Wind Erosion and Visibility Problems

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ABSTRACT

WIND erosion frequently suspends enough particulates to create visibility hazards near highways and airports. How much visibility is reduced depends on both the concentration and size distribution of the particulates. For typical conditions, 100 to 400 mg/m³ are needed to reduce daytime visibility to 200 m. If the background is non-sky, visibility is reduced an additional 50 to 75 percent compared with a sky background and, if one is facing the sun, visibility is reduced even further. Particulate concentrations can be reduced by reducing the source emission rate or by diffusing and trapping the particulates. A combination of these methods may be needed where wind erosion is severe.

INTRODUCTION

Wind erosion frequently suspends enough particulates to cause reduced visibilities. Reduced visibility at airports or along busy highways creates a safety hazard, and news accounts record the unfortunate results. For example, dust from abandoned, irrigated fields in Arizona recently was responsible for two multi-vehicle pileups along Interstate 10 (Drehsler, 1975). The two pileups involved 33 vehicles, 24 injuries, and two deaths. Dust from newly plowed fields near Bakersfield, CA was responsible for 96 injuries, and seven killed in two pileups involving 80 vehicles (Associated Press, 1972).

Because dust sources are generally outside highway rights-of-way, programs to alleviate the visibility hazards caused by dust have been largely confined to airports with consistent problems where expensive chemical or other soil stabilization methods are feasible (Peters, 1964). Highway officials also attempt to reduce visibility hazards from dust, however. In Arizona, signs and radio programs have been used to warn motorists of duststorm hazards. In Kansas this spring, highways were occasionally closed when dust from newly tilled fields caused low visibilities. More permanent solutions to this safety hazard are needed, however. Here, we review effects of dust concentration on visibility, and show the effects of some control strategies on dust concentration.

DUST CONCENTRATION AND VISIBILITY

Visibility depends on light transmission through the atmosphere, and the ability of the eye to distinguish an object because it contrasts with the background. The apparent contrast (C) between an object and its background is reduced by scattering and absorption of light in the intervening path. Change of contrast can be described as

$$dC = \sigma c dx, \qquad [1]$$

which upon integration gives

$$C = C_o e^{-\sigma x}. \qquad [2]$$

The extinction coefficient, σ, includes effects of both absorption and scattering; x is path length, and C_o is actual contrast between and object and its background (Robinson, 1968). In visibility calculations, a black object with $C_o = -1.0$ and a limiting contrast of $C = -0.02$ are used for daytime observations. Then, visibility (V) is

$$-0.02 = -e^{-\sigma V} \text{ or } V = 3.9/\sigma. \qquad [3]$$

Because most particles in duststorms have diameters that exceed wavelength of light, Mie scattering theory applies (Kerker, 1969), and the extinction coefficient (σ) of a group of non-homogeneous dust particles is

$$\sigma = \sum_{i=1}^{n} [N_i Q_i \pi d_i^2/4] \qquad [4]$$

where N_i is the number of particles per unit volume of diameter d_i, and Q_i is the efficiency factor for extinction.

Patterson, Gillette and Grams (1976) plotted Q_i as a function of the Mie size variable for particles with a real part of the index of refraction of 1.525 and a range 0.0 to 0.10 for the imaginary part as shown in Fig. 1. Because the visible spectrum extends over a range of wavelengths, visibility calculations are not appreciably affected by the value of the imaginary part. The index of refraction is typical of quartz particles and is applicable to many erodible mineral soils. Thus, if particle size distribution of the suspended particles is known, a relationship between concentration and visibility can be calculated.

We calculated the extinction coefficient for the particle size distribution shown in Table 1, assuming a

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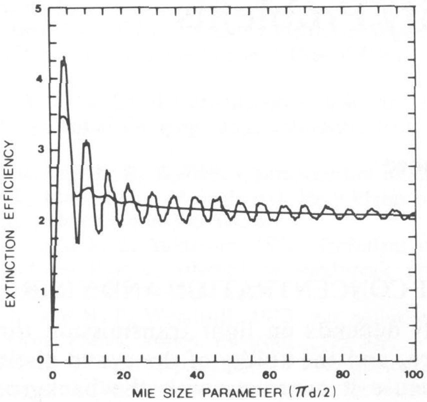

