and verified that all of the data were present. The data sheets remained in the custody of the supervisor. Copies of the sheets were made weekly and sent to the main office. The original sheets were hand carried to the office at the end of each mine visit.

5.3.2 Data Analysis

All calculations were performed on the personal computer. Each type of calculation was independently verified. At least 10 percent of the calculations were checked. If any audited value deviated by more than ±3 percent, all calculations of that type were rechecked.

SECTION 6

TESTING DETAIL

6.1 MINE 1--SOUTHERN ILLINOIS

6.1.1 Test Section Layout

The test section layout is shown in Figure 10. All sections on the north-south running roadway were a minimum of 330 feet in length. The sections on the east-west running road were 400 feet in length which was possible because of the greater length of available roadway.

The north-south roadway was built before the east-west roadway. Therefore, soil analyses were performed on each part. The results appear in Table 17 and are compared to Bureau of Mines standards. A proper stone surface size gradation is necessary to maintain a compact surface. Further, it was hypothesized that a given dust suppressant would perform differently under different road aggregate and sub-base conditions. The Bureau of Mines standards call for clay soils having very low Atterberg limits. Because these type soils have such a small range of moisture content within which they will deform plastically, they are very suitable for road construction. They also have much greater shearing strength than soils with a high liquid limit and plasticity index. Both segments contain a much higher percentage of fines than the Bureau of Mine (1977) suggested gradation. The Atterburg limits and soil classification indicate a soil with a very low bearing capacity (2000-6000 psf versus a Bureau of Mine [1977] suggested level of 16000 psf). These data also confirm the on-site observation that particularly the north-south road became extremely slippery and rutted when wet because of the high clay content.

6.1.2 Chemical Application

Chemical application is described in Table 18. Vendors for all four products were on-site and supervised the application. All chemical sections were watered once per shift (twice a day). The Liquidow and Soil Sement were applied on June 9. It rained 1.2 inches approximately 12 hours after application and before the segments were dry. The impact of the rain is not known. The Flambinder and Petrotac were applied on June 11 with the road still moist.

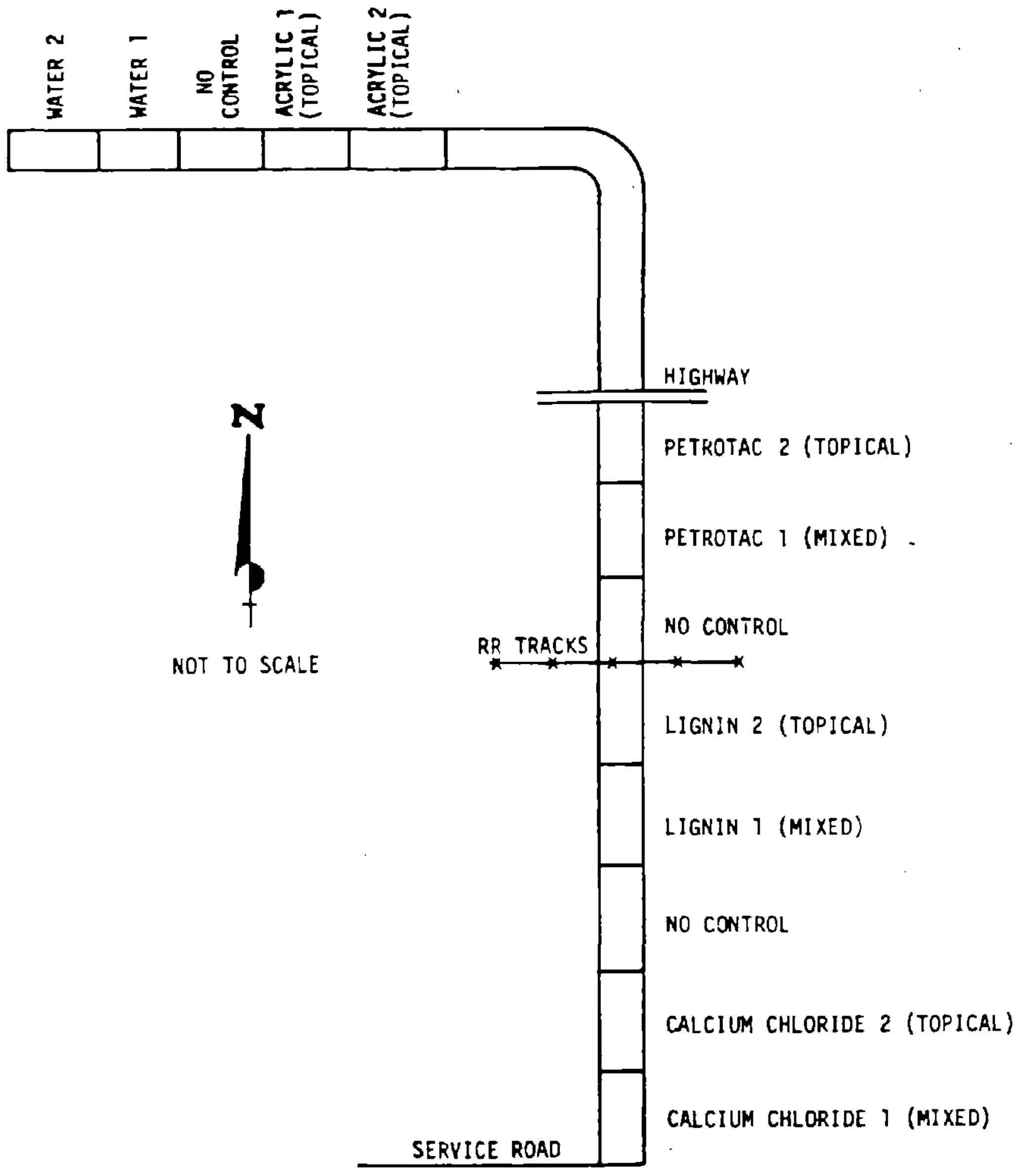


Figure 10. Test Section Layout, Mine 1--Southern Illinois.

TABLE 17. ROADWAY SOIL ANALYSES, MINE 1--SOUTHERN ILLINOIS

	North-south		East-west	Standard[a]
	Top	Remaining		
Gradation, percent passing				
1 inch	99.75	99.57	92.77	98
3/4 inch	98.62	99.08	89.58	92
3/8 inch	94.56	96.70	84.51	82
No. 4[b]	91.34	94.79	80.72	65
No. 10	86.06	86.91	71.25	53
No. 40	79.64	73.45	59.62	33
No. 200	73.45	63.75	49.74	16
Natural moisture, percent	19.9	11.9	9.1	
Atterburg limits				
Liquid limit	43	32	38	25
Plasticity limit	23	16	19	16
Plasticity index	20	16	19	9
Soil classification of minus No. 40	Lean clay	Lean clay	Lean clay	

[a] Bureau of Mines 1977.
[b] Minus No. 4 material analyzed with wet screen technique.

TABLE 18. DUST SUPPRESSANT APPLICATION, MINE 1--SOUTHERN ILLINOIS

	Section 1		Section 2	
Chemical	Rate	Method of application	Rate	Method of application
Liquidow ($CaCl_2$)	0.6 gal/yd^2 of 38%	0.37 gal/yd^2 mixed in place 4 to 6 inches. 0.27 gal topically applied after final grading. Pressurized spray bar	0.27 gal/yd^2 of 38%	Topically with pressurized spray bar
Soil-Sement (acrylic)	1.9 gal/yd^2 of 12%	Topically applied with gravity feed spray bar in multiple passes	3.0 gal/yd^2 of 10%	Topically applied with gravity feed spray bar in multiple passes
Flambinder (lignin)	2.1 gal/yd^2 of 18%	1.8 gal/yd^2 mixed in place 4 to 6 inches. 0.3 gal topically applied after final grading. Pressurized spray bar	0.5 gal/yd^2 of 18%	Topically with pressurized spray bar
Petrotac (emulsified asphalt)	1 gal/yd^2 of 18%	Graded off 1 inch, ½ gal/yd^2 applied. Final grade, remaining applied. Pressurized spray bar	2/3 gal/yd^2 of 18%	Graded off 1 inch, 1/3 gal/yd^2 applied. Final grade, remaining applied. Pressurized spray bar
Water	Unknown	Twice per hour. Water wagon	Unknown	Once per hour. Water wagon

6.1.3 Test Schedule

The test schedule is shown in Table 19. The testing period was plagued with bad weather. Of the 38 days that the crew was in the area, a total of 7.28 inches of rain fell in 12 storm events. Light and variable winds prohibited testing on five additional days.

6.1.4 Sampling Equipment

The sampling array used is described in Table 20. It is the configuration described in the long-range test plan.

6.1.5 Mine Equipment

Equipment type, and salient dimensions and weights, using the haul road tests are described in Table 21.

6.1.6 General Observations

The following general observations can be made apart from the test results reported in Section 8.0:

- The mine personnel complained adamantly about the lignon and emulsified asphalt being slippery when wet. As noted in Subsection 5.1.1, all sections, treated and untreated, were extremely slippery when wet due to the high clay content of the road. PEDCo personnel could not discern that any sections were more slippery than others.

- As a result of the perceived slippery conditions, mine personnel covered the lignon and emulsified asphalt sections with aggregate. When these sections dried, they were the most visibly dusty on the roadway.

- Mine personnel generally favored the calcium chloride as the most useful product of the four chemicals tested (without seeing test results).

- Surface coal mine long-term fugitive dust sampling had never been attempted by anyone as far east as Illinois. In PEDCo's experience, the wet weather and light winds made testing inordinately difficult.

6.2 MINE 2--SOUTHWESTERN WYOMING

6.2.1 Test Section Layout

The test section layout is shown in Figure 11. All sections were on the same roadway segment with each section 400 feet in length.

TABLE 19. TEST SCHEDULE, MINE 1--SOUTHERN ILLINOIS

Material	Date tested	No. of tests
Liquidow	06-21	6
($CaCl_2$)	07-22	6
Soil-sement	06-24	3
(acyrlic)	07-02	6
	07-09	3
	07-15	6
Flambinder	06-23	6
(lignin)	07-19	6
Petrotac (emulsified asphalt)	07-13	3
Water	06-30	6
	07-06	6
	07-16	6

TABLE 20. SAMPLING EQUIPMENT, MINE 1--SOUTHERN ILLINOIS

Location	Dist. from edge of road, m	Equipment	Intake ht, m
Upwind	20	4 profiler heads w/variacs 2 dustfall collectors 1 generator	1, 2.5, 5, 9 1
Downwind (each of 3 sections)	10	4 profiler heads w/variacs 2 dustfall collectors 1 windspeed/direction recorder[a] 1 generator 1 Berkeley Controls quartz crystal cascade analyzer (QCCA)[a] 1 GCA RAM-1 monitor w/recorder[a]	1, 2.5, 5, 9 1 2.5 Varies
Downwind of uncontrolled section	50	2 dustfall collectors 1 profiler head w/variacs	1
	100	2 dustfall collectors 1 profiler head w/variacs	1

[a] Only on one downwind section.

TABLE 21. MINE EQUIPMENT, MINE 1--SOUTHERN ILLINOIS

Vehicle type	Dimensions, ft			Empty/full weight, tons	Wheels	
	Length	Width	Height		No.	Diameter ft
Haul truck	63	14	14.5	58/168	10	7.5
Water truck	55.5	11.5	14.5	30/58	6	7.0
Road grader	34	12	11	55.1	6	4.5
Midsize truck	24	8	7	13.5	6	3.6
Pickup truck	18	6	6	3.0	4	2.0

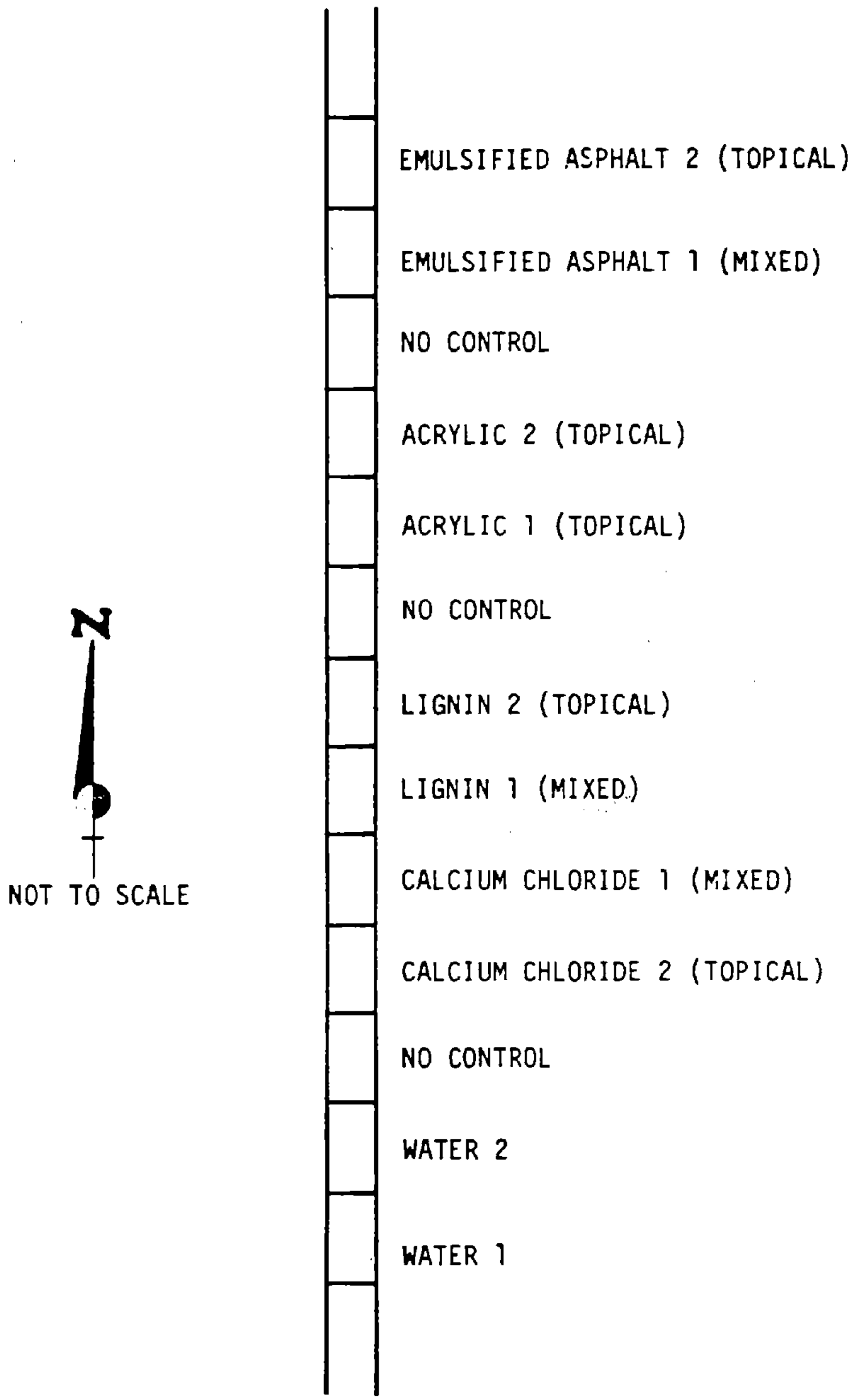


Figure 11. Test Section Layout, Mine 2--Southwestern Wyoming.

