Proceedings of the 1983
Winter Simulation Conference
S. Roberts, J. Banks, B. Schmeiser (eds.)

A PREDICTIVE TOOL FOR QUANTIFYING WIND EROSION FROM COAL SURFACES

Mary Ann Grelinger
Midwest Research Institute
425 Volker Boulevard
Kansas City, Missouri 64110

A simulation computer program is described for the quantification of particulate emissions generated by wind erosion of coal surfaces. Erosion potentials reported by Cowherd provide the basic test data correlating suspended particulate loss with wind speed. Daily fastest miles of wind, precipitation and surface disturbances are stochastically simulated. Erosion loss is shown to vary according to the probability and the amount of rainfall, the frequency of disturbance of the erodible surface and the fastest mile of wind distribution parameters.

1. INTRODUCTION

Degradation of air quality can occur by the natural suspension of small particles from exposed surfaces by wind erosion. Because surface coal mines and industrial plants with large coal storage piles must meet stringent air quality rules, accurate estimates of emissions are required in obtaining permits to construct or expand operations. This paper will assess emission losses per unit erosion surface area using two FORTRAN computer programs, FASTMILE and WINDER. In this stochastic simulation, the erosion is dependent on the daily fastest mile of wind, the frequency of disturbance of the erodible surface, and the daily occurrence or nonoccurrence of rainfall. Only suspended particles (particles of diameter less than 30 μm) will be quantified.

Particulate emissions generated from coal storage piles have been tested with a portable wind tunnel by Midwest Research Institute under dry conditions at several western surface coal mines (Cowherd 1982, and Axtell and Cowherd 1981). The tests quantified suspended and inhalable particulate emissions from both crusted and uncrusted surfaces. C. Cowherd reported that erosion is highly dependent on the simulated wind speed and approaches a limiting value for a particular wind speed. The total particulate present on the surface before the onset of erosion and which is erodible at a particular wind speed is termed the erosion potential. In this paper, the total erosion loss for a strong, steady wind and the erosion potential for that wind speed are assumed to be equal. This corresponds to the sharp decay in emission rate with time reported by Cowherd (1982), where a finite amount of small particles is completely entrained into the air stream within a few minutes of the onset of erosion.

Mined coal ranges in size from submicron to centimeter diameters. Once a strong, steady wind exceeding a threshold value has entrained the finite amount of finer particles from a surface, no other particles will be dislodged unless the wind velocity increases or the surface is disturbed. A disturbance is defined as an action resulting in the presentation of fresh material to the surface, either by dumping new aggregate or by overturning the old surface.

The fastest mile of wind can be pictured as the mean wind speed which would carry an entrained massless particle over the distance of a mile in the shortest time during the period of interest. These measurements and other weather data are available from the National Climactic Center in Asheville, North Carolina. In this simulation, Chicago O'Hare Airport rainfall and fastest miles for March-April 1975 to 1982 were chosen as input data to FASTMILE. This station is representative of the region where studies of the relationship between coal moisture content and rainfall were done by Midwest Research Institute in 1978-1979 (Cowherd et al., 1979).

2. WIND EROSION - RAINFALL RELATIONSHIP

Cowherd et al. (1979) describes a correlation of coal pile surface moisture with daily precipitation. A weighted precipitation value, P_w (mm), was developed which takes into account the observation that the more recent the precipitation, the stronger the effect on observed storage pile moisture.

This relationship is important in this study because of the strong dependence (inverse square) of wind-generated dust emissions on the moisture content of the erodible surface (Cowherd et al., 1979).

The surface moisture content relationship was combined with equations for erosion loss from both crusted and uncrusted coal surfaces under specific wind speed conditions. Figures 1 and 2 show the best fit lines correlating erosion potential with wind speed at 15 cm above the surface as determined from wind tunnel tests on dry coal surfaces. An erosion threshold value of 20 mph was used for both crusted and uncrusted surfaces. The threshold is that wind speed below which little or no wind erosion occur.