FIG. 1 Extinction efficiency for Mie scatterers with $N_{Re} = 1.525$ and $N_{Im} = 0.00$ (large oscillations) and $N_{Im} = 0.10$ (small oscillations). (After Patterson et al., 1976.)

particle density of 2.0 g/cm³ and Q_i as shown in Fig. 1. The result was

$$V = 22.8/\chi \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad [5]$$

where x is in mg/m³ and V is in km. The size distribution in Table 1 is relatively fine, and more than 90 percent of the visibility extinction is caused by 50 percent of the mass containing the smallest particles. In this case, visibility is not a sensitive indicator of changes in mass of particles on the coarse end of the size distribution. Gillette and Walker (1976) also found particle size distribution changed with both windspeed and soil texture.

Chepil and Woodruff (1957) measured visibilities and dust concentrations at the 1.8-m height at various locations in the Great Plains. They found the relation

$$V = 25.0/\chi^{0.8} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad [6]$$

Their result suggests the particle size distribution was coarse at very low visibilities and approached the particle size distribution in Table 1 only at high visibilities. Because visibility depends strongly on particle size distribution, more research is needed to delineate the factors that determine the suspended particulate size in eroding areas.

TABLE 2. CALCULATED RATIO (F) OF ACTUAL VISUAL RANGE TO THEORETICAL VISUAL RANGE UNDER VARIOUS CONDITIONS*

Albedo of object	Albedo of background	F†	
		Overcast sky	Clear sky‡
Black	Sky	1.0	1.0
0.25	Sky	0.97	0.99
Black	0.25	0.50	0.24
0.05	0.25	0.45	0.21
0.15	0.25	0.31	0.12
Black	0.15	0.39	0.17
0.05	0.15	0.31	0.12
Black	0.05	0.21	0.07

*Data from Middleton (1941).
†Theoretical visual range is for a black object against a sky background for an observer with a limiting contrast of 0.02.
‡Observer facing toward the sun with solar elevation of 20 deg.

TABLE 1. SUSPENDED PARTICLE SIZE DISTRIBUTION AND RELATIVE VISIBILITY EXTINCTION DURING A GREAT PLAINS DUSTSTORM

Representative diameter, μm*	Cumulative weight, percent	Relative no. of particles†	Relative extinction, percent
2.5	5	64,000	20.6
3.3	10	27,827	15.3
4.2	15	13,479	11.8
4.9	20	8,500	9.9
5.8	25	5,125	8.3
6.8	30	3,180	7.0
8.1	35	1,882	5.8
9.3	40	1,243	5.1
11.0	45	751	4.2
14.0	50	364	3.3
18.0	55	172	2.5
35.0	60	23	1.4
61.0	65	4.4	0.7
64.0	70	3.8	0.7
67.0	75	3.3	0.7
70.0	80	2.9	0.6
74.0	85	2.5	0.6
79.0	90	2.0	0.6
86.0	95	1.6	0.5
100.0	100	1.0	0.4

*Data from Patterson, et al. (1976).
†Determined by dividing weight of 100-μm particle by weight of smaller particle.

High particulate concentrations are necessary to cause low visibilities during daylight when standard observations procedures are followed. For example, about 100 to 400 mg/m³, depending on particle size distribution, are needed to reduce visibility to 200 m. However, a motorist or pilot often experiences conditions other than optimum that reduce actual visibility (Table 2). When the viewed object varies in color from black to gray, actual visibility is reduced little. If dark objects are viewed against a background that has an albedo typical of most natural surfaces, visibility is reduced 50 to 75 percent. If the viewer is also facing the sun with a solar elevation of 20 deg, actual visibility will be only 7 to 24 percent of the visibility under standard observation conditions. (Table 3 shows albedo ranges for typical natural backgrounds.)

Thus, dust concentrations that exceed 50 to 100 mg/m³ seriously reduce visibility during daylight, and even lower concentrations are hazardous at night.

Visibility is also decreased by high relative humidity, particularly if it is more than 70 percent. High relative humidity and wind erosion are seldom concurrent, however. During the 1950's relative humidity exceeded 70 percent during less than 2 percent of the hours when dust reduced visibility below 4.8 km in the Great Plains (Hagen and Woodruff, 1973). Hanel (1976)

TABLE 3. ALBEDOES FOR SOME BACKGROUND SURFACES* (WAVELENGTHS <4.0 μm)

Surface	Albedo range, percent
Sand dune, dry	35-45
Soil, dark	5-15
Soil, dry light sand	25-45
Concrete, dry	17-27
Road, black top	5-10
Desert	25-30
Meadows, green	10-20
Froest, deciduous	10-20
Forest, coniferous	5-15
Crops	15-25

*Data from Sellers (1965).