Soil analyses were performed on the roadway which was constructed during one time period and which appeared homogeneous throughout its length. The results appear in Table 22. Three discernable layers were found. The size gradation, natural moisture, and Atterberg limits were markedly different than in southern Illinois. The surface material was more coarse than the Bureau of Mine standard, but overall, was a significantly better material than found in southern Illinois.

6.2.2 Chemical Application

Chemical application is described in Table 23. Vendors for Liquidow and Arco 2200 were present and supervised application. PEDCo personnel supervised application of the remaining two substances according to vendor specifications received beforehand. All chemicals were applied on July 31. All chemical sections were watered daily at approximately 7:00 a.m. No sections were regraded during the testing.

The road used for testing had been treated the previous year with a mixed in place application of ammonium lignin sulfonate (ALS). In the spring of 1982, additional aggregate was placed on the roadway at an average depth of about 6 inches. It is likely, however, that traces of the ALS remained in the subbase material. The impact of this is not known. This situation is common in Wyoming where state regulations require all mines subject to the regulation to apply a chemical dust suppressant on their permanent haul roads. Most mines do the primary treatment annually in the late spring/early summer, often with a different product than the previous year.

6.2.3 Test Schedule

The test schedule is shown in Table 24. Reliable winds out of the west-southwest and only two rain days during the testing allowed excellant testing conditions. In total, 123 tests were obtained.

6.2.4 Sampling Equipment

As noted in Section 4, the sampling array was modified from the configuration deployed at the first mine. The basic shift involved removing the profiler head and dustfall buckets from the 50 and 100 m downwind distances, and instead using additional RAM-1 units on both controlled sections, and size-selective inlet hi-vols at all four sampling locations. The array is summarized in Table 25. It should be noted that the maximum height of the towers was 7 m as compared to 9 m at Mine 1. This change was necessary because of high winds.

TABLE 22. ROADWAY SOIL ANALYSIS, MINE 2--SOUTHWESTERN WYOMING

	Top 2 in.	-2 to -7 in.	>7 in. and below	Standard
Gradation, percent passing				
1 inch	79.72	97.56	92.60	98
3/4 inch	71.07	95.50	89.91	92
3/8 inch	59.08	89.38	83.35	82
No. 4[a]	52.51	84.31	80.03	65
No. 10	46.74	74.06	72.37	53
No. 40	31.46	62.99	69.31	33
No. 200	7.20	39.44	53.11	16
Natural moisture, percent	4.0	6.1	11.2	
Atterberg limits				
Liquid limit	b	23	23	25
Plasticity limit		21	22	16
Placticity index		2	1	9
Soil classification of minus No. 40		Sandy silt	Sandy silt to silty sand	

[a] Minus No. 4 material analyzed with wet screen technique.
[b] Noncohesive soil. Limits could not be determined.

TABLE 23. DUST SUPPRESSANT APPLICATION, MINE 2--SOUTHWEST WYOMING

Chemical	Section 1		Section 2	
	Rate	Method of application	Rate	Method of application
Liquidow ($CaCl_2$)	0.6 gal/yd^2 of 38%	0.37 gal/yd^2 mixed in place$_2$ 4 to 6 inches. 0.27 gal/yd^2 topically applied after final grading. Water wagon. Rolled	0.27 gal/yd^2 of 38%	Topically applied with water wagon
Soil-sement (acrylic)	1.0 gal/yd^2 of 13.5%	Topically applied with water wagon in several passes on July 31. Reapplied in same manner on August 14	1.0 gal/yd^2 of 13.5%	Topically applied with water wagon. Reapplied August 14.
Flambinder (lignin)	2.0 gal/yd^2 of 18%	1.5 gal/yd^2 mixed in place$_2$ 4 to 6 inches. 0.5 gal/yd^2 topically applied after final grading. Water wagon. Rolled	0.5 gal/yd^2 of 18%	Topically applied with water wagon
Arco 2200 (emulsified asphalt)	2.8 gal/yd^2 of 12.5%	2.0 gal/yd^2 mixed in place$_2$ 4 to 6 inches. 0.8 gal/yd^2 topically applied after final grading. Water wagon. Rolled.	0.9 gal/yd^2 of 12.5%	Topically applied with water wagon
Water	Unknown	Twice per hour. Water wagon	Unknown	Once per hour. Water wagon

TABLE 24. TEST SCHEDULE, MINE 2--SOUTHWESTERN WYOMING

Material	Date tested	No. of tests
Liquidow ($CaCl_2$)	08-04	3
	08-05	6
	08-11	6
	08-18	6
	08-26	6
Soil-sement (acrylic)	08-03	6
	08-16	6
	08-24	6
	08-30	6
Flambinder (lignin)	08-02	6
	08-10	6
	08-17	6
	08-27	6
	08-31	6
Acro 2200 (emulsified asphalt)	08-09	6
	08-13	6
	08-20	6
	08-25	6
Water	08-12	6
	09-01	6
	09-02	3
	09-03	3

TABLE 25. SAMPLING EQUIPMENT, MINE 2--SOUTHWESTERN WYOMING

Location	Dist. from edge of road, m	Equipment	Intake ht, m
Upwind	20	4 profiler heads w/variacs	1, 2.5, 5, 7
		1 recording wind system	2.5
		2 dustfall collectors	1
		1 SSI	1
		1 generator	
Downwind (all sections)	10	4 profiler heads w/variacs	1, 2.5, 5, 7
		2 dustfall collectors	1
		1 QCCA	Varies
		1 RAM-1 w/strip chart or integrator	1
		1 SSI	1
		1 generator	

6.2.5 Mine Equipment

Equipment type, salient dimensions, and weights, using the haul road tested are described in Table 26.

6.2.6 General Observations

- There were no complaints from mine personnel about slippery conditions on treated sections.

- All treated sections were watered at about 7:00 a.m. and then not again during the first shift. In the afternoon, conditions along the treated sections became extremely dusty. The level of dust often exceeded the level achieved by frequent watering according to mine personnel.

- There was considerable coal spillage along the road causing very high surface loadings and subsequent reentrainment. All chemical dust suppressants share the common failing that the coal dust is not moistened as it would be with frequent watering.

- Mine engineering personnel favored the calcium chloride as the most useful of the four products tested (without seeing test results).

6.3 MINE 3--NORTHEASTERN WYOMING

6.3.1 Test Section Layout

The test section layout is shown in Figure 12. Sections varied in length from 350 to 450 feet, depending on space limitations.

Soil analyses were performed on the roadway which appeared to be of the same construction throughout. The results appear in Table 27. Similarly to Mine 1, the high percentage of fines resulted in relatively low bearing strength. When wet, the material became very muddy and rutted badly. It was common practice in the mine to lay 2 to 4 inches of new aggregate (scoria) on the road after significant rains or snows.

6.3.2 Chemical Application

Chemical application is described in Table 28. Vendors for Liquidow, Biocat, and Arco 2200 were present and supervised application. PEDCo personnel supervised application of the Flambinder according to vendor specifications received beforehand.

The testing period was deliberately scheduled late in the year to meet a project objective of testing dust suppressants

TABLE 26. MINE EQUIPMENT, MINE 2--SOUTHWEST WYOMING

Vehicle type	Dimensions, ft			Empty/full weight, tons	Wheels	
	Length	Width	Height		No.	diameter, ft
Haul truck	64	16	14	60/180	10	7
Water truck	32	15	14	38/92	6	6.5
Fly ash truck	36	18	15	36.9/127.4	6	7.5
Road grader	34	12	11	55.1	6	4.5
Midsize truck	25	9	9	13.5	6	3
Pickup truck	18	6	6	3.0	4	2.0

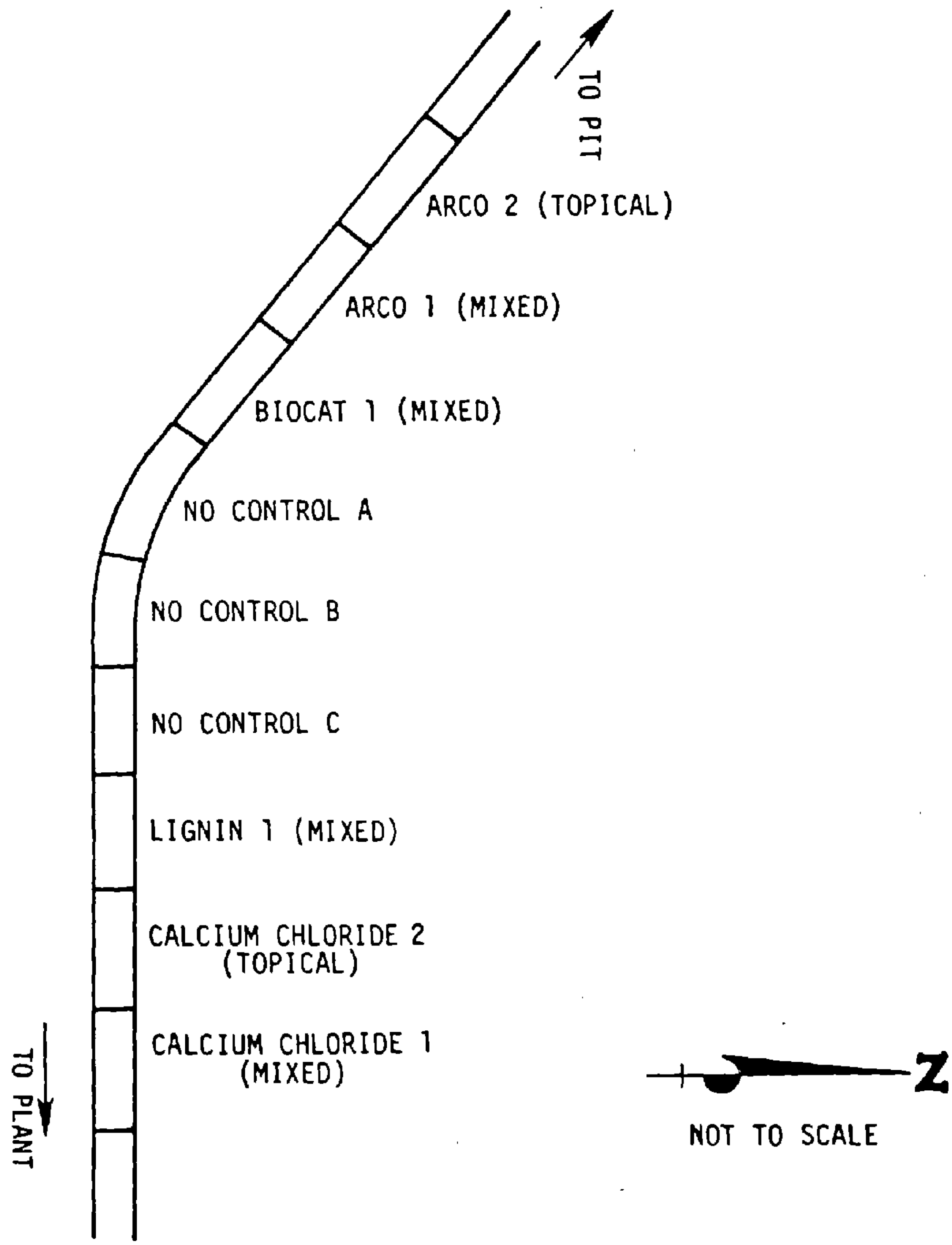


Figure 12. Test Section Layout, Mine 3--Northeastern Wyoming.