Linear erosion loss equations are listed below. For a crusted coal surface:

$$L = (1.98\ v - 42.5)(1.41^2/(0.13\ P_w + 1.41)^2) \quad (1)$$

For an uncrusted coal surface

$$L = (2.88\ v - 54.1)(1.41^2/(0.13\ P_w + 1.41)^2) \quad (2)$$

where L is the daily erosion loss (g/m^2)

v is the 15 cm daily fastest mile wind speed (mph) greater than the erosion threshold speed

P_w is the weighted precipitation (mm)

It should be noted that other studies of wind erosion have found a dependency of wind erosion on the third power of the wind speed (Jutze et al., 1978). If this is true, then the simulation results may vary markedly as a nonlinear response to wind speed is encountered.

3. STATISTICAL DISTRIBUTIONS OF DAILY FASTEST MILES OF WIND

The daily fastest mile distribution parameters were determined by a modified FORTRAN program, FASTMILE, originally developed in 1975 by Simiu and Filliben (Simiu et al., 1975a, 1975b, 1979). Their program predicts extreme wind speeds for U.S. weather stations based on yearly fastest miles of wind. While their program was primarily directed to determine architectural design wind speeds in probabilistic terms, it also produces the statistical parameters needed for Monte Carlo simulation of fastest miles of wind for a specific geographical location. The inverse functions needed for pseudo-random variate generation as derived by Filliben were used in this study once the cumulative distribution function (CDF) estimated parameters were found.

For this wind erosion study, only strong winds occurring on dry days were required. These data were fit to the extreme value distributions to estimate the parameters of the CDF's. Parameter estimates were input to the simulation program, WINDER, which is described later in this paper. Wind speeds at 10 m were then converted to equivalent wind speeds at 15 cm above a storage pile. The adjustments are made using the relationship called the log-law (Haugen, 1980). A Type I (Gumbel) distribution resulted from FASTMILE because fastest miles occurring on days with rainfall were excluded from the sample of daily fastest miles input to the FASTMILE program. According to Thom (1968), about one-third of extreme wind speeds are associated with thunderstorms.

4. RAINFALL ANALYSIS

A rainfall analysis subroutine, RFALL, was added to FASTMILE and determines the Markov chain (Bhat, 1972) probabilities associated with rainfall occurrence.

The probability of rainfall is dependent on a variety of meteorological parameters. A first order Markov process describes the probability of rainfall as conditionally dependent on whether it rained yesterday. This simplification allows rainfall (or dry spells) to occur in extended daily sequences which commonly occur in nature. This is important since long sequences of dry days will produce more emissions than the same number of dry days intermittently interspersed with days of rainfall. A 2 x 2 table can be constructed for the above described rainfall probabilities, where P_{rs} represents the probability of rain (no rain) given that it did (not) rain yesterday.

The subroutine, RFALL, was used to calculate these conditional probabilities of rainfall occurrence for O'Hare Airport which were subsequently input to the wind erosion program, WINDER.

Rainfall amounts were also analyzed in the subroutine to determine the gamma distribution location and scale parameters, α, β, which best fit the distribution of rainfall amounts on the days it rained. Maximum likelihood estimators of α, β, were obtained using Tables 23 and A1 in Fishman (1973). These gamma distribution parameter estimates were input to the WINDER simulation program.

5. SIMULATION RELIABILITY

Each output of WINDER resulted from a 10,000+ day simulation. A baseline run was established with the input data resulting primarily from the FASTMILE analysis of Chicago O'Hare Airport daily fastest miles and precipitation data.

Rainfall amounts proved to be the most difficult parameter to model. Days with no rainfall were excluded from composing rainfall distributions. The fraction of rainfall occurrences between 0.0 and 0.1 in. for the Chicago data was 19% higher than the simulation data from the estimated gamma distribution. A comparison of the gamma distribution parameters from the original Chicago sample and the baseline run sample showed a slight difference.

