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FIELD EVALUATION OF WINDSCREENS AS A FUGITIVE DUST CONTROL MEASURE FOR MATERIAL STORAGE PILES

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ABSTRACT

EPA completed an in-house study designed to determine changes in windspeed (not changes in emissions) due to windscreens. A wind tunnel was used to determine the optimal windscreen porosity, size, and location for control of fugitive dust emissions from storage piles. Before this information could be applied to the design of windscreens, it was necessary to conduct the field study described in this report to validate the wind tunnel studies with respect to windspeed changes, and to determine the relationship between changes in windspeed and changes in fugitive dust emissions. The field study suggests that the optimum windscreen design parameters are porosity = 50 percent; height = 1.0H; width = 5.0D; and distance = 2.0H for a conical pile of height H and diameter D. Analysis of the field data shows that emission rates were directly related to windspeed and inversely related to moisture content of the pile surface. These relationships held regardless of the particle size fraction considered.

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1.0 INTRODUCTION AND SUMMARY

1.1 INTRODUCTION

The Air and Energy Engineering Research Laboratory (AEERL) has instituted a coordinated program to develop control technology for fugitive particulate sources. A major source of fugitive particulate emissions is storage piles. The AEERL has identified windscreens as a promising control technique for this source. However, before this technology can be effectively applied, application criteria need to be developed. These criteria include: (1) screen porosity, (2) screen distance to pile, (3) screen width, and (4) screen height. Answers are needed to these and other related questions before the use of windscreens can be optimized.

AEERL and the Environmental Sciences Research Laboratory (ESRL) have completed an inhouse study (Billman 1985), using the ESRL wind tunnel, designed to determine changes in windspeed (not changes in emissions) due to windscreens. Experiments were conducted to determine the optimal windscreen porosity, size and location for storage-pile fugitive dust emission control. In order for this information to find application in the design of windscreens, it is necessary to conduct a field study to validate the wind tunnel studies with respect to windspeed changes, and to determine the relationship between changes in windspeed and changes in fugitive dust emissions.

More specifically, the three objectives of this study are:

(1) To verify that the data collected in the wind tunnel with respect to changes in windspeed are accurate under field conditions.
(2) To determine the relationship between changes in windspeed and changes in particulate emissions by particle size.
(3) To develop windscreen design parameters.

The remainder of this section presents a summary of the results of the study. Section 2 presents an overview of previous studies on windscreens. Section 3 contains a description of the field sampling for the present study. Section 4 contains the analysis results for Objective 1--Verification of Wind Tunnel Wind Speed Data. The analyses for Objectives 2 and 3 are presented in Sections 5 and 6.

1.2 SUMMARY

The Air and Energy Engineering Research Laboratory (AEERL) and the Environmental Sciences Research Laboratory (ESRL) have completed an inhouse study (Billman 1985), using the ESRL wind tunnel, designed to determine changes in windspeed (not changes in emissions) due to windscreens. Experiments were conducted to determine the optimal windscreen porosity, size and location for storage-pile fugitive dust emission control. In order for this information to find application in the design of windscreens, it was necessary to conduct a field study to validate the wind tunnel studies with respect to windspeed changes, and to determine the relationship between changes in windspeed and changes in fugitive dust emissions.

Previous studies have yielded contradictory results concerning the relationship between particle emissions and windspeed. Similar contradictions were found in the two studies performed to investigate reductions in dust concentrations due to the use of windscreens. The Billman study and the study described herein are the first laboratory and field studies which attempt to measure windspeed or particulate reductions at or near a pile surface.

The Billman study simulated, in a wind tunnel, the effect of a windscreen on reducing windspeed on the surface of a storage pile. The scale model storage pile used was 11 cm tall and was covered with gravel having diameters less than 4 mm. A variety of windscreen parameters were evaluated during the study and isotachs of windspeed and windspeed reduction were presented both for unscreened and screened piles. Based on the results, Billman calculated inferred emission reductions assuming that the change in emission rate was proportional to the cube of the windspeed. No emission measurements were made during the study.

The present study was a field exercise to evaluate the results of the Billman study under actual conditions. The basic sampling protocol used was to measure windspeed and particulate concentrations on two identical storage piles simultaneously. One pile was controlled with a windscreen and one had no windscreen. The control efficiency is then simply the difference between corresponding values for each pile. Instrumentation for each pile consisted of anemometers, RAM-1 monitors and exposure profiler samplers.

The first objective of the study was to compare the wind tunnel data with the windspeed data collected in the field. The comparison had two major elements: comparison of the windspeed isotachs for an unscreened pile and comparison of the windspeed isotachs on screened piles by screen configuration.

For the unscreened pile, composite u/u_r values (windspeed at pile surface/windspeed at the maximum height of the pile) were calculated for 10° incoming wind direction cohorts. The computerized data base developed for this analysis consisted of five minute average windspeed data, stratified by incoming wind direction. As the wind direction moves around the pile, the

stationary sensor locations were effectively shifted to new positions relative to the isotach plots in Figure 3-3.

The results of the analysis showed a good comparison between wind tunnel and field data for the front of the pile. However, the area where the u/u_r ratio is ≥ 1 was substantially larger in the field data. The highest ratios were found on the backside of the pile. The field data suggests that the high windspeed flow lines not only extend around to the back of the pile but are reinforced in some fashion. The basic question relates to the comparability of the idealized wind tunnel experiment to the real-world situation evaluated in the field. In general, the results from the two studies show good agreement for the front of the pile. However, there are some additional physical processes that still need to be investigated and explained.

For screened piles, the wind tunnel data were presented as a series of isotach lines in the form of $1 - (u/u_0)$ for windspeeds with (u) and without (u_0) a windscreen. Similar isotachs could not be developed for the field data, as only four data points were obtained on each pile. However, manipulation and analysis of the data obtained during the study yielded several conclusions. Windspeed reduction was greatest for perpendicular screen orientations. A 2.0-pile-height distance and a 1.25-pile-height screen height were found to be most effective. For aperpendicular winds, a 3.0-pile-diameter screen width was more effective than a narrower screen. For perpendicular winds, on the other hand, the 1.5-pile-diameter screen width was the most effective. In the lee of the pile, negative control efficiencies were recorded.

In comparison to the Billman study, both studies found the taller windscreens to be most effective. Billman found a 3.0-pile-height distance to be

more effective than 1.0-pile-height diameter. A 2.0-pile-height distance was not evaluated. This study found a 2.0-pile-height distance to be more effective than either a 1.0- or 3.0-pile-height-distance. Both studies found a 1.5 screen diameter length to be more effective than a 1.0-screen-diameter length. Both studies recorded negative screen efficiencies in the lee of the pile, but the field study showed this result to a much greater extent. In general, the wind tunnel efficiencies were higher than those measured in the field.

The second objective of the study was to compare windspeed reductions and particulate control efficiencies. Due to problems with the RAM-1 data only the total particulate data were used for this analysis.

Average windspeed reductions were compared with particulate emission reductions for 42 one-hour tests taken with the profilers. It was found that a highly significant relationship exists between windspeed and particulate emission reductions, and the relationship is approximately linear with a slope less than one. Also, there appear to be instances where windspeed on the front of the pile is reduced but emissions actually increase as a result of higher windspeeds on the back of the pile.

The total particulate (TP) data were disaggregated into discrete particle size ranges based on laser diffraction analysis of selected filters. The resulting percentages of net weight by size range were multiplied by the TP emission rate to obtain emission rate by particle size range. These data along with the corresponding windspeed data were subjected to regression analysis. Slopes of regression curves for the two largest particle size ranges showed an emission reduction almost equal to windspeed reduction. The smallest particle size ranges showed no significant relationship.

Further regression analyses showed a strong linear relationship between TP emission rate and windspeed and a strong inverse relationship between TP emission rate and moisture content of the pile. Approximately the same relationship was observed between the two variables and emission rate regardless of the size fraction considered.

The final objective of the study was to develop windscreen design parameters. In terms of screen length, it appears that screen lengths of 5.0-pile-diameter are appropriate for permanent or semi-permanent installations. Given the wind direction variations that occur in real situations the 1.0- to 1.5-pile-diameter lengths tested in the wind tunnel are probably too short. The 2.0-pile-height screen-to-pile distance was found to be optimum. This distance yielded slightly greater emission reductions than either the 1.0- or 3.0-pile-height distance. Both the wind tunnel study and this study showed that the 0.5-pile-height windscreen height was not as effective as screens of 1.0-pile-heights. Also, a screen height of 1.0-pile-height is nearly as effective as higher screens. In general it appears that the optimum design parameters are: height = 1.0-pile-height; width = 5.0-pile-diameters; and distance = 2.0-pile-heights.

The field study has helped to identify several important areas for further investigation. Although the wind tunnel study and the field study are in general agreement for the front of the pile, there was one significant area where the results are contradictory. The field study showed that large portions of the back of the pile had windspeeds higher than the reference windspeed. This observation was reinforced by the particulate emission data. There were a large number of tests where negative emission reductions were noted for the screened pile. This basic result is in direct conflict with the

bulk of the wind tunnel data. Although Billman did find some negative reductions, the field study showed negative reductions as large as 40 percent.

There must be some ongoing physical process or processes that has not been adequately investigated in this study. The results to date raise questions on the applicability of windscreens for reducing emissions from storage piles. Prior to recommending windscreens as a control measure, it is imperative that the observed relationship between the use of windscreens and emission rate be investigated further.

2.0 PREVIOUS STUDIES

2.1 WINDSPEED AND PARTICLE UPTAKE

Several relationships between wind speed and particle emission rate are found in the literature. Bagnold (1941) suggested that the particle emission rate is proportional to the cube of the wind speed. Gillette (1978a), in a wind tunnel test of the effects of sandblasting, wind speed, soil crusting, and soil surface texture on wind erosion, showed that the soil particle flux is proportional to the cube of the friction velocity (u_*), where u_* is determined from the mean velocity profile over a horizontal surface,

$$U = \frac{u_*}{k} \ln \frac{z}{z_0} ,$$

where U is wind speed at height z, z_0 is the surface roughness length, and k is von Karman's constant (~0.4). Blackwood and Wachter (1978) suggested that the storage pile emission rate, Q (mg/s), may be expressed as

$$Q = (cu^3 \rho_b^2 s^{0.345})/(PE)^2,$$

where c is a constant, u is wind speed (m/s), ρ_b is bulk density (g/cm^3), s is pile surface area (cm^2), and PE = Thorntwaite's precipitation-evaporation index (Thorntwaite, 1931).

Field tests with portable, open-floored wind tunnels indicated that threshold speeds, given in terms of threshold friction velocity $(u_*)_t$, are typically 0.2 to 2 m/s depending upon the type of material (Gillette, 1978b; Gillette et al., 1980; and Cowherd et al., 1979). In other field tests, threshold speeds of about 10 m/s at a height of 15 cm above a coal pile

surface were estimated based upon the onset of visible particle uptake (Cowherd, 1982; Cuscino et al., 1983). Extrapolating these speeds to a 10 m reference height from the velocity profile implies that very high mean wind speeds (e.g. 20 m/s) are needed for erosion at the surface (z=0) to commence. Hence, Cowherd (1982) suggested that strong wind gusts, not the mean wind, cause erosion.

In the above relationships for particle emission, emission rate is independent of time. However, unless an unlimited supply of erodible particles is present, erosion will be time dependent. Erosion rate has been observed to decrease with time (e.g. Cowherd et al., 1979). Cowherd (1982) suggested that erosion rate is proportional to the amount of erodible material remaining and that a given storage pile has an "erosion potential" equal to the total quantity of erodible material present on the surface prior to erosion.

Conclusions that can be derived from these studies are that:

(1) Particle emissions are related to windspeed, either directly or at a power of the windspeed. There is a threshold windspeed under which no erosion occurs, although results are contradictory.

(2) Emissions are limited by the amount of erodible material available.

2.2 WINDSCREENS AS A FUGITIVE DUST CONTROL MEASURE FOR STORAGE PILES

The use of windscreens has been proposed for reducing fugitive dust emissions from active and inactive piles. Studies of windscreen effectiveness have been performed on reduction in windspeeds, thereby theoretically reducing emissions, and direct measurement of emission reductions.

Results of reduction in windspeed velocity caused by a porous wood fence are shown in Figure 2-1 (Carnes and Drehmel 1982). Reductions in windspeed

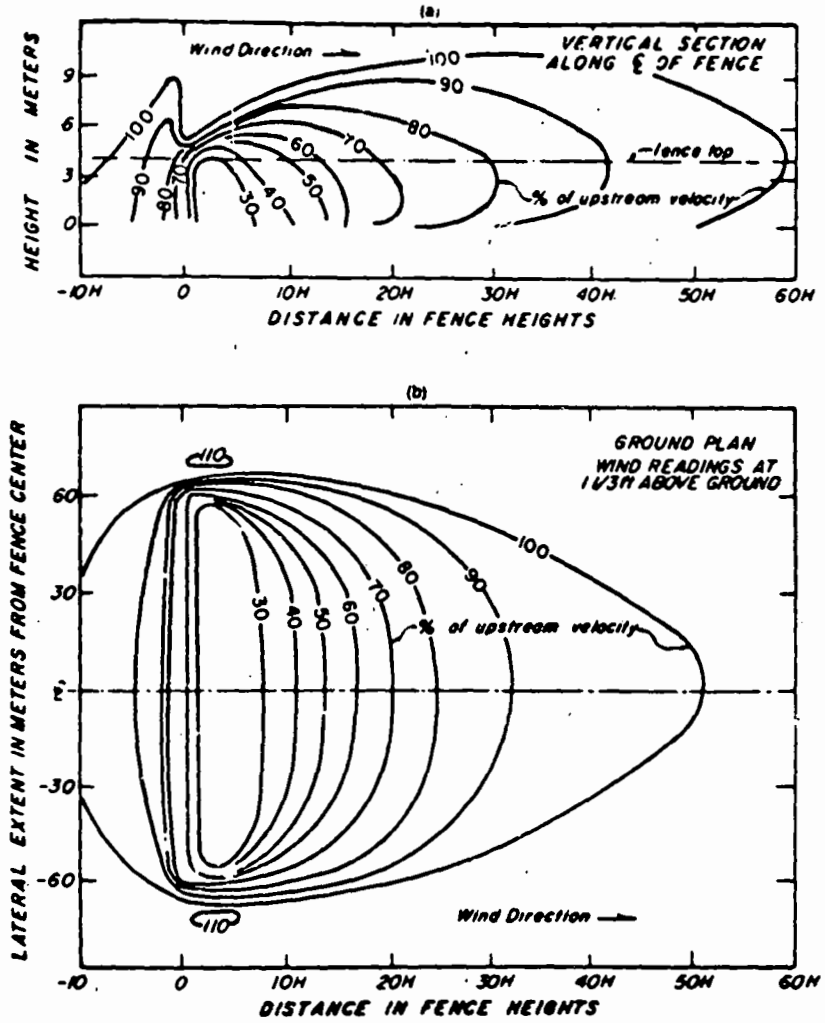


Figure 2-1. Wind velocity pattern above a mown field during a 17 m/sec wind blowing at right angles to a 4.9 m high wood fence 122 m long of 50% porosity. (a) side view profile. (b) plan view profile.

Source: Carnes, D. and D.C. Drehmel. The Control of Fugitive Emissions Using Windscreens. Third Symposium on the Transfer and Utilization of Particulate Control Technology. Orlanado, Florida. March 9, 1981.

velocity of 60 percent were measured at a distance of 10 screen heights. (This does not necessarily mean a corresponding reduction in fugitive dust emissions.) Windspeed reductions downwind of other types of windscreens were measured by TRC-Environmental Consultants, Inc. (Carnes and Drehmel 1982). Using a 65 percent permeable windscreen, with windspeeds of 3.0 m/sec., wind reductions of 70 percent were measured immediately downwind, and wind reductions of 40 percent were measured 14 heights downwind. For a 50 percent permeable windscreen, windspeed reductions were comparable adjacent to the fence, but the reductions were smaller further downwind.

Reductions in fugitive particulate emissions were measured by TRC as well as reductions in windspeed. Total suspended particulate (TSP) emissions were sampled with high volume samplers (hi-vols). Testing was performed on a flyash pile. The study concluded that the windscreen was effective both in reducing wind velocity approximately 66 percent under ordinary conditions and peak gusts by approximately 58 percent, and in reducing TSP and inhalable particulate (IP) concentrations downwind by an average of 75 percent and 60 percent, respectively.

PEDCo (1984) studied windscreens using RAM-1 aerosol monitors and windspeed sensors interfaced with a portable computer to give real-time data results. The analysis indicated that the windscreen did not produce significant reductions in concentrations in the less than 10 micrometer respirable size range. The screen did reduce windspeeds by the amount anticipated, but this did not result in commensurate reductions in particulate concentrations coming from the pile.

An explanation for the windscreen's performance was that wind erosion emission rates in the less than 10 micrometer size range were fairly constant at windspeeds above a threshold of about 7 mph (hourly average). The

additional emissions associated with high wind erosion losses at high windspeeds were larger particles that were not detected by the RAM-1's. The windscreen may be effective in stopping or reducing the movement of these large particles, but many of them do not stay airborne because of their relatively large size, so they present less f a threat of offsite exposure.

In summary, all studies are in fair agreement about reductions in windspeed caused by windscreens. Only two studies have measured reductions in dust concentrations as opposed to reductions in windspeed. The TRC study found reductions in the TSP size range of 60 to 75 percent. The PEDCo study of particles in the less than 10 micrometer size respirable range showed no consistent benefit from the windscreen, but acknowledged that positive control efficiencies of larger size particles were likely.

This contradiction in findings between the TRC study that measured less than 30 micrometer particles, and the PEDCo study which measured less than 10 micrometer particles suggests that particle uptake may respond to windspeed changes differently according to particle size.

No study, laboratory or field base, has attempted to measure windspeed reduction or particulate reductions at or near a pile surface before the Billman Study (1985) and the field study described herein.

2.3 THE BILLMAN STUDY

The Billman study (1985) simulated, in a wind tunnel, the effect of a windscreen on reducing windspeed on the surface of a storage pile.

The experiment was conducted in the EPA Meteorological Wind Tunnel, a low-speed, open-return tunnel having a test section 2.1 m high x 3.7 m wide x 18.3 m long. A neutrally stratified simulated atmospheric boundary layer was

generated by a 15.3 cm high trip fence placed 22.3 cm from the test section entrance. Gravel roughness composed of pebbles having typical diameters of 1 cm covered the tunnel floor downstream of the fence. The boundary layer was characterized by a depth of approximately 1 m, a roughness length (z_0) of 0.1 mm, and a friction velocity (u_*) of $0.048U_0$. The model pile had to be small enough to be within the surface layer but large enough to construct windbreaks of height the same order as the pile height and to facilitate measurements. The results was a model pile 11 cm high (37° slope and base diameter of 29.2 cm). The pile could not be roughened with the same gravel as that covering the floor of the tunnel because the 1 cm gravel was too large with respect to the pile size. Gravel having diameter less than 4 mm was used instead. Heated thermistor beads were mounted directly on the pile to measure windspeed. Nine thermistors were mounted on the simulated pile 2 to 3 mm above the surface. Actual windbreak material could not be used due to scale problems. Nylon mesh screen was used, with the type of screen being selected after wind tunnel testing of wind porosity.

Figure 2-2 shows the top view of the pile with contours of normalized windspeed, u/u_r, where u is the windspeed measured at the pile surface, and u_r is the incoming windspeed at the equivalent full scale height of 10 m. The areas of maximum wind speed are near the top of the upwind face but toward the sides of the pile. A high speed region ($u/u_r > 0.75$) is on the upstream face, extending from near the crest down both sides. The area of minimum wind speed is in the lee near the top of the pile with regions of low wind speed extending down the pile on both sides of the centerline. High speeds along the pile sides are expected because the flow is accelerating around the pile. The flow

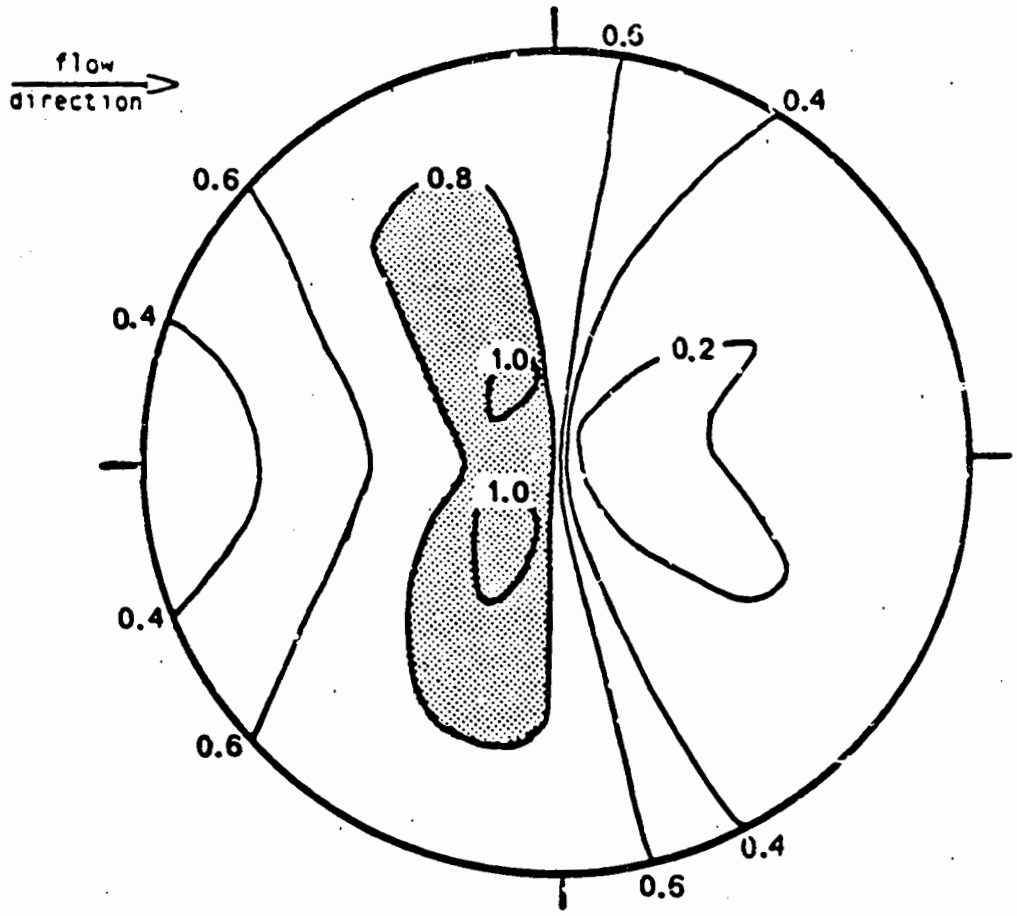


Figure 2-2 u/u_r about conical pile for no windbreak case.

separates on the lee side, resulting in a region of low-speed recirculating flow.

Windscreen/pile variables tested by Billman were (Billman 1985):

- Pile shape--conical and oval
- Screen porosity--50 and 65 percent
- Screen height--0.5, 0.75, 1.0, 1.25 and 1.5 pile heights
- Screen length--1.0 and 1.5 pile diameters
- Screen position--on pile, 1.0 and 3.0 pile heights
- Screen orientation--perpendicular, ± 20 and ± 40 degrees to wind direction

An example plot of windspeed reductions is shown in Figure 2-3. Windspeeds in the example were reduced 40 percent over most of the pile face, with a small area of 60 percent reduction.

Windspeed reductions are summarized in tabular form in Table 2-1. When the reduction was averaged over the entire pile surface, values ranged from 21 to 51 percent. Considering the reduction in maximum values, windspeed reductions ranged from 17 to 94 percent.

Since no changes in emissions were measured, Billman calculated inferred emission reductions assuming that the change in emission rate is proportional to the cube of the windspeed, and that all windspeeds exceed the erosion threshold level. The latter assumption results in a maximum predicted impact. The calculated inferred emission reductions ranged from 66 to 99 percent.

Concerning design parameters, conclusions reached based on area average windspeed reduction were:

- Screen porosity--The 50 percent porocity was more effective.

- Screen height--The 0.5 height was less effective than the 1.0 and 1.5 heights. The latter two heights showed similar effectiveness except for the 50 percent porosity screen at 3.0 heights downwind, where the 1.5 height was slightly more effective.

- Screen length--Screen length made little difference in most cases. This is due to the perpendicular flow of wind to the screen in the experiment. The greater length did provide increased effectiveness when winds were not perpendicular to the screen.

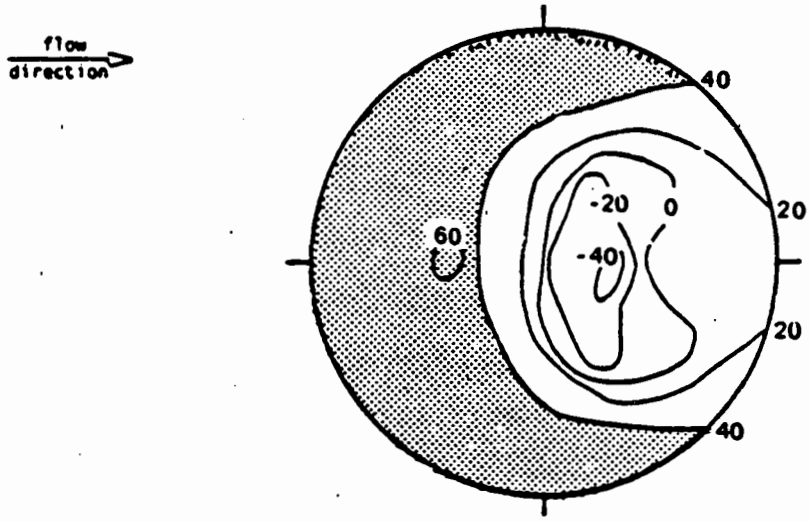


Figure 2-3 Wind speed reduction factor for the 65% porous windbreak of height 0.5H and length 1.0D placed 1H from the conical pile base.

TABLE 2-1. WINDSCREEN IMPACT FOR VARIOUS WINDBREAK CASES--
BILLMAN STUDY (percent reduction)

Screen to pile distance	Screen length	Screen Height					
		65% Porosity			50% Porosity		
		0.5 H	1.0 H	1.5 H	0.5 H	1.0 H	1.5 H
Area Average Windspeed Reduction							
1.0 H	1.0 D	26	45	45	36	60	60
	1.5 D	25	42	43	36	60	58
3.0 H	1.0 D	21	48	51	27	57	62
	1.5 D	22	47	51	26	62	70
Maximum Windspeed Reduction							
1.0 H	1.0 D	.91	.55	.56	.90	.31	.39
	1.5 D	.93	.59	.60	.93	.34	.42
3.0 H	1.0 D	.91	.54	.50	.82	.37	.25
	1.5 D	.94	.56	.52	.86	.27	.17
Calculated Inferred Emission Reduction[1]							
1.0 H	1.0 D	74	88	86	82	97	95
	1.5 D	72	85	82	80	97	95
3.0 H	1.0 D	66	91	92	76	97	98
	1.5 D	67	90	91	76	98	99

[1] Assumes that the change in emission rate is proportional to the cube of the windspeed.

- Screen position--At higher windscreen heights, the 3.0 pile height distance was generally more effective than a 1.0 pile height distance.

3.0 FIELD SAMPLING

3.1 STUDY DESIGN

A detailed study design was set forth in a 1985 sampling report. Reiterating from Section 1.0, the three study objectives were:

(1) To verify that the data collected in the wind tunnel with respect to changes in windspeed are accurate in field conditions.

(2) To determine the relationship between changes in windspeed and changes in particulate emissions by particle size.