TABLE 27. ROADWAY SOIL ANALYSIS, MINE 3--NORTHEASTERN WYOMING

	Top 3 in.	-3 to -8 in.	>8 in. and below	Standard
Gradation, percent passing				
1 inch	83.25	75.28	99.21	98
3/4 inch	77.02	69.65	98.07	92
3/8 inch	64.08	56.43	92.72	82
No. 4[a]	57.38	49.43	79.56	65
No. 10	45.85	39.91	26.30	53
No. 40	33.88	31.37	6.43	33
No. 200	23.38	24.39	1.16	16
Natural moisture, percent	4.3	14.2	15.7	
Atterberg limits				
Liquid limit	42	35	49	25
Plasticity limit	25	21	23	16
Placticity index	17	14	26	9
Soil classification of minus No. 40	Lean clay	Lean clay	Lean clay to fat clay	

[a] Minus No. 4 material analyzed with wet screen technique for the top and middle layers.

[b] The lower level was dry screened because the sample was predominantly shale which decomposes when wet.

TABLE 28. DUST SUPPRESSANT APPLICATION, MINE 3--NORTHEAST WYOMING

Chemical	Rate	Method of application	Rate	Method of application
Liquidow ($CaCl_2$)	0.6 gal/yd^2 of 35%	0.4 gal/yd^2 mixed in place 6 inches. 0.2 gal/yd^2 topically applied after final grading. Water wagon	0.3 gal/yd^2 of 35%	Topically applied with water wagon
Biocat (surfactant/ enzyme)	2.0 gal/yd^2 of 0.005%	1.0 gal/yd^2 mixed in place 6 inches. 1.0 gal/yd^2 topically applied after final grading. Water wagon		
Flambinder (lignin)	1.8 gal/yd^2 of 18%	0.9 gal/yd^2 mixed in place 4 to 6 inches. 0.9 gal/yd^2 topically applied after final grading. Water wagon		
Arco 2200 (emulsified asphalt)	2.3 gal/yd^2 of 14%	1.2 gal/yd^2 mixed in place 4 to 6 inches. 1.1 gal/yd^2 topically applied after final grading. Pressurized spray bar	1.1 gal/yd^2 of 14%	Topically applied with pressurized spray bar

when freeze/thaw cycles were prevalent. The scheduled date for chemical application was October 9. A blizzard forced cancellation of the application. During the following week, mine personnel placed new aggregate along the entire roadway. All chemicals were applied on October 16.

During testing, sections were watered very infrequently (less than once/shift) because of moist, freezing conditions.

6.3.3 Test Schedule

The test schedule is shown in Table 29. The testing was continually hampered by poor weather. Snow and/or high winds (>25 mph) occurred on October 27, November 1, 2, and 5. After the November 1 and 2 snow event, the entire road was covered with scoria. This application effectively eliminated any additional control measure evaluations. Testing crews remained on site to test the impact of covering and grading the test sections and to test watering. Testing was performed on November 2 and 3 ($CaCl_2$ and Lignin). Testing of water could not be performed because temperatures were below freezing. After the November 5 snow event, the road was again recovered with scoria and regraded. The five-day forecast was for sub-freezing temperatures throughout the period. The testing was cancelled on November 5.

6.3.4 Sampling Equipment

The sampling array used at Mine 3 was identical to the array used at Mine 2 (Subsection 6.2.4).

6.3.5 Mine Equipment

Equipment type, salient dimensions, and weights using the haul road tested are described in Table 30. The smaller haul trucks were used for moving overburden and only used the test segment near shift change times. The larger trucks were used for coal hauling and were the vehicles measured during the testing as haul trucks.

6.3.6 General Observations

- Between October 15 and April 15 in Wyoming mines, the dust suppression program normally consists of only light grading. No watering is used because of moist conditions (rain-snow) and sub-zero temperatures. While it is a laudible research effort to investigate the effectiveness on dust-suppressants under freeze/thaw conditions, as a practical matter, no watering or application of chemical dust suppressants are normally used during this period.

TABLE 29. TEST SCHEDULE, MINE 3--NORTHEASTERN WYOMING

Material	Date tested	No. of tests
Liquidow ($CaCl_2$)	10-26 11-02[a]	6 6
Flambinder (Lignin)	10-19 10-25 10-28 11-03[a]	6 6 6 6
Biocat (Enzyme-surfactant)	10-20 10-22 10-29	6 6 6
Arco 2200 (Emulsified asphalt)	10-21	6

[a]segment covered with scoria on Nov. 1.

TABLE 30. MINE EQUIPMENT, MINE 3--NORTHEASTERN WYOMING

Vehicle type	Dimensions, ft			Empty/full weight, tons	Wheels	
	Length	Width	Height		No.	Diameter, ft
Haul truck - 7 units	32.8	18.5	17.5	69.5/189.5	6	12.8
- 5 units[a]	39.0	22.8	20.0	106.3/276.3	6	12.8
Water truck	28.5	13.3	14.0	41.7/87.1	6	5.8
Road grader	32.8	10.1	11.5	27.0	4	4.2
Midsize truck	25.0	9.0	9.0	13.5	6	3.0
Pickup truck	18.0	6.0	6.0	3.0	4	2.0

[a] Primary coal haulers.

- At a mine where the road requires rebuilding through the addition of aggregate after all significant precipitation events, the use of relatively high-cost, long-lasting, dust suppressants becomes problematical.

SECTION 7

CALCULATION PROCEDURES

The following instrumentation was used during the project at one or more of the mines:

1. Exposure profiling towers
2. RAM-1 monitors
3. Quartz Crystal Cascade Impactor
4. Size-selective inlet high-volume samplers
5. Dustfall buckets

The purpose of this section is to describe the calculation procedures for each sampling device. Each of the five devices is discussed in a separate subsection below. Finally, a description of the procedure for statistically analyzing results is included.

7.1 EXPOSURE PROFILING TOWER

7.1.1 Theoretical Basis

The emission calculations for exposure profiling are based on the concept of conservation of mass. The inherent assumption in these calculations is that the total mass of particulate emissions is constant per unit length of road for a given time. Consequently, a sample taken at any point along the road should be representative of the entire road section.

Mathematically, the emission rate per length of road for a given test is expressed as follows:

$$E = \int_{0}^{H} \frac{M(h)}{a} dh \qquad \text{(Eq. 1)}$$

where E = emission rate
M = net particulate mass collected by profiler sampler
a = sampler intake area
h = vertical distance of sampler above ground level
H = vertical extent of plume above ground level

In other words, the quantity of emissions (emission rate) is obtained by numerical integration of exposure measurements (mass/area) over the vertical cross section of the plume. This concept is presented graphically in Figure 13.

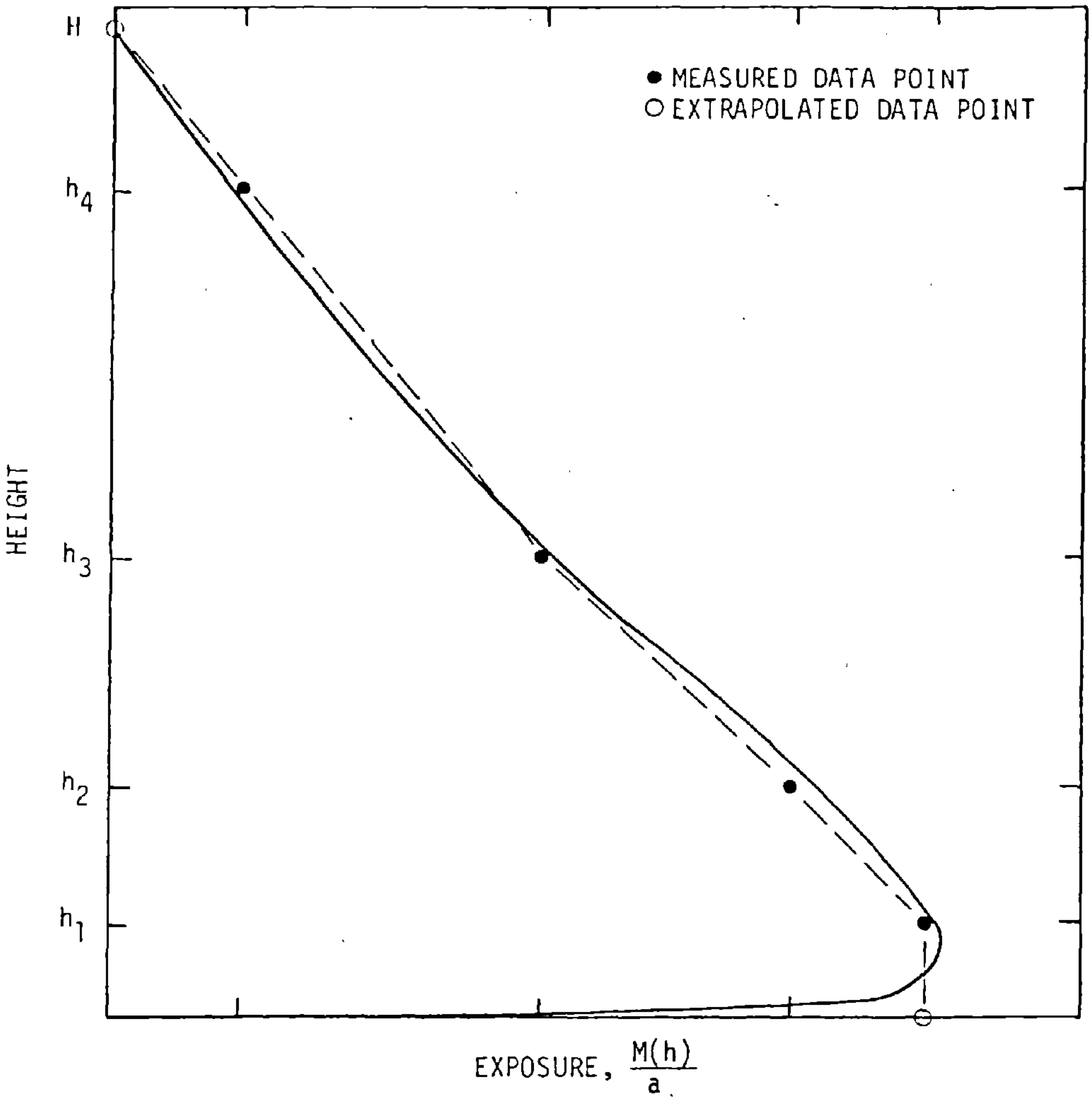


Figure 13. Typical exposure profile.

As shown in Figure 13, the net exposure values should be equal to zero at the vertical extremes of the profile. At ground level the wind velocity is zero and at the effective height of the plume the net exposure is zero. The effective height of the plume is determined by extrapolation of the measured values at the top two heights. In order to obtain accurate measurements of particulate exposure, the sampling intake must be aligned parallel to the wind direction and the sampling velocity must correspond to the ambient wind velocity, i.e., isokinetic sampling.

The step by step calculation procedures for emission rates are presented in subsection 7.1.2.

Due to the design of this study, the calculation of control efficiencies is straightforward once the emission rates have been calculated. For each set of three simultaneous tests, the control efficiency for each controlled section can be calculated as:

$$C = \left(1 - \frac{E_c}{E_u}\right) \times 100 \qquad \text{(Eq. 2)}$$

where C = control efficiency, %
E_c = controlled emission rate
E_u = uncontrolled emission rate

Every set of three tests yields two specific control efficiency values. This simple calculation is possible because all variables except application of the dust suppressant are the same for the three simultaneous tests.

7.1.2 Calculation Procedures

The four necessary steps to calculate the emission rate for each test are described below.

Step 1. Calculate Weights of Collected Samples--

In order to calculate the weight of particulate matter collected by a profiler sampler, the weights of the Nuclepore filters are determined before and after use. The following equation then yields the amount of particulate collected:

$$\begin{pmatrix}\text{Particulate}\\ \text{sample}\\ \text{weight}\end{pmatrix} = \begin{pmatrix}\text{Final}\\ \text{weight}\end{pmatrix} - \begin{pmatrix}\text{Tare}\\ \text{weight}\end{pmatrix} \qquad \text{(Eq. 3)}$$

Step 2. Calculate Particulate Exposures by Particle Size Range--

For the isokinetic directional samplers used in this study, particulate exposure may be calculated with the following equation:

$$P = \frac{M}{a} \qquad \text{(Eq. 4)}$$

where P = particulate exposure, mg/cm^2
M = particulate weight collected by sampler, mg
a = sampler intake area, cm^2

With the two Nuclepore filters generated by each sampler, a TSP (<30 micrometers) and FP (<2.5 micrometers) exposure are obtained for each profiler, both upwind and downwind:

$$P_{TSP} = \frac{M_T}{a} \qquad \text{(Eq. 5)}$$

$$P_{FP} = \frac{M_{FP}}{a} \qquad \text{(Eq. 6)}$$

where P_{TSP} = total suspended particulate exposure, mg/cm^2
P_{FP} = fine particulate exposure, mg/cm^2
M_T = Sum of the weights collected on both filters, mg
M_{FP} = weight collected on FP Nuclepore filter, mg
a = intake area of sampler, 5.07 cm^2

Step 3. Calculate Net Exposures and Graph Net Profiles to Determine Plume Boundaries--

Once the upwind and downwind particulate exposures have been determined by particle size, the next step is to define the net exposure, attributable to the haul road, by particle size range. The net exposure is simply the difference between total downwind and upwind exposures at each height. These net exposures are then plotted as shown in Figure 14. Three assumptions are made in order to define the profile for each particle size range. First, the vertical extent of the plume is defined by extrapolation of the net exposure values found at 5 and 7 or 9 m to the y-axis. Second, the 1 m net exposure value is constant down to ground level. This assumption represents the offsetting effects of maximum exposure below 1 m and the decay to zero exposure at ground level as depicted in Figure 13. The third assumption is that the net exposure is a linear continuous function between any two consecutive data points.