$\hat{\alpha}$		$\hat{\beta}$	
Chicago	Baseline	Chicago	Baseline
0.735	0.685	0.387	0.415

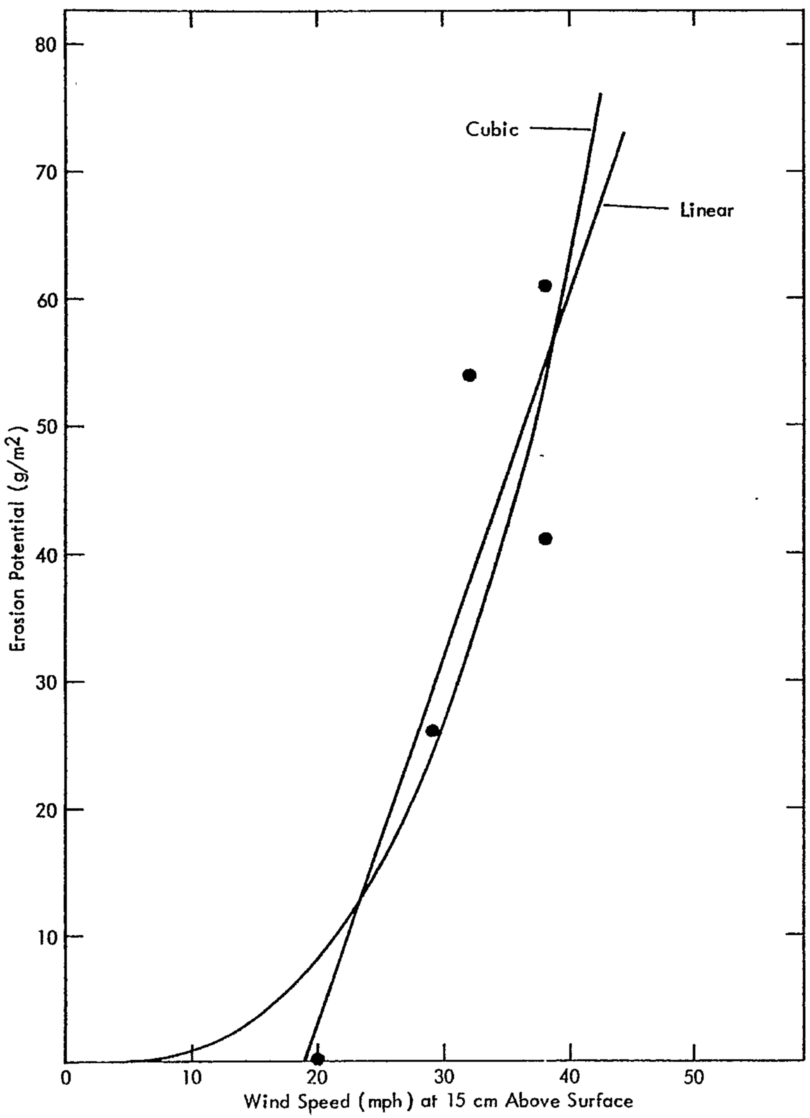

Figure 1: Calculated Erosion Potential versus Wind Speed for Uncrusted Coal Surface