(3) To develop windscreen design parameters.

By way of overview, the basic sampling protocol was to measure two identical storage piles simultaneously, one controlled with a windscreen and one without. The control efficiency is then simply the difference between corresponding values for each pile. To meet objective 1 (windspeed reductions), several anemometers were placed on each pile to measure windspeed. The field results were compared to the values in previously cited Figures 2-2 and 2-3, and Table 2-1. To meet objective 2 (windspeed/emissions), emissions were measured by exposure profiling and RAM-1 aerosol monitors. To meet objective 3 (design parameters), the change in emissions data developed for objective 2 were used.

3.1.1 Pile/Windscreen Configuration

Reiterating, the basic test protocol was to establish two identical piles, and to sample around the two piles simultaneously when one was controlled with a windscreen and the other was not. A critical parameter in

such a test protocol is that the piles be identical initially and throughout the test period with respect to dust emitting characteristics. The piles were constructed out of the same highly erodible material, and were exactly the same shape. After initial construction, both piles were sampled with RAM-1 monitors with both piles uncontrolled. The RAM-1 monitors output real-time concentration data that can be used to instantaneously determine if both piles are emitting dust in a similar manner.

It was anticipated that as testing began and continued over time, that the uncontrolled pile would begin to emit dust at a different rate than the controlled pile. To the extent that this occurred, the control efficiency data derived from simultaneous comparative testing would be inaccurate. This problem was overcome in three ways. These were:

(1) Outside of the eight hour test period, the windscreen on the controlled pile was dropped. Consequently, for 16 of every 24 hours, both piles were subject to the same erosional forces. This aided in keeping the two piles similar.

(2) On a daily basis, at the beginning of each test day, instantaneous RAM-1 measurements and windspeed measurements were made. Real-time computerized five-minute averages were compared. If the pile emission rates were ± 10 percent, the piles were considered to be emitting at the same rate. If the difference was greater, the pile emitting at the lower rate was raked to expose new soil. Comparative readings were again taken until the values reached the desired comparative level. A similar procedure was used with the windscreen sensors to insure a ± 10 percent value for corresponding sensors on each pile.

(3) At the beginning and end of the testing and after every 25 tests, a complete test was run with all instrumentation in place and without the wind screen. The results from the tests will show the overall comparability of the piles.

3.1.2 Variables Tested

Because one of the objectives of the sampling was to verify the wind tunnel testing, it was appropriate to analyze similar variables. The EPA-

sponsored wind tunnel study (Billman 1985) contained examinations of the following variables:

1. Pile shape--conical and oval
2. Screen porosity--50 and 65 percent
3. Screen height--0.5, 0.75, 1.0, 1.25 and 1.5 pile heights
4. Screen length--1.0 and 1.5 pile diameters
5. Screen position--on pile, 1.0 and 3.0 pile heights
6. Wind direction/Screen orientation--perpendicular, ± 20 and ± 40 degrees

These variables represent 360 total combinations. Each combination required several repetitive tests.

It was estimated that 75 to 100 field test pairs could be completed with available project resources. This range in tests allowed for an average number of 3 tests per day, with the lower number representing test days lost to rain or unmanageable winds. Therefore, it was apparent that not all wind tunnel results could be verified in the field.

The choice of how many and which combinations to test was determined using the following considerations:

1. How many tests for each combination are required to produce statistically significant results?

2. Are results for certain of the variables already conclusive based on the wind tunnel testing and other field testing?

3. Which variables most represent typical potential industrial applications?

3.1.2.1 Number of Tests Required--

The purpose of this subsection is to estimate the number of test values of control efficiency that will be required to establish the mean control efficiency with a predetermined precision and confidence. A control efficiency value is actually composed of two separate tests, one for an uncontrolled condition and the other for the controlled condition. Previous

studies have shown that uncontrolled emission rates for the dust producing activities are not normally distributed (PEDCo/MRI 1984). Consequently, controlled emission rates and control efficiencies are probably not normally distributed either. Therefore, Stein's relatively simple two-stage method for estimating required sample sizes cannot be properly 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 a recent study (PEDCo 1984a). In addition to the assumption of lognormality, the derivation also assumed that the relative standard deviations of the uncontrolled and controlled data sets (untransformed) are equal. With the latter assumption, the standard deviation from tests taken under a previous EPA-sponsored windscreen study can be used to estimate expected variance in the test data for this study (PEDCo 1984).

The equation derived in a recent study for estimating sample size is:

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

where:

- n = number of control efficiency values (CE), equal to number of uncontrolled or controlled tests
- t = tabled t-value for specified confidence level and n-1 degrees of freedom
- s = estimate of population standard deviation (ln-transformed), obtained from previous testing
- K = ratio of upper limit value to lower limit value for confidence interval around (1-CE)

The estimate of standard deviation (of ln-transformed values) was obtained from sampling of a topsoil stockpile performed by PEDCo in 1984 (PEDCo 1984). It was felt that this operation was a reasonable approximation of the proposed field tests in this study. The calculated value for the standard deviation was 0.35 and the value of K selected was 3.

Using Equation 1 and trial substitutions of t-values with n-1 degrees of freedom and 90 percent confidence, the required number of control efficiencies values of a control option can be calculated to be 4 as follows:

$$\sqrt{n} = \frac{(2.828)(2.132)(0.35)}{\ln 3}$$

$$n = 3.7$$

This value represents the number of control efficiency values required. In other words, a total of 4 paired field tests (4 control, 4 no-control) need to be taken for each control evaluated.

3.1.2.2 Variables for which Conclusive Data Exist--

Of the six variables listed in Section 2, the only variable for which data are reasonably documented and consistent is screen porosity. Data (Carnes and Drehmel 1981; Lawrence 1983; PEDCo 1984) indicate that a 50 percent porosity is more effective than 65 percent porosity presumably because an optimum balance of shielding and low turbulance is achieved. In addition, the Billman (1985) wind tunnel study also verified that a 50 percent porosity screen was superior to a 65 percent porosity screen. Therefore, a 65 percent screen porosity was not tested.

3.1.2.3 Typical Industrial Applications--

Typical piles found in industries such as the steel, cement, aggregate and power industries come in all sizes and shapes. Piles may be conical or rectangular in shape.

Pile heights vary but usually do not exceed 30 feet. On 30 foot tall piles, screens as tall as the pile, or 1.5 times the pile height are difficult to install, maintain and move, and therefore, a screen height of less than one pile height would be desirable if it was effective. Another option used on

large tall piles with a flat top is to place the screen on top of the pile to shield the flat top.

Base dimensions may be as small as a few feet, or as large as several hundred feet in the case of coal piles for the power industry, or waste piles for other industries. For smaller piles, pile screen lengths of 2 and 3 times the pile base are feasible. For large piles, a 1.0 diameter screen length is more feasible.

With regard to wind direction/screen orientation, windscreens are most feasible installed perpendicular to the predominant wind direction. However, when wind directions vary, angles of 20 and 40 percent are likely and very often exceeded. For small screens, screens can be purchased in eight foot heights on portable stands. In other applications, standards are placed in cement slabs or other movable platforms. The slabs can be moved by forklift so that the wind direction/screen orientation is more correct.

3.1.2.4 Variables to be Tested--

As shown in this section approximately 18 to 25 variable combinations can be examined. Variables to be tested are indicated in Table 3-1. Twenty-five variable combinations are identified. In addition, 4 tests were performed with both piles uncontrolled for quality assurance related reasons.

3.2 FIELD SAMPLING PROGRAM

3.2.1 Test Plot Layout

The field site was located on a privately owned farm in the Wichita, Kansas area. Wichita, Kansas had the desirable characteristics of relatively high speed winds with a predominent direction. The 24-acre field is located in a rural area about 7 miles northwest of the Wichita Mid-Continent Airport.

TABLE 3-1. VARIABLES TO BE TESTED

Screen to pile distance	Screen length	Screen height			
		0.5h	1.0h	1.25h	1.50h
1h	1.5D	x	x	x	o
	3D	x	x	x	o
	5D	o	o	o	o
2h	1.5D	x	x	x	x
	3D	x	x	x	x
	5D	o	x	o	x
3h	1.5D	o	x	x	o
	3D	x	x	x	x
	5D	o	x	x	x

h = pile height
D = pile diameter
x = combination to be tested

It is level except for a gully that projects into the middle of the field from a stream bed that forms the southern and eastern boundaries of the field. The western edge of the field is bounded by a paved road. The northern edge (downwind) is bounded by an unpaved road.

The entire field was covered with grass, which grew to a height of 2 to 6 inches. There were no continually active particulate sources in the upwind direction (south) from the field, just additional pastures and fields with mature crops. However, for the first few tests there was some construction activity at a bridge located south of the site. This activity did not occur beyond the first few tests. Also, there were no tall windbreaks within one-half mile to the south. Trees that grew along the stream at the south end of the field only extended 10 to 15 ft above field level and were at least 500 ft distant from the sampling area. A sketch of the site is shown in Figure 3-1.

The storage piles were constructed identically from dried, shredded topsoil. The piles were conical in shape, with a height of 8 feet and a base diameter of 25 feet.

A detailed test plot is shown in Figure 3-2. The piles were located 150 feet apart. The instrument trailer was located 75 feet downwind of the piles. Screen widths up to five pile diameters were accommodated with this layout. Since all downwind instrumentation were located on the pile, a wind direction shift of 90 degrees from perpendicular would be required for cross-contamination. Test abort protocol called for test cessation when winds average greater than 30 degrees from perpendicular for a five minute period. Therefore, this test plot layout and the test abort protocol eliminated cross-contamination.

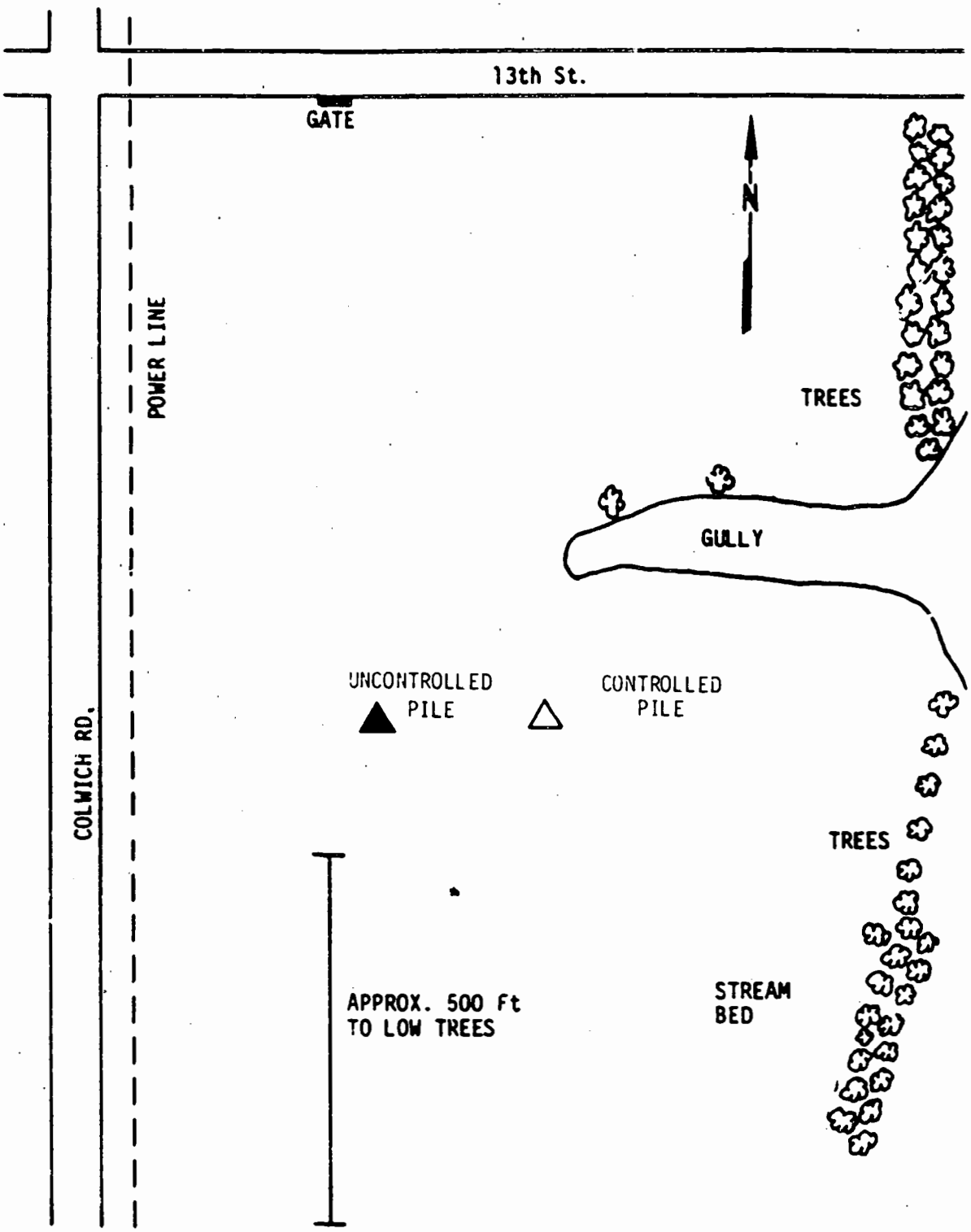


Figure 3-1. Test site

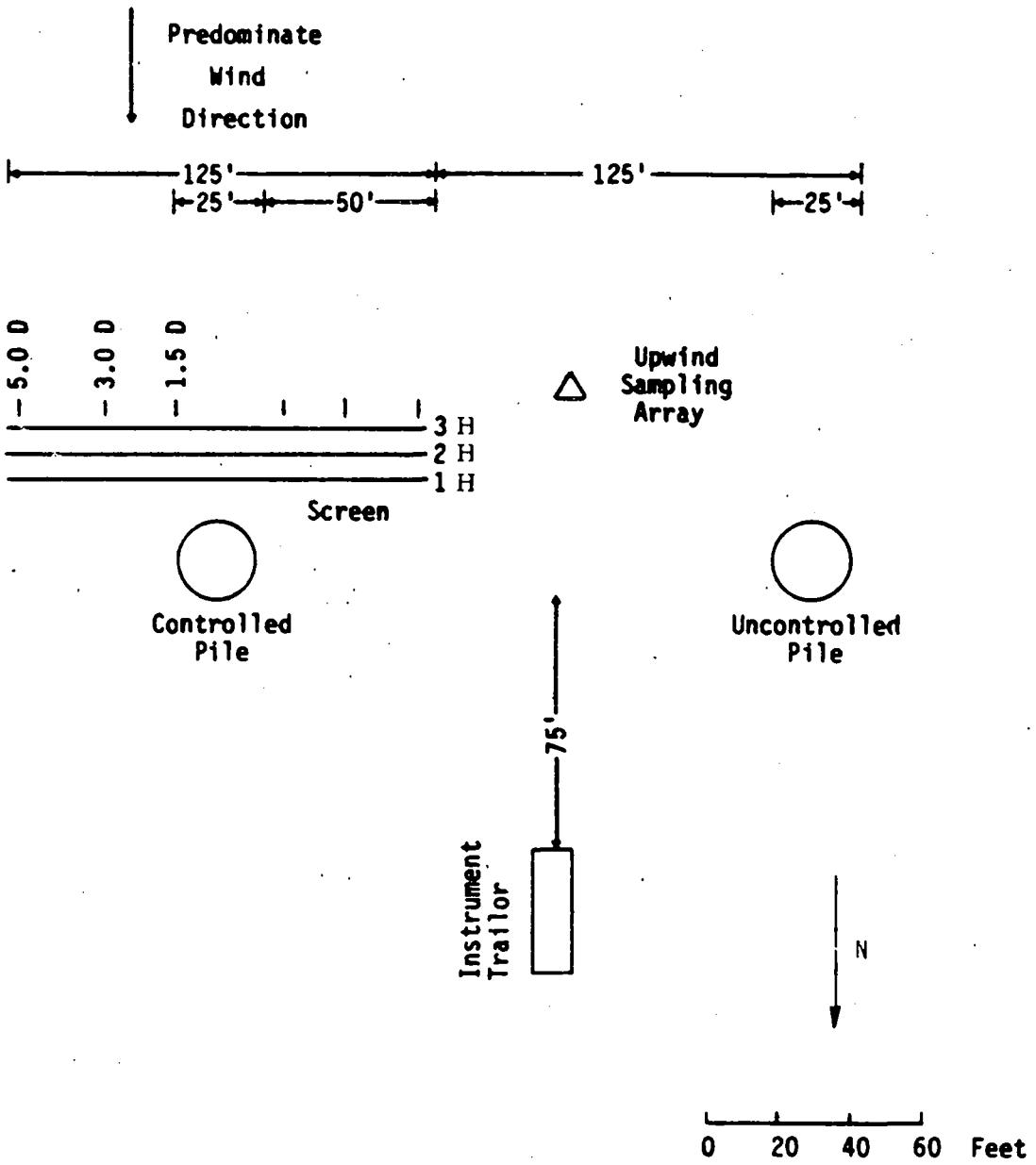


Figure 3-2. Test Plot Layout

3.2.2 Sampling Equipment and Deployment

3.2.2.1 Windspeed and Wind Direction--

Windspeed was monitored with several MET ONE Wind Speed Sensors, Model 14a. This sensor has an accuracy of ± 0.25 mph, a starting threshold of 1.0 mph, and a temperature operating range of -50°C to +70°C, over a range of 0 to 100 mph. The sensor is a rotating cup assembly with a pulsed output. The output is directed through a wind speed translator module that converts the signal to a standardized analog voltage. This signal is translated to a digital signal through the use of an analog to digital converter. This signal was then processed by a personal computer.

Wind direction was monitored with a MET ONE Wind Direction Sensor Model 24a. The instrument has a threshold of 1 mph and an accuracy of ±5 degrees. The signal is input to a translator module and an analog to digital converter for computer processing.

A total of 10 windspeed sensors were used. One sensor was located upwind at a height of 8 feet, corresponding to the height of the storage pile. A logarithmic wind speed profile was assumed for lower heights. This assumption was based upon standard references as well as previous PEI field experience testing windscreens and storage piles (PEDCo 1984).

Placement of the sensors was guided by study objective 1, i.e. verification of wind tunnel testing. It was desirable to obtain wind speed measurements at the same locations as in the wind tunnel testing (Billman 1985). However, the wind tunnel testing included 108 wind speed measurement locations, nine sensors at a time. Pile rotation to 12 positions yielded 108 measurements. Such a protocol was impractical for a field test because of the

equipment requirement and because wind direction in the field was not fixed as in a wind tunnel test.

A total of nine wind speed sensors were deployed downwind of the screen, five on the no control pile, and 4 on the control pile. The sensors were set at a fixed position on the pile, about 6 inches above the surface of the pile, and perpendicular to the ground. The positions were set relative to the prevailing wind direction, and the positions remained fixed over the eight-week test period. The positions on the pile were set in order to be able to evaluate Figure 5.1, 6.3, 6.6 and 6.8 of the Billman (1985) report. Sensor placement for the uncontrolled pile is shown in Figure 3-3. The sensor locations are superimposed over Figure 5.1 from the Billman (1985) report. Because the isotach lines are symmetrical, and because of the inability to fully instrument each pile, sensors were only placed on one-half of the pile. Sensor placement on the controlled pile were in exactly the same locations as the uncontrolled pile, except location 1 was not used.

In order to position identical instruments at the same relative locations on each pile, a true north and true south point was determined for the base of each pile. Then, a string was run across the peak of the pile connecting the two points. Vertical distances were measured along the string, while horizontal dimensions were measured perpendicular to the string. Tape measurements were accurate to less than one inch.

While it is possible that the instrumentation interfered with the flow field around the piles, since both piles were instrumented exactly the same, identical changes occurred on each pile. In order to make such measurements, instruments must be placed on the pile even though the measurement systems may slightly interfere with what is being measured.

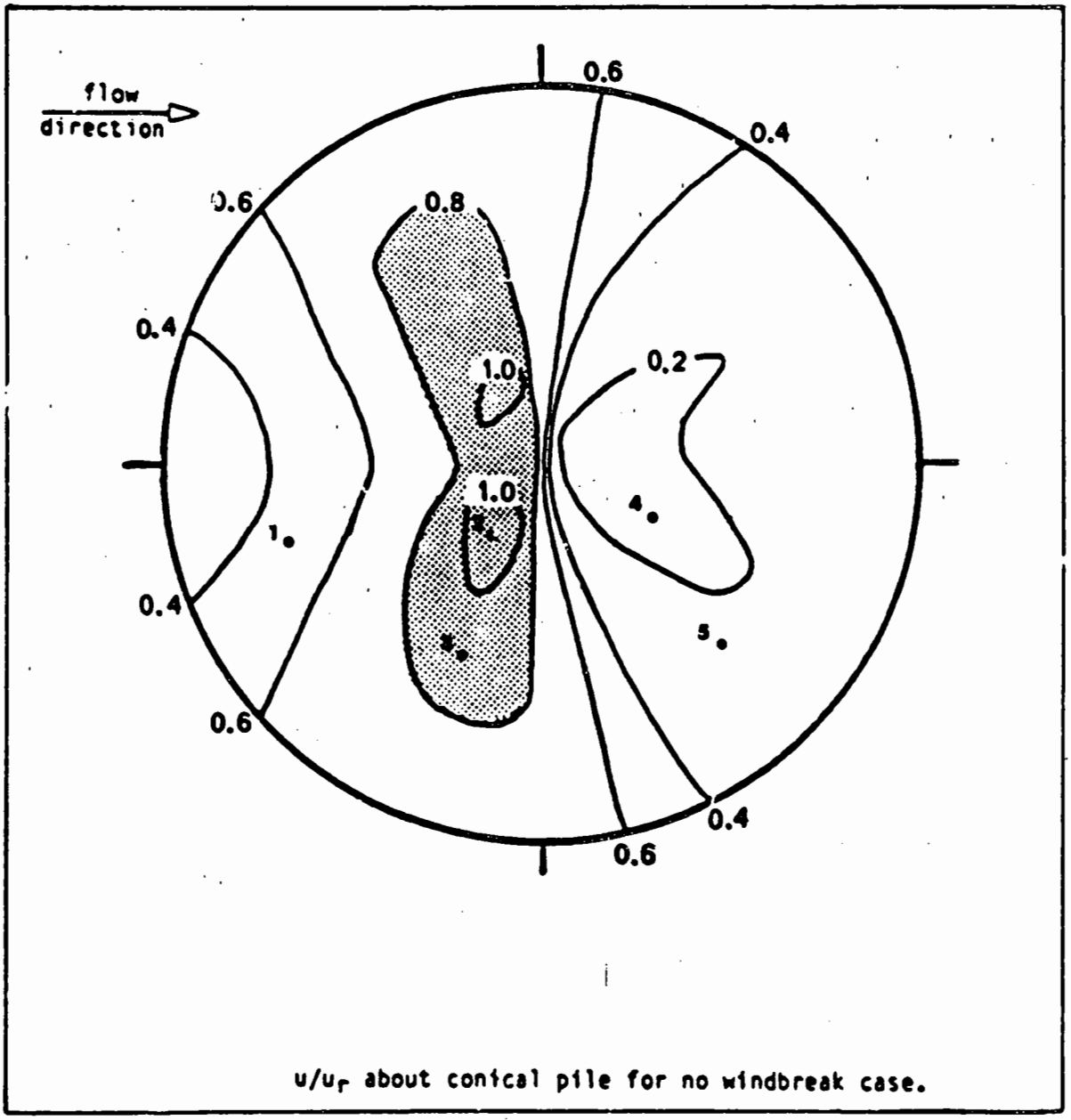


Figure 3-3. Wind Sensor Placement, Uncontrolled Pile

A wind direction sensor was placed upwind. The height of the sensor was eight feet, the height of the storage pile. The data were used to determine the angle of the wind to the windscreen.

3.2.2.2 Particulate--

Particulate was measured with 2 devices, a total particulate exposure profiler head, and a model RAM-1 aerosol monitor, manufactured by GCA Environmental Instruments; Bedford Massachusetts.

Profiler Head--

The exposure profiler heads consisted of an adjustable flowrate high-volume motor, a filter holder, and a cylindrical intake nozzle which was oriented directly into the wind during testing. The filter media was the standard glass fiber high-volume filter. Since the sampler collects all ambient particles non-discriminately, the emission data obtained represented total particulate (TP).

The sampling heads were operated at a near isokinetic flowrate so as not to skew the particle size distribution of the collected sample. This design was potentially difficult since the pile and windscreen induced wind currents would not follow the standard logarithmic profile, and would change with changing wind direction and windscreen height. This problem was overcome by mounting rotating cup anemometers near each profiling head mounted on the profiling tower. The anemometers sent data to the Apple computer. Windspeeds for each sampling height were averaged from the computer every ten minutes, and sampler flow rates were checked and adjusted accordingly to maintain a near isokinetic flowrate.

This exposure profiler head has been used in numerous Environmental Protection Agency (EPA) emission factor studies and has a long field history. Quality assurance procedures are well documented and reproducibility is excellent. The heads were calibrated to actual field conditions.

It was desirable to obtain particle size data from the exposure profiler filters. These data permitted a determination of windscreen control efficiency by particle size. Alternative methods to obtain the size distribution from the filter were optical microscopy, scanning electron microscopy and laser diffraction. All methods share the same two weaknesses, i.e. material must be removed from the filter, and physical size data must be converted to aerodynamic size data. The most reliable and cost efficient of the methods is laser diffraction, using the Microtrac Particle Size Analyzer manufactured by Leeds and Northup. This device outputs particle size distributions in up to 13 particle size classes over a range of 1 to 175 micrometers.

Project resources were adequate to use laser diffraction on one filter from each tower per test. Each sample was then subjected to the particle sizing analysis.

The laser diffraction technique requires a relatively large amount of mass for analysis. This placed two requirements on the sampling. They were:

(1) That the profiler heads be located very close to the source to collect the maximum amount of material.

(2) That the upwind samples be combined for a single days testing. If sampling is conducted in an area with very low background concentrations, this combination will not compromise the data to an unacceptable level.

There are two basic methods to perform exposure profiling sampling of dust emissions, as a point source, or as a line source. Sampling the pile as a point source requires that both a horizontal and vertical plume profile be obtained. This would require eight to twelve sampling heads per pile, an unreasonable number of samplers in light of the desired 100 to 125 test pairs. If the source is considered to be a line source, only a vertical profile is required. If a pile is to be considered a line source, however, the concept

of a line source must be extended to include a "bent line source". To make this assumption, it must be assumed that the area in the shaded 0.8 area on previously sited Figure 3-3 is emitting at a relatively uniform rate across its longest dimension.