Step 4. Integrate Profiles and Calculate Emission Rates--

After the profiles have been defined, as in the Figure 14 example, the area under the curves is determined by graphical or

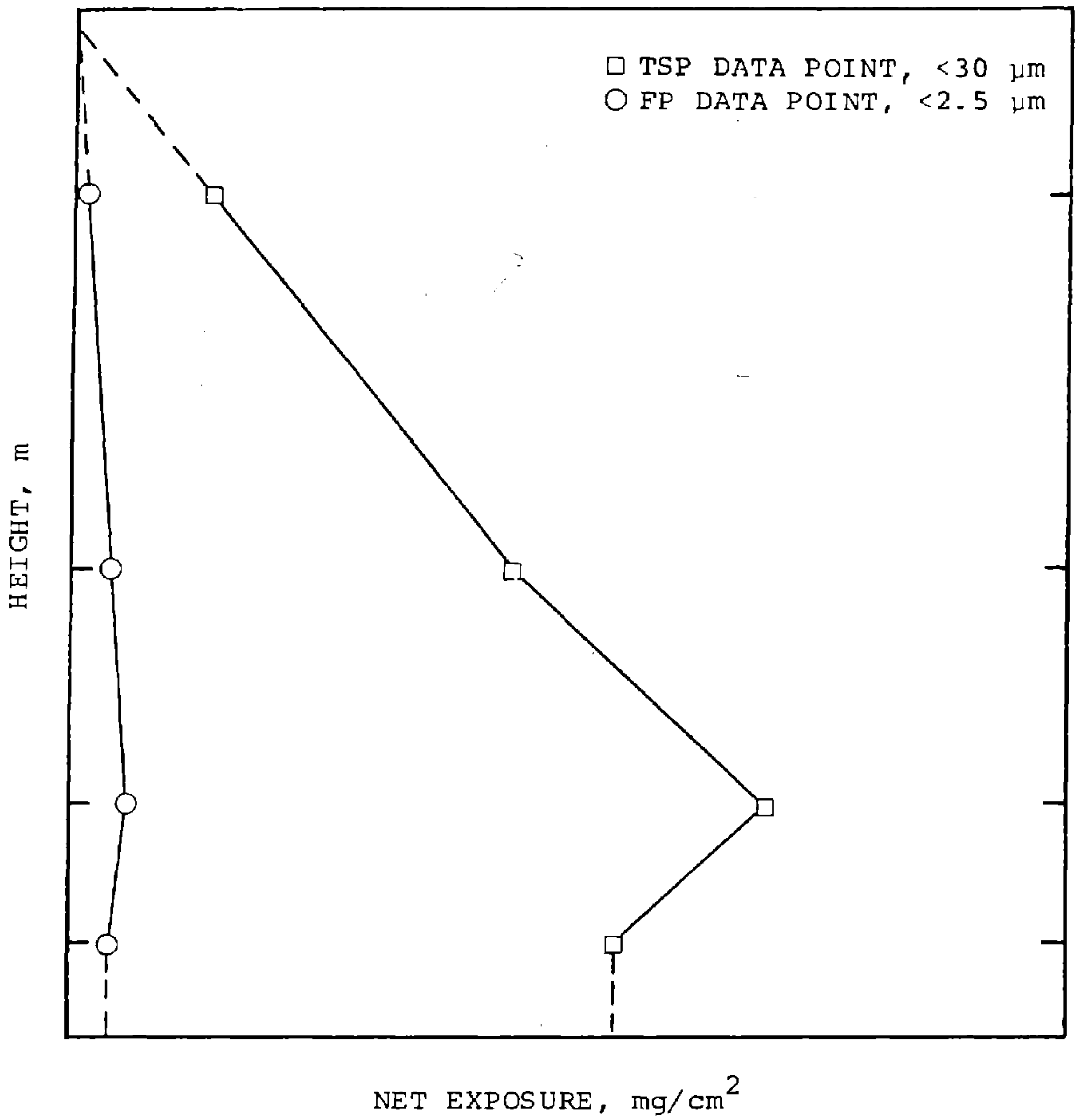


Figure 14. Vertical exposure by particle size.

numerical integration techniques, using triangular and trapezoidal areas.

The emission rate for airborne particulate of a specific particle size range, generated by vehicles traveling along a straight line road segment, is given by:

$$E = 35.5 \frac{A}{N} \quad \text{(Eq. 7)}$$

where E = particulate emission rate, lb/VMT
A = integrated exposure (area under the curve), m-mg/cm²
N = number of vehicle passes, dimensionless

The coefficient in Equation 7, 35.5, is a conversion factor needed to satisfy the equality of the given units. The TSP, and FP emission rates are calculated separately from their respective curves.

When the emission rates have been determined for each of the three simultaneous tests, the control efficiencies of the two control sections are determined with Equation 2.

7.2 RAM-1 MONITORS

As discussed previously in the report, three RAM-1 Monitors were used at Mines 2 and 3. At the uncontrolled section one of the monitors was connected to a strip chart recorder. At each of the control sections the monitor was connected to a GCA Analog Signal Averager/Integrator Model ASA-1. At Mine 1 only the RAM-1 with the strip chart recorder was used.

For the RAM-1 monitors used with the ASA-1 no calculations were required. At the end of each test the integrated concentration value from the vehicles passing the monitor was simply read from the digital display and recorded on the data sheets.

In order to directly compare the results obtained from the ASA-1 to the strip chart trace, it was necessary to integrate the trace over the test period. For each vehicle that passed the monitor a steeply sloped peak was generated on the strip chart. During periods of no vehicular activity the strip chart recorded a zero trace. To integrate the strip chart for a given test, the maximum value of each peak and the total time of each peak were recorded. For the total number of vehicle passes, the integrated value for the test was obtained as follows:

$$I = \frac{\sum_{i=1}^{N} \left(\frac{P_i t_i}{2}\right)}{T} \quad \text{(Eq. 8)}$$

where I = integrated value, mg/m³
P_i = peak value for i^{th} vehicle, mg/m³
t_i = time for peak of i^{th} vehicle pass, min.
T = total time of test, min
N = number of vehicle passes

In other words, for a given peak the shape can be approximated by a triangle. Consequently, the area of a given triangle is obtained as ½(P)t. By summing the areas of all triangular peaks and dividing by the total time of the test the average concentration is obtained.

Once the integrated concentration values for all three test sections are available the control efficiency for one of the control sections is obtained from the following equation.

$$C = \left(1 - \frac{R_c}{R_u}\right) X\ 100 \qquad \text{(Eq. 9)}$$

where C = control efficiency, percent
R_c = integrated concentration value from control section, mg/cm³
R_u = integrated concentration value from uncontrolled section, mg/cm³

7.3 QUARTZ CRYSTAL CASCADE IMPACTOR

As discussed earlier in the report, the Berkeley Controls QCM Cascade impactor was deployed to obtain an estimate of inhalable particulate (IP) (<10 micrometers) for each tower. For each of the first two heights at each tower concentration data generated with the QCCA and the FP exposure were to be used to calculate IP exposure as follows:

$$P_{IP} = P_{FP}\ X\ \frac{QCAA_{10}}{QCAA_{2.5}}, \text{ where} \qquad \text{(Eq. 10)}$$

P_{IP} = inhalable particulate exposure, mg/cm²
P_{FP} = fine particulate exposure, mg/cm²
$QCAA_{10}$ = concentration determined from QCAA, μg/m³ <10 μm
$QCAA_{2.5}$ = concentration determined from QCAA, μg/m³ <2.5 μm

In actual field use the limitations of this analyzer precluded the use of the data for the calculation of IP. Throughout the entire study, significant problems were encountered which severely limited the usefulness of this device. The routine reoccuring-problem was related to the measurement of frequency change by stage. Problems were described in a previous section.

Consequently, the data from the instrument were deemed too suspect for use in the calculations. The data summaries in the Appendix include these data where 0 or negative frequency changes are recorded as 1. None of the resulting IP values were used in the results. Consequently, no measurement of IP control efficiencies was obtained for the towers.

7.4 SIZE-SELECTIVE HIGH-VOLUME SAMPLERS

At Mines 2 and 3 after the recurring problems with the QCCA, a Size-Selective High-Volume Sampler (SSI) was added to the equipment deployed at each tower. The purpose of this deployment was to generate inhalable particulate (IP < 15 micrometers) control efficiency data.

The four necessary steps to calculate control efficiencies are described below.

Step 1. Calculate Weights of Collected Sample

$$\begin{pmatrix}\text{Particulate}\\ \text{sample}\\ \text{weight}\end{pmatrix} = \begin{pmatrix}\text{Final}\\ \text{weight}\end{pmatrix} - \begin{pmatrix}\text{Tare}\\ \text{weight}\end{pmatrix} \qquad \text{(Eq. 11)}$$

Step 2. Calculate IP Concentrations

The SSI samplers are flow controlled to operate at a constant 40 ft^3/min (1.13 m^3/min). Consequently, concentration can be calculated as follows:

$$IP = \frac{(1 \times 10^6) \times (W)}{1.13\ T} \qquad \text{(Eq. 12)}$$

where IP = SSI concentration, $\mu g/m^3$
W = Net weight, grams
T = sample time, minutes

Step 3. Calculate Net Downwind Concentrations

Once the upwind and downwind particulate concentrations have been determined, the next step is to define the net downwind concentration, attributable to the haul road. The net concentration is simply the difference between downwind and upwind concentration for each downwind sampler.

Step 4. Calculate Control Efficiencies

Due to the design of this study, for each test the IP control efficiency can be calculated as:

$$C_{IP} = \left(1 - \frac{S_c}{S_u}\right) X\ 100 \qquad \text{(Eq. 13)}$$

where C_{IP} = IP control efficiency, percent
S_c = SSI controlled concentration
S_u = SSI uncontrolled concentration

7.5 DUSTFALL BUCKETS

The results obtained with the dustfall buckets were originally intended to be used with measured concentration values from the first height on each tower to calculate deposition velocity by particle size. Dustfall amounts are calculated by dividing total collected weight by the collection area and sample time (reported as mg/m^2-s). During the study, collocated dustfall buckets were deployed at each tower. At Mine 1 additional pairs were deployed at 50 and 100 m downwind of the uncontrolled section. With the additional equipment deployed for testing at the last two mines, these additional downwind collocated buckets were eliminated from the array.

Preliminary analysis of the dustfall data showed that the results were highly variable between the collocated pairs and between the three sections with differences between collocated pairs as high as a factor of 7. Given this extreme variability, the data were not used as intended. The results are merely reported in the Appendix and the variability in the data are examined in the next section.

7.6 STATISTICAL ANALYSIS OF RESULTS

Once the emissions and control efficiencies are obtained it is possible to calculate the confidence limits for the median control efficiency. The calculation procedure is based on the assumptions that emission rates are lognormally distributed and that the relative standard derivations of the controlled and uncontrolled data sets (untransformed) are equal. The derivation of this process is fully described in Appendix B of the Long-Range Test Plan. Briefly, the calculation of confidence intervals is based on the control efficiency.

1. Let the control efficiency be measured by

$$C = 1 - \frac{E_c}{E_u} \qquad \text{(Eq. 14)}$$

where C = control efficiency
E_c = controlled emission rate
E_u = uncontrolled emission rate

It is more convenient to first calculate confidence intervals for:

$$1 - C = \frac{E_c}{E_u} \qquad \text{(Eq. 15)}$$

and then transform the results to an interval for C.

Given this transformation, the confidence limits for the median control efficiency are determined from those for 1-C using:

$$\exp \left\{ \overline{\ln E_c} - \overline{\ln E_u} \pm ts\sqrt{\frac{2}{n}} \right\} \qquad \text{(Eq. 16)}$$

where $\overline{\ln E_c}$ = observed sample mean of the logarithms of the controlled emission rates

$\overline{\ln E_u}$ = observed sample mean of the logarithms of the uncontrolled emission rates

t = value from the statistical t-Table for the prescribed confidence level and the number of degrees of freedom

s = standard derivation of the ln emission factor

n = the number of the measured control efficiency ratios.

Once the confidence limts are calculated for 1 - C they are transformed to limits around C.

The calculation of the confidence limits for control efficiency is relatively straight forward. However, in the case of using the log transforms and various independent variables to develop an emission factor equation from the raw uncontrolled data, the calculations are substantially more detailed. A full description of this process can be found in a previous report (EPA, 1981).

SECTION 8

RESULTS

This section presents the results of the various data analyses performed. Included are the calculated emission rates and control efficiencies from the profiling towers, the various independent variables monitored, the results from the ancillary equipment used in the field, and a comparison of study results to those obtained in previous studies.

8.1 EXPOSURE PROFILING TOWER RESULTS

8.1.1 Emission Rates

Average emission rates are shown in Table 31. The computer generated results for individual tests are contained in Appendix A and are sorted by mine and control method. A summary of the results in Appendix A is presented in Appendix B along with the results for the ancillary equipment. It should be noted that the results in Table 31 and Appendices A and B are emission rates, not emission factors. In order to obtain an emission factor equation that could be applied over a broad range of conditions, the variation in measured emission rates must be evaluated with respect to simultaneously monitored independent variables. Much of the observed variation in the emission rates will be attributable to these variables. As the primary thrust of this study was to define control efficiencies, this exercise was beyond the scope of work. The data base, however, could be further analyzed to develop emission factors (see Section 8.2).