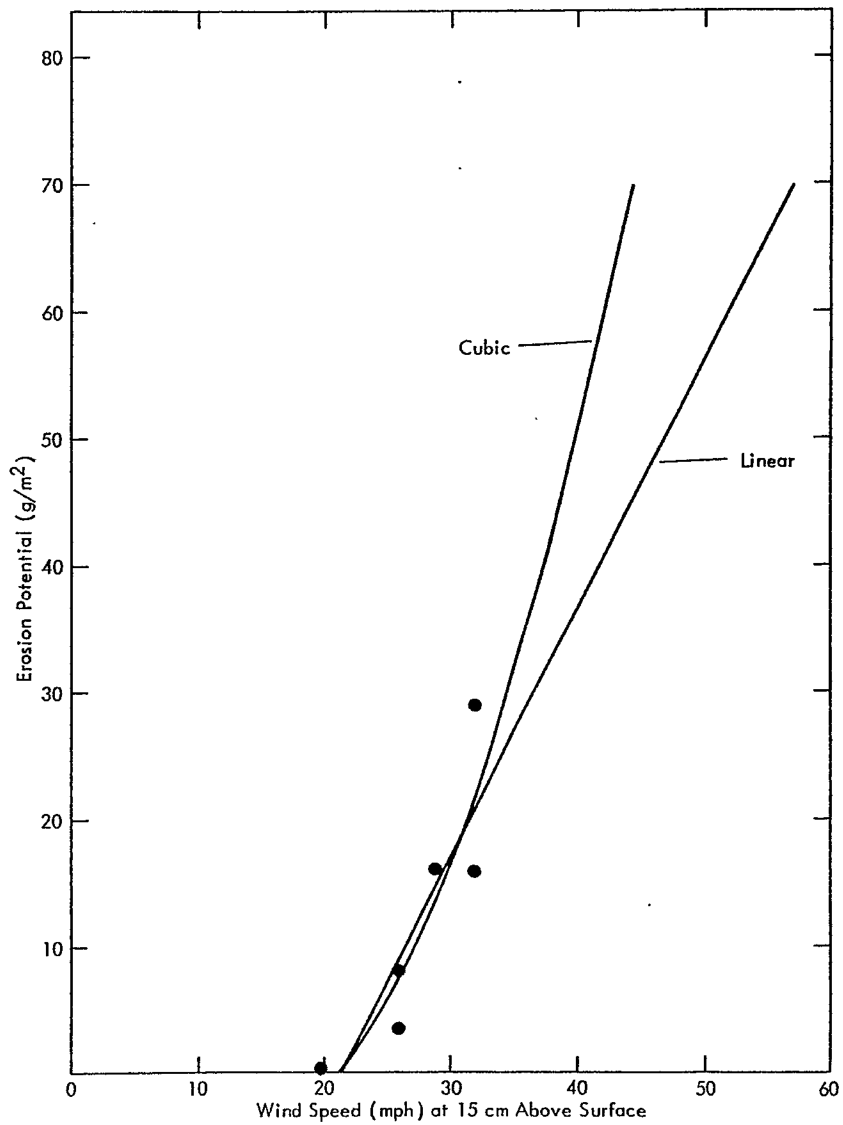

Figure 2: Calculated Erosion Potential versus Wind Speed for Crusted Coal Surface

Rainfall occurrence was modeled reliably as is shown in the table below, where P_1 is the overall probability of rainfall occurrence.

	P_1	
Chicago	FASTMILE	Baseline
0.398	0.398	0.405

The fastest mile of wind simulation gave the following results.

$\overline{X}$		S	
Chicago	Baseline	Chicago	Baseline
19.91	19.94	5.86	5.93

These figures indicate the reliability of the simulation of fastest miles of winds on days with no rainfall. The probability correlation coefficient for the Type I distribution was 0.9913 and confirms this observation.

6. SIMULATION RESULTS

Simulation runs were used to determine the sensitivity of erosion loss under typical conditions to:

- Rainfall probability
- Mean time between disturbances
- Location parameter of the Type I distribution of fastest miles
- Erosion loss equation type (linear, quadratic, cubic)

The wind erosion simulation assumed that no erosion occurred on rainy days. Also if it rained, a crust was assumed to form by the following day and remained until the next disturbance of the coal surface.

Figure 3 shows the results of the baseline run and four other runs where the Markov probability matrix for rainfall occurrence was modified as shown in the following table. P_{10} and P_{11} remained constant from run to run; P_{10} = 0.4691 and P_{11} = 0.5309 from the O'Hare baseline data.