A second issue was where to place the samplers relative to the pile. Options were: on the pile; immediately downwind of the pile; or >10 feet downwind of the pile. Four factors influenced this decision. They were:

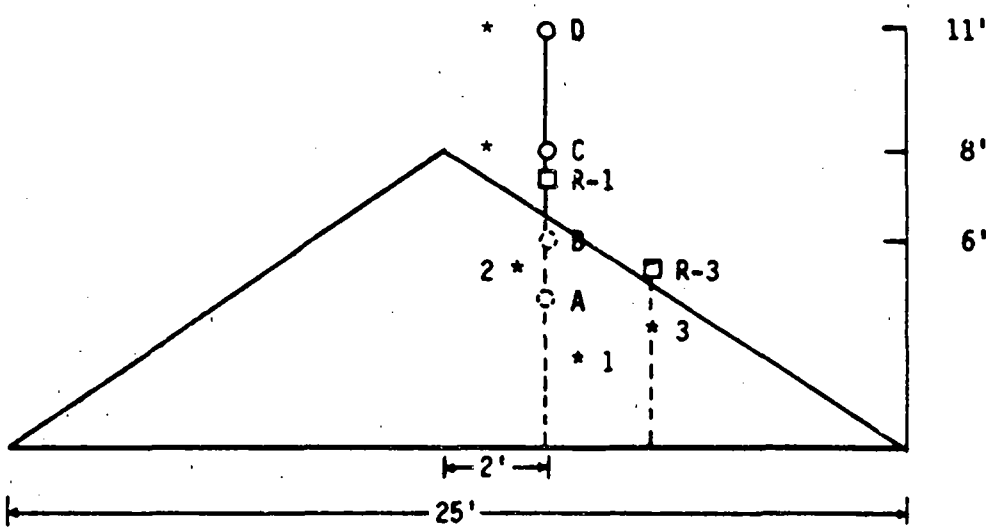
- Laser diffraction, to be used for particle sizing, requires a relatively large sample.
- Exposure profile calculation assumptions require that the plume be sampled before the largest particle size of interest has fallen out of the plume. Total particulate data are of interest.
- There is an area of wind eddy behind the pile for an unknown distance where the plume behaves abnormally.
- To satisfy study objective 2, i.e. determine the relationship between changes in windspeed and changes in emissions, it is desirable to associate a specific dust measurement with a specific wind sensor. The further the sampling head is located from the wind sensor, the more difficult the association becomes.

These four factors all directed that the samplers be placed on the pile.

In order to sample the pile as a bent line source with the exposure profiling technique, 4 exposure profilers were mounted on an 11 foot tower. The tower was located on the pile, 10 feet behind the midline of the pile, and 2 feet to the side of the top of the conical pile (Figure 3-4). Profiler head heights were 4, 6, 8, and 11 feet off the ground. Samplers A and B were associated with windspeed sensor 2.

RAM-1 Monitor--

The RAM-1 monitor is a portable sampler for respirable particulate. Its measurement is based on detection of near-forward scattered electromagnetic radiation by particles passing through the optical chamber. Air flow is



* Wind Sensor
O Profiler Head
□ RAM-1

Note: Profiler heads behind pile at 4 and 6 feet heights.

Figure 3-4. View of Sampling Array from Upwind of Pile

maintained at a constant rate of about 2 liter/min. The sampler has a D_{50} of 10 microns. 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). The instrument outputs an analog signal, which when used with an analog to digital converter, outputs a digital signal suitable for use with a computer.

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.

A total of five RAM-1 monitors were used. One was located at the eight foot height upwind. Two others were located at each pile. Again to satisfy study objective 2, it was desirable to associate each RAM-1 monitor with a specific windspeed monitor. The locations of the RAM-1 monitors are also shown in Figure 3-4. RAM R-1 can be associated with windspeed measurements from windspeed sensor 2. RAM R-3 can be associated with wind sensor 3.

3.2.2.3 Independent Variables--

Independent variables monitored were:

- Temperature
- Pile surface silt content
- Pile surface moisture

Soil samples were taken from the pile by removing the top ½ inch of soil in a vertical strip of 1 x 48 inches from the middle of the pile.

Samples of soil were stored briefly in their airtight containers, then reduced with a 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°F 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 could be sieved.

Sieving of these samples was done with mechanical dry sieves. The portion of the material passing a 200 mesh screen is defined as 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 samples, both halves of the final split were analyzed for moisture and silt content. This duplication allows determination of the reproducibility of the methods.

Temperature data was collected because of previous experience that the RAM data becomes inaccurate at temperatures greater than 105°F.

No data related to dispersion (e.g. cloud cover and solar intensity) were collected because no dispersion calculations were required.

4.0 QUALITY ASSURANCE

4.1 QUALITY ASSURANCE PLAN

A detailed quality assurance (QA) plan was prepared prior to starting the field sampling. The report was used as a guideline throughout the field sampling, data analysis, and data evaluation portions of the project. Principal elements of the QA procedures are contained and reviewed in this section.

4.1.1 Precision, Accuracy, and Completeness Objectives

Objectives for precision, accuracy, and completeness as stated in the QA plan are shown in Table 4-1. Table 4-2 shows the criteria for precision, accuracy, and completeness met during the sampling phase of the project. Precision is defined as a measure of mutual agreement among individual measurements of the same property under similar conditions. It was difficult to establish the precision for the exposure profiler samples used in this study. Precision is normally determined from measurements taken with a pair of collocated instruments. In general, for particulate measurements, the siting guidelines require that the samplers be separated by at least 2 meters. For the test procedures scheduled for this study location, differences of only several inches could yield drastically different results. Consequently, precision could not be properly evaluated within the constraints of any specific test.

In the case of the RAM-1 and windspeed sensors, a special array of paired instruments of each type was erected once during the study. These instruments were deployed to measure ambient conditions in close proximity to each other

TABLE 4-1. PRECISION, ACCURACY AND COMPLETENESS OBJECTIVES

Measurement Parameter	Reference	Experimental Conditions	Precision Std. Dev.	Accuracy	Completeness
RAM-1	Appendix A	Ambient Air	± 15%	± 5%	> 80%
Exposure profiler heads	EPA-600/4-77-027a May 1977	Ambient Air	N/A[a]	± 7%	> 80%
Windspeed	Appendix B	Ambient Air	± 5%	± 5%	> 80%
Wind direction	Appendix B	Ambient Air	N/A[a]	± 5°	> 80%

[a] N/A - not applicable - see text

TABLE 4-2. PRECISION, ACCURACY AND COMPLETENESS RESULTS

Measurement Parameter	Precision Std. Dev.	Accuracy	Completeness
RAM-1	2.2%	≤3.9%	20.0%
Exposive profiler heads	N/A	≤6.3%	85.4%
Windspeed	3.9%	±5.0%	98.1%
Wind direction	N/A	0.0%	100.0%

[a] N/A - not applicable - see text

in a location removed from the test area and away from local obstructions and interferences. Since the computerized data capture occurred at 1-minute intervals only a short exposure was necessary. Precision test data are displayed in Tables 4-3 through 4-6. For these data, both the windspeed sensors and the RAM-1 instruments agreed to within 5 percent of full scale. Sensors and instruments showing the greatest differences in recorded values were cleaned and recalibrated to improve comparability.

For the exposure profiler heads, no precision determinations were made. In the ambient air, collocated samplers would need to operate for up to 8 hours to obtain an adequate mass for analysis. It was not feasible to remove two instruments from the sampling array on a regular basis to perform such a comparison. In the plume downwind of the storage piles, any comparisons of closely located samplers would be meaningless due to concentration variations within the plume. No precision estimates of wind direction were obtained since only one wind direction sensor was deployed.

The accuracy determinations for the exposure profiler heads were obtained from single point flow checks performed twice during the study using a standard orifice calibration kit different from the one used for calibration. Similarly for the RAM-1 instruments, a standard bubble tube was used to audit the RAM-1 instrument flowrates once during the field portion of the project. Exposure profiler sampler flow checks are summarized in Table 4-7 and 4-8. RAM-1 audit flow rate results are displayed in Table 4-9. All audited values for the RAM-1 were within 3.9 percent of the original calibration. For the profilers, all values were within 6.3 percent.

For windspeed accuracy, the manufacturer's stated accuracy of ± 5 percent was used. Wind direction accuracy was determined using a compass. The

TABLE 4-3. SCREENED PILE WINDSPEED SENSOR PRECISION TEST

PEI ASSOCIATES, INC.
WINDSCREEN MODEL VERIFICATION

Location: SCREENED PILE
Test Description: SENSOR TEST
Date: 07-22-85

Time	Elapsed Time	---- (-----)	RAM2 (UG/M2)	RAM4 (UG/M3)	PWS2 (FT/M)	PWS4 (FT/M)	PWS6 (FT/M)	PWS8 (FT/M)	HWS5 (FT/M)	HWS8 (FT/M)	HW11 (FT/M)	UWRM (UG/M3)	WSPD (FT/M)	WDIR (SEC)
15:00	0	0	0	0	367	363	356	298	321	263	348	272	307	4
15:05	5	0	0	0	287	289	282	226	276	204	272	1072	228	3
15:10	10	2322	2	0	336	322	321	251	293	199	290	817	362	2
15:15	15	2053	12	14	208	202	194	100	192	105	188	879	263	2
15:20	20	0	19	0	414	383	382	336	395	310	386	1440	484	3
15:25	25	0	0	0	320	324	330	192	275	176	252	541	424	3
15:30	30	0	0	0	371	338	354	278	360	296	358	300	358	2
15:35	35	0	0	0	347	334	384	254	309	262	374	175	477	2
15:40	40	0	1147	1063	239	223	219	113	195	110	197	2321	268	2
15:45	45	0	4139	4456	388	370	354	306	333	284	387	5541	709	3
15:50	50	0	4127	4428	328	294	315	231	301	243	324	5759	388	3
15:55	55	0	4097	4409	299	273	278	184	255	162	244	5587	425	3
Mean		365	1129	1198	325	310	314	231	292	218	302	2159	391	3
Maximum		2322	4139	4456	414	383	384	336	395	310	387	5587	709	4
Time at maximum		15:10	15:45	15:45	15:20	15:20	15:35	15:20	15:20	15:20	15:45	15:55	15:45	15:00

TABLE 4-4. EXPOSED PILE WINDSPEED SENSOR PRECISION TEST

PEI ASSOCIATES, INC.
WINDSCREEN MODEL VERIFICATION

Location: EXPOSED PILE
Test Description: SENSOR TEST
Date: 07-22-85

Time	Elapsed Time	RAM1 (UG/M3)	RAM3 (UG/M2)	PWS1 (FT/M)	PWS3 (FT/M)	PWS5 (FT/M)	PWS7 (FT/M)	PWS9 (FT/M)	HWS5 (FT/M)	HWS8 (FT/M)	HW11 (FT/M)	UWRM (UG/M3)	WSPD (FT/M)	WDIR (SEC)
15:00	0	0	0	382	377	385	416	338	382	0	258	1218	319	4
15:05	5	0	0	315	311	328	331	325	327	0	225	926	234	4
15:10	10	59	0	369	339	343	368	316	341	0	257	460	355	2
15:15	15	66	0	215	199	203	291	195	193	0	131	1448	270	2
15:20	20	0	0	424	416	425	435	428	447	0	376	1141	493	3
15:25	25	0	0	360	350	357	321	298	304	0	244	1913	413	3
15:30	30	0	0	345	344	322	302	325	338	0	279	114	328	2
15:35	35	0	0	465	414	372	372	331	332	0	269	102	483	2
15:40	40	240	2094	248	227	212	214	173	195	0	109	2455	271	2
15:45	45	2762	4430	459	410	379	423	404	395	0	325	5880	717	3
15:50	50	2805	4433	404	349	347	316	354	315	0	270	5874	395	3
15:55	55	2820	4446	354	313	316	319	278	296	0	223	5912	428	3
Mean		729	1284	362	338	332	335	315	322	0	247	2289	392	3
Maximum		2820	4446	465	416	425	435	428	447	0	376	5912	717	4
Time at maximum		15:55	15:55	15:35	15:20	15:20	15:20	15:20	15:20		15:20	15:55	15:45	15:00

TABLE 4-5. SCREENED PILE RAM-1 INSTRUMENT PRECISION TEST

PEI ASSOCIATES, INC.
WINDSCREEN MODEL VERIFICATION

Location: SCREENED PILE
Test Description: RAM TEST
Date: 07-22-85

Time	Elapsed Time	---- (-----)	RAM2 (UG/M2)	RAM4 (UG/M3)	PWS2 (FT/M)	PWS4 (FT/M)	PWS6 (FT/M)	PWS8 (FT/M)	HWS5 (FT/M)	HWS8 (FT/M)	HW11 (FT/M)	UWRM (UG/M3)	WSPD (FT/M)	WDIR (SEC)
16:45	0	0	27	27	376	354	376	305	339	261	346	37	428	3
16:50	5	0	20	28	211	192	1°7	108	194	120	177	52	209	3
16:55	10	0	5	30	518	506	525	461	496	419	486	50	563	3
Mean		0	17	28	368	351	366	291	343	267	337	46	400	3
Maximum		0	27	30	518	506	525	461	496	419	486	52	5[illegible]7	3
Time at maximum			16:45	16:55	16:55	16:55	16:55	16:55	16:55	16:55	16:55	16:50	16:55	16:45

TABLE 4-6. EXPOSED PILE RAM-1 INSTRUMENT PRECISION TEST

PEI ASSOCIATES, INC.
WINDSCREEN MODEL VERIFICATION

Location: EXPOSED PILE
Test Description: RAM TEST
Date: 07-22-85

Time	Elapsed Time	RAM1 (UG/M3)	RAM3 (UG/M2)	PWS1 (FT/M)	PWS3 (FT/M)	PWS5 (FT/M)	PWS7 (FT/M)	PWS9 (FT/M)	HWS5 (FT/M)	HWS8 (FT/M)	HW11 (FT/M)	UWRM (UG/M3)	WSPD (FT/M)	WDIR (SEC)
16:45	0	0	30	425	404	412	418	362	383	0	303	43	436	3
16:50	5	2	35	211	291	216	206	215	203	0	146	41	206	3
16:55	10	2	30	634	584	593	572	538	564	0	489	41	563	3
Mean		2	32	423	396	407	399	372	384	0	313	42	402	3
Maximum		2	35	634	584	593	572	538	564	0	489	43	563	3
Time at maximum		16:55	16:50	16:55	16:55	16:55	16:55	16:55	16:55		16:55	16:45	16:55	16:45

TABLE 4-7. EXPOSURE PROFILER SAMPLER AUDIT RESULTS, JULY 29, 1985

Sampler	Flow Rate CFM	Audit Flow CFM	Difference CFM	Percent Difference
1	35.99	37.58	-1.59	-4.22
2	37.32	38.10	-0.78	-2.05
3	33.76	36.03	-2.27	-6.30
4	35.23	36.29	-1.06	-2.92
5	33.39	35.52	-2.13	-6.00
6	35.56	37.84	-2.28	-6.03
7	34.18	35.78	-1.60	-4.47
8	34.10	36.03	-1.93	-5.36
9	35.23	37.58	-2.35	-6.25

TABLE 4-8. EXPOSURE PROFILER SAMPLER AUDIT RESULTS, AUGUST 28, 1985

Sampler	Flow Rate CFM	Audit Flow CFM	Difference CFM	Percent Difference
1	44.43	44.71	-0.28	-0.63
2	37.87	38.61	-0.74	-1.92
3	27.61	26.91	0.70	2.59
4	29.16	28.45	0.71	2.48
5	47.05	47.46	-0.41	-0.87
6	43.15	44.08	-0.92	-2.10
7	30.42	31.31	-0.89	-2.84
8	27.97	26.37	1.60	6.08
9	27.06	28.45	-1.39	-4.90

TABLE 4-9. INSTRUMENT FLOW RATE AUDIT RESULTS

Site: Wichita
Date: 07-29-84
Auditor: K Rosbury
Audit Device: Bubble Tube (500 cc)

Sampler	Time	Flow Rate	Diff	% Diff
UWRM S/N 1393	14.84 sec 14.79 sec	2025 cc/min	25.0 cc	1.25 %
RAM2 S/N 1302	15.39 sec 15.30 sec	1955 cc/min	-5.0 cc	-0.25 %
RAM1	15.64 sec 15.57 sec	1922 cc/min	-78.0 cc	-3.90 %
RAM3 S/N 1230	15.14 sec 15.22 sec	1976 cc/min	-24.0 cc	-1.20 %
RAM4 S/N 1394	15.33 sec 15.32 sec	1958 cc/min	-42.0 cc	-2.10 %

accuracy of the sensor was determined during the audit on July 29, by comparing the displayed directional value, on the computer, to a compass reading. During the audit, there was no difference between the compass and computer reading.

The use of the RAM-1 aerosol monitors was discontinued after test 18 and data collected between tests 11 and 18 were voided when the instruments failed to meet quality control requirements. Data from the instruments were only used for eleven of the fifty-five tests resulting in a 20 percent data capture.

Because of a high moisture content on the pile surface, eight tests were performed without the exposure profiler samplers. This lowered the completeness of the data for the exposure profiler heads to 85.4 percent. Some windspeed data was voided because of sensor malfunctions. This deletion, however, resulted in less than a 2 percent data loss. Data completeness for the windspeed sensors was 98.1 percent. No wind direction data were lost, resulting in 100 percent data completeness for wind direction.

4.2 SAMPLING PROCEDURES FOR CRITICAL MEASUREMENTS

4.2.1 Daily Procedures

Each test day a wind forecast was obtained from the National Weather Service (NWS) station at the Wichita Mid-Continent Airport, which was located about 7 miles from the site. If appropriate winds were forecast, the upwind and downwind sampling arrays were deployed appropriately for the expected wind direction. Next, the RAM-1 instruments were electronically zeroed and spanned. The windspeed sensors were also zeroed and electronically spanned. The wind direction instrument was steadied and aligned to magnetic north with a compass.

After all instruments and samplers were checked for calibration drift criteria, a short comparative test was made to check pile comparability and sensor precision. Windspeed sensors located on the pile surface and the RAM-1 monitors were run for short periods (10 to 15 minutes) before the screen was put in place to compare instrument readings between paired sensors on the two piles. Windspeed sensors whose reading did not agree within 10 percent of each other were checked for free cup rotation and were cleaned and lubricated as necessary. RAM-1 instruments whose readings showed noticeable differences were checked for correct calibration factors, re-spanned, and the calibration factors were updated as necessary.

The windscreen was erected as needed for the test and sampling commenced when ambient windspeed exceeded 6 mph. A soil sample was taken from the surface of each pile for later moisture and silt analyses. The appropriate flowrate for the isokinetic exposure profile heads was determined based on ambient windspeed and the samplers were set accordingly at the start of the test. Computerized data capture for the RAM-1 instruments and the windspeed/wind direction sensors was begun simultaneously. The exposure profiler heads were started individually. All instruments were started within a 3-5 minute time span.

During the 1-hour test, the computerized data collection required little attention. Two of 24 input signals were monitored each test by temporarily hooking the channels into a strip chart recorder. The computer monitor indication was compared to the trace on the recorder to ensure that each channel was performing correctly. In all cases, the computer indication and the strip chart trace agreed within 5 percent of full scale. A summary of chart recorder audits of computer data unputs is displayed in Table 4-10.

TABLE 4-10. SUMMARY OF CHART RECORDER AUDITS OF COMPUTER DATA INPUTS

Date	Test	Screened/ Exposed	Channel	Time	Computer Average	Chart Average	Difference	% Diff.	% Full Scale
07-18	6	Exposed	UWRM	1530-1540	14.5 μg/m³	70.0 μg/m³	55.5 μg/m³	79.3 %	0.28%
07-18	6	Exposed	HW11	1545-1555	826.5 ft/min	880 ft/min	53.5 ft/min	6.08 %	1.22%
07-18	7	Screened	RAM4	1715-1730	51.3 μg/m³	200 μg/m³	148.7 μg/m³	74.4%	0.74%
07-18	7	Exposed	PWS3	1735-1745	1224.5 ft/min	1320 ft/min	95.5 ft/min	7.23%	2.17%
07-18	9	Screened	RAM2	1025-1040	49.7 μg/m³	160 μg/m³	110.3 μg/m³	68.9%	0.55%
07-18	9	Screened	WSPD	1045-1055	1016 ft/min	1232 ft/min	216 ft/min	17.5%	4.91%
07-24	11	Exposed	RAM3	1530-1540	5 μg/m³	200 μg/m³	195.0 μg/m³	97.5%	0.98%
07-27	12	Screened	RAM4	1400-1410	3.5 μg/m³	120 μg/m³	116.5 μg/m³	97.1%	0.58%
07-27	13A	Screened	RAM4	1510-1520	3.0 μg/m³	120 μg/m³	117.0 μg/m³	97.5%	0.59%
07-27	13A	Screened	PWS2	1525-1535	403.5 ft/min	440 ft/min	36.5 ft/min	8.30%	0.83%
07-27	13B	Screened	HWS8	1645-1655	123 ft/min	264 ft/min	141 ft/min	53.4%	3.20%
07-27	13B	Exposed	UWRM	1630-1640	12.5 μg/m³	100 μg/m³	87.5 μg/m³	87.5%	0.44%
07-30	15A	Exposed	PWS9	1546-1556	610.5 ft/min	616 ft/min	5.5 ft/min	0.89%	0.13%
07-30	15B	Exposed	RAM3	1649-1659	5.5 μg/m³	70 μg/m³	64.5 μg/m³	92.1%	0.32%
07-30	15B	Exposed	WSPD	1710-1725	1106 ft/min	1144 ft/min	38.0 ft/min	3.32%	0.86%
07-30	16	Exposed	HW11	1840-1850	738 ft/min	704 ft/min	34.0 ft/min	4.61%	0.77%
07-30	16	Exposed	RAM3	1800-1810	6 μg/m³	80 μg/m³	74 μg/m³	92.5%	0.37%
07-30	17	Exposed	PWS7	1934-1944	230 ft/min	264 ft/min	34 ft/min	12.9%	0.77%
07-30	17	Exposed	UWRM	1948-1958	9 μg/m³	74 μg/m³	65 μg/m³	87.8%	3.25%
07-31	18	Screened	RAM3	1421-1431	11.5 μg/m³	55 μg/m³	43.5 μg/m³	79.1%	2.18%
07-31	18	Screened	PWS2	1435-1445	253.5 ft/min	176 ft/min	77.5 ft/min	30.6%	1.76%
08-02	19A	Screened	HWS5	1325-1340	301.7 ft/min	334.4 ft/min	32.7 ft/min	9.79%	0.74%
08-02	19A	Screened	PWS8	1354-1404	365.5 ft/min	352.0 ft/min	13.5 ft/min	3.69%	0.31%
08-02	19B	Screened	PWS6	1447-1500	570 ft/min	616 ft/min	46 ft/min	7.47%	1.04%
08-02	19B	Screened	PWS4	1506-1520	295 ft/min	264 ft/min	31 ft/min	10.5%	0.70%
08-02	20	Screened	PWS2	1623-1633	500 ft/min	528 ft/min	28 ft/min	5.3%	0.64%
08-02	20	Screened	HWS8	1638-1652	593.0 ft/min	616 ft/min	23 ft/min	3.73%	0.52%

continued

Table 4-10 (continued)

Date	Test	Screened/ Exposed	Channel	Time	Computer Average	Chart Average	Difference	% Diff.	% Full Scale
08-03	22	Exposed	WSPD	1605-1620	1143 ft/min	1232 ft/min	89 ft/min	7.22%	2.02%
08-03	23A	Exposed	HWS5	1717-1733	904 ft/min	968 ft/min	64 ft/min	6.61%	1.45%
08-06	23B	Exposed	HW11	1445-1455	409.5 ft/min	528 ft/min	118.5 ft/min	22.4%	2.69%
08-06	24	Exposed	HWS8	1642-1655	695 ft/min	704 ft/min	9 ft/min	1.28%	0.20%
08-08	25A	Exposed	HW11	1225-1237	1004.5 ft/min	1056 ft/min	51.5 ft/min	4.88%	1.17%
08-08	25A	Exposed	PWS7	1240-1250	612.0 ft/min	7040 ft/min	92 ft/min	13.1%	2.1%
08-08	25B	Exposed	PWS1	1403-1436	495.5 ft/min	528 ft/min	32.5 ft/min	6.16%	0.74%
08-09	26	Exposed	PWS7	1217-1236	588.7 ft/min	616 ft/min	27.3 ft/min	4.43%	0.62%
08-09	27	Exposed	PWS5	1355-1412	949 ft/min	968 ft/min	19.0 ft/min	1.96%	0.43%
08-12	28A	Exposed	HWS5	1345-1350	856 ft/min	880 ft/min	24.0 ft/min	2.73%	0.55%
08-16	28B	Exposed	PWS7	1130-1155	422.8 ft/min	440 ft/min	17.2 ft/min	3.91%	0.39%
08-16	28B	Exposed	PWS3	1200-1219	904.4 ft/min	968 ft/min	63.6 ft/min	6.57%	1.45%
08-16	29	Screened	WSPD	1315-1335	719 ft/min	836 ft/min	177 ft/min	14.0%	2.66%
08-16	29	Screened	WDIR	1336-1340	192.4 deg	196.4 deg	3.97 deg	2.02%	0.73%
08-16	30A	Exposed	PWS1	1505-1520	418.3 ft/min	440 ft/min	21.7 ft/min	4.93%	0.49%
08-16	30B	Exposed	PWS3	1615-1630	815 ft/min	880 ft/min	65.0 ft/min	7.39%	1.48%
08-16	30B	Exposed	HW8	1630-1655	770.6 ft/min	836 ft/min	65.4 ft/min	7.82%	1.49%
08-16	31	Screened	PWS2	1750-1815	293.2 ft/min	440 ft/min	146.8 ft/min	33.4%	3.34%
08-16	31	Screened	PWS4	1815-1830	304.7 ft/min	396 ft/min	91.3 ft/min	23.1%	2.08%
08-16	32	Screened	HWS8	1915-1930	491.3 ft/min	616 ft/min	124.7 ft/min	20.2%	2.83%
08-16	32	Screened	HW11	1930-1950	610.5 ft/min	704 ft/min	93.5 ft/min	13.3%	2.13%
08-26	34A	Screened	HWS8	1322-1332	411.5 ft/min	440 ft/min	28.5 ft/min	6.48%	0.65%
08-26	34A	Screened	HW11	1345-1400	343 ft/min	396 ft/min	53 ft/min	13.4%	1.20%
08-26	34B	Screened	PWS6	1500-1515	428 ft/min	484 ft/min	56 ft/min	11.6%	1.27%
08-26	34B	Screened	WSPD	1516-1529	340.7 ft/min	484 ft/min	143.3 ft/min	29.6%	3.26%
08-27	35	Exposed	HWS5	1035-1050	555.7 ft/min	616 ft/min	60.3 ft/min	9.79%	1.37%
08-27	35	Exposed	WDIR	1050-1110	167 deg	163.6 deg	3.36 deg	2.01%	0.62%
08-27	36	Exposed	PSW5	1206-1225	358.7 ft/min	396 ft/min	37.3 ft/min	9.42%	0.85%
08-27	36	Exposed	WSPD	1226-1240	537 ft/min	660 ft/min	123 ft/min	18.6%	2.80%
08-27	36	Exposed	PSW3	1250-1300	489 ft/min	528 ft/min	39 ft/min	7.39%	0.89%
08-21	54	Exposed	WSPD	1355-1410	950.7 ft/min	1012 ft/min	61.3 ft/min	6.06%	1.39%
08-21	54	Exposed	PWS1	1415-1430	522.7 ft/min	528 ft/min	5.3 ft/min	1.0%	0.12%
08-21	55A	Exposed	PWS3	1453-1510	853.3 ft/min	924 ft/min	70.7 ft/min	7.65%	1.61%
08-21	89	Exposed	PWS9	1647-1705	618.5 ft/min	616 ft/min	2.5 ft/min	0.40%	0.06%
08-21	90	Exposed	PWS7	1740-1755	618.7 ft/min	660 ft/min	41.3 ft/min	6.26%	0.94%

A manual flow system was used for each profiler head to maintain nearly isokinetic flow. Such a system has been used for every profiler determined fugitive dust emission factor presently in AP-42. The 10-15 min. average adjustment period has been found to be adequate. As noted in a previous section, anemometers were collocated with the profiling heads at each height of the towers. It was necessary to have anemometers at each height since the pile influenced wind flow and the wind profile could not be assumed to be lognormal. The anemometer signals were input to the on-site computer. Every 10 minutes during testing, an average windspeed was obtained for each of the eight sampling heads, and flows on the profiling heads were adjusted accordingly. Isokinetic ratios (windspeed/inlet velocity) varied from 0.2 to 1.3. The extremely low ratios occurred under low windspeeds. The samplers could be adjusted for windspeeds down to about 750 ft/min. For lower windspeeds the samplers had to be run superisokinetic. Wichita was selected as a test location because of the area's high persistent winds. It was planned that normally testing would begin when the wind averaged approximately 750 ft/min. Since adverse weather conditions prevailed (excess rain, northerly winds, and low windspeeds), and because more than two weeks of data were lost as a result of equipment damaged by lightning, every effort was made to complete as many tests as possible. Numerous tests were run below the minimum windspeed threshold since other test conditions were favorable (wind direction and soil moisture content).