Since the calculated control efficiencies are so directly dependent on the measured uncontrolled emission rates, it is interesting to examine these data. Figure 15 presents a plot of uncontrolled TSP emission rates over time for each mine. Figure 16 shows plots of the uncontrolled FP ($\leq$ 2.5 micrometers) emission rates. One or two estimates of uncontrolled emission rate were obtained each test day. The plots in Figures 15 and 16 represent the average value for the day if two tests were taken.

Visual interpretation of Figures 15 and 16 reveals several interesting relationships. First, the results for Mine 2 are substantially higher than those for the other two mines. Second, the measured TSP and FP emission rates at all mines show a high degree of variability. Third, the measured Mine 1 and Mine 3 TSP

TABLE 31. AVERAGE EMISSION RATES

Location	TSP		FP		No. of Tests
	Range	Mean	Range	Mean	
Southern Illinois (spring)	0.7-7.8	4.5	0.1-1.4	0.8	20
Southwest Wyoming (summer)	2.9-37.5	14.4	0.2-3.0	1.3	39
Southeast Wyoming (early winter)	1.4-6.8	3.4	0.1-0.8	0.5	17

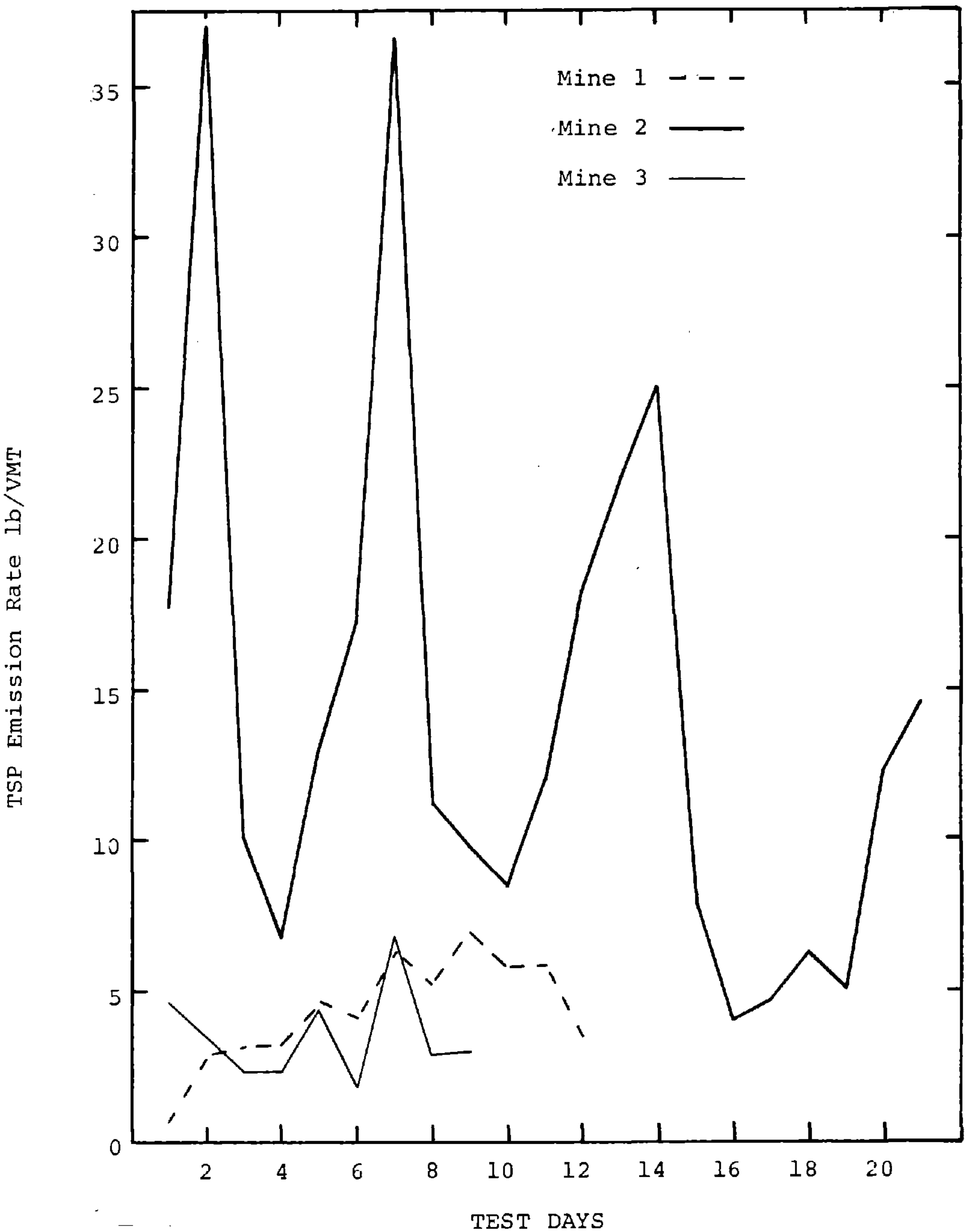


Figure 15. TSP Uncontrolled Emission Rates

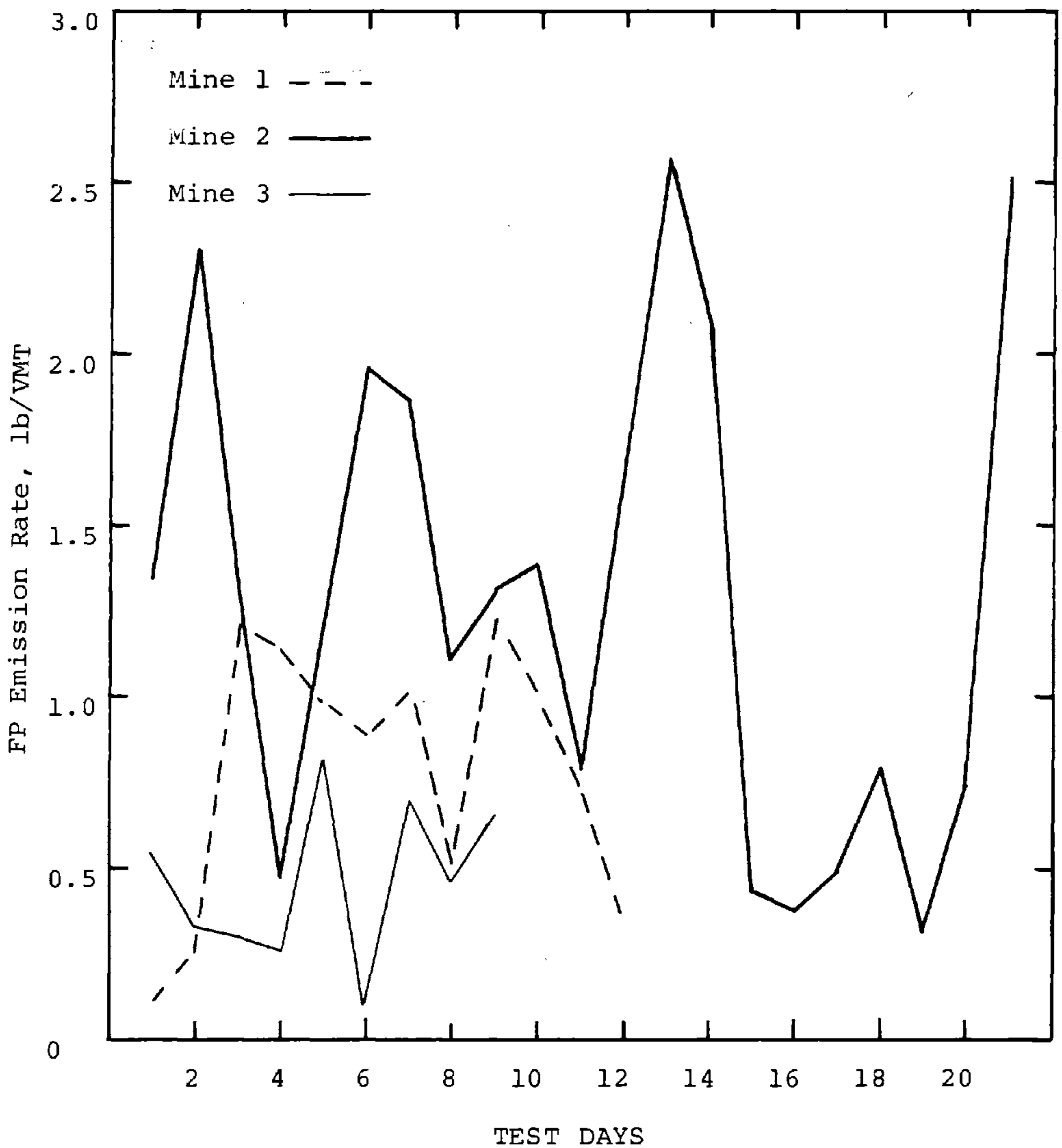


Figure 16. FP Uncontrolled Emission Rates.

emission rates are of approximately the same magnitude. Fourth, at Mines 1 and 3 the measured TSP generally increased over time while those at Mine 2 generally decreased.

Much of the variation within a mine can probably be traced to the effects of precipitation, vehicle mix, or other independent variables. The between mine variation may also be attributable to a certain extent to the same variables. However, it is felt that the greater amount of precipitation encountered at Mines 1 and 3 is the most significant difference between those mines and Mine 2.

Figures 15 and 16 further demonstrate the advantage of simultaneous testing of adjacent test sections as compared to testing at two points in time. With the broad swings in uncontrolled emission rates exemplified by the graphs, sampling at a single point in time for the uncontrolled emission rate and at another point in time for the controlled emission rate would yield possibly erroneous results. For example, initially high measurements of uncontrolled emission rates would yield highly optimistic estimates of control efficiency while low initial measurements would result in understated control effectiveness. While it is potentially feasible to normalize the data to a single time period by adjusting the measured data with factors accounting for silt, speed, weight, wheels and moisture, the data adjustments are large in magnitude and allow for large possible errors. With the design used in this study, every measurement of a controlled emission rate has a corresponding uncontrolled measurement with all independent variables held constant, resulting in a potentially more accurate picture of control efficiencies.

The Mine 1 emission data represent the only field testing known to the authors of a mine haul road east of the Mississippi. Many eastern mine operators have long claimed that emission factors developed in western mines were not applicable to eastern mines because of the different meteorological and soil conditions that would result in lower emission rates. The Mine 1 data would add some support to that claim.

The Mine 3 data add to a very limited data base of testing conducted during snow and freeze/thaw cycles. The low emission rates suggest that use of one emission factor to represent emissions over four seasons, a frequent practice in mine permit work, may not be appropriate.

8.1.2 Control Efficiencies

Average daily control efficiencies were calculated for each test day. These data were then split into groups representing weeks since control application. The measured data within each week were averaged and the average value reported for that week.

These data are summarized in Table 32, and are presented by chemical, mine, application method, time since application, and vehicle passes since application.

A similar data summary was compiled for the watering tests. Each set of test data were divided into one of three groups depending on the frequency of watering for the test. These three groups were as follows: every 30 minutes, every 60 minutes, every 120 minutes. The data in each group were averaged. These results are shown in Table 33.

8.1.3 Interpretation of Control Efficiency Results

Effectiveness By Dust Suppressant Type--

Salt--The highest measured control efficiency of any of the controls was for calcium chloride two weeks after application--82 percent for TSP. The topical application section performed better than the mixed-in-place sections with the exception of the FP data at Mine 3. The Mine 2 results show an increase in control efficiency between the first and second week and then a decline over the remainder of the time. The manufacturer's representative reported that this phenomena has been visually observed in other applications. The performance of the salt at Mine 3 was clearly inferior to performance at the other two mines.

It is generally accepted that water soluble dust suppressants may leach from the roadway during rain events, although the amount of leaching associated with dust suppressants has never been comprehensively studied. The precipitation encountered at Mine 1 and Mine 3 probably did cause sufficient leaching of the chemical from the road to explain the low final values at Mines 1 and 3 as compared to Mine 2.

Surfactant--At Mine 1, the stronger application of the Soil Sement performed better than the weaker solution, and both sections held up surprisingly well through the precipitation events. At Mine 2, by the end of the fifth week, there was essentially no effect of the chemical present (in spite of the fact that the product was reapplied two week after initial application).

Adhesives--At both Mines 1 and 2, the mixed in place section of lignosulfonate performed better than the topical application. There is an evident decrease in effectiveness over time but not as pronounced as for other chemicals. By the end of the fourth week at Mine 2, control efficiencies were still hovering around 50 percent for both TSP and FP.