	P_{00}	P_{01}	P_1
	0.50	0.50	0.520
	0.60	0.40	0.463
Baseline	0.69	0.31	0.405
	0.80	0.20	0.307
	0.90	0.10	0.183

A number of simulation runs were made changing only the mean time between disturbances and the erosion loss equation type. This was done to determine the relationship between coal surface activity and mean daily erosion loss and to see the effect of a cubic versus quadratic versus linear erosion loss equation. The results are shown in Figure 4. The systematic operation of bulldozers, trains, and other coal-handling processes was modeled using a normal distribution pseudo-random number generator to produce the number of days between disturbances of the coal surface. The relative standard deviation of the time between disturbances was held steady at 10%.

Figure 5 shows the effect of changing the erosion surface roughness parameter, Z_0. A change in this parameter has the direct effect of changing the ratio of the 0.15 m wind speed above the erosion surface to the 10 m observed wind speed.

Figure 6 illustrates the effect of increasing the mean of the fastest miles. The location parameter of the Type I distribution is directly related to the mean fastest mile and is also shown for comparison purposes. The Type I scale parameter remained the same for each of the simulation runs shown here. As is seen from Figure 6, an increase of about 3 mph in the mean daily fastest mile doubles the expected erosion loss in the span of pictured wind speeds. If strong North Dakota or Montana winds were to be modeled, an appreciable increase in emissions would be expected as compared to the Chicago O'Hare location.

7. CONCLUSIONS

This simulation has permitted various meteorological parameters to be "factored into" the wind speed - wind erosion relationship developed by Cowherd. The results show the importance of adequately characterizing the erosion potential loss as a function of wind speed and surface moisture content. A better definition of this relationship will provide a firmer determination of the mean daily erosion loss for specific site, disturbance and meteorological conditions. A cubic dependence of erosion potential on wind speed will magnify the erosion loss total compared to a linear or quadratic dependence in a simulation with small mean disturbance intervals. No substantial difference in erosion loss is seen when using a linear versus quadratic erosion equation.

ACKNOWLEDGEMENT

The author wishes to acknowledge the support and interest of Dr. Chatten Cowherd in this project. His concept of erosion loss potential as related to the fastest mile wind speed is the basic premise used in this paper to model wind erosion.