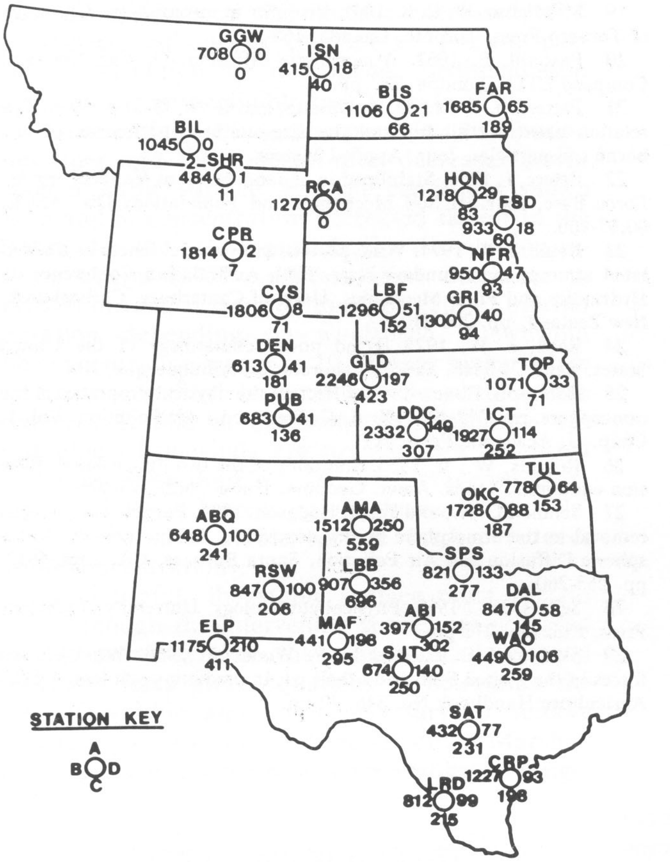

FIG. 2 Plot of stations showing station abbreviation (A), average annual number of hours windspeeds at anemometer height were ⩾ 8.5 m/s (B), maximum annual number of dusty hours (C), and average annual number of dusty hours (D) in the Great Plains. (Windspeed data are averages for 5 years or more from Reed, 1975, and dust data are for decade of 1950's from Hagen and Woodruff, 1973.)

computed the effects of relative humidity on particulates for a wide range of conditions.

Weather records show that the potential is high for reduced visibilities due to wind erosion. At Great Plains locations, windspeeds above threshold velocity average from 400 to 2000 hr annually (Fig. 2). The number of dusty hours (i.e., visibility less than 14.5 km) is less than the hours of high windspeed and ranges from 0 to 696 hours annually. Because visibility is reported as the greatest visibility occurring over at least half the horizon circle, annual dusty hours represent periods when particulate sources are large in size. The frequency of occurrence of various reduced visibilities is nearly equal; thus, hours of very low visibility in an area can be roughly estimated from the total dusty hours in Fig. 1.

REDUCTION OF DUST CONCENTRATION

Dust concentration near a road or airport can be reduced by decreasing the source emission rate, diffusing the dust cloud, or trapping the suspended particles. A combination of these methods is often desirable.

Source Reduction

The effect of source emission rate on downwind concentration can be determined from the diffusion equation for a steady, crosswind line source:

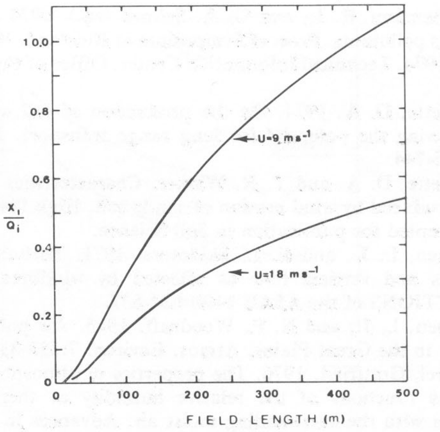

FIG. 3 Calculated dust concentration (χ_1) in mg/m$_3$ at 1-m height leeward of various length fields when emission rate (Q) is 1 mg/m^2/s. (Windspeeds are at 10-m height and z_0 is 0.001 m.)