Bitumen--As was found with the salt, the topical application of the Arco 2200 performed better initially than the mixed-in-

TABLE 32. AVERAGE DAILY CONTROL EFFICIENCY

Control	Weeks Since Application													
	1		2		3		4		5		6		7	
	M[a]	T[b]	M	T	M	T	M	T	M	T	M	T	M	T
	Salt (LiquiDow, $CaCl_2$)													
Mine 1														
TSP, %			82	76									14	18
FP, %			50	50									56	64
Vehicle passes			4,608										17,581	
Mine 2														
TSP, %	24	51	59	64	50	55	42	41						
FP, %	45	49	46	52	31	27	50	36						
Vehicle passes	4,476		10,188		16,518		24,084							
Mine 3														
TSP, %			20	26	0	16								
FP, %			42	16	6	0								
Vehicle passes			4,449		8,119									
	Surfactant													
Mine 1 (Soil Sement)[c]														
TSP, %					30	34	59	81	37	52	4	14		
FP, %					58	79	50	74	35	36	0	22		
Vehicle passes					6,161		9,567		12,422		14,726			

(continued)

TABLE 32 (continued)

Control	Weeks Since Application													
	1		2		3		4		5		6		7	
	M[a]	T[b]	M	T	M	T	M	T	M	T	M	T	M	T
Mine 2 (Soil Sement)														
TSP, %		71				24				3				
FP, %		53				21				0				
Vehicle passes	2,622				14,046				26,706					
Mine 3 (Biocat-Enzyme)														
TSP, %	38		0											
FP, %	20		46											
Vehicle passes	2,891		6,561											
	Adhesives (Flambinder, lignon)													
Mine 1														
TSP, %			59	55										
FP, %				31										
Vehicle passes			4,608											
Mine 2														
TSP, %	63	25	52	39	50	32	52	42						
FP, %	46	21	22	27	28	22	53	50						
Vehicle passes	1,386		8,952		15,282		25,320							
Mine 3														
TSP, %	45		38		31									
FP, %	44		49		46									
Vehicle passes	729		4,801		8,823									

(continued)

TABLE 32 (continued)

Control	Weeks Since Application													
	1		2		3		4		5		6		7	
	M[a]	T[b]	M	T	M	T	M	T	M	T	M	T	M	T
	Bitumen (Arco 2200, Emulsified Asphalt)													
Mine 2														
TSP, %	30	38	0	25	28	29	20	4						
FP, %	42	41	0	17	36	28	25	26						
Vehicle passes	7,716		12,660		18,990		22,848							
Mine 3														
TSP, %	44	56												
FP, %	33	73												
Vehicle passes	2,187													

a Mixed in place application.
b Topical application.
c Both are topical applications. The "M" section represents Section 1 in Table 6-2.

TABLE 33. COMPOSITE CONTROL EFFECTIVENESS OF WATER

	Watering Frequency, minutes		
	120	60	30
Mine 1			
TSP, %	16	37	51
FP, %	29	40	43
Vehicles/hr	32	24	28
Mine 2			
TSP, %		41	59
FP, %		26	47
Vehicles/hr		65	78

place section. At Mine 3 the initial control efficiency was higher than that at Mine 2.

Water--The data for water are fairly uniform. Watering once per hour resulted in a TSP control efficiency of about 40 percent. Doubling the application rate increased the control effectiveness by about 15 percent to 55 percent.

Generalized Control Efficiencies--

In general, measured control efficiencies are less than 60 percent for both TSP and FP. There are only 7 values in Table 32 that are in excess of 60 percent. Two of these values were greater than 80 percent. With the exception of water, no measured data points were taken within 48 hours after application. In most previous studies, controlled measurements were taken within 48 hours after application, resulting in artificially high estimates of long-term control efficiency.

After the fifth week, the few data points suggest a control efficiency of less than 20 percent. It could be argued that the moist conditions at Mines 1 and 3 caused lower estimates of control efficiencies because of the moisture in the uncontrolled sections and resulting comparatively lower uncontrolled emission rates. However, the testing at Mine 2 was performed under hot and dry conditions which were ideal for evaluating the effectiveness of the dust suppressants.

TSP vs. FP Control Efficiencies--

The results were examined to determine the comparative control effectiveness for TSP vs. FP. The t-test was run for each chemical and for the entire data set. The t-test results indicated there was no statistically significant difference between the TSP and FP control efficiencies.

Control Efficiencies Over Time--

Various mechanisms affect the longevity of a dust suppressant, including leaching, weathering and the grinding action of tires on the road surface. Intuitively, it would seem that all these phenomena are cumulative, and that a curve of control efficiencies should indicate a smooth decreasing function. However, examination of the data indicate that this is not the case. The curve of control efficiencies is very irregular.

To investigate this factor further, emission rates over time for the no-control and controlled sections were examined. Typical results appear in Figure 17, which shows results from Mine 2 for $CaCl_2$ and Lignosulfonate. Evident from the figure is that emission rates for all curves fluctuate widely, presumably because of precipitation differences and vehicle differences

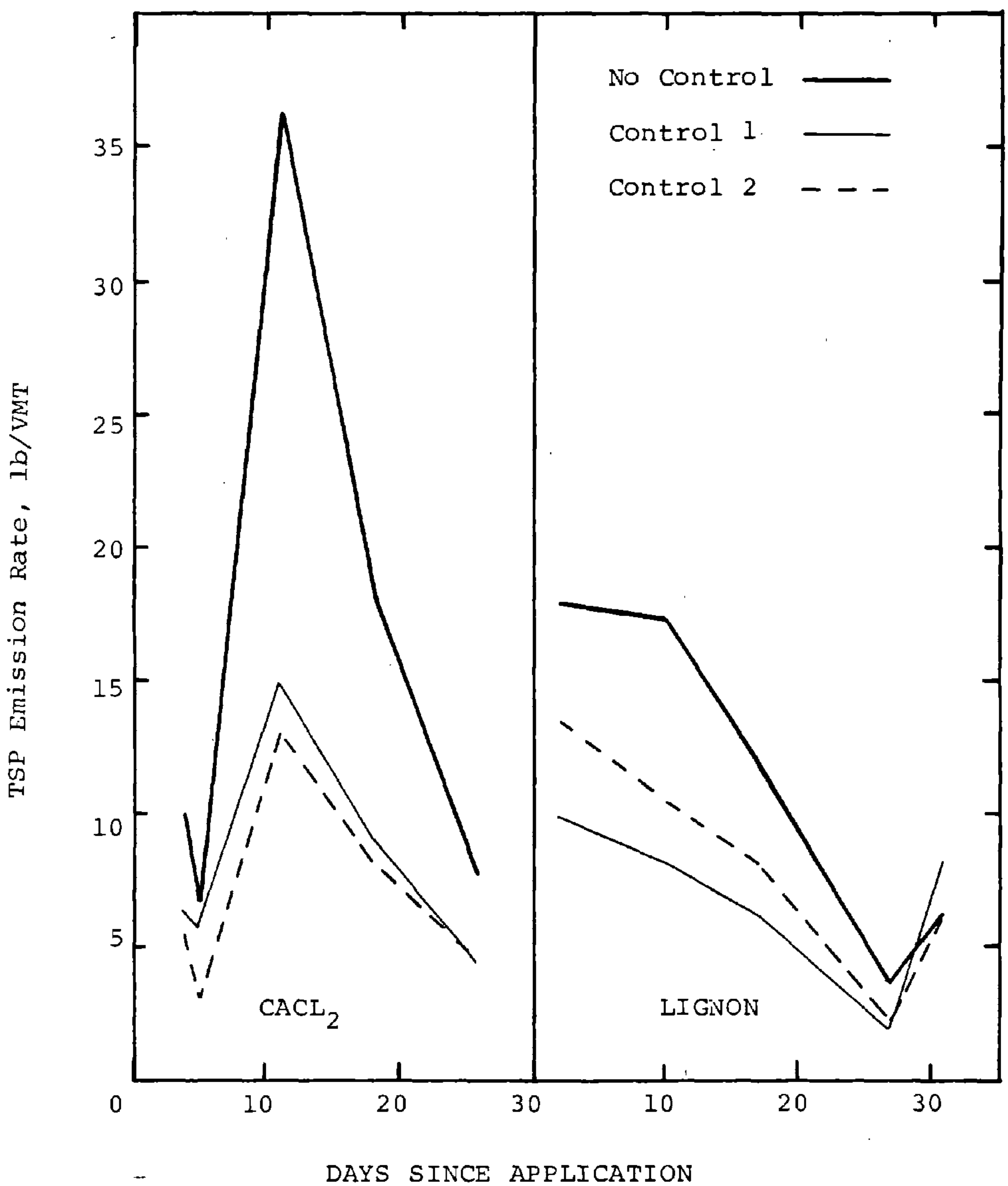


Figure 17. Control and No Control TSP Emission Rates over Time.

between tests. Also evident is that the curves vary together, but that emission rates vary more for the uncontrolled sections than for the control sections. From this exercise at least two conclusions can be drawn.

(1) The controls minimize the impact of changing vehicle types and precipitation differences.

(2) The actual pounds of emissions controlled varies widely from day to day. In the $CaCl_2$ example in Figure 17, the amount of dust controlled on a given day ranged from less than 1 lb/VMT to about 23 lbs/VMT.

Mixed vs. Topical Application--

From an air quality perspective, the relative merits of topical application versus mixed in place application are unclear. The salt and bitumen generally performed better when only topically applied. Conversely, the lignon mixed-in-place sec-tions were superior. An explanation based on observation of the roadway is possible. Prior to chemical application, the road surface is generally well compacted. Topical application does not disturb the compactness. Scarifying and subsequent windrowing and blading associated with mixed-in-place application initially results in a less compacted surface. Based on visual observations, the lignon appeared to bind the surface more quickly than the salt. The salt required a period of time to draw moisture from the atmosphere, recompact the road surface, and attain maximum effectiveness.

In light of the greatly higher cost involved with mixed-in-place application as opposed to topical application, these test results suggest that the $CaCl_2$ and bitumens be applied topically (see Section 9).

Influencing of Receiving Surface on Suppressant Effectiveness--

It has been hypothesized that a given dust suppressant would provide different control effectiveness when applied to different roadway surfaces. Similarly, it has been hypothesized that certain types of dust suppressants would perform better in certain types of roadway surfaces. To examine these hypotheses, the soil testing reported in Section 6.0 was performed (size gradation of each road strata, Atterburg limits and soil classification).

Unfortunately, the testing performed under this effort still does not allow a rigorous examination of the hypotheses. The hypotheses, however, can be refined and should be investigated further. These refined hypotheses are based on the concept that chemical dust suppressants work in primarily three ways: (a) by providing water or an adhesive to compact the roadway (b) by providing a new surface; and (c) by weighting particles down with moisture. Conversely, watering works primarily by weighting down particles with moisture, although long-term watering will usually result in greater compaction. Based on these central concepts, the following refined hypotheses are offered:

(1) In road surfaces with too much gravel, only watering will be effective. Chemical dust suppressants can neither compact the surface, because of the poor size gradation, nor form a new surface.

(2) In sandy soils, bitumens, which are not water soluble will be the most effective. Water soluble suppressants such as salts, lignons, and acrylics will leach from the upper road surface.

(3) In road surfaces with a good surface gradation, all chemical suppressant types offer potential for equal control.

(4) In road surfaces with too much silt (greater than about 20 to 25 percent as determined from a scoop sample, not a vacuum or swept sample) no dust suppression program will be effective and the road should be rebuilt. In high silt locations, the dust suppressants will tend to make the road slippery, will not be able to compact the surface, or maintain a new road surface because of poor bearing capacity. Further, rutting under high moisture conditions will often require that the road be regraded, which almost completely destroys chemical dust suppressant effectiveness. If the road cannot be rebuilt, watering is the best program.

Control Effectiveness After Reapplication--

One of the limitations of the results from this study is that no estimate of the effectiveness of chemical reapplication was tested. Testing after reapplication would probably result in higher control efficiencies than the initial application because of residual traces of the material left in the road.

Continued Watering After Application of Chemical Suppressants--

The use of the chemicals in the three mines did not eliminate the need to water the roads on a regular basis. At each mine, the operators were requested to apply as little water as possible to the chemically treated surfaces to maintain safe driving conditions. For the test periods at each mine, this resulted in passes by the water wagon of usually once each shift during dry and non-freezing conditions.

Regulatory Implications--

EPA Region VIII currently suggests allowance of 85 percent control for use of chemical dust suppressants in mines. The State of Wyoming allows 60 percent. Examination of the results in Table 32 indicates that the 85 percent control figure is perhaps optimistic. Further testing is required to determine if application at more frequent intervals, or the cumulative impact of multiple applications, would markedly increase control effectiveness. Based on study results in this study, a 50 to 60 percent control effectiveness over the long term appears more reasonable.

8.1.4 Other Consideration Influencing Dust Suppressant Use

All chemical dust suppressants (with infrequent watering) share one common failing as compared with frequent watering. Material spillage on roadways is extremely common in mines, particularly if ash haulers are also using haul roads. Material spilled is subject to reentrainment. With frequent watering, the spilled material is moistened at approximately hourly intervals. With chemicals, the spilled material could remain dry 8 to 24 hours before being moistened, and the material would again redry. Therefore, in mines where spillage cannot be effectively controlled, watering is probably more effective at reducing dust.

Chemical dust suppressants are not feasible in mines where road construction is so poor that the road must be regraded or rebuilt with new aggregate after all major storms. Regrading or rebuilding almost totally destroys chemical effectiveness. Thousands of dollars of chemicals could conceivably be wasted within days of application.

In both Mines 1 and 3, mine operators claimed that the chemically treated road sections were more slippery than the water-treated sections. Both mines had road surfaces high in silt and clay content, which lead to slippery conditions when moisture is present. Chemical suppressants probably do aggravate this problem because the hygroscopic salts and the surfactants keep the road surface wetter longer and the adhesives and bitumens can act as a lubricant between the fine particles. In Mine 2, no slippery problems were experienced. This mine had a coarser (better-drained) road surface with a silt percentage of less than 10 percent.