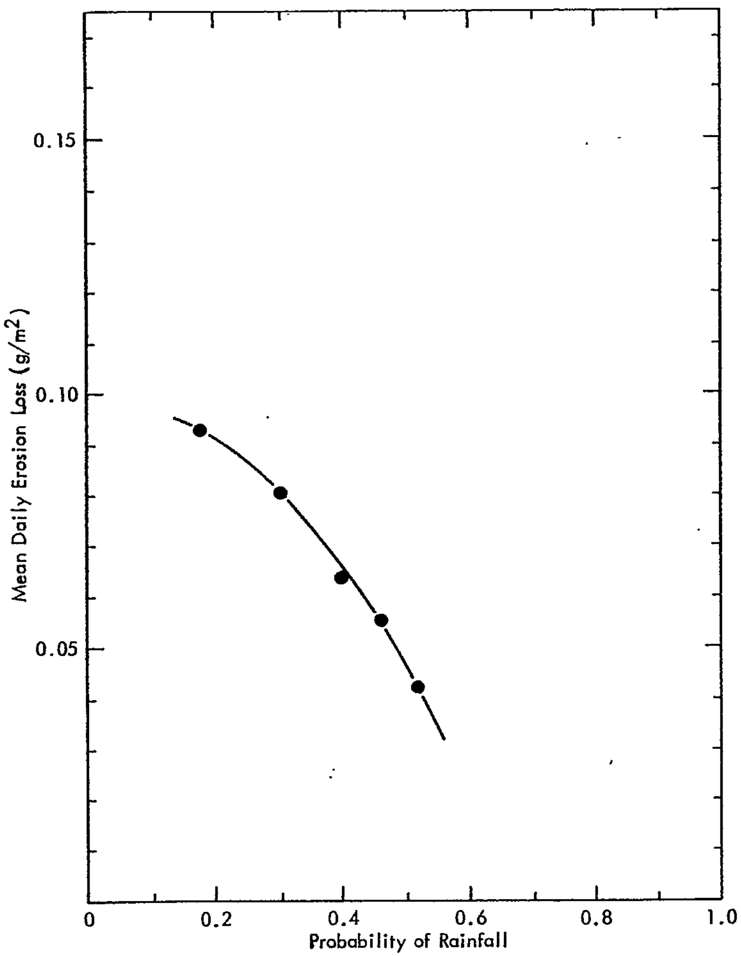

Figure 3: Sensitivity of Erosion Loss to Precipitation

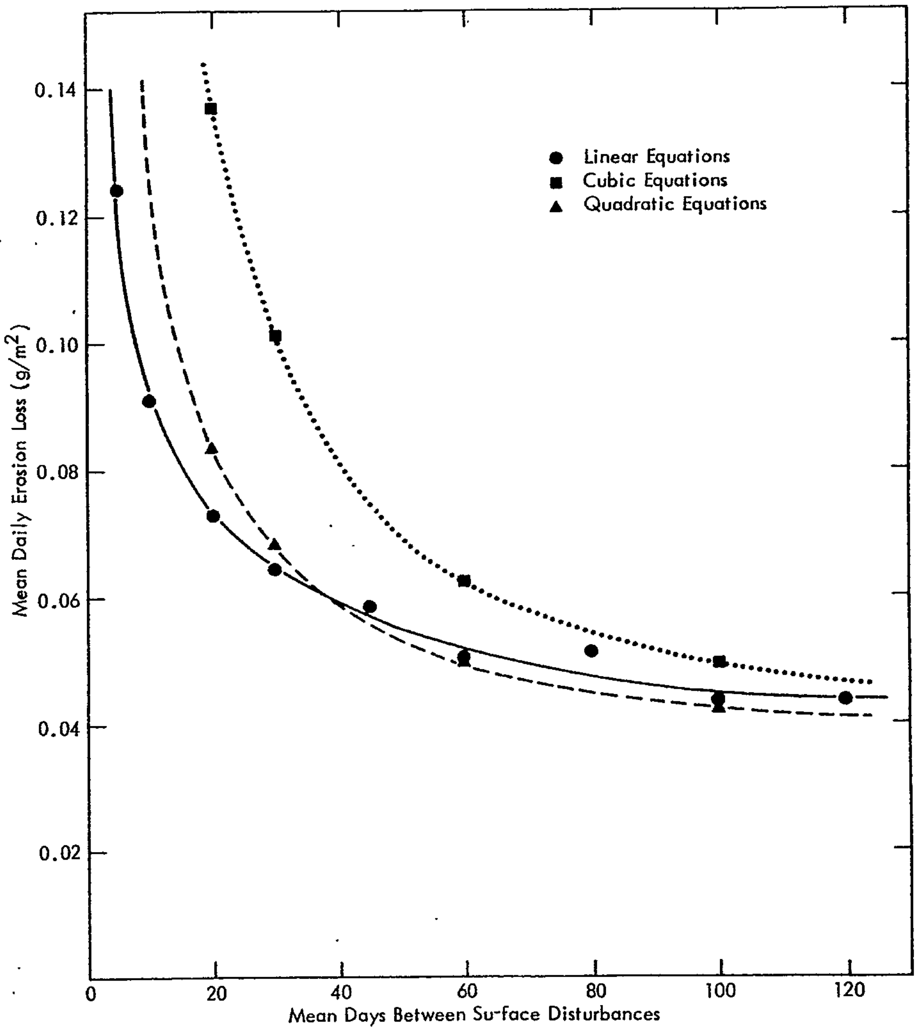

Figure 4: Sensitivity of Erosion Loss to Pile Activity