At the end of each test, the RAM-1 instruments and meteorological sensors were placed in a standby mode until the beginning of the next test. The exposure profiling heads were brought into the trailer where all filter recovery activity took place. The exposed filters from the samplers were

removed, logged into the field log book and new filters were installed. The samplers were then redeployed for the next test.

At the end of the day, the RAM-1 instruments were routinely recalibrated to check for drift during the day. Any drift over 2 percent required that corrective action be taken during the data reduction. All sampler filters, computer printouts and disks, and log books were stored in the locked trailer overnight. If rain or high winds were forecast overnight, the storage piles were covered with tarpaulins prior to leaving the site.

4.2.2 Sample Handling

Only two types of samples were handled in this study. The first type consisted of standard glass fiber hi-vol filters. All handling procedures conformed to the standard operating procedures (SOP) for ambient TSP monitoring (EPA 1977). Filters were equilibrated at a constant temperature and at a relative humidity of less than fifty percent for 24 hours before weighing. Every tenth filter was reweighed. No filter weights differed by more than 5 mg. from the original weight after 24 additional hours in the controlled temperature and humidity environment. The balance used for filter weighing was checked for accuracy with class S weights during each weighing session. Data records for these filters were maintained in two locations. First, the field data sheets for each test contained all aspects of the test conditions plus the filters used for each test. Second, a separate filter log book was maintained to record the filters used each day.

The exposed filters remained within the field trailer until they were hand carried back to the laboratory for gravimetric and laser diffraction analyses.

The second type of sample generated during the study was the soil sample taken from each storage pile. A sample of the soil of each pile was taken

prior to each test by removing the top half inch of soil in a vertical strip of 1x48 inches from the front mid section of the pile. Samples were stored briefly in a clean, airtight sample jar, then reduced with a sample spliter (riffle) to about 1 kg. The final split samples were placed in a tared metal pan, weighed, and dried in an oven at 110°F 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. For ten percent of the samples taken a moisture content for both sides of the final split was determined and the results for the two portions were then compared. In all cases, the moisture analysis of both splits of the same original sample agreed within 5 percent.

The silt content, that portion of the sample passing through a 200 mesh screen after being shaken for 15 minutes, was then determined for each soil sample. The duplicate moisture analysis samples were compared for silt content. All duplicate samples analyzed for silt content compared within ten percent. This duplication of analysis allowed a QC determination of the reproducibility of the method.

4.2.3 Data Records

A number of separate data records and log books were maintained by the field team. Separate logs were maintained for filters, soil samples, equipment calibrations and maintenance, and other notes on events that affected the testing. In addition, a computer-generated printout of the test results, a field data sheet and a magnetic disk were obtained for each test. The field records were coded with unique identification for each test. The field data sheets were developed specifically for the testing and contained all relevant support data for each test. The field supervisor had the responsibility for maintenance of these records, and reviewed all records on a daily basis to

ensure their completeness and accuracy. These records remained within the field trailer or in the custody of the field supervisor at all times. When not in the personal custody of the supervisor, they were in the locked trailer.

4.3 EQUIPMENT CALIBRATION

All equipment used in the study was in proper working order at the outset of the study. At the beginning of the testing, the exposure profile heads were calibrated on-site according to accepted SOP for the high volume method (Section 2.2.2 of the QA Handbook, EPA 1977). Once during the study, single point flow checks of each instrument were performed.

The RAM-1 instruments had been calibrated against a primary standard within 6 months prior to the testing. Then, at least twice a day during the testing, the samplers were electronically zeroed and spanned.

The exposure profiler heads were calibrated with a standard orifice calibration kit. The flows for the RAM-1 instruments were calibrated with a bubble tube. Each of the calibration devices was traceable to a primary standard within 6 months of this study.

5.0 OBJECTIVE 1--VERIFICATION OF WIND TUNNEL WIND SPEED DATA.

The first objective of the study was to compare the wind tunnel data (Billman 1985) with the windspeed data collected in the field. The comparison had two major elements. They were:

1. Comparison of the windspeed isotachs on an unscreened pile.
2. Comparison of the windspeed isotachs on screened piles by screen configuration.

5.1 WINDSPEED COMPARISONS BETWEEN WIND TUNNEL AND FIELD TESTING FOR AN UNSCREENED PILE

As noted in Section 2, the Billman (1985) windspeed data are presented as a set of contours of normalized windspeed, u/u_r, where u is the windspeed at the pile surface, and u_r is the windspeed at the maximum height of the pile measured in the absence of the pile. Previously cited Figure 2-2, taken from the Billman (1985) report, summarized the wind tunnel data for windflow on an unscreened pile.

In order to directly compare the field data to previously cited Figure 2-2, the following data manipulations of the unscreened pile data were required:

1. Prepare a data base with 5-minute average data, of windspeeds when the incoming wind direction value was ±5° of perpendicular to the sampling array. The wind direction restriction is necessary because Figure 2-2 wind tunnel data was derived from a perpendicular wind direction.
2. For each sampler location, prepare u/u_r values.
3. Summarize u/u_r values derived from the field for comparison to the wind tunnel data.

A computerized data base was prepared consisting of five minute average windspeed data, stratified by incoming wind direction in 10° cohorts. Using the 175 to 185° cohort data base for the unscreened pile, u/u_r values were calculated. These data are shown in Table 5-1. Incoming wirdspeed varied from 207 to 1172 feet/minute.

The five composite u/u_r values from the field measurements are overlayed on the isotach lines from the wind tunnel data in Figure 5-1. Based on the results shown in Table 5-1 several preliminary conclusions can be drawn.

- The field u/u_r values obtained on the front side of the pile match extremely well with the wind tunnel data.
- The field ratios on the back of the pile are much higher than the wind tunnel data. The reason is not readily apparent. The field data suggest that the isotach lines curve around the pile much more in the field than in the wind tunnel.
- At positions 2 through 5, the u/u_r values appear to be related to incoming windspeeds. At the lower windspeeds, the ratios are higher. The ratios decrease as the windspeed increases. This phenomena was not investigated in the wind tunnel.

With the data developed to this point, it is not possible to construct isotach lines from the field data, because the samplers were deployed at only five locations on the pile.

Composite u/u_r values were then calculated for the other 10° wind direction cohorts as shown in Table 5-2. As the wind direction moves around the pile, the sensors locations are effectively shifted to new positions. This same approach was used by Billman in the original wind tunnel study. However, in the field study the wind direction was varied rather than the pile orientation. Utilizing the entire data base yields a total of 80 data points. As only 160 degrees of the compass were sampled, a substantial portion of the compass is left unresolved. Some of the data points are plotted in Figure 5-2. The data are plotted over the isotachs from the wind tunnel study.

TABLE 5-1. U/U_r VALUES FOR THE UNSCREENED PILE WITH WINDS 175-184°

Incoming Windspeed, ft/min	Position 1			Position 2			Position 3			Position 4			Position 5		
	u/ur	N	u/ur / x	u/ur	N	u/ur / x	u/ur	N	u/ur / x	u/ur	N	u/ur / x	u/ur	N	u/ur / x
0-299	0.50	3	0.94	1.33	3	1.22	0.96	3	1.14	1.23	3	1.31	1.15	3	1.21
300-399	0.47	2	0.89	1.28	2	1.17	0.96	2	1.14	1.02	2	1.09	0.99	2	1.04
400-499	0.59	6	1.17	1.03	6	0.94	0.84	6	1.00	0.72	6	0.77	0.85	6	0.89
500-599	0.66	13	1.25	1.07	13	0.98	0.93	13	1.11	0.99	13	1.05	0.94	13	0.99
600-699	0.45	9	0.96	1.11	9	1.01	0.85	9	1.01	0.98	9	1.04	0.96	9	1.01
700-799	0.46	12	0.87	1.11	12	1.01	0.79	12	0.95	1.01	12	1.07	0.98	12	1.03
800-899	0.50	8	0.94	1.10	8	1.01	0.80	8	0.95	0.92	7	0.98	0.93	7	0.98
900-999	0.49	3	0.92	1.07	3	0.98	0.80	3	0.95	0.90	3	0.96	0.95	3	1.00
>1000	0.52	20	0.98	1.05	20	0.96	0.81	20	0.96	0.87	15	0.93	0.92	18	0.97
Mean Value	0.53	76	---	1.09	76	---	0.84	76	---	.94	70	---	.95	73	---

[a] For position locations, see Figure 5-1
N = Number of data points
x = Mean value of u/u_r

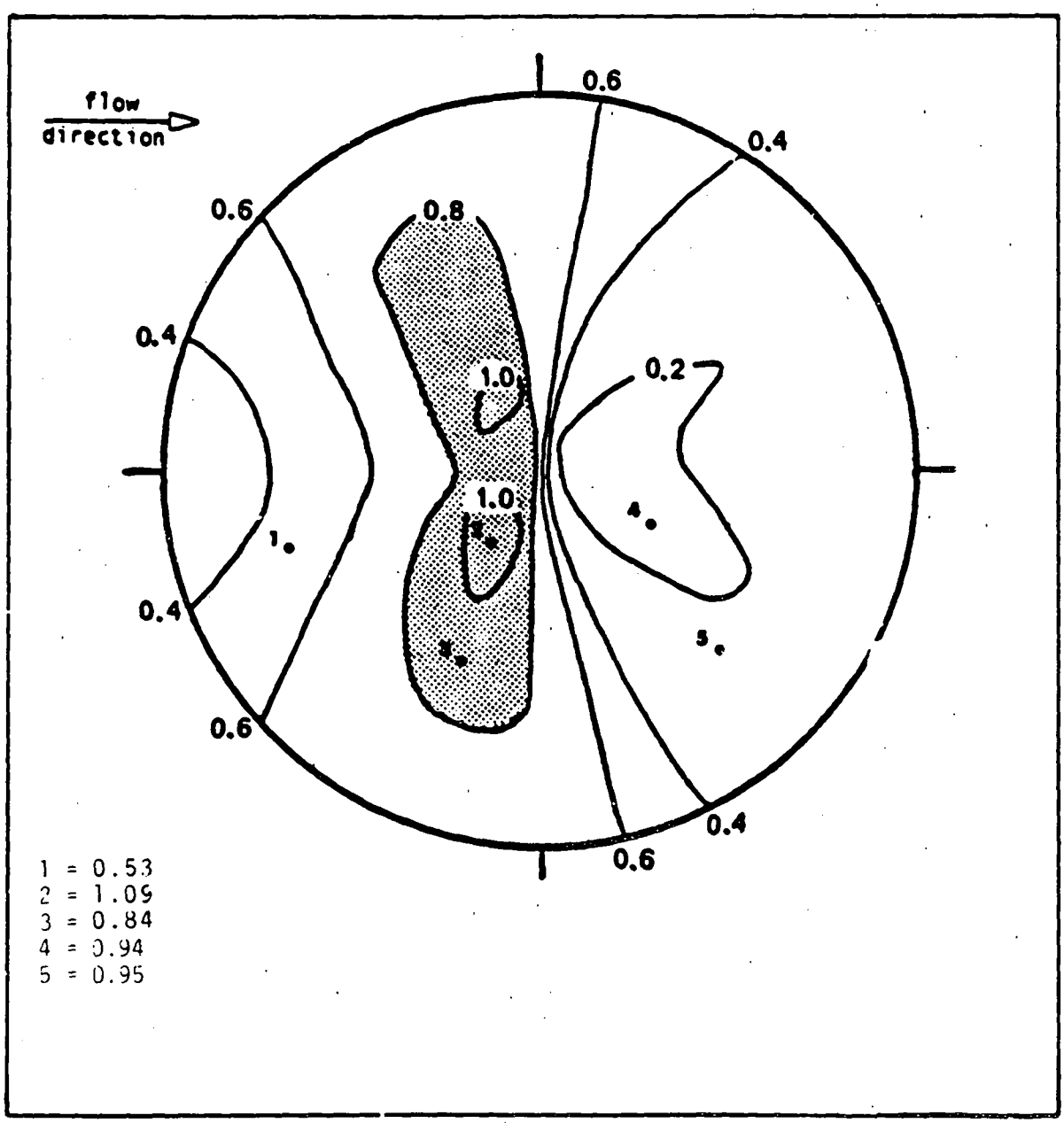


Figure 5-1 Composite u/ur values for an unscreened pile field testing compared to wind tunnel data.

TABLE 5-2. U/U_r VALUES FOR THE UNSCREENED PILE
105°-264° WIND DIRECTIONS

Wind Direction 10° Cohort	Position 1		Position 2		Position 3		Position 4		Position 5	
	N	X	N	X	N	X	N	X	N	X
105-114	2	0.94	2	1.25	2	0.84	2	1.55	2	1.12
115-124	2	1.01	2	1.13	2	0.84	2	1.30	2	0.95
125-134	9	0.82	9	1.08	9	0.72	9	1.36	9	1.05
135-144	19	0.68	19	1.08	19	0.71	19	1.34	19	1.08
145-154	35	0.65	35	1.13	35	0.83	33	1.35	35	1.14
155-164	69	0.56	69	1.07	69	0.81	61	1.21	69	1.06
165-174	77	0.46	77	1.09	77	0.82	73	1.07	77	1.00
175-184	76	0.53	76	1.09	76	0.84	70	0.94	73	0.95
185-194	79	0.57	79	1.11	79	0.88	62	0.74	72	0.82
195-204	101	0.60	101	1.08	99	0.86	94	0.45	99	0.64
205-214	47	0.67	47	1.11	47	0.88	47	0.33	47	0.49
215-224	25	0.82	25	1.16	25	1.02	25	0.20	25	0.39
225-234	17	0.88	19	1.25	19	1.07	19	0.28	19	0.38
235-244	3	1.02	3	1.17	3	0.98	3	0.23	3	0.33
245-254	1	1.02	1	1.24	1	0.97	1	0.42	2	0.26
255-264	2	1.00	5	1.23	5	1.00	5	0.87	5	0.42

N = Number of data points
X = Mean Value of u/u_r

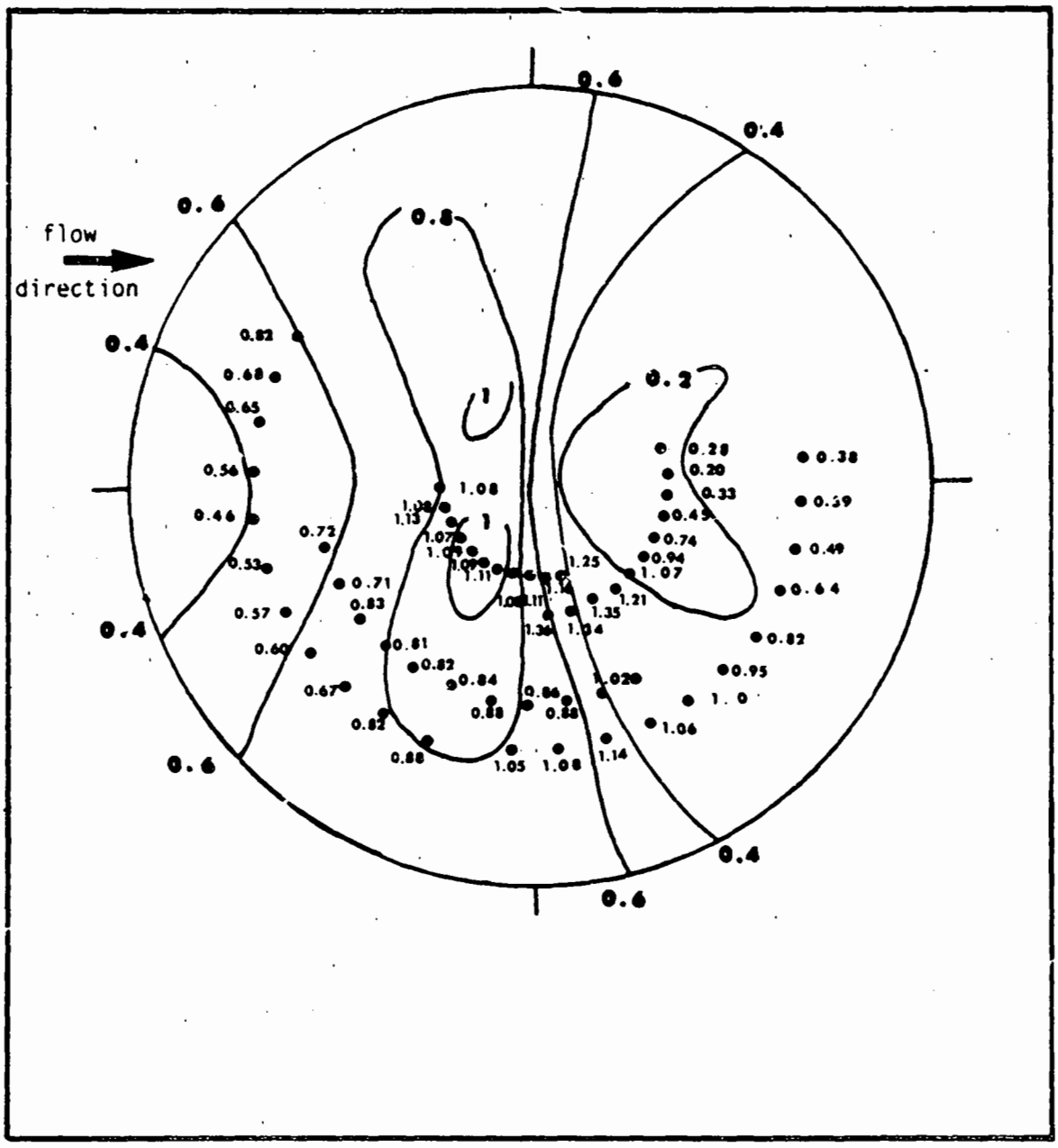


Figure 5-2. Composite u/u_r values for an unscreened pile-field testing and wind tunnel data.

Those data <105° and ≥265° are not included in the figure. The data were outside the acceptable wind direction limits for the testing. Hence, they were not assigned to a specific wind direction cohort. Also, only those wind directions with N>5 are plotted (55 data points) as it was felt that 5 or less data points in a particular 10° wind direction cohort was insufficient to calculate an average u/u_r ratio given the variability in the data.

As can be seen in Figure 5-2, the data on the front of the pile match reasonably well for u/u_r <0.8. However, the area where the ratio is ≥1.0 appears to be larger than was found in the wind tunnel. The field data for the back side of the pile yielded significantly higher u/u_r ratios than the wind tunnel study. In fact, the highest ratios measured during the field testing occurred on the back of the pile. The testing suggests that the high wind speed flow lines not only extend around to the back of the pile, but are reinforced in some fashion.

The differences noted between this study and the Billman study can be attributed to a number of factors. (1) Ambient wind speeds and direction measured in the field are much more variable than that observed in the wind tunnel resulting in higher turbulence. (2) Actual pile configuration and composition during the field testing may not have been comparable to the idealized scale model pile used in the wind tunnel. This factor may be significant. (3) Experimental equipment used in the two studies may not have been comparable. It is unknown to what extent the wind sensors correspond to the laboratory thermistors. (4) Experimental errors between the two studies may not have been of comparable magnitude. (5) The presence of reentrained dust from the pile surface may have some effect in the measurements. For example, it may be that the kinetic energy inherent to the entrained particles

from the front of the pile can be transferred to the wind sensors behind the pile, thereby yielding higher apparent windspeeds.

In general, the results from the two studies are comparable for the front of the pile. There are some additional ongoing physical effects on the back of the pile that still need to be investigated and explained.

5-2 WINDSPEED CONTROL EFFECTIVENESS

The Billman (1985) windspeed data for screened piles are presented as a series of isotach lines. The isotach lines are presented in the form of $1 - (u/u_0)$, where u and u_0 are windspeeds with and without a windbreak.

The field data were also manipulated into the $1 - (u/u_0)$ format and are shown as Table 5-3. Data are also stratified in the table by incoming wind direction and screen configuration. Data could not be presented as a series of isotach line like the Billman report, because only four data points on the pile were obtained (in contrast to 108 data points in the Billman study).

Ideally, much of the field data and the Billman wind tunnel data would have been derived from directly comparable wind direction/windscreen configuration combinations. The situation did not occur. Almost all the wind tunnel data was gathered for the condition of perpendicular winds. Of the screen combinations tested by PEI, four were directly comparable to wind tunnel work. Other combinations tested by Billman, e.g. one screen width configurations, were thought to be inappropriate for real world field application where wind directions are constantly changing.

No perpendicular winds were recorded during field testing of 3 of 4 combinations. Wind tunnel testing with aperpendicular winds was limited to one pile diameter width screens. PEI did not test the one pile diameter width screen for reasons previously stated.

TABLE 5-3. SCREEN EFFECTIVENESS, $(1- u/u_0)$

Incoming Wind Direction	Screen Configuration[a]	No. Pts.	Position 2	No. Pts.	Position 3	No. Pts.	Position 4	No. Pts.	Position 5
< 105	1-3.0-1.25	3	0.034	3	0.265	3	0.265	3	0.128
105-114	1-3.0-1.25	1	0.056	1	0.184	1	0.221	1	0.078
	2-1.5-1.25	1	0.438	1	0.209	1	0.142	1	0.188
115-124	1-3.0-1.25	2	0.042	2	0.181	2	0.220	2	0.106
125-134	1-3.0-1.25	4	0.129	4	0.226	4	0.300	4	0.171
	2-3.0-1.0	4	0.122	4	0.018	4	0.125	4	0.093
135-144	1-3.0-1.25	3	0.172	3	0.235	3	0.252	3	0.151
	2-1.5-1.0	2	0.016	2	-0.115	2	-0.030	2	-0.061
	2-3.0-1.0	7	0.074	7	-0.024	7	0.054	7	0.018
	2-5.0-1.0	2	0.358	2	0.306	2	0.270	2	0.244
	2-1.5-1.25	5	0.433	5	0.086	5	0.136	5	0.116
145-154	1-3.0-1.0	2	0.259	2	0.333	2	b	2	0.232
	1-1.5-1.25	1	0.337	1	0.219	1	0.272	1	0.198
	1-3.0-1.25	3	0.304	3	0.365	3	0.361	3	0.274
	2-1.5-1.0	7	0.077	7	-0.023	7	0.102	7	0.047
	2-3.0-1.0	1	0.168	1	0.039	1	0.043	1	0.077
	2-5.0-1.0	3	0.329	3	0.306	3	0.199	3	0.256
	3-3.0-0.5	5	0.151	5	0.044	5	0.105	5	0.106
	2-1.5-1.25	6	0.373	6	0.089	6	-0.003	6	0.074
	2-3.0-1.25	2	0.066	2	0.579	2	-0.059	2	0.204
	NONE	5	0.253	5	-0.141	5	-0.084	5	-0.052
155-164	1-3.0-1.0	8	0.281	8	0.331	8	b	8	0.255
	1-1.5-1.25	5	0.286	5	0.244	5	0.178	5	0.132
	1-3.0-1.25	4	0.190	4	0.285	4	0.209	4	0.160
	2-1.5-1.0	6	0.174	6	0.089	6	0.022	6	0.048
	2-5.0-1.0	7	0.455	7	0.441	7	0.310	7	0.359
	3-3.0-0.5	5	0.112	5	0.006	5	0.003	5	0.027
	3-5.0-1.0	11	0.462	11	0.166	11	0.078	11	0.086
	2-1.5-1.25	4	0.442	4	0.175	5	0.009	4	0.004
	2-3.0-1.25	14	0.408	14	0.391	14	0.105	14	0.163
	2-1.5-0.5	2	0.283	2	-0.049	2	-0.042	2	-0.039
	NONE	3	0.317	3	-0.098	3	0.104	3	0.147
165-174	1-1.5-1.0	2	0.286	2	0.302	2	b	2	0.207
	1-3.0-1.0	2	0.425	2	0.504	2	b	2	0.421
	1-1.5-1.25	3	0.478	3	0.407	3	0.416	3	0.327

[a] Distance, H - Width, D - Height, H
[b] No data

TABLE 5-3 (continued)

Incoming Wind Direction	Screen Configuration	No. Pts.	Position 2	No. Pts.	Position 3	No. Pts.	Position 4	No. Pts.	Position 5
165-174	1-3.0-1.25	3	0.384	3	0.508	3	0.359	3	0.369
	2-3.0-1.0	4	0.471	4	0.443	4	0.137	4	0.288
	2-5.0-1.0	15	0.479	15	0.457	15	0.295	15	0.361
	3-3.0-0.5	7	0.238	7	0.106	7	0.002	7	0.104
	3-3.0-1.0	4	0.465	4	0.221	4	0.070	4	0.146
	3-5.0-1.0	6	0.655	6	0.452	6	0.273	6	0.385
	2-1.5-1.25	1	0.759	1	0.513	1	0.169	1	0.338
	2-3.0-1.25	5	0.456	5	0.417	5	0.107	5	0.166
	2-1.5-1.0	8	0.343	8	0.188	8	0.061	8	0.145
	2-1.5-0.5	13	0.329	13	0.041	13	-0.006	13	0.066
	NONE	4	0.288	4	-0.040	4	-0.129	4	0.003
175-184	1-1.5-1.0	5	0.381	5	0.421	5	b	5	-0.068
	1-3.0-1.0	1	0.372	1	0.443	1	b	1	b
	2-3.0-0.5	3	0.265	3	0.264	3	-0.738	3	0.097
	2-3.0-1.0	7	0.516	7	0.509	7	0.186	7	0.376
	2-5.0-1.0	6	0.490	6	0.496	6	0.217	6	0.361
	3-3.0-0.5	9	0.232	9	0.129	9	-0.024	9	0.101
	3-3.0-1.0	15	0.525	15	0.312	15	0.075	15	0.218
	3-5.0-1.0	5	0.635	5	0.434	5	0.249	5	0.334
	2-1.5-1.25	5	0.645	5	0.361	5	0.166	5	0.240
	2-3.0-1.25	6	0.533	6	0.601	6	0.195	6	0.109
	2-1.5-1.0	7	0.416	7	0.263	7	-0.039	7	0.148
	2-1.5-0.5	3	0.430	3	0.140	3	0.060	3	0.199
	NONE	4	0.191	4	-0.075	4	-0.150	4	0.042
185-194	1-3.0-0.5	8	0.230	8	-0.326	8	0.405	8	0.237
	1-1.5-1.0	10	0.499	10	0.479		b	10	-0.284
	1-3.0-1.0	7	0.507	7	0.630		b	7	0.301
	1-3.0-1.25	4	0.434	4	0.525	4	0.154	4	0.258
	2-1.5-0.5	1	0.399	1	0.372	1	-0.858	1	-0.060
	2-3.0-0.5	8	0.232	8	0.246	8	-1.173	8	0.019
	2-3.0-1.0	4	0.561	4	0.578	4	0.133	4	0.403
	3-3.0-0.5	5	0.306	5	0.236	5	-0.102	5	0.160
	3-1.5-1.0	3	0.375	3	0.270	3	-0.216	3	0.010
	3-3.0-1.0	12	0.594	10	0.468	10	0.051	10	0.288
	2-1.5-1.25	5	0.685	5	0.488	5	0.118	5	0.317
	2-3.0-1.25	1	0.513	1	0.381	1	-0.132	1	-0.243
	2-1.5-1.0	8	0.561	8	0.415	8	0.064	8	0.294
	NONE	3	0.130	3	0.005	3	-0.234	3	0.036
195-204	1-1.5-0.5	11	0.197	11	0.346	11	-3.044	11	0.034
	1-3.0-0.5	9	0.224	9	0.365	9	0.119	9	0.130
	1-1.5-1.0	4	0.456	4	0.517		b	4	0.169
	1-3.0-1.0	3	0.533	3	0.656		b	3	0.421
	1-1.5-1.25	6	0.628	6	0.588	6	0.880	6	0.411
	2-1.5-0.5	11	0.280	9	0.232	11	-1.151	11	-0.137

continued

TABLE 5-3 (continued)