8.2 INDEPENDENT VARIABLES

During the course of the field testing various independent variables were monitored. These variables can be categorized as vehicle related, and road surface related. The individual measurements taken for each test are reported in Appendix C. Specifically, the data included in Appendix C are:

Vehicle Related

- average weight
- average speed
- average number of wheels

Road Surface Related

- surface loading
- silt, percent
- moisture, percent

For each test, every vehicle passing the sampling array was classified by type and speed. Specific data on vehicle weights were obtained from the individual mines. Given the distribution of vehicles for each test, average vehicle characteristics for each test were calculated.

The road surface related data were obtained by vacuuming a one foot strip across the traveled way for each test section. The collected material was weighed, oven dried, and sieved to obtain the silt (<200 mesh) and moisture percents. In Appendix C, surface loading is reported as g/ft^2. Both silt and moisture are reported as percentages of the surface loading sample.

One additional variable is reported in Appendix C--cumulative vehicle passes since application. Using vehicle records kept by the mines and observations made during the tests, an estimate of the vehicle travel over the course of the sampling at each mine was made.

In addition to the data reported in Appendix C, other measurements were taken. These included: vehicle dimensions, tire geometry, rainfall, wind speed, wind direction, and road base construction. The details of the road base analyses and rainfall data were presented in a previous section. Wind data were used during testing to set isokinetic sampling flowrates and to evaluate test abort conditions. Data on vehicle and tire dimensions were taken but the data were not reduced for this compilation.

The primary utility of the independent variable data in Appendix C would be in the development of a universal emission factor equation appropriate for use in diverse geographic areas. Inherent in the development of a universal equation is the assumption that independent variables can be found that adequately explain the observed variance in measured emission rates.

The primary method used to evaluate the relationships between measured emission rates and measured independent variables is stepwise Multiple Linear Regression (MLR). To summarize the method briefly, MLR is a statistical technique, utilizing the method of least squares, for determining a linear prediction equation from a set of simultaneously-obtained data points for independent and dependent variables.

The stepwise regression computer program first selects the independent variable that is the best prediction of emission rate (dependent variable). The emission rate values are then changed to reflect the effect of this independent variable. The process is repeated with the remaining independent variables until all variables are included in the MLR equation or until no improvement in the equation is obtained by adding another variable. The MLR prediction equation forms the basis for the final emission factor equation. Other outputs of the program enable the determination of confidence intervals for the results.

Since the primary effort of the present study was to define control efficiencies, the detailed statistical analyses required to obtain an emission factor equation were not performed.

8.3 ANCILLARY EQUIPMENT USAGE

The following discussion presents the results from the ancillary equipment used during the study. Included are the results for the RAM-1 monitors, SSI, dustfall buckets, and the quartz crystal cascade analyzer. Each of these is discussed below.

8.3.1 RAM-1

As discussed earlier in the report, the initial purpose in deploying the RAM-1 monitor was to provide a continuous record of the downwind concentrations during the sampling period. This record provided a check on: the manual vehicle counts taken, impact or lack of downwind impact from passing vehicles during wind fluctuations, and the relative impacts of various vehicles during a test. To these ends a single RAM-1 was used downwind of the uncontrolled test section. Subsequent modifications for Mines 2 and 3 resulted in additional RAM-1 monitors, equipped with integrators, being deployed downwind of each control section. These monitors were located alongside each of the profiling towers about 1.0 m above the ground. During the test the RAM-1 was operated through the same time period as the tower. Since the RAM-1 measures particulate concentrations less than about 3.0 μm in size, the results from these instruments are somewhat comparable to the FP measured at the 1.0 m height on the tower. However, there is no reason to expect that the comparisons of control efficiency based on 1.0 m concentration measurements would directly correspond to those based on the integrated exposure plots from the profiling towers. The results for each individual test are contained in Appendix B.

From each set of three simultaneous tests it was possible to calculate the average daily control efficiencies in a manner similar to that used for the tower data. A compilation of the results is shown in Table 34. As only one RAM-1 was deployed at Mine 1, only Mine 2 and Mine 3 control efficiencies are presented in the Table.

For its original intended purpose the RAM-1 performed well, allowing each vehicle pass to be identified on the strip chart. For the purposes of calculating control efficiencies the RAM-1 had several shortcomings as deployed in the field. The monitors were placed at very low (1.0 m) heights compared to the overall height of the plume as determined from the plots of exposure from the towers. In the future use of this instrument at a 2-3 m height would possibly yield more consistent results. The use of a strip chart on one RAM-1 and integrators on the others was less than satisfactory, requiring laborious integration of the charts and possibly compromising the control comparisons. In future applications, sufficient hardware should be made available to use integrators at all locations and still have the strip chart at the uncontrolled location. Finally, the monitors should not be considered for use in subfreezing conditions. The manufacturer specifies a temperature operating range of 0-50° C.

8.3.2 SSI

The rationale for the deployment of the size selective inlet (SSI) monitors was to obtain estimates of IP control efficiency in the absence of good data from the quartz crystal impactor. Consequently, four SSI samplers were deployed for each set of three simultaneous tests beginning at Mine 2. One sampler was placed upwind and one was placed at each of the downwind towers. Sampler heights were approximately 1.5 m. The nominal aerodynamic particle size cutpoint of the SSI is 15 µm. However, the inlet design causes a windspeed-dependent variation in this cutpoint.

A compilation of the SSI control efficiency results is shown in Table 34 along with the RAM-1 data. Because SSI samplers were not deployed at Mine 1 average control efficiencies are shown for only Mine 2 and Mine 3. The individual daily concentration results from the control efficiency data were calculated and are shown in Appendix B.

There is one documented feature of the SSI sampler design that caused problems in the field and that may have a bearing on the results. The design of the filter support for the SSI requires that unsupported filters be exposed to wind currents when the filter is removed. A filter cartridge arrangement such as is available for the high-volume sampler would be much more practical for this instrument and would help to eliminate filter

TABLE 34. ANCILLARY EQUIPMENT AVERAGE DAILY CONTROL EFFICIENCIES, %

Control	Weeks Since Application									
	1		2		3		4		5	
	M[a]	T[b]	M	T	M	T	M	T	M	T
	Salt ($CaCl_2$)									
Mine 2										
SSI	43	54	70	53	34	51	62	65		
RAM-1	0	37	73	69	64	67	38	10		
Mine 3										
SSI			14	20	0	0				
RAM-1			12	0	0	0				
	Surfactant									
Mine 2 (Soil Sement)										
SSI		41				9				7
RAM-1		66				72				0
Mine 3 (Biocat)										
SSI	49		0							
RAM-1	55		0							
	Adhesive (Lignon)									
Mine 2										
SSI	78	47	41	28	44	26	23	16		
RAM-1	23	59	89	83	11	49	20	0		
Mine 3										
SSI	58		57		32					
RAM-1	54		28		0					

(continued)

TABLE 34 (continued)

Control	Weeks Since Application									
	1		2		3		4		5	
	M[a]	T[b]	M	T	M	T	M	T	M	T
	Bitumen (Arco 2200)									
Mine 2										
SSI	24	54	16	26	32	54	17	8		
RAM-1	36	36	29	8	76	79	73	81		
Mine 3										
SSI	55	80								
RAM-1	50									

[a] Mixed in place application.
[b] Topical application.

handling problems and sample loss in the field. Additionally, for single point sampling in the plume, a 2-3 meter sampling heights would be preferable, although such an increase would severely restrict the portability of an already awkward device.

8.3.3 Dustfall

The dustfall samplers were originally intended to be used to calculate settling velocities by particle size range. Composite samples were to be prepared for each test section at a mine and then analyzed by sonic sieving for particle size distribution. However, these analyses were not performed. Preliminary analysis of the dustfall data showed that the results were highly variable between the collocated pairs of dustfall buckets and between the three sections. Measured differences between collocated pairs differed by as much as a factor of 7. The calculated average absolute relative difference in the measured dustfall values was 37 percent. These results were somewhat better than the 42.6 percent difference measured in another recent study (EPA, 1981b). However, given the extreme measured variability, no further analyses were pursued. The paired values for each test can be found in Appendix B.

In the opinion of the authors, dustfall sampling in conjunction with short-term fugitive dust testing has limited merit. To date, no useable dustfall data have generated by dustfall buckets located close to the source for short-term testing. While these data might be interesting, the variability in the small samples obtained over a 1-2 hour sampling exercise precludes their usefulness in any definitive analysis.

8.3.4 QCCA

As discussed earlier in the report, the Berkeley Controls QCM was deployed in order to estimate IP exposures and control efficiencies in conjunction with the profiling towers. In actual field use the limitations of this analyzer precluded the use of the data for these calculations. Use of the instrument can be described as a total failure. The instrument gave impossible results exhibiting particle bounce similar to a standard cascade impactor. In an attempt to rectify this situation, the crystals in each stage were tediously cleaned every night resulting in many broken crystals and many manhours. The instrument was returned to the manufacturer for repair, but no improvement in performance was realized upon its return.

Given these problems, the data from the instrument were deemed too suspect for use in the calculations. The data summaries in Appendix A include the measured data. Negative or zero values for frequency change by stage are recorded as one. None of the resulting IP values were used in the results.

Consequently, no measurements of IP control efficiency were obtained for the towers.

The suitability of this type of instrument for fugitive dust testing is doubtful. Well documented problems have been observed relative to its accuracy and particle bounce through problems. Also, since only very small amounts of particulate can be collected prior to cleaning, its use is restricted to short sampling times (<5 minutes) in the dusty environment downwind of a haul road. The RAM-1 strip chart results show that many vehicle passes must be measured to obtain a reasonable estimate of average emission rate for a test. Use of this instrument should be restricted to fugitive dust surveys requiring only an order of magnitude estimate of particulate concentration differences between two areas.

8.3.5 Comparison of Results from all Sampling Devices

Comparison of control efficiencies from the profiler heads, SSI's and RAM-1's is difficult for the following reasons:

1. The particle size cut-off of all samplers was different. The exposure profiler tower heads fractionated at 30 and 2.5 micrometers. The SSI had a windspeed sensitive cut-off of 15 micrometers. The RAM-1 had a cutpoint of 3.0 micrometers.

2. The exposure profiling towers were operated isokinetically. The SSI and RAM-1 had a fixed flow rate.

3. Exposure profiling occured at four points in the plume. The SSI and RAM-1 measured at only one point, 1.5 and 1.0 meter.

4. No upwind values were subtracted from the downwind RAM-1 results. This has the effect of slightly decreasing the measure of control efficiencies.

5. Field experience by PEDCo and others has demonstrated that different sampler types, even with the same particle size cut-off, seldom produce identical results. In this field experiment, the tower head drew the sample through a 1.0 inch nozzle to a Nuclepore filter, the SSI drew the sample through a large circular impaction head to a fiberglass filter, and the RAM-1 drew the sampler through a 10 mm nozzle and is a light scattering device.

Given the disparity in equipment design, deployment and operation, it was not expected that totally consistent results would be obtained. Some data anomalies were expected and are present in the data. However, it is interesting to compare the overall results for each device operated at the three mines. In interpreting the results, it should be remembered that differences could be due to difference in sampler designs and deployment, measurement error, and real differences in control efficiency over the range of particle sizes.

For each control tested at each mine the average control efficiency was derived from data in Tables 32, 33 and 34 for each device. These data are presented in Table 35 for the chemicals and in Table 36 for water. Within each control/application method at each mine there is a range of control efficiency estimates for the three devices. Agreement ranges from good (Mine 2, salt, mixed-in-place) to poor (Mine 2, Bitumen, mixed-in-place).

To determine if there was a systematic bias between sampler types, a sampler average control efficiency was calculated. Resulting averages for the TSP Profiler, FP Profiler, SSI and RAM-1 were 31.9, 35.4, 35.7, and 37.5 percent respectively. When these values were subjected to ANOVA, the observed difference was not statistically significant.

Overall, the results are fairly consistent. They do, however, point out the difficulties in using multiple equipment to obtain results.

8.4 COMPARISON WITH OTHER STUDIES

8.4.1 Emission Rates

The primary purpose of this study was to determine control effectiveness. However, the study provided the opportunity to complete 76 tests of uncontrolled emission rates. These data are compared to those obtained in other studies in Table 37. This comparison enlarges the total data base for coal haul road testing and serves as a check on the performance of the stacked filter sampling heads.

The results for the three mines in Table 37 fall within the range of experimentally derived data from three previous studies and represent a favorable check on the sampling head. The mean emission rate for Mine 2 is within 1.5 lb/VMT of the mean emission rate measured with hi-vols by PEDCo at the same mine on the same haul road during 1977.

8.4.2 Control Efficiencies

The control efficiency data obtained during the study are presented in Table 38 in comparison to all other field study results for control effectiveness known to the authors. Tests

TABLE 35. COMPARISON OF CONTROL EFFICIENCY RESULTS FOR CHEMICALS

					Average Calculated Control Efficiency, %					
					Mine 2			Mine 3		
Control	Device	Particle size cut, μm	Height m	Isokinetic Flow	Mix	Top	Time, weeks	Mix	Top	Time, weeks
Salt	Tower, TSP	30	1-9	yes	44	53	1-4	10	21	2-3
	SSI	15	1.5	no	52	56		7	10	
	Tower, FP	2.5	1-9	yes	43	41		24	8	
	RAM-1	3.0	1.0	no	44	46		6	0	
Surfactant[a]	Tower, TSP	30	1-9	yes		33	1-5		19	1-2
	SSI	15	1.5	no		19			25	
	Tower, FP	2.5	1-9	yes		25			33	
	RAM-1	3.0	1.0	no		46			28	
Adhesive	Tower, TSP	30	1-9	yes	54	35	1-4	38		1-3
	SSI	15	1.5	no	47	29		49		
	Tower, FP	2.5	1-9	yes	37	30		46		
	RAM-1	3.0	1.0	no	36	48		27		
Bitumen	Tower, TSP	30	1-9	yes	20	24	1-4	44	56	
	SSI	15	1.5	no	22	36		55	80	
	Tower, FP	2.5	1-9	yes	26	28		33	73	
	RAM-1	3.0	1.0	no	54	51		50		

[a] All topical applications.