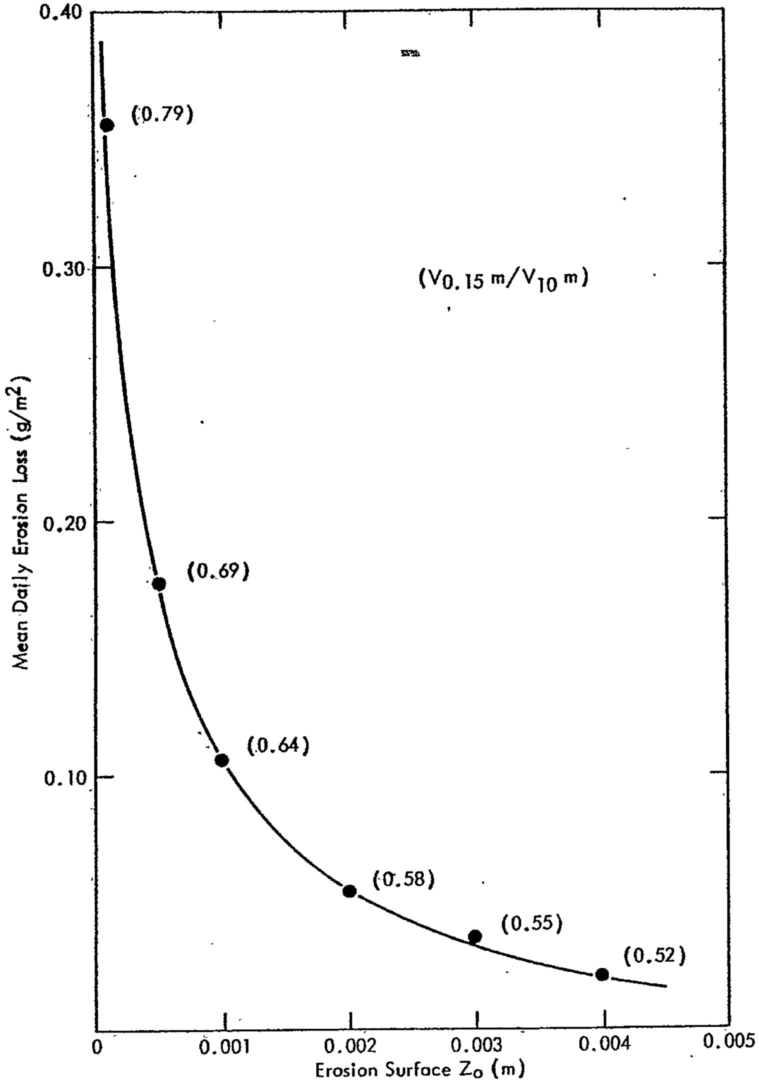

Figure 5: Sensitivity of Erosion Loss to Erosion Surface Roughness Parameter (30-day mean disturbance interval)