$$\frac{u\partial\chi}{\partial x} = \frac{\partial}{\partial z}\left(K_z\frac{\partial\chi}{\partial z}\right) + V_s\frac{\partial\chi}{\partial x} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots [7]$$

where

u = windspeed in horizontal direction x,
χ = particulate concentration,
K_z = is eddy diffusivity in the vertical direction z, and
V_s = particle sedimentation velocity.

For a ground-level line source with $V_s = 0$, an approximate solution for the diffusion equation is

$$\chi = \frac{Q}{ku^*x}\exp\left[\frac{-uz}{ku^*x}\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots [8]$$

where

Q = vertical flux per unit length,
u* = friction velocity
k = a constant ≅ 0.4, and
K_z = ku*z (Pasquill, 1962).

Using equation [8], we calculated the dust concentration at a height of 1 m at the leeward edge of an eroding field for various lengths of upwind field (Fig. 3). The eroding field was treated as a series of 1-m-wide line sources of unit emission rate. Because $V_s = 0$, the results underestimate the concentration slightly when V_s is significant. For example, Rounds (1955) showed maximum ground level concentration from a line source increased about 10 percent from $V_s = 0$ to $V_s = 0.1\ u_H$; u_H is windspeed at source height.

The results in Fig. 3 show that leeward concentration is nearly linearly related to field length for fields shorter than about 200 m, but diffusion begins to reduce rate of concentration increase on longer fields; about half the dust concentration is supplied by the first 175 m of the 500-m field. These results assume a uniform Q, which likely occurs only over highly erodible fields when the saltation flux is constant along the wind direction.

While we can determine the Q necessary to produce a given downwind concentration, we can not yet accurately predict Q from a knowledge of the field con-

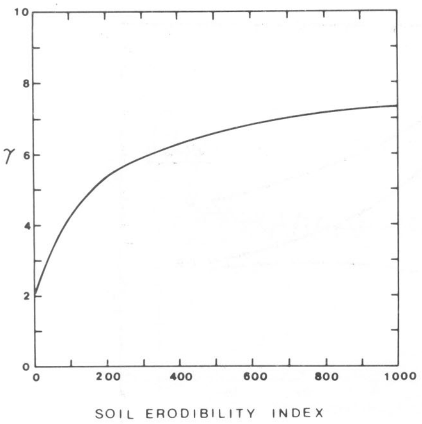

FIG. 4 Experimental relationship of γ and soil erodibility index. (Relationship from Anspaugh, et al., 1975).

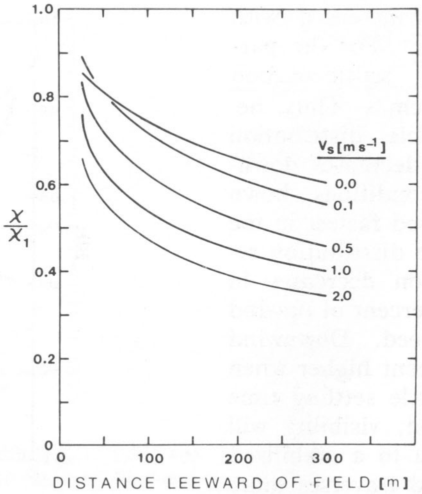

FIG. 5 Ratio of downwind ground level concentrate (χ) to concentration at 1-m height on leeward edge of an eroding field (χ_1) for particles with various sedimentation velocities (V_s). Conditions assumed were u* = 0.52 m/s, z_0 = 0.01 m, and an initial particle concentration of $\chi/\chi_1 = z^{-0.3}$.