Incoming Wind Direction	Screen Configuration	No. Pts.	Position 2	No. Pts.	Position 3	No. Pts.	Position 4	No. Pts.	Position 5
195-204	2-3.0-0.5	8	0.274	8	0.149	8	-1.266	8	-0.098
	2-3.0-1.0	6	0.563	6	0.632	6	-0.050	6	0.428
	3-3.0-0.5	6	0.291	6	0.233	6	-0.244	6	0.106
	3-1.5-1.0	13	0.494	13	0.419	13	-0.145	13	0.185
	2-1.5-1.25	4	0.688	4	0.509	4	-0.016	4	0.323
	2-1.5-1.0	11	0.638	11	0.543	11	0.018	11	0.389
	NONE	6	0.108	6	0.005	6	-0.231	6	-0.095
205-214	NONE	4	0.049	4	0.012	4	-0.760	4	0.007
	1-1.5-0.5	9	0.252	9	0.413	9	-2.071	9	0.051
	1-3.0-0.5	6	0.217	6	0.361	6	-0.097	6	0.074
	1-1.5-1.25	2	0.677	2	0.667	2	0.952	2	0.381
	2-3.0-1.25	3	0.463	3	0.554	3	-0.685	3	0.059
	2-1.5-0.5	9	0.397	9	0.334	9	-0.774	9	-0.165
	2-3.0-0.5	4	0.311	4	0.126	4	-1.030	4	-0.189
	2-3.0-1.0	2	0.592	2	0.672	2	0.005	2	0.499
	3-1.5-1.0	7	0.495	7	0.477	7	-0.251	7	0.206
215-224	NONE	14	0.031	14	0.020	14	-2.297	14	-0.064
	1-1.5-0.5	4	0.100	4	0.356	4	-0.809	4	-0.057
	1-1.5-1.25	2	0.664	2	0.693	2	0.933	2	0.505
	2-3.0-1.25	3	0.365	3	0.504	3	-0.780	3	-0.201
	3-1.5-0.5	1	0.427	1	0.416	1	-0.289	1	0.194
	2-3.0-0.5	1	0.232	1	0.078	1	-0.383	1	-0.198
225-234	NONE	10	0.012	10	-0.007	10	-2.827	10	-0.133
	2-1.5-1.0	5	0.066	5	0.145	5	-0.253	5	-0.194
	2-1.5-1.25	2	0.638	2	0.658	2	0.0	2	0.642
	2-3.0-0.5	4	0.183	4	-0.020	4	-0.019	4	-0.46
235-244	NONE	2	0.093	2	0.104	2	-1.416	2	-0.027
	2-1.5-1.0	1	0.053	1	0.387	1	0.147	1	-0.364
245-254	2-1.5-1.0	1	0.025	1	0.049	1	0.272	1	-0.135
	2-3.0-0.5	1	0.242	1	0.017	1	0.357	1	-0.055
255-264	2-1.5-1.0	2	0.081	2	0.212	2	0.555	2	0.141
	2-3.0-0.5	3	0.096	3	0.041	3	0.256	3	-0.141
> 265	2-1.5-1.0	7	-0.379	7	0.166	7	0.360	7	-0.150
	2-1.5-1.25	1	0.537	1	0.304	1	-0.031	1	-0.060
	2-3.0-0.5	11	0.311	11	0.110	11	0.160	11	-0.035

A portion of the data shown in Table 5-3 were reformated in Table 5-4 to indicate the maximum windscreen wind reduction by incoming windspeed and screen configuration. These data are also shown in Figures 5-3 through 5-5.

In interpretation of these data, the following can be said:

- Efficiencies were greater when winds were near perpendicular to the screen. This is true for all screen heights and screen widths.
- Maximum efficiencies

		D W H*	Incoming WD
1.25 H height	.759	2/1.5/1.25	170°
1.00 H height	.672	2/3.0/1.00	210°
0.50 H height	.430	2/1.5/0.50	180°

* D = distance, W = width, H = height

- The 2 pile height distance was the most efficient.
- At near perpendicular winds, the 1.5 diameter width screen was the most effective. For aperpendicular wind direction, 3.0 D screen width was more efficient than 1.5 D screen width.
- The 1.25 pile height screen was the most effective.
- The location of maximum efficiency was almost always position 2, except where winds were >±35° from perpendicular.
- In the lee (backside) of the pile, the windscreen produced a negative control efficiency that was often significant. This was evident at position 4 when the wind direction was >180°, and at position 5 when winds were greater than 205°.
- In comparison of the field work to the Billman (1985) work:
  - Only one windscreen efficiency can be compared because configurations were not identical.

TABLE 5-4. MAXIMUM MEASURED WINDSCREEN REDUCTION FACTOR
$[1 - (u/u_o)]$ = SCREEN EFFICIENCY

Incoming WD = <105

Position:	1			2			3		
Length:	1.5	3.0	5.0	1.5	3.0	5.0	1.5	3.0	5.0
Height:									
0.50									
1.00									
1.25		.265(3/4)[1]							
1.50									

Incoming WD = 115-124

Position:	1			2			3		
Length:	1.5	3.0	5.0	1.5	3.0	5.0	1.5	3.0	5.0
Height:									
0.50									
1.00									
1.25		.220(4)							
1.50									

Incoming WD = 125-134

Position:	1			2			3		
Length:	1.5	3.0	5.0	1.5	3.0	5.0	1.5	3.0	5.0
Height:									
0.50									
1.00					.125(4)				
1.25		.300(4)							
1.50									

Incoming WD = 135-144

Position:	1			2			3		
Length:	1.5	3.0	5.0	1.5	3.0	5.0	1.5	3.0	5.0
Height:									
0.50									
1.00				.016(2)	.074(2)	.358(2)			
1.25		.252(4)		.433(2)					
1.50									

[1] Pile position with highest windspeed reduction

continued

TABLE 5-4 (continued)

Incoming WD = 145-154

Position:	1			2			3		
Length:	1.5	3.0	5.0	1.5	3.0	5.0	1.5	3.0	5.0
Height:									
0.50								.151(2)	
1.00		.333(3)		.077(2)		.329(2)			
1.25	.337(2)	.365(3)		.373(2)	.579(3)				
1.50									

Incoming WD = 155-164

Position:	1			2			3		
Length:	1.5	3.0	5.0	1.5	3.0	5.0	1.5	3.0	5.0
Height:									
0.50				.283(2)				.112(2)	.462(2)
1.00		.331(3)		.174(2)		.455(2)			
1.25	.286(2)	.285(3)		.442(2)	.408(2)				
1.50									

Incoming WD = 165-174

Position:	1			2			3		
Length:	1.5	3.0	5.0	1.5	3.0	5.0	1.5	3.0	5.0
Height:									
0.50				.329(2)				.238(2)	
1.00	.302(3)	.504(2)		.343(2)	.471(2)	.479(2)		.465(2)	
1.25	.478(2)	.508(3)		.759(2)	.456(2)			.655(2)	
1.50									

Incoming WD = 175-184

Position:	1			2			3		
Length:	1.5	3.0	5.0	1.5	3.0	5.0	1.5	3.0	5.0
Height:									
0.50				.430(2)	.265(2)			.232(2)	
1.00	.421(3)	.443(3)		.416(2)	.516(2)	.496(3)		.525(2)	.635(2)
1.25				.645(2)	.601(3)				
1.50									

Incoming WD = 185-194

Position:	1			2			3		
Length:	1.5	3.0	5.0	1.5	3.0	5.0	1.5	3.0	5.0
Height:									
0.50		.230(2)		.399(2)	.246(3)			.306(2)	
1.00	.499(2)	.630(3)		.561(2)	.578(3)		375(2)	.594(2)	
1.25		.525(3)		.685(2)	.513(2)				
1.50									

continued

TABLE 5-4 (continued)

Incoming WD = 195-204

Position:	1			2			3		
Length:	1.5	3.0	5.0	1.5	3.0	5.0	1.5	3.0	5.0
Height:									
0.50	.346(3)	.365(3)		.280(2)	.274(2)			.291(2)	
1.00	.517(3)	.656(3)		.638(2)	.632(3)		.494(2)		
1.25	.628(2)			.688(2)					
1.50									

Incoming WD = 205-214

Position:	1			2			3		
Length:	1.5	3.0	5.0	1.5	3.0	5.0	1.5	3.0	5.0
Height:									
0.50	.413(3)	.361(3)		.397(2)	.311(2)				
1.00					.672(3)		.495(2)		
1.25	.677(2)				.554(3)				
1.50									

Incoming WD = 215-224

Position:	1			2			3		
Length:	1.5	3.0	5.0	1.5	3.0	5.0	1.5	3.0	5.0
Height:									
0.50	.356(3)								
1.00									
1.25	.693(3)				.504(3)				
1.50									

Incoming WD = 225-234

Position:	1			2			3		
Length:	1.5	3.0	5.0	1.5	3.0	5.0	1.5	3.0	5.0
Height:									
0.50					.183(2)				
1.00				.145(3)					
1.25				.658(3)					
1.50									

Incoming WD = 255-264

Position:	1			2			3		
Length:	1.5	3.0	5.0	1.5	3.0	5.0	1.5	3.0	5.0
Height:									
0.50					.256(4)				
1.00									
1.25									
1.50									

continued

TABLE 5-4 (continued)

Incoming WD = >265

Position:	1			2			3		
Length:	1.5	3:0	5.0	1.5	3.0	5.0	1.5	3.0	5.0
Height:									
0.50					.311(2)				
1.00	.360(4)								
1.25									
1.50									

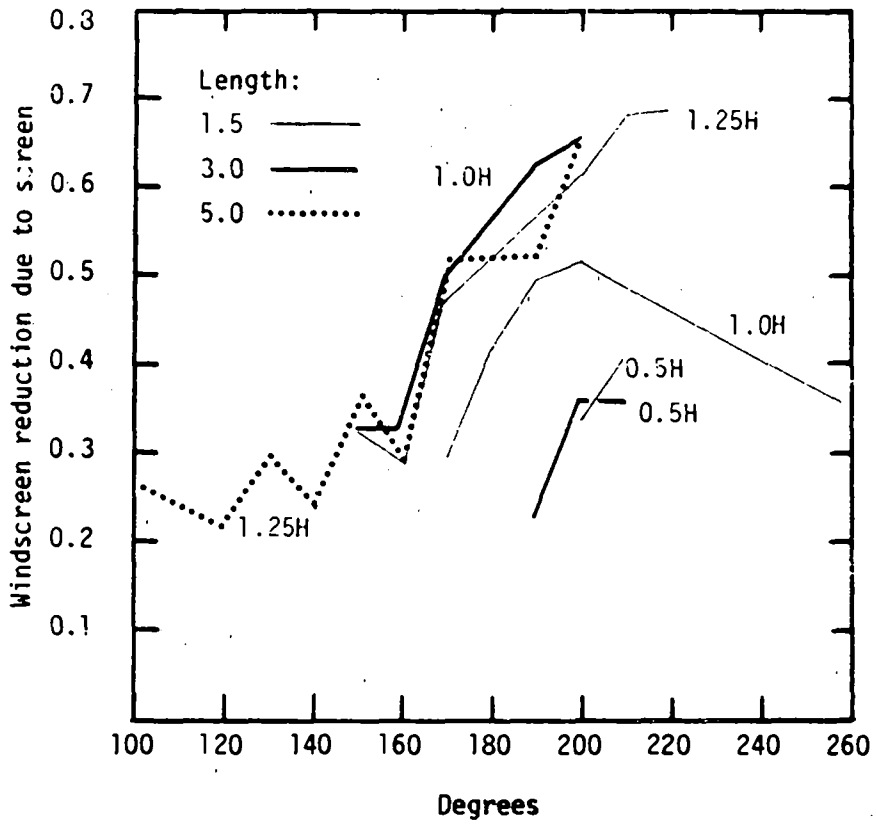


Figure 5-3. Windscreen control efficiencies for Position 1H by screen length and screen height.

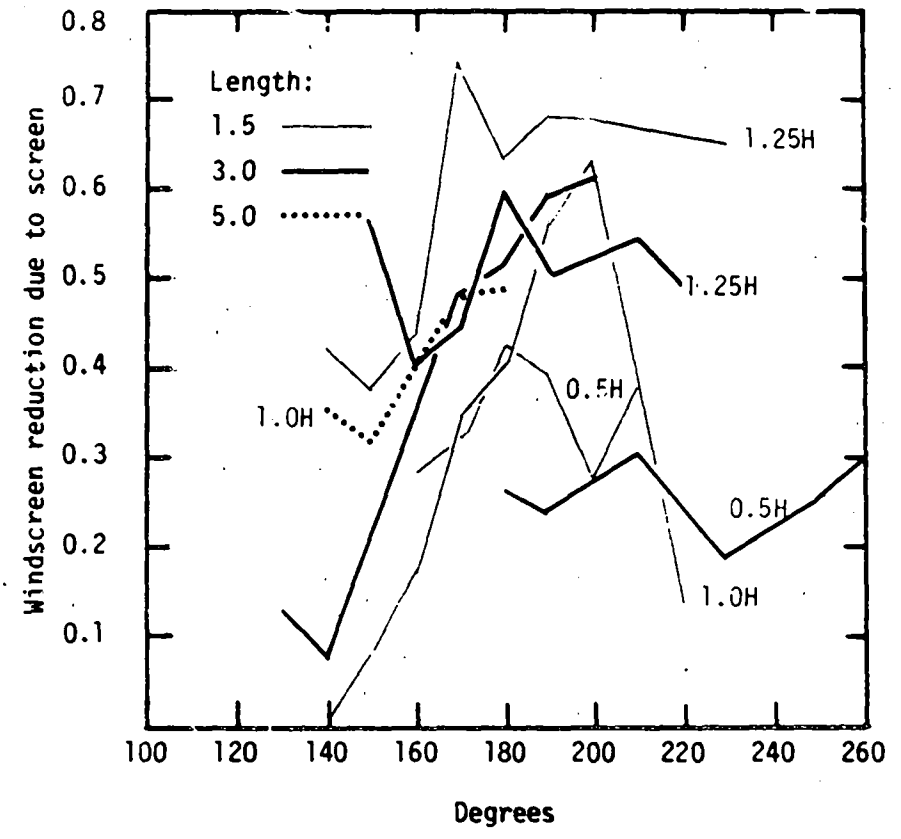


Figure 5-4. Windscreen control efficiencies for Position 2H by screen length and screen height.

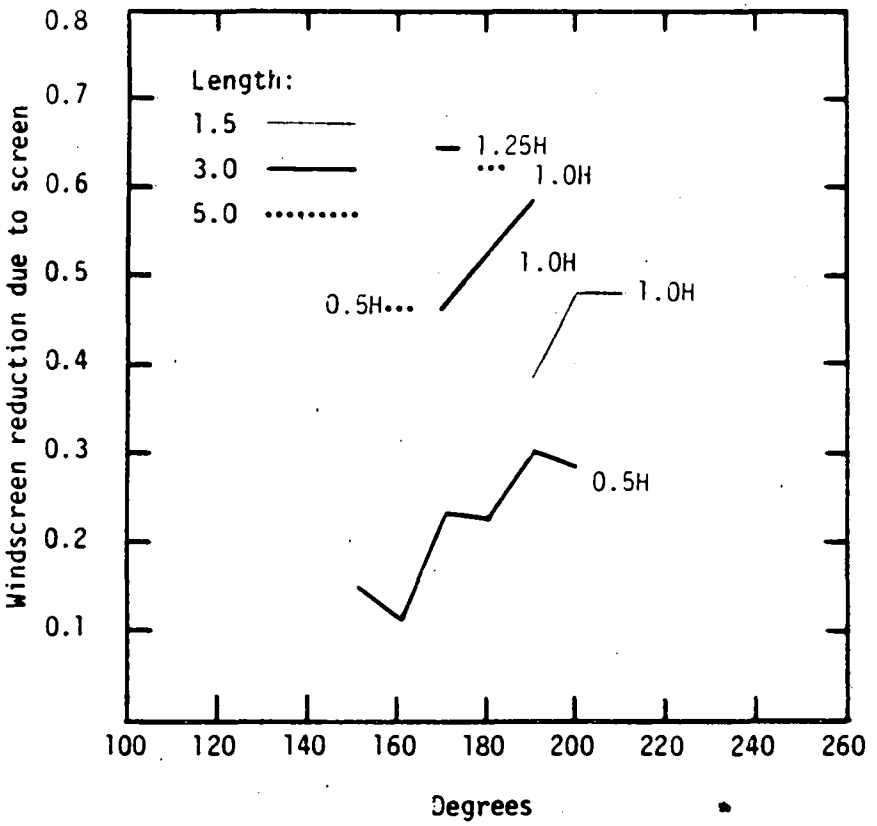


Figure 5-5. Windscreen control efficiencies for Position 3H by screen length and screen height.

- Isotach diagrams similar to Billmans' work could not be constructed because only four data points were available.
- Like Billmans findings, the taller windscreen was more effective.
- Billman found a three pile diameter distance to be more effective than a one pile diameter distance. A two pile diameter distance was not tested. The field study indicated the two pile diameter distance to be the most effective.
- Billman found a 1.5 diameter length screen to be more effective than a 1.0 diameter screen. The field study indicated that the 1.5 diameter length screen produced a higher reduction than a wider screen when winds were perpendicular, but not when they were aperpendicular.
- Billman recorded some negative screen efficiencies in the lee of the pile, but to a much lesser extent than the field data indicated.
- Although difficult to compare exactly, the wind tunnel appears to have produced efficiencies 10 to 20 percent higher than the field data on the front of the pile at position 2. In the one directly comparable test, wind tunnel values were about 40 percent higher than field data.

SECTION 6.0 OBJECTIVE 2--COMPARISON OF WINDSPEED REDUCTIONS AND PARTICULATE CONTROL EFFICIENCIES

6.1 RAM-1 PARTICULATE DATA

The first comparison of windspeed reductions versus particulate control efficiencies caused by the windscreen was with the RAM-1 data because of the potentially large data set generated by the RAM-1 samplers and because these samplers were essentially collocated on the piles with the windspeed sensors. The other available particulate data for windspeed versus particulate reductions were the profiling data, which were generated such that only a single control efficiency value was available for each test period and it applied to the entire pile rather than a specific location on the pile's surface.

RAM-1 data collection was suspended after Test 18 because of continued difficulty getting the instruments to work properly. A post-test quality assurance check of data for the first 18 tests indicated a sharp reduction in quality of data after Test 11 when the readout scale was changed (from 0-20 mg/m^3 to 0-2 mg/m^3) in an attempt to measure the very low particulate concentrations associated with periods of low windspeed. Data for Tests 12 through 18 were disqualified as a result of this QA review.

For Tests 1 through 11, collocated windspeed and RAM-1 data were available in 5 minute increments for two different positions on each pile. These positions, labeled 2 and 3 in Figure 3-3, corresponded to expected locations of maximum wind erosion on the faces of the piles. However, average windspeed

reductions were first compared with corresponding particulate reductions for entire test periods to determine general relationships. The reductions were calculated as $(1 - u_{scr}/u_{unscr})$ and $1 - (RAM_{scr}/RAM_{unscr})$ as in Section 5. The results are shown in Table 6-1.

Instead of the positive correlations that would be expected between windspeed and particulate reductions, the data in Table 6-1 yielded negative correlations of -0.708 at location 2 and -0.168 at location 3. Windspeed reductions were all in the range of 0 to 0.65, depending on the windscreen configuration, but particulate reductions were rarely within this range and showed no consistent relationship with windspeed reduction.

With the hourly average data producing such unreasonable results, it was unlikely that the 5 minute average values would produce any usable findings. Scanning of the data revealed that the 5 minute averages were indeed similar to the hourly averages and could not provide any interpretable results.

The upwind RAM-1 data were examined for possible explanations for the poor performance of the instruments. As shown in Table 6-2, the upwind concentrations were all within the expected range of values, especially considering that some construction activity occurred upwind of the study area during Test 1A. Also, the background concentrations varied with windspeed in a normal manner. The range of upwind concentrations and the relationship with windspeed were indistinguishable from those measured at the same study location in a windscreen study conducted the previous summer.

Based on the apparent validity of the upwind RAM-1 data, it would be concluded that the instruments were functioning properly but were unable to obtain accurate samples when placed near the pile surface in a quasi-source test position. The low airflow rate and vertical probe orientation on the

TABLE 6-1. EVALUATION OF AVERAGE WINDSPEED REDUCTION AND PARTICULATE REDUCTION (RAM-1) BY TEST

Test	Time period	Wind dir., °	Windspeed reduction		Particulate reduction	
			Location 2	Location 3	Location 2	Location 3
1A[a]	1300-1340	217	.02	.03	.50	.50
1B[a]	1415-1515	227	.04	.06	.57	.39
2	1130-1230	204	.36	.21	.78	.77
3	1305-1405	213	.37	.16	.75	-.24
4	1200-1240	203	.36	.21	.52	.30
5	1400-1500	194	.36	.22	.71	ND
6	1515-1600	190	.50	.44	-2.50	-1.42
7	1700-1800	186	.44	.40	-9.25	-.50
8	1800-1900	161	.36	.30	-7.00	-2.20
9	1005-1100	192	.62	.50	-.63	-.86
10	1515-1600	163	.30	.36	-8.00	.82
11	1500-1555	206	.64	.65	-1.11	-9.29

[a] No windscreen for this test. Reductions at both locations should be 0.

TABLE 6-2 UPWIND RAM-1 CONCENTRATIONS

Test	Upwind conc., μg/m³	Windspeed	
		ft/min	mph
1A	202	1704	19.4
1B	140	1745	19.8
2	42	1582	17.8
3	40	1777	20.2
4	45	1316	15.0
5	28	1383	15.7
6	11	1044	11.9
7	29	1040	11.8
8	20	819	9.3
9	26	1066	12.1
10	28	564	6.4
11	20	982	11.2

RAM-1 could contribute to this problem. Regardless of the cause of the problem, it was concluded that the RAM-1 data could not be used in the analysis.

6.2 EXPOSURE PROFILER DATA

6.2.1 Total Particulate

The next step was to compare average windspeed reductions with particulate emission reductions for entire tests as measured by the exposure profilers. There were 42 valid tests in the data set. Two alternative sets of windspeed values could potentially be the most appropriate to estimate overall pile windspeed reduction, depending on incoming wind direction during the test. Location 2 (see Figure 3-3) was near the crest of the pile in the area of maximum erosion; location 3 was about midway between the crest and bottom of the pile. With winds from the south or southeast (200° to 150°), the average of windspeed reductions at locations 2 and 3 was used as the measure of WS reduction for the test. With winds from the southwest (200° to 230°), location 3 was in the lee of the pile so location 2 alone was used to measure windspeed reductions for the test.

All applicable data for windspeed (WS) versus total particulate (TP) emission reductions are shown in Table 6-3. A linear regression of WS versus TP reductions from the table (columns 6 and 9) revealed a correlation of 0.372, R^2 of 0.138, significance level of 0.015, slope of 0.841, and y-intercept of -0.150. This indicated a significant relationship between the two variables that was nearly one to one. The data pairs for this regression are plotted in Figure 6-1.

If the linear regression was forced through zero (no windspeed reduction results in no TP reduction), the correlation improved to 0.417, R^2 was 0.174,

TABLE 6-3. COMPARISON OF WINDSPEED AND TOTAL PARTICULATE REDUCTIONS

Test	Wind dir.°	Best sensor	Wspd, ft/min screen	Wspd, ft/min exposed	Wspd rdn.	T. Partic., lb/m screen	T. Partic., lb/m exposed	T. Partic. rdn.
1B	228	2	1679	1755	.043	9.82	8.36	-.175
2	204	2	951	1480	.357	1.45	1.34	-.082
3	213	2	1039	1653	.371	2.92	2.34	-.250
4	203	2	791	1228	.356	1.04	.98	-.058
5	194	2, 3	1128, 810	1451, 1257	.289	1.26	2.52	.499
6	190	2, 3	630, 460	1129, 920	.471	.54	.66	.180
7	186	2, 3	682, 515	1134, 918	.419	.46	.49	.051
9	192	2, 3	582, 364	1174, 966	.564	.38	.47	.197
10	163	2, 3	372, 329	578, 469	.327	.02	.04	.453
11	206	2	312	869	.641	.02	.04	.471
12	166	2, 3	310, 204	462, 356	.378	.03	.03	-.061
13B	209	2	198	314	.369	.01	.01	.371
14	212	2	477	1018	.531	.04	.06	.394
15A	204	2	661	1020	.352	.03	.02	-.188
15B	203	2	641	679	.056	.03	.03	.101
16	201	2	493	580	.150	.01	.01	.029
17	187	2, 3	446, 327	583, 433	.240	.03	.08	.588
19A	200	2	256	294	.129	.03	.02	-.596
19B	162	2, 3	398, 301	456, 320	.093	.01	.01	-.111
20	208	2	343	342	-.003	.01	.01	.180
21A	196	2, 3	473, 332	1102, 884	.598	.04	.04	.108
21B	179	2, 3	556, 432	1119, 851	.498	.06	.34	.825
22	172	2, 3	587, 438	1173, 846	.491	.07	.91	.928
23A	169	2, 3	645, 479	1201, 861	.453	.20	2.15	.908
23B	157	2	230	380	.395	.02	.04	.486
24	157	2	426	455	.064	.02	.03	.192
25A	190	2, 3	771, 658	1084, 838	.252	.29	.19	-.509
25B	178	2, 3	744, 616	948, 693	.163	.15	.10	-.555
26	196	2, 3	950, 854	1091, 882	.080	.04	.03	-.431
27	202	2[a]	577	1009	.428	.17	.12	-.403
28B	203	2	424	721	.412	.09	.13	.290
29	187	2[a]	375	609	.384	.01	.02	.358
30A	185	2	419	680	.384	.04	.03	-.599
30B	180	2	433	620	.302	.02	.03	.301
31	173	2	313	545	.426	.01	.01	.357
32	160	2	305	356	.143	.01	.01	.063
33	186	2	174	289	.398	.04	.03	-.147
34A	170	2	214	275	.222	.01	.01	.391
34B	168	2	198	272	.272	.01	.01	-.071
35	162	2	310	410	.244	.01	.01	.218
36	167	2	256	380	.326	0	0	.000
105	166	2	408	389	-.049	0	0	.000

[a] Beginning with Test 27, the sensor at location 3 on the screened pile began giving erroneous readings. Therefore, only data from location 2 were used for subsequent tests.