TABLE 36. COMPARISON OF CONTROL EFFICIENCY RESULTS FOR WATER

Watering Frequency	Device	Calculated Control Efficiency, %
60 minutes	Tower TSP	41
	SSI	42
	Tower FP	26
	RAM-1	36
30 minutes	Tower TSP	59
	SSI	51
	Tower FP	47
	RAM-1	53

TABLE 37. COMPARISON OF EMISSION RATES FOR UNCONTROLLED COAL MINE HAUL ROADS (lbs/VMT)

Location	TSP		FP		No. of Tests	Reference
	Range	Mean	Range	Mean		
Mine 1	0.7-7.8	4.5	0.1-1.4	0.8	20	
Mine 2	2.9-37.5	14.4	0.2-3.0	1.3	39	This study
Mine 3	1.4-6.8	3.4	0.1-0.8	0.5	17	
Two Western Mines	3.0-21.1	13.3	--	--	11	EPA 1978b
Northeast Wyoming	14.2-31.2	20.4	--	--	6	TRC 1981
New Mexico, Montana, and North Dakota	0.6-73.1	14.0	0.02-2.9	0.4	28	EPA 1981b

TABLE 38. COMPARISON OF MEASURED CONTROL EFFICIENCIES

Control	No. of Samples	Location of Test	Vehicle type[a]	Time Since Application	Control Efficiency	Particle Size[b]	Reference
Water	3	I&S[c]	HD	0.5-4.5h[d]	96-55	TP	EPA 1982
					98-50	IP	
					98-61	FP	
	9	Coal Mine	HD	0-1h	69-59	SP	EPA 1981b
					73-61	IP	
					58-54	FP	
	3	Coal Mine	HD	0-0.5h	88	TSP	ARCO 1980
	3			0-0.25h	97	TSP	
	26	Coal Mine	HD	0.3-1.0h	75-25	TSP	TRC 1981a
	3	I&S	HD	1.0-4.8[d]	98-61	TP	EPA 1983
					98-78	IP	
					98-79	PM_{10}	
					96-67	FP	
	24	Coal Mine	HD	0.5-2.0h	77-12	TSP	This study
	12			1.0-2.0h	66-31	IP	
	24			0.5-2.0h	60-15	FP	
Bitumens	2	I&S	LD	< 1 day	97-84	TSP	EPA 1979a
					97-83	FP	
	4	I&S	HD	0-48h	98-92	TP	EPA 1982
					96-91	IP	
					97-90	FP	
	5	I&S	LD	25-51h	100-94	TP	EPA 1982
					99-91	IP	
					97-94	FP	
	2	I&S	NR	28-29 days[e]	95-90	TP	USS 1981
	24	Other	LD	0-3.5mo	80-0	TSP	EPA 1981a
	24	Other	LD	0-3.5mo	86-36	TSP	EPA 1981a

(continued)

TABLE 38 (continued)

Control	No. of Samples	Location of Test	Vehicle type[a]	Time Since Application	Control Efficiency	Particle Size[b]	Reference
	4	Coal Mine	HD	0-3 days	89-59	TSP	ARCO 1980
	4	Coal Mine	HD	3.5 weeks	35	TSP	ARCO 1980
	8	I&S	HD	2-116 days	100-21	TP	EPA 1983
					100-0	IP	
					100-0	PM_{10}	
					99-0	FP	
	8	I&S	HD	7-77 days	87-16	TP	EPA 1983
					86-22	IP	
					97-36	PM_{10}	
					100-25	FP	
	4	I&S	HD	4-35 days[f]	98-88	TP	EPA 1983
					98-91	IP	
					100-90	PM_{10}	
					100-25	FP	
	30	Coal Mine	HD	1-4 weeks	64-0	TSP	This study
	18				85-0	IP	
	30				88-0	FP	
Adhesives	3	Other	HD	0.5-1 day	83-91	TSP	MPCO 1979
	36	Coal Mine	HD	1-4 weeks	80-0	TSP	This study
	25				91-0	IP	
	36				75-0	FP	
Salts	1	Coal Mine	HD	3mo[g]	95	TSP	EPA 1981b
					95	IP	
					88	FP	
	34	Coal Mine	HD	1-7 weeks	83-0	TSP	This study
	26				74-0	IP	
	34				80-0	FP	
Surfactants	27	Coal Mine	HD	1-6 weeks	87-0	TSP	This study
	20				68-0	IP	
	27				85-0	FP	

(continued)

TABLE 38 (continued)

[a] HD Heavy duty.
LD Light duty.
NR Not reported.

[b] TP Total particulate.
TSP Total suspended particulate (<30 μm).
IP Inhalable particulate (<15 μm).
PM_{10} Particulate matter <10 μm.
FP Fine particulate (<2.5 μm).

[c] Iron and Steel.

[d] Testing began at 3:00p.m. and continued past dusk.

[e] Time since third application.

[f] Time since second application.

[g] Road was watered prior to test.

for the effectiveness of watering are fairly consistent. Taken in total, the data suggest that the 50 percent control effectiveness commonly credited for watering is realistic with once/hour or greater watering frequencies during hot and dry summer daytime hours. Greater or longer lasting control effectiveness may be realized during evening hours or during cooler, more moist, spring and fall periods.

Many of the previous testing efforts for chemical dust suppressants share a common failing: the data were collected within two days of application. These data are highly misleading for two reasons:

1. Cost of chemical dust suppressants is $1,000-15,000/ mile application. Therefore, application is usually feasible on a monthly or less-frequent basis.

2. Chemical dust suppressants are typically applied at rates of 0.3-3.0 gal/yd^2. At these rates, the roadway is likely still wet or moist for 24 to 48 hours depending on humidity, temperature, and solar intensity. Therefore testing during this "wet-road" period is evaluating moisture (water), not the effectiveness of the dust suppressant over the long term in a dry state.

Testing of dust suppressants in coal mines at time-since-application of greater than 7 days is limited. The only other coal mine long-term testing results are Arco tests (4 data points) which showed a control efficiency of 35 percent. PEDCo tests (166 data points) of several suppressants showed a control effectiveness of 30 to 55 percent.

SECTION 9

COST-EFFECTIVENESS ANALYSIS

The ultimate objective of the project is to quantify the cost-effectiveness of using dust suppressants on surface coal mine haul roads. The ability of the dust suppressants studied to control dust was reviewed in Chapter 8. The economic element is added in this section.

9.1 DETERMINING BENEFITS AND COSTS

The benefits for a mine operator using a dust suppressant can include the following:

1. Allow maximum haul truck speed commensurate with safety--The shorter time the haul requires the less it costs. If dust levels decrease visibility to the point that vehicular speed must be decreased for safety, haul time and cost is increased. Similarly, if road conditions (e.g., pot holes, ruts) cause haul trucks to slow, haul costs are increased.

2. Decrease haul road and vehicle maintenance expense--The use of any dust suppressant including water probably reduces the need for road maintenance. All suppressants bind the fines to the road to a certain extent. The smoother the road surface, the less wear on virtually all haul truck parts. Similarly, reduction of dusty conditions reduces the abrasive effect of all moving parts and may result in reduced costs for maintaining brakes, air filters, hydraulic lifts, etc.

3. Air quality--Haul roads can contribute as much as 85 percent of the dust emitted from a surface coal mine. Controlling this source can result in significant increases in air quality, and presumeably, less worker days lost to illness.

All dust suppressant programs have certain costs to the mine operator. Involved are labor and material costs associated with road surface preparation, the dust suppressant used, application costs, and road maintenance (grading, watering, and aggregate cost).

Components to determine the costs and benefits from using a dust suppressant are summarized in Table 39. Although the components can be identified, it is extremely difficult to attach a dollar value to many of them. For example, on the benefit

TABLE 39. COMPONENTS TO DETERMINE THE COSTS AND BENEFITS FROM USING A DUST SUPPRESSANT

Benefits	Included	Not included	Costs	Included	Not included
1. Allow maximum haul truck speed commensurate with safety			1. Allow maximum haul truck speed commensurate with safety		
° Increase truck speed		X	° Surface preparation	X	
° Decrease accident costs		X	° Suppressant cost	X	
			° Application cost	X	
2. Haul road and vehicle maintenance expense			2. Haul road and vehicle maintenance expense		
° Reduction in grading cost	X		° Remaining grading cost	X	
° Reduction in aggregate cost		X	° Remaining aggregate cost		X
° Reduction in watering cost	X		° Remaining watering cost	X	
° Reduction in vehicle down time		X	° Remaining vehicle down time		X
° Reduction in vehicle maintenance		X	° Remaining vehicle maintenance (some reported problems of corrosion with chlorides, electrical system problems with emulsified asphalts)		X
3. Air quality			3. Air quality		
° Increase in ambient air quality		X	° Cost of worker exposure to dust suppressants		X
° Reduction in worker days missed from work		X			

side, no dollar value can readily be placed on the benefits of improved air quality. Thus, determining the total benefit from using dust suppressants is problematical since one of the primary benefits, improved air quality, cannot be costed.

Many of the analysis problems can be eliminated if the comparison is based on the cost to achieve a specified level of control efficiency. In this instance, many of the costs associated with chemicals and watering become equal or do not apply. For example, the comparative dollar benefits from air quality (cleaner environment, fewer worker days lost) become equal. Therefore, chemicals and water were compared for a specific control level. The control level used for this analysis is 50 percent. Based on the review of control efficiencies in Section 8.0, no higher control level could be sustained over a period of weeks.

9.2 ANALYSIS PROCEDURES

Assumptions used for the analysis are shown in Table 40. These assumptions are based on the following.

- Product costs were obtained from each vendor and represent the least expensive per gallon cost available. Shipping costs represent the least expensive method of shipping to an eastern mine (southern Illinois) and a western mine (southern Wyoming). This removes locational advantages.

- Labor and machinery values are industry averages obtained from mine personnel by PEDCo. Rates vary by mine depending on local contracts and machinery type and age.

- The cost of water was assumed to be free. This is an inaccurate assumption but no reliable cost data could be found.

- Activity parameters (miles graded per hour, etc.) are industry averages and vary by mine. Actual time to apply the suppressants for the tests was not used since the relatively short test segments did not facilitate optimum application procedures. Identical parameters were used for all chemicals mixed in place, with a second set of activity parameters for all topical applications.

These assumptions were used to calculate costs associated with the use of chemicals and water for dust suppression. The analysis of chemical dust suppressants had to be limited to calcium chloride (mixed and topical applications) and lignon

TABLE 40. ASSUMPTIONS FOR COST-EFFECTIVENESS ANALYSIS

Benefit/cost differential indices	$/h	Hours/mile			Frequency
		Chemicals			
		Mixed	Topical	Water	
Application					
Surface prep	75	16	8	0	1/application
Material cost	--	--	--	--	1/application
Application	45	8	2	0.15	1/application
Grading cost	75	0	0	4	Water, 1/wk Chemicals, 1/ application
Remaining watering	95	0.15	0.15	0.15	Water, 1.5/h Chemicals, 1/ shift

(mixed in place only), since testing data for the other product/application combinations did not allow as accurate estimation of the required reapplication interval to maintain a minimum 50 percent control efficiency.

9.3 COST-EFFECTIVENESS COMPARISON

The results of the cost-effectiveness comparison to achieve a minimum 50 percent control level are shown in Table 41. The limited results show that the topically applied salt or the mixed in place adhesive is more cost effective than watering. However, the choice of dust suppressant strategies should also include other considerations related to road construction and spillage as explained in Section 8-1.

Reapplications of the chemicals would probably result in higher control efficiencies than the initial application because of residual traces of the material. Therefore, this analysis based on initial applications may overestimate the cost of a long-term chemical program. Conversely, watering displays no such cumulative control effects.

TABLE 41. PRELIMINARY COST-EFFECTIVENESS COMPARISON TO ACHIEVE 50 PERCENT CONTROL

Control[b]	Cost of chemical application/mile, $[a]		Cost of grading, watering/week, $		Applications required to average 50% control	Cost per week	
	East	West	Grading	Water		East	West
Salt							
Mixed	7240	11,263	0	143	1/4 weeks	1953	2959
Topical	3260	5,058	0	143	1/4 weeks	958	1408
Adhesive							
Mixed	4813	7,644	0	143	1/4 weeks	1346	2054
Water			375	1710	120/week	2085	2085

[a] Includes surface preparation, material cost, and application. Material cost is delivered cost in East (southern Illinois) and West (Rock Springs). Material cost is: Liquidow, $0.36/gallon East, $0.47/gallon West; Flambinder $0.33/gallon East, $0.47/gallon West. Assumes 50-foot and 60-foot-wide road in East and West.

[b] Required application intervals could not be estimated for adhesive--topical, surfactant, or bitumens. Comparative costs could not be calculated.

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