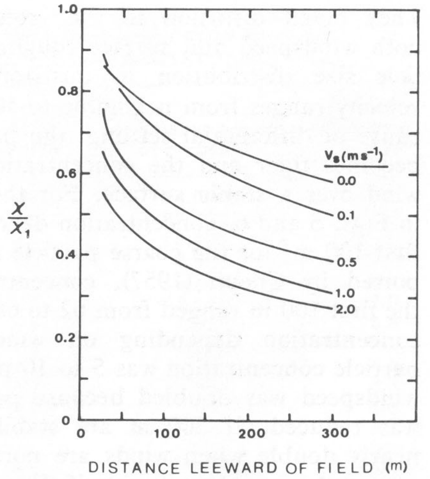

FIG. 6 Ratio of downwind ground level concentration (χ) to concentration at 1-m height on leeward edge of an eroding field (χ) for particles with various sedimentation velocities (V_s). Conditions assumed were u* = 0.14 m/s, z_0 = 0.01 m, and an initial particle concentration of $\chi/\chi_1 = z^{-0.3}$.

ditions. However, predicting Q is a subject of much current research (Englemann and Sehmel, 1974). Anspaugh et al. (1975) suggested Q is related to windspeed as

$$Q = Q_o(u^*/u_o)^{\gamma+1} \quad \ldots\ldots\ldots\ldots [9]$$

where Q_o and u_o are a reference vertical flux and friction velocity on a given field. The exponent γ increases with soil erodibility and ranges from about 2 to 7. Anspaugh et al. (1975) gave a tentative relation between γ and soil erodibility index (I), where I is the soil removed from a tray in a wind tunnel test (u* = 0.61 m/s) normalized by the weight of soil removed from the same soil when 60 percent of the particles by weight exceed 0.84 mm (Fig. 4) (Chepil and Woodruff, 1959). Gillette (1974) suggested the increase in γ with soil erodibility is caused by an increase in rate of abrasive breakdown of large particles to suspension size.

The effect of various erosion control practices on total soil loss can be evaluated from the wind erosion equation (Skidmore and Woodruff, 1968). The relative effects of various erosion controls on Q can be evaluated in the same way, but Q appears to be more sensitive than total soil loss to field erodibility. Thus, estimates of changes in Q due to a control practice will be conservative.

Diffusion of the Dust Cloud

The upwind erosive area often is large, and it is practical to create a stable area only near the roadway or airport. Diffusion of the dust cloud over the stable area will reduce concentration and, thus, improve visibility.

Typical dust concentration profiles measured over large eroding areas can be described by

$$\chi/\chi_1 = z^{-d} \quad \ldots\ldots\ldots\ldots [10]$$

where

χ_1 = concentration at 1 m,
z = height,

and the exponent d ranges from 0.25 to 0.35 (Anspaugh et al., 1975; Chepil and Woodruff, 1957). Using the concentration profile in equation [10], one can calculate the emission rate per unit length (Q) of an elevated line source as

$$Q = \chi_1 z^{-d} u_H \Delta z \quad \ldots\ldots\ldots\ldots [11]$$

where

u_H = windspeed at source height H and
Δz = a height interval.

We combined a solution to the diffusion equation reported by Pasquill (1962) and equation [11] to give

$$\frac{\chi(0,x)}{\chi_1} = \frac{\gamma \exp[-A/x]}{\Gamma(1-p)} \left[\frac{x}{A}\right]^{p-1} H^{-1.3}. \quad \ldots\ldots\ldots\ldots [12]$$

H is source height, γ = *a* + 1, where *a* is the exponent for a power law description of the windspeed profile, A = $H^2u_H/{:}\gamma^2ku^*H)$ and p = $V_S/(ku^*\gamma)$. We assumed d = 0.3, *a* = 0.176, and ΔH = 0.5 m. Relative ground level concentrations downwind over a stable surface are shown in Figs. 5 and 6 for two windspeeds and various sedimentation velocities.

Boundary conditions for equation [12] are that the amount of particles reaching the surface by sedimentation are retained, but net diffusion of particles to the surface is zero. These are probably realistic conditions, where some of the particles bounce on impact and are resuspended. However, there is little information on the ability of various kinds of surfaces to retain impacting particles. Sehmel and Hodgson (1974) have given empirical formulas for calculating the rate of dry deposition on surfaces that retain all particles.