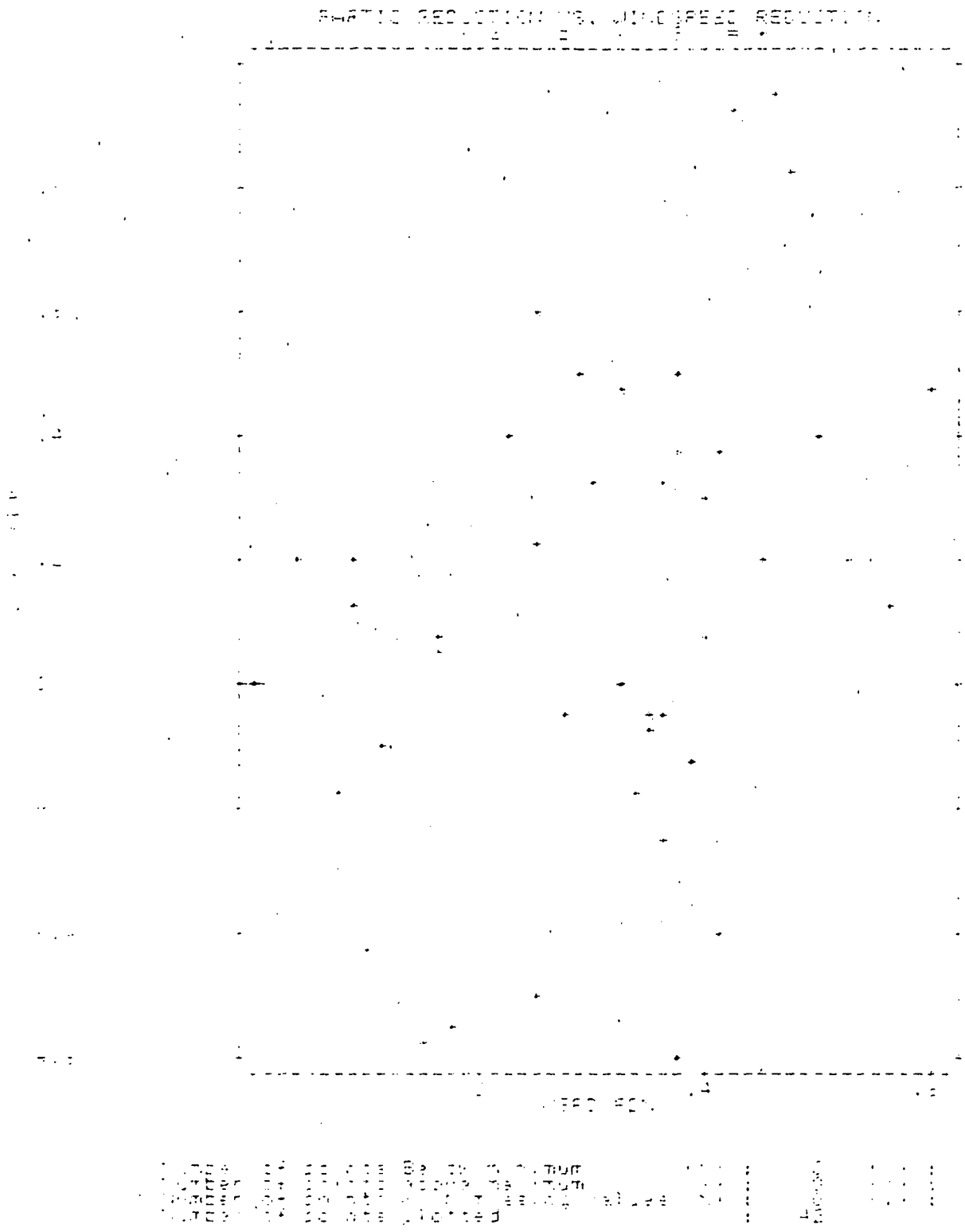


Figure 6-1. Windspeed Reduction Versus Particulate Reduction

significance level was 0.005, and the slope was 0.466. This relationship was more significant than the one above and indicated TP reductions slightly less than half of the corresponding WS reductions.

There were 15 negative TP reductions in the 42 tests (see Figure 6-1). A negative TP reduction meant that a higher emission rate was measured on the screened pile than on the exposed pile. Many of these tests in which the screen appeared to increase emissions could be the result of differences that were less than the measurement error for exposure profiling, but several of the differences in emission rate were large enough that these measurements probably reflected real occurrences of increased emissions. This observation agreed with the findings in Section 5 and in the Billman study that the windscreen actually produced increased windspeeds on the lee side of the pile during several tests.

A preliminary examination of windscreen parameters (distance, height, length) did not isolate any specific design parameter closely associated with the negative TP reductions. This topic is examined in greater detail in Section 7.

If the negative TP reductions were assumed to be due to measurement errors and set at zero, the correlation was virtually unchanged at 0.404, R^2 was 0.163, significance level was 0.010, the slope was 0.626, and the y-intercept was 0.175.

It was observed that many of the tests were taken at windspeeds too low to cause wind erosion and during other tests the moisture content of the pile was so high that erosion would not occur even with high windspeeds. Twenty of these tests with negligible emissions were eliminated to see whether the windspeed-emission rate relationship was stronger during tests with wind

erosion. The results of this regression analysis were: $R = 0.287$, $R^2 = 0.082$, significance level = 0.184, slope = 0.859, and y-intercept = -0.122. According to this analysis, the tests with negligible emissions did not appear to be distorting the calculated relationship between the two variables.

If the relation between WS and TP reductions is not linear, the correlation between these variables would be improved by transforming one of the variables to its natural logarithm (ln) form. When WS was ln-transformed, the results were: $R = 0.362$, $R^2 = 0.131$, and significance level = 0.022. This result indicated that WS and TP reductions were approximately linearly related rather than to some power.

From the above regression analyses, it can be concluded that a highly significant relationship exists between windspeed and particulate emission reductions, and that the relationship is approximately linear with a slope less than one (one percent reduction in windspeed results in less than one percent reduction in particulate emissions). Also, there appear to be instances in which windspeed on the front face of the pile is reduced by the windscreen but emissions from the pile actually increase as a result of higher windspeeds on the back side of the pile. In general, windscreen configuration should not affect the relationship between windspeed and emission reduction.

6.2.2 Particle Size Data

The emission rates of particles within several size ranges were determined by selecting a heavily loaded filter from each profiling test and subjecting it to laser diffraction analysis. The resulting percentages of net sample weight by particle size range were then multiplied by the TP emission rate for the test to get emission rate by particle size range. The effectiveness of the windscreen in reducing emissions for each size range was then

calculated as $(1 - ER_{scr}/ER_{exp})$ for that range, as shown in Table 6-4.

Next, the particulate reductions by size range (from the last five columns on Table 6-4) were compared with corresponding windspeed reductions in the same manner as with the TP reduction data, i.e., regression analysis. The results of these analyses are summarized in Table 6-5. The entire sequence of regressions performed for TP was not repeated for the size fractions. The regular binary regression and the regression forced through zero were done for each size range; but removal of negative emission reductions, removal of tests with negligible emissions, and ln transformation were not performed.

None of the particle size ranges had as significant a relationship with windspeed as TP did, partially because of the smaller data sets available with the particle size data (19 tests instead of 42). Particle size data could not be obtained on many filters because of their light mass loadings. The particle size emission reductions that had the highest correlations with windspeed reduction were 30-62 μm and 62-176 μm. The two small particle size ranges both had poor correlations. Slopes of regression lines for the two particle sizes that were reasonably significant were higher than slopes for TP, indicating an emission reduction (in those size ranges) almost equal to windspeed reduction. No explanation was apparent for differences in variation with windspeed for the different particle sizes.

The same frequent negative emission reductions were observed in all particle size ranges as for TP (see Table 6-5). This is a good indication that increased emissions were actually occurring as a result of the screen, rather than anomalous results from sampling or lab analysis errors. The negative reductions did not all occur in the same tests, or in the tests that had negative TP reductions.

TABLE 6-4. CALCULATION OF EMISSION RATES BY PARTICLE SIZE RANGE

Test	Pile	Sample wt. by particle size, %					Em. rate by particle size, lb/meter					Rdr by screen by size				
		<10	10-30	30-62	62-175	>175	<10	10-30	30-62	62-176	>176	<10	10-30	30-62	62-176	>176
1B	E	1.2	8.4	25.5	40.9	24.0	.10	.70	2.13	3.42	2.01					
1B	S	1.1	8.0	18.9	40.6	31.4	.11	.79	1.86	3.99	3.08	-.10	-.13	.13	-.17	-.53
2	E	1.8	8.7	23.7	52.2	13.6	.03	.12	.32	.70	.18					
2	S	3.4	15.9	26.5	45.0	9.2	.05	.23	.38	.67	.13	-.67	-.92	-.19	.04	.28
3	E	1.8	13.7	27.0	46.4	11.1	.04	.32	.63	1.09	.26					
3	S	1.5	6.2	24.7	44.8	22.8	.04	.18	.72	1.31	.67	0	.44	-.14	-.20	-1.58
4	E	4.3	7.3	27.4	43.6	17.4	.04	.07	.27	.43	.17					
4	S	2.0	7.1	24.8	48.0	18.1	.02	.07	.26	.50	.19	.50	0	.04	-.16	-.12
5	E	0.9	8.1	19.4	43.4	28.2	.02	.21	.49	1.09	.71					
5	S	2.6	7.8	22.7	45.7	21.2	.03	.10	.29	.57	.27	-.50	.52	.41	.48	.66
6	E	2.8	4.6	15.5	41.5	35.6	.02	.03	.10	.27	.24					
6	S	0.4	1.9	6.6	56.9	34.2	.01	.01	.04	.31	.18	.50	.67	.60	-.15	.25
7	E	1.5	4.3	10.9	61.2	22.1	.01	.02	.05	.30	.11					
7	S	1.5	2.5	11.6	64.1	20.3	.01	.01	.05	.29	.09	0	.50	0	.03	.18
9	E	0.9	2.5	14.1	52.7	29.8	.01	.01	.07	.24	.14					
9	S	5.0	8.5	13.0	46.4	27.1	.02	.03	.05	.18	.10	-1.0	-2.0	.29	.25	.29
14	E	4.3	5.1	9.8	39.4	40.4	0	0	.01	.02	.03					
14	S	1.6	2.0	12.3	46.9	37.2	0	0	.01	.02	.01	0	0	0	0	.67
17	E	4.5	5.3	12.4	30.2	47.6	0	.01	.01	.02	.04					
17	S															
21A	E	1.3	0.8	10.9	70.4	16.6	0	0	.01	.03	.01					
21A	S	9.2	0	15.6	37.4	37.2	0	0	.01	.02	.02	0	0	0	.33	-1.0
21B	E	4.1	7.7	17.1	53.9	17.2	.01	.03	.06	.18	.06					
21B	S	2.7	3.4	13.1	40.6	40.2	0	0	.01	.03	.02	1.00	1.00	.83	.83	.67
22	E	3.5	6.0	24.9	43.1	22.5	.03	.06	.23	.39	.20					
22	S	0.4	3.5	9.9	43.0	43.2	0	0	.01	.03	.03	1.00	1.00	.96	.92	.85

TABLE 6-4 (continued)

Test	Pile	Sample wt. by particle size, %					Em. rate by particle size, lb/meter					Rdn by screen by size				
		<10	10-30	30-62	62-175	>175	<10	10-30	30-62	62-176	>176	<10	10-30	30-62	62-176	>176
23A	E	1.3	7.7	22.7	39.1	29.2	.03	.17	.49	.84	.62					
23A	S	2.5	4.5	9.9	42.4	40.7	.01	.01	.02	.08	.08	.67	.94	.96	.90	.87
23B	E	0	3.8	16.3	49.3	30.6	0	0	.01	.02	.01					
23B	S															
25A	E	4.6	9.7	12.5	37.2	36.0	.01	.02	.02	.07	.07					
25A	S	3.6	8.3	10.8	50.6	26.7	.01	.02	.03	.15	.08	0	0	-.50	-1.14	-.14
25B	E	2.1	2.3	17.5	59.9	18.2	0	0	.02	.06	.02					
25B	S	5.2	7.1	11.9	58.0	18.8	.01	.01	.02	.09	.03	-∞	-∞	0	-.50	-.50
27	E	0.5	2.3	16.8	69.5	10.9	0	.01	.02	.08	.01					
27	S	1.6	2.5	14.4	51.7	29.8	0	.01	.02	.09	.05	0	0	0	-.13	-5.00
28B	E	0.3	4.7	16.1	43.2	35.7	0	.01	.02	.06	.04					
28B	S	2.0	7.1	10.0	54.4	26.5	0	.01	.01	.05	.02	0	0	.50	.17	.50
30A	E	2.1	0.2	13.8	48.5	35.4	0	0	.01	.01	.01					
30A	S	0.4	7.5	11.6	47.2	33.3	0	0	.01	.02	.01	0	0	0	-1.0	0
12	E	0.2	0.7	12.6	49.9	36.6	0	0	.01	.01	.01					
12	S	1.0	2.1	8.8	35.9	52.2	0	0	0	.01	.02	0	0	1.0	0	-1.0
26	E	2.0	1.3	22.0	62.0	12.7	0	0	.01	.02	0					
26	S	0.7	1.8	15.3	63.4	18.8	0	0	.01	.02	.01					

Note: E = exposed (no windscreen), S = screened

TABLE 6-5. IMPACT OF WINDSPEED REDUCTIONS ON PARTICLE SIZE EMISSION REDUCTIONS

Dependent variable	Regression against windspeed reduction				
	R	R^2	Signif. level	Slope	y-int.
Emission rdn. in size range:					
<10 μm	.166	.028	.510	.674	-.195
10-30 μm	-.018	.000	.945	-.099	.152
30-62 μm	.301	.091	.210	.971	-.124
62-176 μm	.426	.181	.069	1.860	-.651
>176 μm	.269	.072	.266	1.368	-.545
TP	.372	.138	.015	.841	-.150
Regression line forced through zero					
<10 μm	.194	.038	.425	.233	0
10-30 μm	.147	.022	.547	.245	0
30-62 μm	.572	.327	.008	.688	0
62-176 μm	.263	.069	.263	.370	0
>176 μm	.075	.006	.755	.121	0
TP	.417	.174	.005	.466	0

6.3 FACTORS OTHER THAN WINDSCREEN AFFECTING EMISSION RATES

6.3.1 Total Particulate

The approach used to identify external variables that affected emission rates from the piles was multiple linear regression (MLR) analysis. Only test data from the unscreened pile were utilized, since these emission rates were not altered by the presence of the windscreen.

The variables included in the analysis were windspeed, moisture content, and silt content of surface material. Particle size was also a variable in that MLR analyses were run with four different sets of emission rates (<10 μm, <30 μm, <62 μm, and TP) as dependent variables to examine the effects of the external variables on different size ranges of particles. Analyses with size fractions are presented in the next subsection of this report. Wind direction was not considered to be a variable because the sampler inlets were pointed directly into the wind on each test and the profiling tower was placed in approximately the same location downwind of the pile.

Initially, all 42 tests with exposure profiling data were included in the MLR run. As shown in Table 6-6, the multiple-R^2 with all three variables was 0.481 and the MLR equation was significant at the 0.000 level. In other words, the three specified variables explained 48.1 percent of the variation in TP emission rates and the probability that the three variables were not related to emission rate was less than 0.05 percent.

From the initial run, windspeed and moisture content appeared to be highly significant variables, but silt content was marginal. Silt had a negative coefficient, indicating a decrease in emissions with increased fine

TABLE 6-6. MLR RUNS TO IDENTIFY VARIABLES THAT AFFECT EMISSION RATES

Description of MLR Run	No. of Tests	Indep. Variable	Simple Correl.	Partial Correl.	Signif. of var. in egn.	Coeff.	Inter-cept	Mult. R^2	Adjusted R^2	Signif. of eqn
1. Initial	42	wndspd	.614	.535	.000	0.002	0.091	.481	.439	.000
		moist	-.352	-.292	.018	-0.401				
		silt	-.312	-.100	.018	-0.061				
2. Eliminate low WS and high MC tests	22	wndspd	.719	.284	.083	0.002	0.812	.570	.498	.002
		moist	-.677	-.204	.205	-1.261				
		silt	-.371	-.103	.514	-0.080				
3. Eliminate silt	22	wndspd	.719	.278	.005	0.004	-2.537	.507	.458	.001
		moist	-.677	-.242	.008	0.081				
4. ln-transformed variables	22	wndspd	.629	.032	.845	0.158	1.068	.763	.726	.000
		moist	-.871	-.569	.000	-2.067				
		silt	-.405	-.116	.629	-0.489				
5. ln-transformed	22	wndspd	.629	.030	.785	.214	-0.485	.760	.736	.000
		moist	-.871	-.604	.000	-2.108				
6. ln-transformed back to full data set	42	wndspd	.486	.387	.000	1.118	-6.572	.683	.667	.000
		moist	-.730	-.668	.000	-1.346				

particles in the pile, and a significance of 0.402. Also, when the variables were placed in the equation stepwise, the root mean square error (RMSE) term increased when silt was added as the third variable.

As part of the regression analysis, each of the independent variables was plotted against TP emission rate. The resulting graphs are shown in Figures 6-2 through 6-4. It was observed that tests with windspeeds less than about 900 ft/min (10.2 mph) and tests with moisture contents greater than about 1.5 percent all had very low emission rates.

Since these appeared to be thresholds beyond which the variable no longer reduced emission rates, some of the test data in these insensitive zones were eliminated from the data set to see if correlation could be improved for the smaller data set. The cut points arbitrarily used were 500 ft/min (5.7 mph) and 2.0 percent moisture content (MC). This eliminated 20 of the 42 tests. None of the eliminated tests had a TP emission rate greater than 0.08 lb/meter.

The MLR results for the smaller data set (run 2) were slightly better, with a multiple-R^2 of 0.570 and a significance level of 0.002 (see Table 6-6). Again, the silt variable was not highly significant and had a negative coefficient. It should probably not be included in an MLR predictive equation. Without the silt variable, multiple-R^2 was 0.507 and the significance level improved to 0.001. The MLR equation was: $ER = 0.48\ WS - 2.31\ MC - 2.537$ lb/meter.

Most current emission factors for fugitive dust sources adjust for the effect of external variables by use of multiplicative correction parameters. For instance, the most widely used emission factor equation for unpaved roads is:

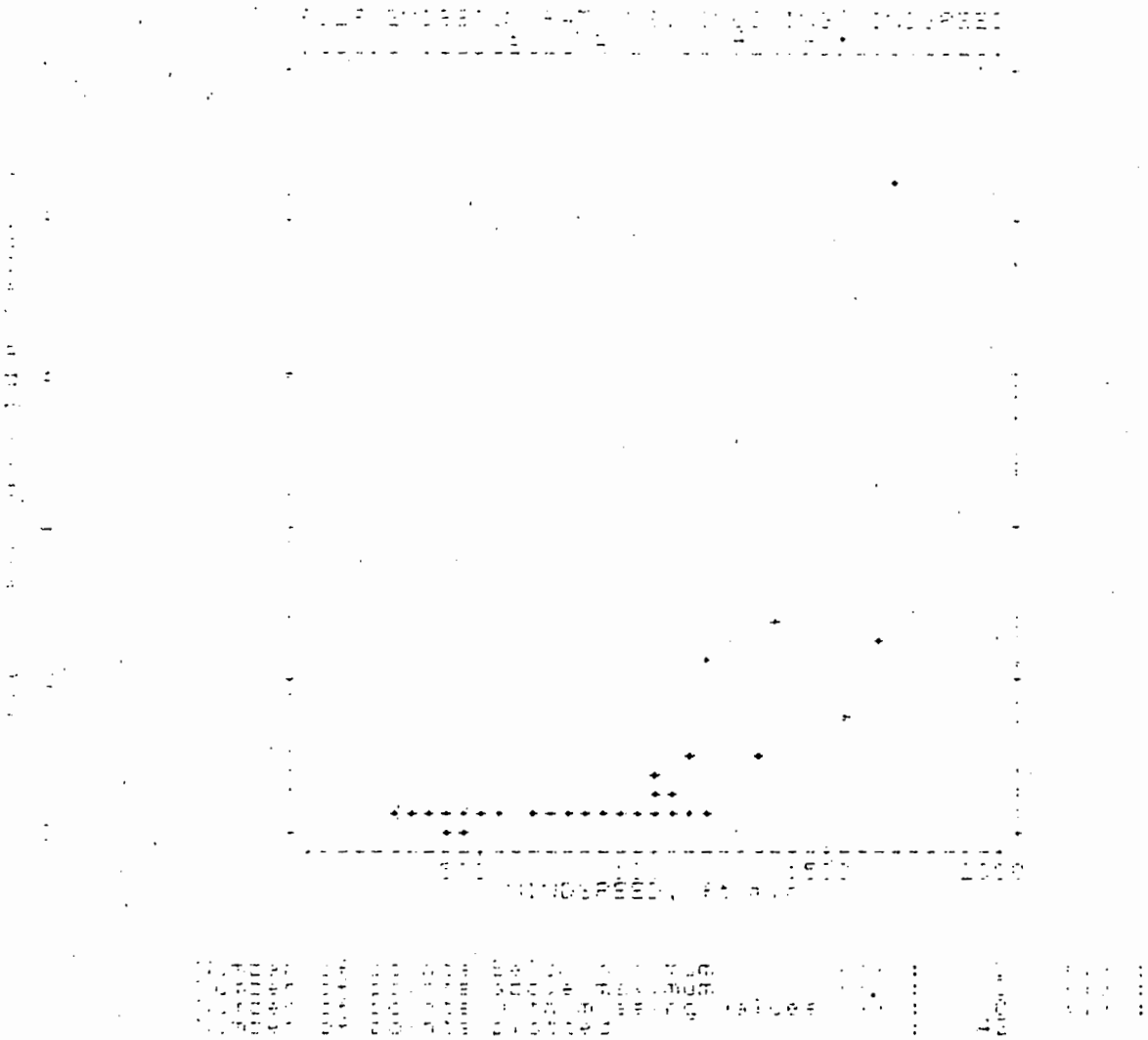


Figure 5-2. Scatter Plot of Emission Rate vs. Windspeed.

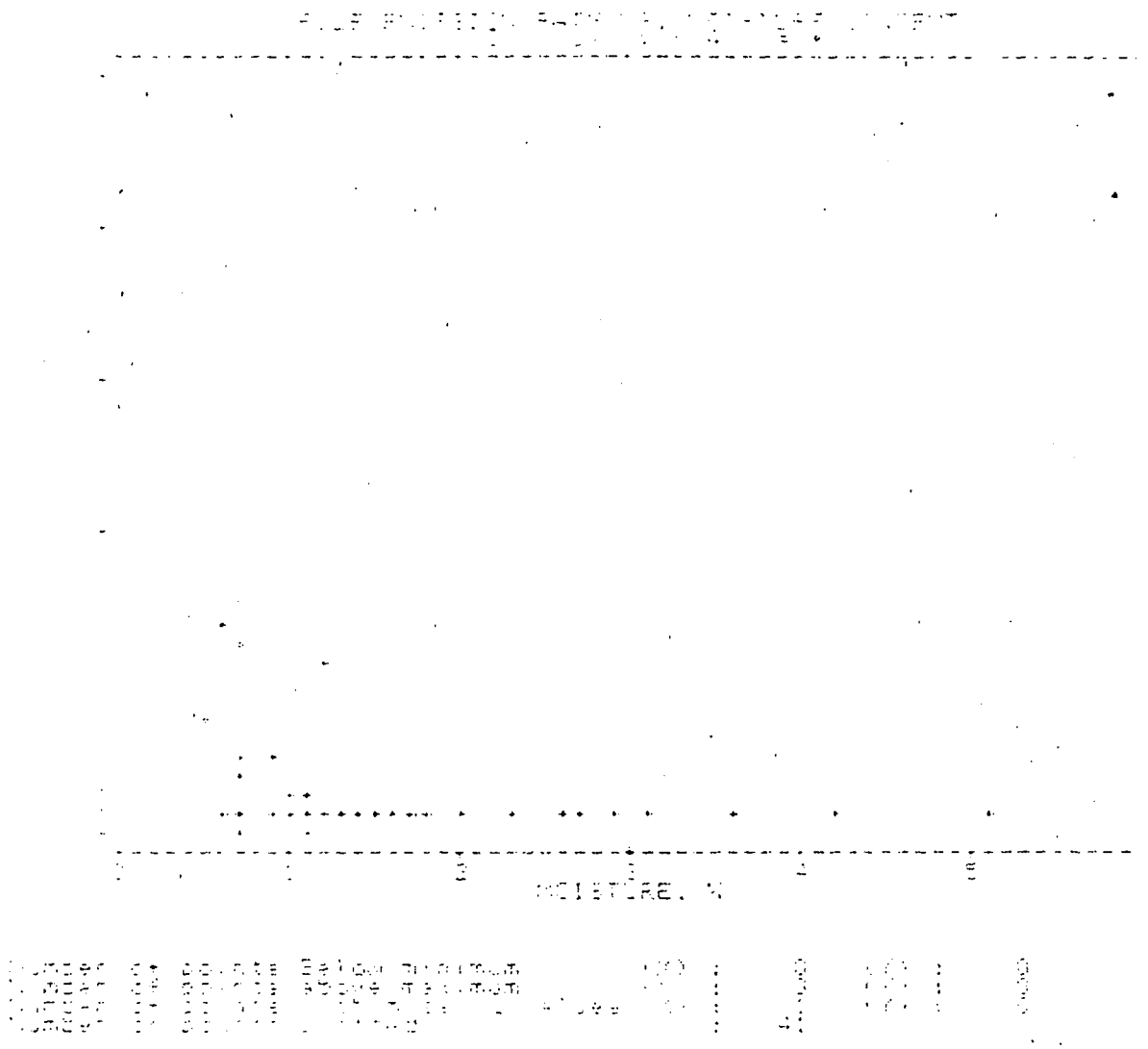


Figure 6-3. Scatter Plot of Emission Rate vs. Moisture Content

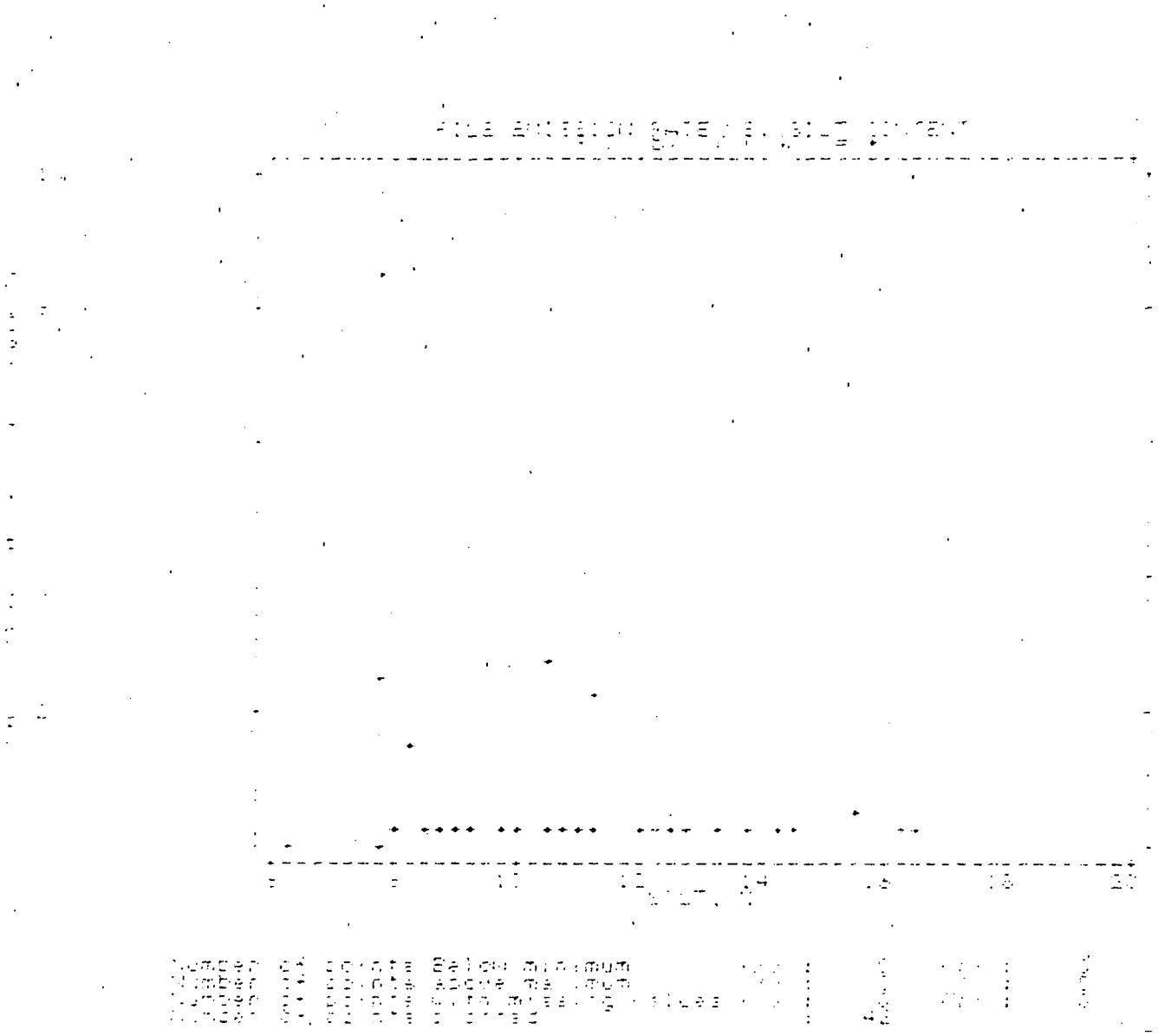


Figure 6-4. Scatter Plot of Emission Rate vs. Silt Content

$$E = 5.9\ (k)\left(\frac{s}{12}\right)\left(\frac{S}{48}\right)\left(\frac{W}{2.7}\right)^{0.7}\left(\frac{w}{4}\right)^{0.5}\left(\frac{365-P}{365}\right) \text{lb/VMT}$$

in which k, s, S, W, w, and P are correction parameters to adjust for significant variables such as silt content, vehicle speed, vehicle weight, and days per year with measurable precipitation. In order for a multiple regression equation for storage pile emissions to be in a multiplicative form, the variables to be included must be transformed to their natural logarithms (ln) and the MLR rerun.