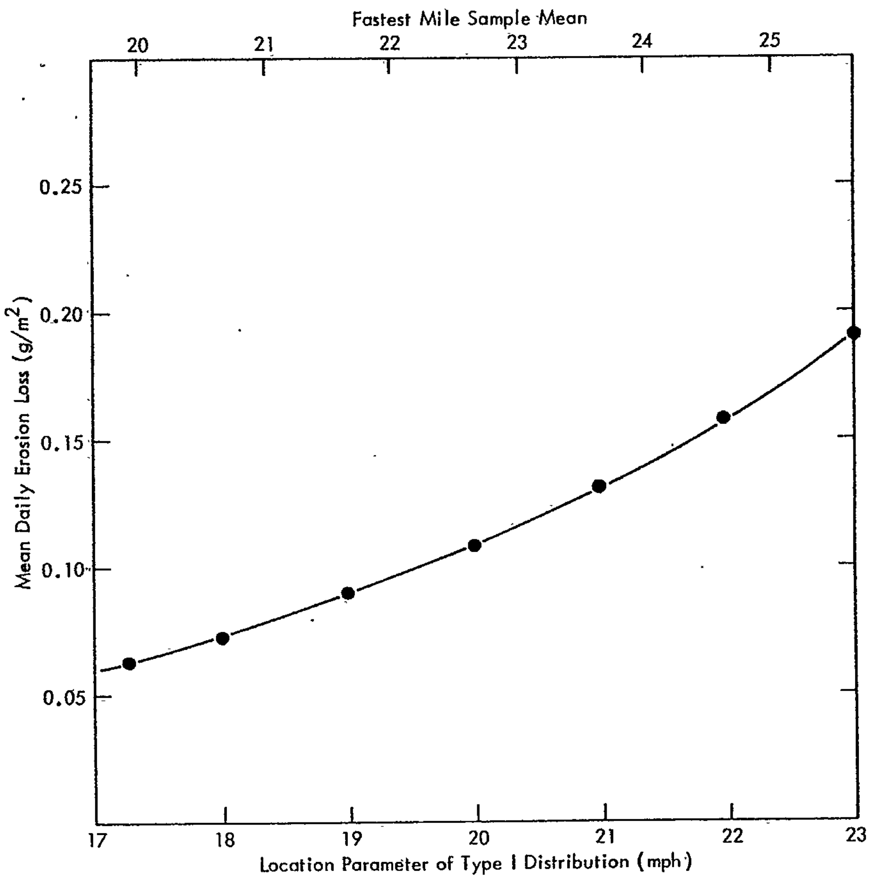

Figure 6: Sensitivity of Erosion Loss to the Mean Daily Fastest Mile

REFERENCES

Axetell, K., Jr., and C. Cowherd, Jr. (July 1981), "Improved Emission Factors for Fugitive Dust from Western Surface Coal Mining Sources," Volumes I and II, EPA Contract No. 68-03-2924, U.S. Environmental Protection Agency, Cincinnati, Ohio.

Bhat, U. N. (1972), Elements of Applied Stochastic Processes, John Wiley and Sons.

Cowherd, C., Jr. (June 1982), "Emission Factors for Wind Erosion of Exposed Aggregates at Surface Coal Mines," Presented at Annual Meeting of the Air Pollution Control Association, New Orleans, Louisiana.

Cowherd, C., Jr., R. Bohn, and T. Cuscino (May 1979), "Iron and Steel Plant Open Source Fugitive Emission Evaluation," U.S. Environmental Protection Agency, EPA-600/2-79-103, Washington, D.C.

Fishman, G. S. (1973), Concepts and Methods in Discrete Event Digital Simulation, John Wiley and Sons.

Haugen, D., "Boundary Layer Winds" (1980), in Wind and Seismic Effects, Proceedings of the Tenth Joint UJNR Panel Conference, National Bureau of Standards, Special Publication 560.

Jutze, G. A., J. M. Zoller, T. A. Janszen, R. S. Amick, C. E. Zimmer, and R. W. Gerstle (1978), "Techical Guidance for Control of Industrial Process Fugitive Emissions," U.S. Environmental Protection Agency, 450/3-77-010, Research Triangle Park, North Carolina.

Simiu, E., and J. J. Filliben (June 1975a), "Statistical Analysis of Extreme Winds," National Bureau of Standards Technical Note, Washington, D.C.

Simiu, E., and J. J. Filliben (1975b), "Probabilistic Models of Extreme Wind Speeds: Uncertainties and Limitations," in Proceedings of the Fourth International Conference on Wind Effects on Buildings and Structures, K. J. Eaton, ed., Cambridge University Press.

Simiu, E., M. J. Changery, and J. J. Filliben (March 1979), "Extreme Wind Speeds at 129 Stations in the Contiguous United States," National Bureau of Standards Science Series 118, Washington, D.C.

Thom, H. C. S. (July 1968), "New Distributions of Extreme Wind Speeds in the United States," J. Struct. Div., ASCE, No. ST7, Proc. Paper 6038.