They noted diffusion to the surface increased with both windspeed and surface roughness. For the particle size distribution in duststorms, sedimentation velocity ranges from negligible to 100 cm/s. Thus, because of differential settling, the particle distribution becomes finer and the concentration decreases downwind over a stable surface. For the conditions shown in Figs. 5 and 6, concentration decreased fastest in the first 100 m; for the coarse particle size distribution reported by Chepil (1957), concentration decreases in the first 100 m ranged from 62 to 68 percent of upwind concentration depending on windspeed. Downwind particle concentration was 5 to 10 percent higher when windspeed was doubled because particle settling time was reduced. If 300 m are stabilized, visibility will nearly double when winds are normal to a stabilized area and more than double if the wind traverses more of a stabilized area. Increasing roughness or particle-retaining ability of a stable surface further reduces downwind concentrations.

To remain useful, the stable surface must remain stable even though the intervening spaces are occupied by erodible particles. For that condition, Lyles and Allison (1976) have given equations to determine the amounts of stubble and clods necessary to achieve surface stability with various friction velocities. Marshall (1970) also has given some results for shrubs on rangelands.

TRAPPING SUSPENDED DUST

Wind barriers can be used to trap suspended dust, but their trapping efficiency is not well documented. Barriers separate particles from the flow by both inertia impaction and interception. Belot and Gauthier (1974) measured collection efficiencies of 20 and 30 percent on oak and pine shoots, respectively, for 10-μm particles in a wind tunnel at windspeeds of 10 m/s. They found collection efficiency was proportional to both windspeed squared and particle diameter to the fourth power for 1- to 10-μm-diameter particles. They concluded that elements of fibrous shape were more efficient than those of bluff shape. Honda (1974) used industrial dusts to test the dust-trapping ability of 10 plant species. Individual plants trapped 35 to 80 percent of the dust; most species trapped 50 to 60 percent. From these results, we would expect a single-row plant barrier to trap about 50 percent of the dust and 3 rows to trap about 88 percent.

To trap suspended dust near a roadway, a barrier probably should be placed 10 to 20 barrier heights upwind from the leeward side of the roadway. If the barrier is closer, it tends to shade the roadway and to serve as an undesirable background for distinguishing other vehicles, as shown in Tables 2 and 3. If the barrier is placed far from the road, dust concentration over the roadway will be about as high as without the barrier, as shown in Fig. 7. Eddy diffusivity was assumed equal with and without the barrier in calculating concentrations in Fig. 7. Near the top of a low porosity barrier, eddy diffusivity would be increased, however, and leeward concentration would approach open field concentration more rapidly than shown in Fig. 7.

Barriers with a porosity of 20 percent or less induce a leeward recirculation zone (Baltaxe, 1967), and dust coming over the top of the barrier would likely be drawn into this zone and again cause low visibilities. Thus, barriers near a roadway should be about 40 percent porous to maximize their trapping abilities and still prevent overhead dust from diffusing rapidly back to the surface.

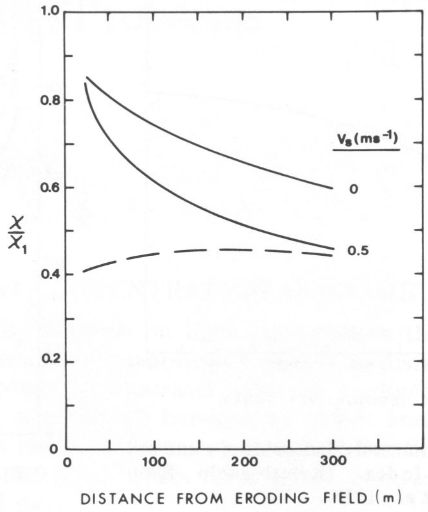

FIG. 7 Ratio of downwind ground level concentration (χ) to concentration at 1-m height [χ_1] on leeward edge of an eroding field without barrier [solid lines] and with 5-m-tall wind barrier on leeward edge which is a 50 percent efficient dust trap (dashed line). Conditions assumed were $u_* = 1.04$ m/s, $z_0 = 0.01$ m, and initial particle concentration of $\chi/\chi_1 = z^{-0.3}$.

In addition to dust trapping, barriers also can be used in the upwind area to enhance diffusion and reduce field erodibility. Both the turbulence and airflow patterns caused by barriers of various porosity have been reported (Hagen and Skidmore, 1971; Raine, 1974). In general, an erosive surface will be stabilized when 30 to 40 percent porous barriers are spaced 10 barrier heights apart normal to the wind direction. If the upwind area is only partly stabilized, the size of dunes created by entrapment of saltating particles should be calculated and their effects also considered in design of the barrier system.

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