When the windspeed and moisture data were transformed, the resulting MLR results (with the smaller data set) were greatly improved, as shown in Table 6-6. The multiple-R^2 was 0.760 and the significance level was 0.000. The individual variables were significant at the 0.784 level for WS (not significant) and at the 0.000 level for MC.

The regression coefficients of the transformed WS and MC terms were 0.214 and -2.108, respectively, and the best fit equation was:

$$ER = 0.0078\ (WS)^{0.21}(MC)^{-2.1}$$

The -2.1 power agrees quite well with exponents in other fugitive dust emission factor equations, which generally range from -1.3 to -2.0. The 0.21 power for windspeed, however, indicated that emissions were much less than lineraly related to windspeed, in contrast to the cubic relationship cited in Section 2 of this report. WS was not significant in the equation, so it is not likely that its exponent is meaningful.

If the entire data set of 42 tests were used with ln transformation, the percent of variation explained (multiple-R^2) was lower at 0.683, but the significance level of the overall equation and the two individual variables were 0.000. With the addition of the data points that were insensitive to

changes in windspeed and/or moisture content, the coefficients became 1.118 for WS and -1.346 for MC and the best fit equation was:

$$ER = 0.00012\ (WS)^{1.12}(MC)^{-1.35}$$

The exponents in this equation agree better with previous published work, and this equation is more stable over the entire range of WS and MC values tested.

Silt data were input as their ln-transformed values into the above two MLR runs. Results were essentially the same as with the untransformed data: the ln silt variable did not increase the Multiple-R^2, it had a relatively low simple correlation with emission rate, it had about a 0.40 significance level, and it varied inversely with emission rate.

An independent statistical review of the data was performed and is reported in Appendix A. Their analyses indicated an exponent of 2.53 for WS which agrees well with previous fugitive dust control research which suggests an exponent of 3.

6.3.2 Particle Size Data

The MLR analysis described above for total particulate was also done for emission rates in the particle size ranges of <10, <30, and <62 μm. Emission rate data by size range, obtained by laser diffraction of the filters were previously presented in Table 6-4. The whole sequence of MLR runs was not repeated, just those runs with ln-transformed variables and the full data set. However, the ln silt variable was included in one run for each size range to determine whether silt in the pile had an effect on emission rates of smaller particles. The results of the particle size MLR analyses are summarized in Table 6-7.

The multiple-R^2 were greatest for the smallest size range and consistently decreased with larger particle sizes. This result could be interpreted

TABLE 6-7. MLR RUNS WITH EMISSION DATA BY PARTICLE SIZE RANGE

Dependent variable	Indep. variable	Simple correl.	Partial correl.	Signif. of var. in eqn.	Coeff. (expon.)	Mult. R^2	Adjusted R^2	Signif. of eqn.
Total particulate	wndspd	.486	.373	.000	1.104	.684	.658	.000
	moist	-.730	-.636	.000	-1.334			
	silt	-.324	-.021	.824	-.141			
Total particulate	wndspd	.486	.387	.000	1.118	.683	.667	.000
	moist	-.730	-.668	.000	-1.346			
<10 μm	wndspd	.646	.258	.031	.019	.780	.743	.000
	moist	-.831	-.552	.000	-.019			
	silt	-.462	-.088	.437	-.011			
<10 μm	wndspd	.646	.285	.018	.021	.772	.748	.000
	moist	-.831	-.596	.000	-.019			
<30 μm	wndspd	.592	.196	.124	.115	.735	.691	.000
	moist	-.811	-.541	.000	-.143			
	silt	-.499	-.150	.233	-.143			
<30 μm	wndspd	.592	.235	.071	.135	.713	.683	.000
	moist	-.811	-.602	.000	-.153			
<62 μm	wndspd	.560	.159	.212	.331	.728	.683	.000
	moist	-.821	-.574	.000	-.537			
	silt	-.476	-.130	.305	-.440			
<62 μm	wndspd	.560	.193	.134	.391	.711	.681	.000
	moist	-.821	-.631	.000	-.569			

to mean that windspeed and moisture content have a greater or more predictable effect on emissions of small particles, which certainly agrees with the theoretical discussions in Section 2.

The significance of the equations for the size fractions was just as high as for TP (0.000) even though a smaller data set was used. Size data were not available for some of the tests because very light filter loadings did not permit the laser diffraction method to be used.

The exponents for WS and MC in the MLR equation were smallest for the <10 μm size range and were consistently larger as the particle size range increased. An explanation for this is not apparent, but this same variation has been observed with other fugitive dust emission factor equations that have been derived separately for different size ranges (e.g., coal mining factors).

Moisture was the variable with the highest simple and partial correlation in every particle size range. It was also the most significant variable in every MLR equation. Windspeed was highly significant in the TP and <10 μm runs, but only marginally significant (0.071 to 0.212) for the <30 μm and <62 μm runs. Silt was not a significant variable for any of the size ranges in addition to not being significant in the TP run. This was an unexpected finding, and indicates that wind erosion rates are relatively independent of available silt-sized material near the surface or that the material sampling procedure does not accurately reflect the size distribution of material available for erosion.

In summation, two external variables--windspeed and moisture content--explained an extremely high percent of variance in emission rates from the unscreened storage pile. Approximately the same relationship was observed between the two variables and emission rate regardless of the size fraction of

emissions used in the analysis. Some interrelationship was anticipated, in that fractional emission rates were calculated as a percent of total mass flux rate for each test, providing a fixed upper limit value for the emissions for each test. The additional information furnished by the particle size MLR runs was that the size distribution of emissions from test to test had to be quite consistent in order to achieve the similar MLR results.

Also, several data subsets and additional external variables were examined in different MLR runs. The relationship between windspeed, moisture content, and emission rate demonstrated good stability in these different runs.

SECTION 7.0 OBJECTIVE 3--DEVELOPMENT OF WINDSCREEN DESIGN PARAMETERS

7.1 SCREEN HEIGHT, LENGTH, AND DISTANCE FROM PILE

For the three windscreen design parameters that were varied by test, the field test results should provide better information than wind tunnel data for optimizing design values. This is because conditions such as wind direction variation, surface moisture content, and crusting could be incorporated in field testing but not in wind tunnel studies.

The statistical test employed was stepwise MLR. This procedure identified which variables had the closest relationship to (and presumably the greatest effect on) emission rate reduction. The three windscreen variables--height, length, and distance from pile--were entered along with exogenous variables such as windspeed, surface moisture content, and silt content. Stepwise MLR also removed the effect of one or more variables from the data set (by modifying values of the dependent variable) so that the effect of remaining variables could be examined better.

Originally, these analyses were to be performed with the sub-10 μm and sub-30 μm data sets. However, the smaller number of tests available (19 versus 42) and the generally good agreement between analyses done with TP and those done with specific particle sizes resulted in a change to TP emission reductions as the dependent variable in all these MLR runs. The full data set and the subset of 22 tests in which wind erosion losses were probable because of high winds and dry soil surface were both subjected to the MLR analysis.

Results of the two stepwise MLR runs are presented in Table 7-1. In both cases, screen length and screen height were the two most significant variables. In particular, screen length seemed to be highly correlated with emission reductions. According to the coefficients in the final equations, each increase of one pile diameter would cause emission reductions to improve by 13 to 16 percent. The corresponding coefficients when screen length was regressed alone with TP emission reduction were 22 and 28 percent. Screen height had much lower correlation and was a less significant variable in the equations than screen length, but it had a consistent coefficient in the range of 38 to 45 percent reduction in emissions for each increase of one pile height in the screen height. Of course, these regression equations are only applicable over the range of the test data, which was 1.5 to 5 pile diameters for screen length and 0.5 to 1.25 pile heights for screen height.

As indicated in Table 7-1, the screen-to-pile distance did not appear to be related to emission reductions. The test range of 1.0 to 3.0 pile heights distance was a narrower range than used in previous field testing or in the wind tunnel work. It was an attempt to "fine tune" this design parameter, but for MLR analysis it resulted in no definitive findings.

None of the exogenous variables had such an overriding effect on relative emission rates with and without the screen that they obscured the impacts of changes in screen parameters. By including these variables in the MLR, the relatively small effects of these variables were taken into account rather than acting as interferences in the direct comparison of test results.

In the study design, four separate tests with the same combination of screen length, height, and distance were planned. This would have allowed the plotting of emission rates as a function of each variable separately (e.g.,

TABLE 7-1. STEPWISE MLR TO EVALUATE WINDSCREEN DESIGN PARAMETERS

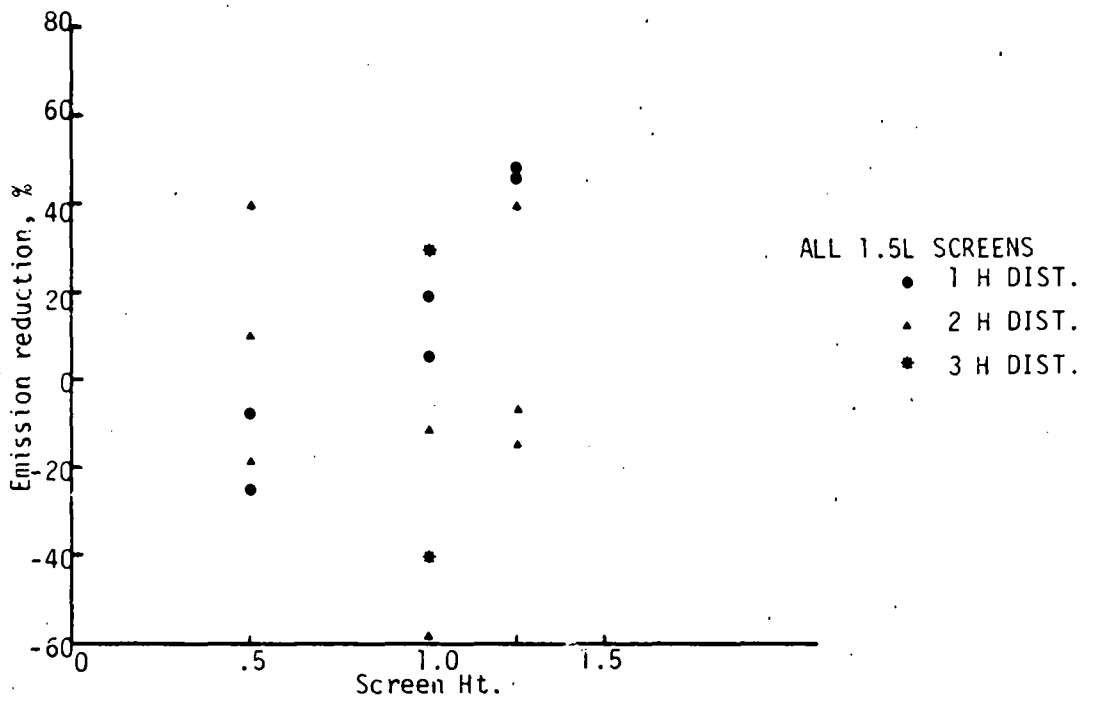
Description of run	Indepen. Variable	Simple correl.	Signif. of var. in final eqn.	Coeff.	Mult. R^2	RMSE	Signif. of eqn.
All 42 tests	Screen length	.474	.016	.13	.225	.345	.000
	Screen height	.293	.171	.38	.242	.345	.007
	Moisture	.100	.240	.07	.260	.346	.017
	Windspeed	.046	.312	.0002	.274	.347	.038
	Screen distance	.277	.512	.03	.283	.350	.052
	Silt	.186	.823	.0057	.283	.355	.063
22 tests with high winds and low moisture	Screen length	.532	.089	.16	.284	.377	.002
	Screen height	.355	.301	.45	.305	.380	.021
	Windspeed	.243	.383	.0004	.316	.387	.050
	Moisture	.186	.515	.19	.332	.392	.096
	Silt	.373	.603	.04	.342	.400	.184
	Screen distance	.226	.777	.02	.345	.410	.238

screen height) with the other two parameters being held constant (e.g., only tests with screen length of 3 diameters and pile distance of two heights). However, with the shortfall in total tests--100 were planned--not enough data points were generated to carry out this plan. Curves have been generated which eliminate one of the other two variables. These are presented as Figure 7-1, 7-2 and 7-3, which look at screen height, screen length, and screen-to-pile distance, respectively.

From these plots, it did not appear that screen height had an effect on emission reductions in the range of heights tested. Also, the pronounced scatter in the data is accentuated by this type of presentation. It is unfortunate that none of the 1.5-pile-height screen height tests specified in the study design were conducted. Screen length had an obvious effect on emissions when tests of 5.0 diameter screen length were included (upper right graph in Figure 7-2). The advantage of a 3.0-pile-diameter screen over a 1.5-pile-diameter screen was not apparent in the other two graphs. This could tentatively lead to a conclusion that a screen length longer than 3.0 diameters is needed to get consistent emission reductions. Given the >40° variations in wind direction that occurred during some of the one-hour tests periods, the 5.0-pile-diameter length seems reasonable for a permanent or semi-permanent installation.

Although the MLR results did not reveal any trend in emission rates with screen distance from the pile, the plots in Figure 7-3 appear to show that the 2.0-pile-height distance is superior to either the 1.0- or the 3.0-pile-height distances. Again, the scatter in these data points makes conclusive findings difficult.

By combining the results of the MLR and graphic analyses, the following



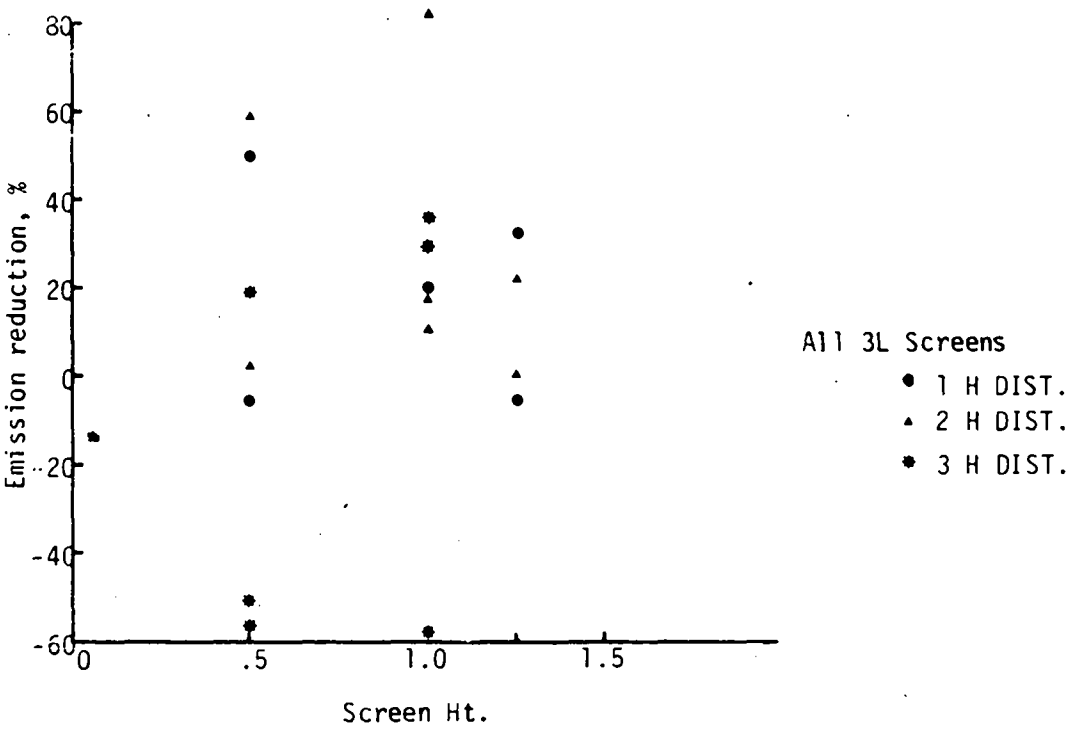


Figure 7-1. Evaluation of Screen Height.

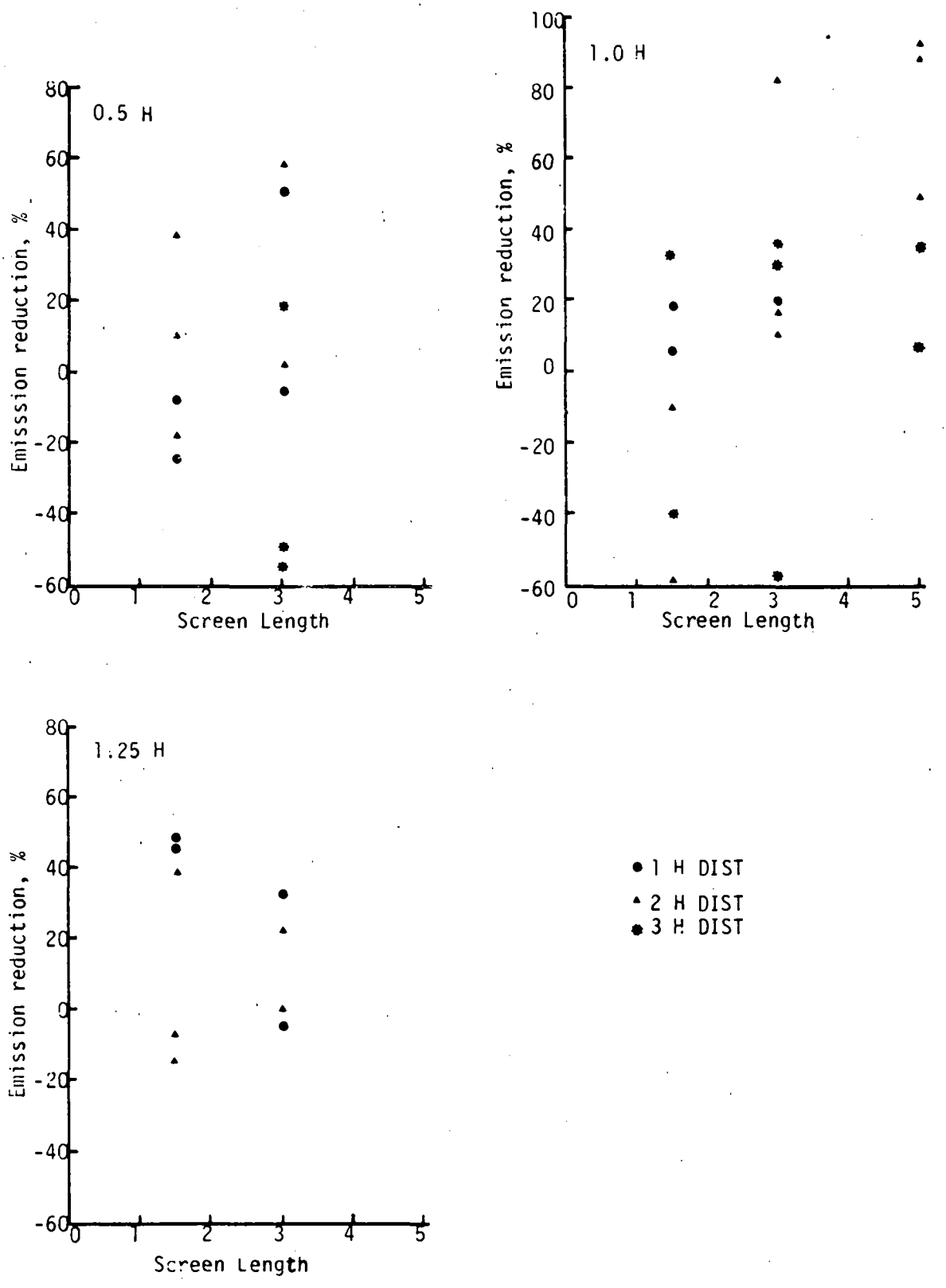
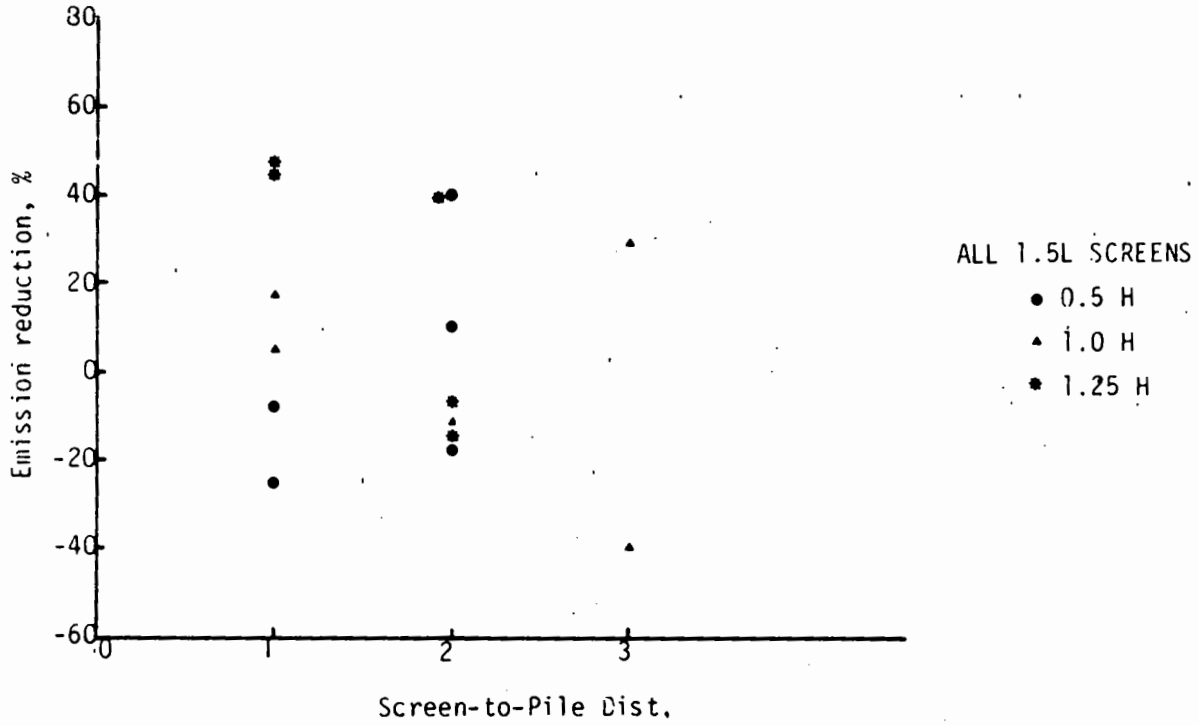


Figure 7-2. Evaluation of Screen Length



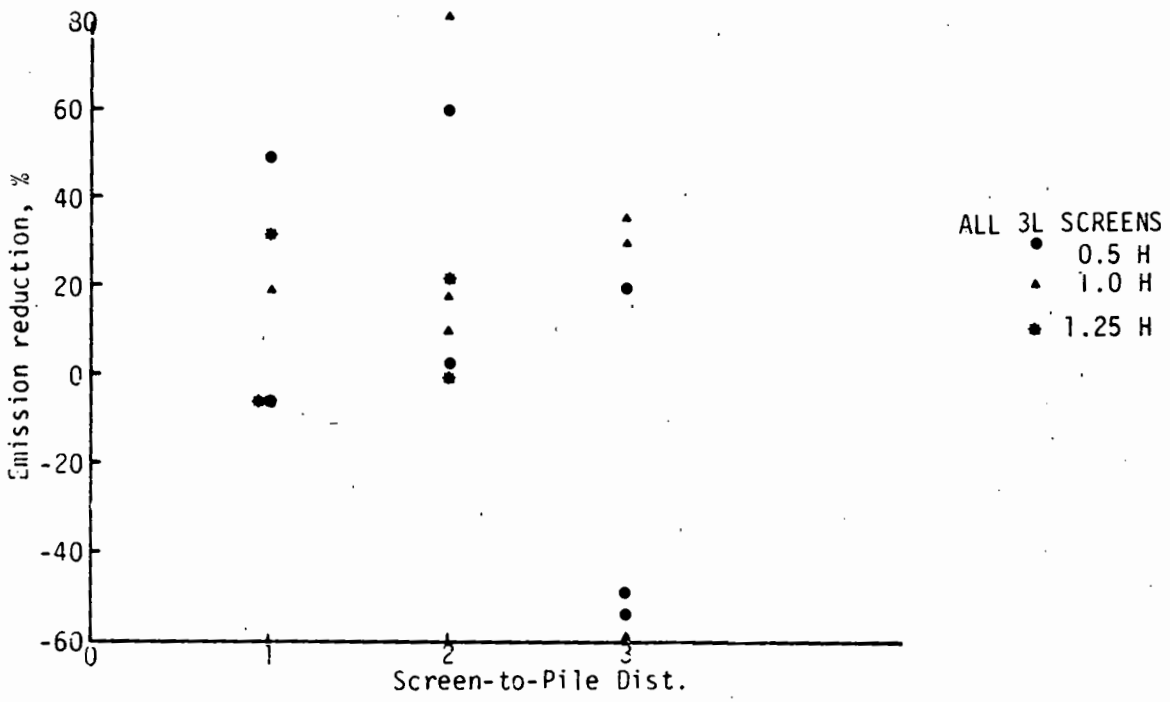


Figure 7-3 Evaluation of Screen-to-Pile Distance

design conclusions could be drawn:

- Screen length--This parameter does not optimize at a certain length. In general, the longer the screen (or in the case of a curved screen, the greater the arc covered) the lower the emissions should be.
- Screen height--The large reductions in emissions estimated by MLR (38 to 45 percent per pile height) are not apparent in the plots. It should be emphasized that the MLR results were not highly significant for screen height. Screens higher than the pile appear to be only marginally beneficial.
- Screen-to-pile distance--Previous studies had shown distances of 1.0- to 3.0-pile-heights to be better than shorter or longer distances. Within that range, the 2.0-pile-heights distance may be the optimum distance.

These results confirmed conclusions of Billman's wind tunnel study for screen height and distance but differed with respect to design of screen length. The wind tunnel study found that increasing length from 1.0- to 1.5-pile-diameters caused only slight improvement in screen efficiency. No greater lengths could be tested in the wind tunnel. Therefore, recommendations were that the screen should be at least as long as the pile. With wind direction variations that occur in real situations, such a short screen does not seem to be an optimum design.

The Billman study found that the 0.5-pile-height windscreens were not as effective as higher screens, but that screens as high as the pile (1.0-pile-height) were nearly as effective as higher ones. This is essentially identical to the field study findings. In the wind tunnel, the effect of

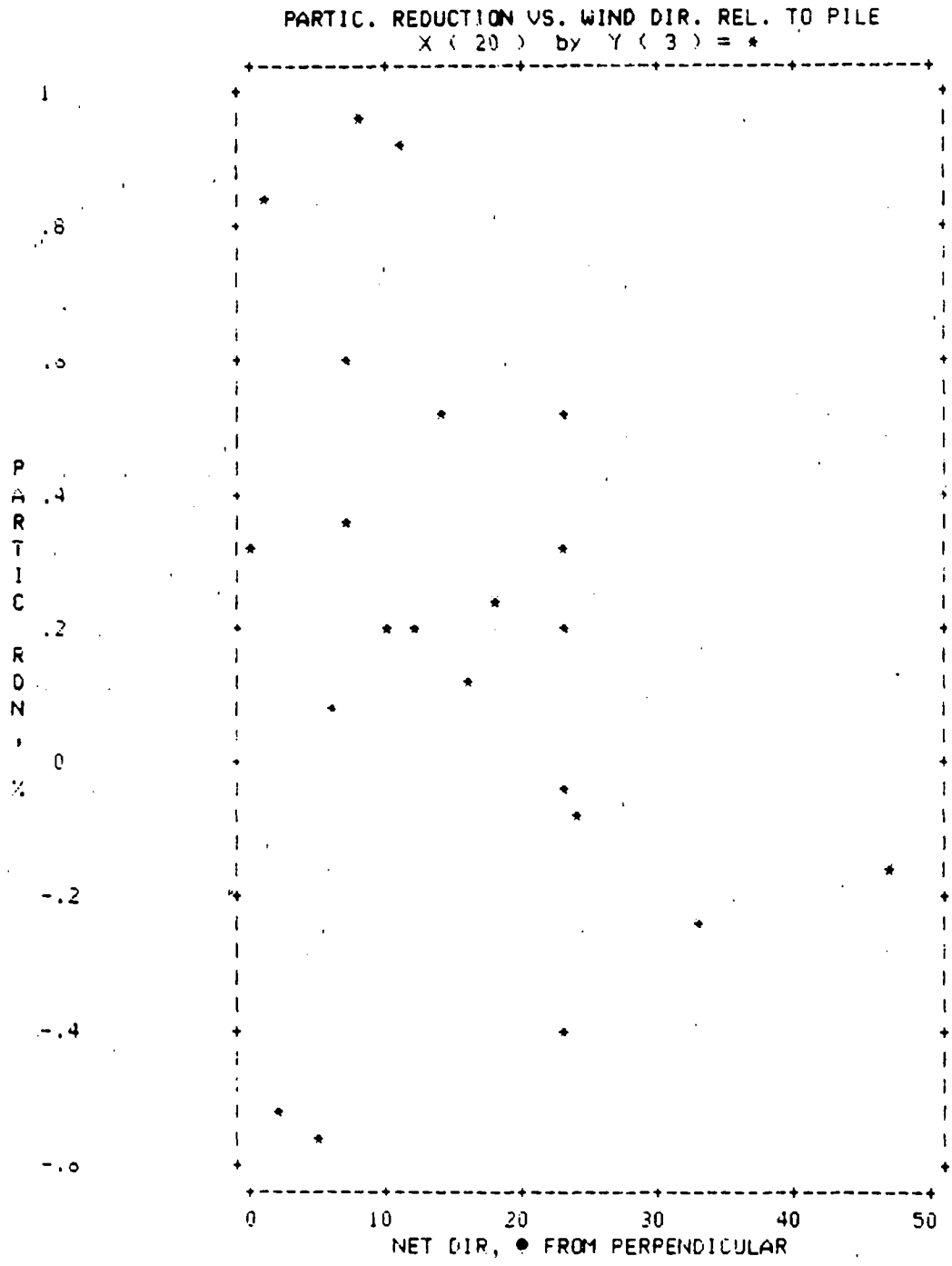
screen-to-pile distance was found to be interrelated with screen height. A screen of 1.0-pile-height placed at a distance of 3.0-pile-heights away from the pile caused greater windspeed reduction on the windward face of the pile but less reduction in the lee of the pile than the same screen at a 1.0-pile-height distance. The net result was approximately equivalent reductions at screen-to-pile distances of 1.0- and 3.0-pile-heights. The 2.0-pile-height distance was not tested in the wind tunnel. In the field, the 1.0- and 3.0-pile-height distances had about the same efficiency, with the 2.0-pile-height distance arguably having slightly greater emission reductions.

7.2 WIND DIRECTION RELATIVE TO SCREEN

For tests in which the resultant wind direction was not perpendicular to the windscreen, some reduction in control efficiency would be expected as the pile might become exposed at the end of the screen. When wind direction deviation from perpendicular was plotted against total particulate emission reduction associated with the screen, the line of best fit had a slope of -0.012 and an intercept of 0.356 (see Figure 7-4). In other words, the average control efficiency of 35.6 percent for the screen positioned perpendicular to the wind was reduced by 1.2% for every degree deviation from perpendicular in the wind direction.

The correlation coefficient for the data in Figure 7-4 was -0.300, and the probability that the two variables were not related was 0.164. The correlation was relatively low because of other variables in the tests that also affected emission reductions--in particular, the length, distance and height of the windscreen.

The original study design specified that four repetitive tests be taken for each windscreen configuration (combination of length, distance and



Number of points Below minimum	(X) :	0	(Y) :	0
Number of points above maximum	(X) :	0	(Y) :	0
Number of points with missing values	(X) :	0	(Y) :	19
Number of points plotted	:	23		

Figure 7-4. Scatter plot of particulate emission reduction vs wind direction deviation from perpendicular.

height). However, because of the reduced number of tests completed and the further reduction caused by tests with negligible emissions (due to low wind speeds and/or high moisture content), separate curves of emission reduction versus wind direction could not be drawn for each configuration. If only screen length is considered as a variable, the series of curves shown in Figure 7-5 can be produced. The three curves are almost parallel, indicating a similar impact on emission rates over a wide range of screen lengths. The slopes of these estimated curves are about -1.2% for a short screen, -1.6% for a medium screen, and -2.0% for a long screen. The individual curves would not be highly significant because of the few data points used in their derivation.

Figure 7-5 helps to explain the negative emission reductions, or increased emission rates which were observed for several tests. Generally, these tests had short screens and oblique winds that may have resulted in localized turbulence and increased surface erosion compared with conditions on the unscreened pile. The two outlier data points, for test 25B and 30A, were attributed to low emission rates on both piles during these tests.

A separate statistical review was performed by Brian Aldershof and David Ruppert of the Statistics Department of the University of North Carolina at Chapel Hill. This review, entitled "Statistical Revision of Field Evaluation of Windscreens as a Fugitive Dust Control Measure for material storage piles is contained in the appendix.

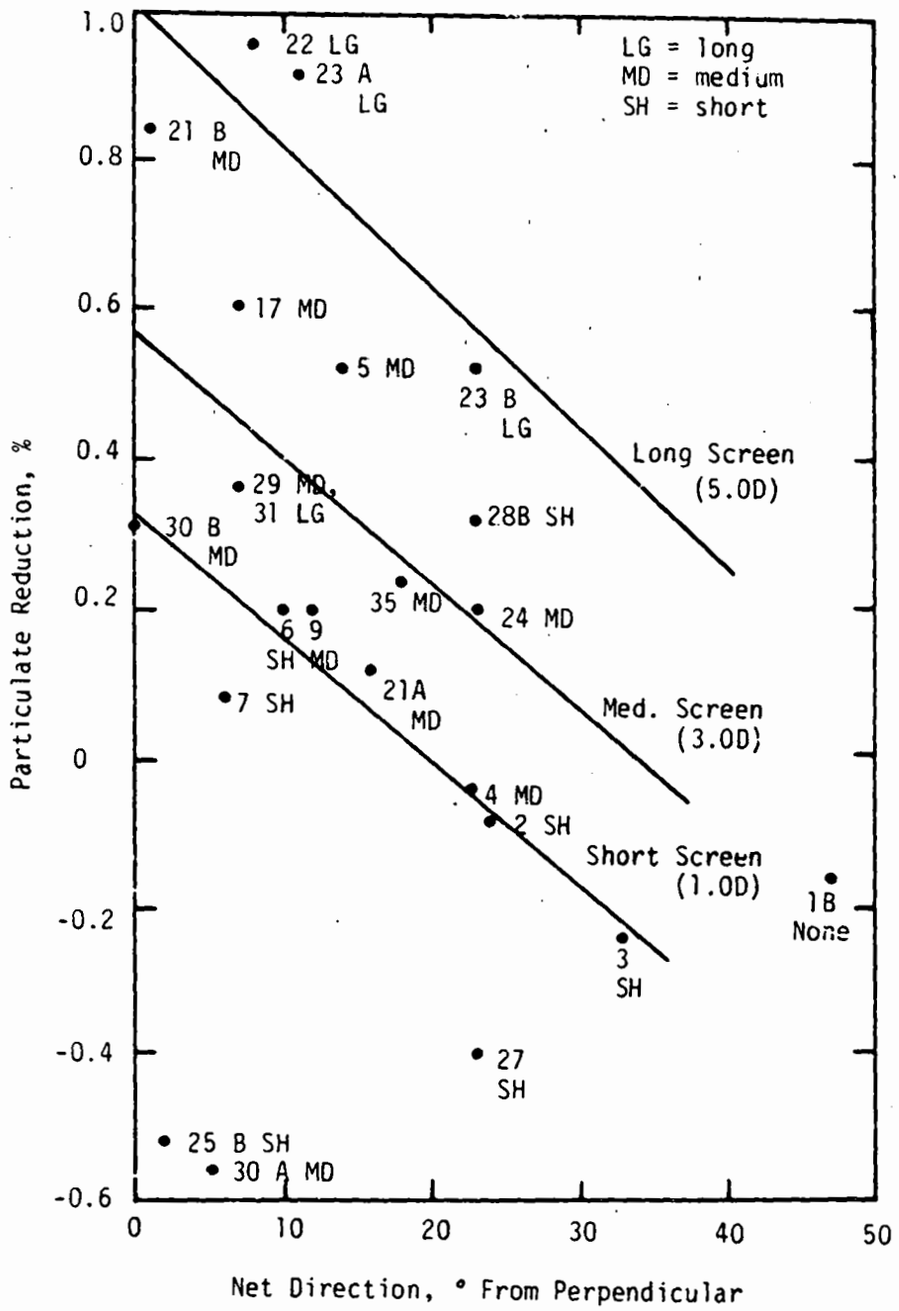


Figure 7-5. Scatter plot of particulate reduction vs. wind direction by screen length.

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APPENDIX

STATISTICAL REVIEW OF FIELD EVALUATION OF WINDSCREENS AS A FUGITIVE DUST CONTROL MEASURE FOR MATERIAL STORAGE PILES

Statistical Review of Field Evaluation of Windscreens as a Fugitive Dust Control Measure for Material Storage Piles

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May 1986

The focus of our analysis of the windscreen data was twofold: to develop a model relating total particulate emission to windspeed and soil moisture content, and to determine the relationship between various windscreen parameters and particulate reductions. The analyses suggest optimal windscreen configurations as well as some overall guiding principles in windscreen design.

Modelling total particulate emissions.

Examination of plots of particulate emissions against windspeed and moisture content of the soil suggest that a power model is probably appropriate. Since this is supported by theoretical results as well, our analysis proceeded directly to power models. Of the 42 tests given in table 5.3, only 39 were used in the analysis. Test 32 was eliminated because there was no information given on soil moisture content. Tests 36 and 105 were eliminated because the 0 particulate emissions did not allow log transformations. The simplest model was the power model:

$$ER = \beta_1 (WS)^{\beta_2} (MC)^{\beta_3} \epsilon$$

where ER is the particulate emission rate in lb/m^3, WS is the windspeed in ft/min, MC is the moisture content as percent of weight, and ϵ is the error term. The multiplicative error term was assumed to be log-normally distributed. This model was analyzed using ordinary least squares regression after log transforming both sides of the equation. The resulting

coefficients are $\beta_1 = 6.16 \times 10^{-9}$, $\beta_2 = 2.53$, $\beta_3 = -0.99$ (See Table 1). Plots of the residuals confirmed that the assumption that the error terms are log-normally distributed was reasonable. These values agree well with previous fugitive dust control research which suggest that β_2 should be about 3 and β_3 between -1.3 and -2.0. The resulting R^2 for this model is 0.796 and the R^2 adjusted for the degrees of freedom is 0.785. The model and all the regression coefficients are significant at the 0.001 level. The Akaike's information criterion (AIC)[1] for this model is -68.37.

A plot of the residuals against the predicted values of particulate emissions suggest a slight quadratic relationship. Examination of the plots of the residuals against the windspeed suggest that this can best be modelled using another term to account for differing effects of windspeed beyond a threshold value of 1000 ft/sec. The model examined was:

$$ER = \beta_1 (WS)^{\beta_2} (MC)^{\beta_3} (WS^*/1000)^{\beta_4} \epsilon$$

where $WS^* = WS$ for $WS \geq 1000$ and $WS^* = 1000$ for $WS < 1000$. The model was examined by taking logarithms of both sides of the equation and then applying ordinary least squares. Again, the error term was assumed to be log-normally distributed.

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[1] The AIC is a relative measure of goodness-of-fit. Models that minimize the AIC fit the data well. The AIC favors models with a small number of parameters and high log-likelihoods.

The resultant model is:

$$\log(ER) = \log(\beta_1) + \beta_2 \log(WS) + \beta_3 \log(MC) + \beta_4[\log(WS) - \log(1000)] + \epsilon' \qquad \text{for } WS \geq 1000$$

$$\log(ER) = \log(\beta_1) + \beta_2 \log(WS) + \beta_3 \log(MC) + \epsilon' \qquad \text{for } WS < 1000$$

There were 17 tests with windspeeds greater than 1000 ft/min. The resulting least squares coefficients are $\beta_1 = 5.8 \times 10^{-7}$, $\beta_2 = 1.75$, $\beta_3 = -0.43$, and $\beta_4 = 5.18$ (See Table 1). The R^2 for this model is 0.833 and the adjusted R^2 is 0.819. The overall model is significant at the 0.001 level. Each of β_1 and β_2 are significant at the 0.001 level. β_3 is significant at the 0.15 level and β_4 is significant at the 0.01 level. The AIC for this model is -73.02.

In several respects the second model seems better than the first. The R^2, adjusted R^2, and AIC all seem to indicate that the second model more adequately summarizes the data. A threshold effect of windspeed on many large particles also seems plausible. However, there were not enough tests (17) done in high windspeeds to estimate β_4 accurately. The standard error for β_4 was 1.86. While the model seems to fit very well within the range tested, some caution must be taken in extrapolating the model to higher windspeeds.

Regardless of which model is chosen the important feature is the very high exponent of windspeed in the models. Both models agree reasonably well with the cubic relationship found in the previous research on fugitive dust control. The importance of this cubic relationship is that in many regards the comparison of windspeed reductions at a single sensor and total particulate reductions is irrelevent. Comparison of the windspeed reductions

at sensor 2 and sensor 3 shows that the variability in windspeed is very high across the pile. Since particulate emissions are proportional to the cube of windspeed, small overall reductions in windspeed are easily outweighed by large local windspeeds created by turbulence caused by the screen. This observation is supported by the many (14) tests where reduced windspeed at either or both sensors was accompanied by an increase in particulate emission. An important characteristic for an effective windscreen is that it does not create turbulence.

Modelling the effect of windscreen configuration on particulate reduction.

Regression analysis was next employed to determine the factors causing reductions in particulate output associated with the windscreen. Again, several models are suggested. The dependent variable used in the analysis was $1 - (ER_{scr}/ER_{unscr})$. This dependent variable can also be expressed as $(ER_{unscr} - ER_{scr})/ER_{unscr}$ and should be interpreted as a proportional reduction in particulate emission rate. Only 37 of the 42 tests were originally used in the analysis. Test 1b and 26 were eliminated because windscreens were not used in these tests. Test 32 was excluded because of its missing value for moisture content. Tests 36 and 105 were eliminated because of their 0 particulate emission rates.

Regression using windspeed, moisture content, and three screen dimensions as independent variables showed that the only

significant factors affecting particulate reductions were windspeed measured on the unscreened pile, length of the windscreen, and height of the windscreen. The analysis continued by considering only these three independent variables. Test 32, which was originally excluded from the analysis because of its missing value for moisture content, was then included. In all, 38 tests were used in the analysis of particulate reductions. Examination of the plots of the data suggested log transformations of the independent variables. Maximizing the log-likelihood with respect to the Box-Cox transformation exponent, λ, suggested that the dependent variable should not be transformed at all. The resulting model is:

$$1 - (ER_{scr}/ER_{unsc}) = \beta_1 + \beta_2 \ln(WS) + \beta_3 \ln(L) + \beta_4 \ln(H) + \epsilon$$

where L is length of the windscreen in pile diameters and H is height in pile diameters. The resulting least squares coefficients are $\beta_1 = -1.59$, $\beta_2 = 0.22$, $\beta_3 = 0.34$, $\beta_4 = 0.38$ (See Table 2). R^2 for this model is 0.274 and the adjusted R^2 is 0.210. The overall model is significant at the 0.01 level. The regression coefficient β_1 is significant at the 0.002 level, β_2 at 0.07, β_3 at 0.02, β_4 at 0.04. The AIC for the model is -72.9.

This model is rather complicated but its importance is in the positive coefficients for height and length. Within the ranges tested, the greater the height and length, the more effective was the windscreen. Also, greater reductions in particulate emissions were found with higher winds, confirming that windscreens are particularly effective and necessary with high winds.

Examination of interaction terms suggested a better, if

conceptually more difficult. model. The same dependent variable was regressed on the untransformed values of windspeed, length, and height and their interactions. The best model using these terms was found to be:

$$1 - (ER_{scr}/ER_{unsc}) = \beta_1 + \beta_2(L) + \beta_3(H^{\dagger}) + \beta_4(WS^{\dagger}) + \beta_5(H^{\dagger} \times WS^{\dagger}) + \epsilon$$

where $H^{\dagger}$ is the mean-centered height (ie. $H - \bar{H}$), $WS^{\dagger}$ is the mean-centered windspeed, and $WS^{\dagger} \times H^{\dagger}$ is the interaction between the mean-centered windspeed and mean-centered height. The least squares values for the coefficients are $\beta_1 = 0.33$, $\beta_2 = 0.24$, and $\beta_3 = 0.43$, $\beta_4 = 3.4 \times 10^{-4}$, $\beta_5 = 1.0 \times 10^{-3}$ (See Table 2). This model fit the data better than the previous model. R^2 increased to 0.354, the adjusted R^2 decreased to 0.275, and the AIC improved to -74.22. The overall model was significant at the 0.01 level. The coefficient β_1 is significant at 0.3, β_2 at 0.02, β_3 at 0.06, β_4 at 0.05, β_5 at 0.05.

Mathematically, the second model is probably better than the first. The R^2 and AIC are improved in the second model and the significant interaction should not be ignored. The interpretation of the interaction between height and windspeed can be misleading. For fixed values of L and $WS^{\dagger}$, particulate reduction is a linear function of $H^{\dagger}$ with estimated slope:

$$\beta_3 + \beta 4(WS^{\dagger}) = 0.43 + (3.4 \times 10^{-4})\ (WS^{\dagger})$$

This slope increases with $WS^{\dagger}$. Thus, low windspeeds lessen the effectiveness of increased height in reducing relative particulate output. In fact, the estimated slope is negative for large negative values of $WS^{\dagger}$ suggesting that low windscreens are

actually more efficient than high screens at low windspeeds. However, since high windspeeds cause much greater particulate emission rates, it is much more desirable to have a windscreen that is efficient at high windspeeds rather than low windspeeds.

To further investigate the interaction, a hypothesis test was performed by testing:

$$H_0 : \beta_3 + \beta_5(\overline{WS}) \geq 0$$

$$\text{vs. } H_1 : \beta_3 + \beta_5(\overline{WS}) < 0$$

This tests the null hypothesis (H_0) that increasing the height of the screen at zero windspeed causes a decrease in particulate emission versus the alternative hypothesis (H_1) that increasing the height causes a decrease in particulate output. The t-statistic for this test is -0.507, which is not significant. There is no evidence to suggest that a low screen is really more effective in low windspeeds than a high screen. It is clear that increasing the height of the windscreen at low windspeeds does not increase its efficiency.

Our analysis did not show any effect of distance between the pile and the windscreen. Distance obviously has some effect (a reasonable sized screen two blocks from the pile will probably not reduce particulate emissions), but within the range of values studied there does not seem to be any preferable distance.

The analysis of the first model (the non-linear model without the interaction) suggested that increased length and height reduced particulate emissions similarly. Since it is probably less expensive to build a screen a unit longer than a unit higher, building a long screen is more cost effective in reducing

particulate emissions than building a high one. The second model (the linear model with the interaction) summarizes the data fairly well, but leads to some difficult conclusions about screen design. Apparently, the most efficient screen per unit area would be infinitesmally high and infinitely long. This ridiculous conclusion is the result of the limited range of heights studied. The important conclusion from the interaction model is that if high winds are encountered on the pile, high screens are more efficient than long ones.

The original report presents only a linear model of particulate reduction and does not examine interactions. This linear model is not satisfactory since plots of the residuals reveals that it does not fit the error structure of the data well. Addition of the interaction term helps in understanding the dynamics of particulate reduction caused by the windscreen.

Some additional comments

Section 5.2.1 concludes that "windscreen configuration should not affect the relationship between windspeed and emission reduction". In fact, this is not true as is suggested by the emission reduction model using the interaction between height of the windscreen and windspeed.

We did not do any analyses using the particle size data. Section 5.2.2 concludes that the negative particulate reductions in all the particle size ranges confirm that the increased emissions found in the total particulate data resulted from actual

increases caused by the screen. This does not follow because these are not independent observations. Total particulate emissions are probably highly correlated with emissions in every size range which are also probably highly correlated among themselves.

The equation for total particulate output given in the original report is $ER = 0.0078\ (WS)^{0.21}(MC)^{-2.1}$. Our equation, based on the same data set, is $ER = 6.2\times10^{-9}\ (WS)^{2.53}(MC)^{-0.99}$. This discrepancy seems to be caused by an error in the original report. Apparently, the untransformed ER was regressed on the log transformed independent variables. The model that results from this regression is :

$$\exp(ER) = \beta_1(WS)^{\beta_2}(MC)^{\beta_3}\ \epsilon$$

not

$$ER = \beta_1(WS)^{\beta_2}(MC)^{\beta_3}\ \epsilon$$

as reported. This exponential model does not fit the data as well as the power model. It appears that a similar error occurs in the analysis of the particle size data. The dependent variables in Table 5.7 are actually $\exp(ER_{part})$ rather than ER_{part}.

We did not find that wind direction significantly affected particulate reductions. While it seems obvious that wind directions that are very aperpendicular to the screen must undermine its effectiveness, this was not seen in the narrow range of wind directions tested.

We feel that the rather simple multiple regression models presented here summarize the data quite well. The analysis presented here is not intended to replace all of the analysis in

Chapters 5 and 6 of the original report. Rather, we feel that these models supplement the longer analyses in the original report, as well as emend some of them.

Table 1: Modelling Total Particulate Output

Model: $ER = \beta_1 (WS)^{\beta_2} (MC)^{\beta_3} \epsilon$

Coefficient	Value (se)	P-value
β_1	6.16×10^{-9} (3.1×10^{-8})	0.001
β_2	2.53 (0.27)	0.001
β_3	-0.99 (0.21)	0.001

R^2=0.796 adj. R^2=0.785 AIC=-68.37

Model: $ER = \beta_1 (WS)^{\beta_2} (MC)^{\beta_3} (WS^*/1000)^{\beta_4} \epsilon$

Coefficient	Value (se)	P-value
β_1	5.8×10^{-7} (5.3×10^{-7})	0.001
β_2	1.75 (0.37)	0.001
β_3	-0.43 (0.27)	0.15
β_4	5.18 (1.86)	0.01

R^2=0.833 adj. R^2=0.819 AIC=-73.02

Table 2: Modelling the effect of windscreen configuration on particulate reductions.

Model: $1 - (ER_{scr}/ER_{unsc}) = \beta_1 + \beta_2 \ln(WS) + \beta_3 \ln(L) + \beta_4 \ln(H) + \epsilon$

Coefficient	Value (se)	P-value
β_1	-1.59 (0.76)	0.002
β_2	0.22 (0.11)	0.07
β_3	0.34 (0.13)	0.02
β_4	0.38 (0.17)	0.04

R^2=0.274 adj. R^2=0.210 AIC=-72.9

Model: $1 - (ER_{scr}/ER_{unsc}) = \beta_1 + \beta_2(L) + \beta_3(H^{\dagger}) + \beta_4(WS^{\dagger}) + \beta_5(H^{\dagger} \times WS^{\dagger}) + \epsilon$

Coefficient	Value (se)	P-value
β_1	-0.14 (0.15)	0.33
β_2	0.11 (0.05)	0.02
β_3	0.43 (0.21)	0.06
β_4	3.4×10^{-4} (1.6×10^{-4})	0.05
β_5	1.0×10^{-3} (5.2×10^{-4})	0.05

R^2=0.35 adj. R^2=0.275 AIC=-74.2

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16. ABSTRACT The report gives results of a field study to validate earlier wind tunnel studies with respect to windspeed changes, and to determine the relationship between changes in windspeed and changes in fugitive dust emissions. (The earlier studies were to determine changes in windspeed--not changes in emissions--due to windscreens, and utilized a wind tunnel to determine the optimal windscreen porosity, size, and location for control of fugitive dust emissions from storage piles.) The field study suggests that the optimum windscreen design parameters are: porosity = 50%, height = 1.0 H, width = 5.0 D, and distance = 2.0 H for a conical pile of height H and diameter D. Analysis of the field data shows that emission rates were directly related to windspeed and inversely related to moisture content of the pile surface. These relationships held regardless of the particle size fraction considered.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN-ENDED TERMS	c. COSATI Field/Group
Pollution	Storage	Pollution Control	13B 15E
Dust	Wind Velocity	Stationary Sources	11G
Leakage		Particulate	14G
Particles		Fugitive Dust	
Windbreaks		Windscreens	04B
Protectors		Storage Piles	

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