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Literature Review of Models for Estimating Soil Erosion and Deposition from Wind Stresses on Uranium Mill Tailings Covers

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U.S. Nuclear Regulatory Commission

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ABSTRACT

Pacific Northwest Laboratory (PNL) is investigating the use of a rock armoring blanket (riprap) to mitigate wind and water erosion of an earthen radon suppression cover applied to uranium mill tailings. The mechanics of wind erosion, as well as of soil deposition, are discussed in this report. Several wind erosion models are reviewed to determine if they can be used to estimate the erosion of soil from a mill tailings cover. One model, developed by W. S. Chepil, contains the most important factors that describe variables that influence wind erosion. Particular features of other models are also discussed, as well as the application of Chepil's model to a particular tailings pile. For this particular tailings pile, the estimated erosion was almost one inch per year for an unprotected tailings soil surface. Wide variability in the deposition velocity and lack of adequate deposition models preclude reliable estimates of the rate at which airborne particles are deposited.

SUMMARY

Pacific Northwest Laboratory (PNL) is investigating the use of a rock armoring blanket (riprap) to mitigate wind and water erosion of an earthen radon suppression cover applied to uranium mill tailings. The purpose of this earthen cover is to reduce radon-222 exhalation from the tailings and to provide long-term stability for the tailings impoundments. Because of the length of time the cover must remain intact (up to 1000 years or longer), the soil must be protected from natural erosional forces, hence the need for a long-term mitigation technique such as a riprap blanket. At the same time, this rock blanket must itself withstand natural weathering processes that promote deterioration of the rock.

In this document, prepared for the U.S. Nuclear Regulatory Commission (NRC), several wind erosion models are reviewed to determine if they can be used to estimate the erosion of soil from a uranium mill tailings cover. The model that contains most of the factors needed to describe wind erosion from this type of structure is the wind erosion equation developed by Chepil. According to Chepil's model, the unprotected soil surface of a tailings pile can erode at a rate of almost one inch per year. The usefulness of particular features of other models for describing aspects of wind erosion is discussed. If a tailings cover includes vegetation or riprap, the thickness of the cover could increase as surrounding soil is deposited. Models describing this phenomenon are briefly discussed and how the models may be applied to particular tailings piles is introduced.

CONTENTS

1.0 INTRODUCTION

Large quantities of radioactive mill tailings are generated by the milling of uranium ore, and are a source of radon gas and particles that can be dispersed by the wind. The release of radon gas to the atmosphere can be decreased by covering the tailings pile. One type of cover that has been recommended is a layer of soil several meters thick over the tailings pile. This type of cover, however, is susceptible to wind and water erosion. Stabilizing the surface of inactive mill tailings sites by using rock or vegetation covers has been investigated by Beedlow, McShane and Cadwell (1982).

The purpose of this literature review is to examine soil erosion caused by wind stresses on a tailings pile cover. Important parameters that are involved in the mechanics of wind erosion are presented in Section 3.0. The literature pertaining to wind erosion mechanics spans almost fifty years, from von Karman (1934) to the present. Section 4.0 discusses several wind erosion models. The first model discussed is the wind erosion equation developed by Chepil; it is the model most applicable to describing soil erosion of a tailings pile cover (Skidmore 1974). This section also mentions several models that depict soil erosion in terms of a horizontal or vertical flux of soil particles. The final model presented involves the stochastic properties of the wind, which makes it a more physically realistic model for describing the effects of the wind.

Section 5.0 discusses soil deposition because this is another physical phenomenon that can change the soil cover of a tailings pile. Soil deposition would be of particular relevance if, in addition to the soil cover over the tailings pile, a layer of riprap was put on top of the cover.

Application of the various models to a tailings pile is presented in Section 6.0. In particular, the factors used in the wind erosion equation are estimated for a tailings pile at Grand Junction, Colorado. Figures illusrating the results are provided.

2.0 CONCLUSIONS AND RECOMMENDATIONS

The model that best describes the wind erosion of a tailings pile is the wind erosion equation developed by Chepil (Skidmore 1974). Chepil's equation contains more factors describing the variables that influence wind erosion from a tailings pile than any other model reviewed. Charts and graphs for obtaining the various factors in the equation, and the development of a computerized program, make the equation fairly easy to use.

The amount of soil lost from a tailings pile as a result of wind erosion over many years is provided by the wind erosion equation. For a tailings pile in western Colorado, an unprotected soil surface can erode at a rate of almost one inch per year. However, for any particular year, the amount of soil lost can vary, depending on the wind and precipitation for any particular location. If considered on a seasonal basis, the variations from average values would be even greater. One way to improve the accuracy of the equation and to estimate the variability of the annual values predicted would be to incorporate probability functions for some of the dynamic variables (Skidmore 1974).

Many methods for decreasing the soil erosion from a tailings pile will increase soil deposition. The use of wind breaks or riprap are two such methods. Increasing the surface roughness of a tailings pile with riprap will cause wind-blown soil to fill in the spaces between the riprap. The increase in surface cover resulting from deposition over long time periods will have both positive and negative implications. Changes in the distribution of soil moisture could enhance revegetation. However, some chemical effects on the riprap could be detrimental. Some experiments should be designed for different sizes of riprap to determine the amount of deposition that would occur. The experiments could be scaled for wind tunnel testing. Whether deposition is helpful or harmful for different methods of decreasing wind erosion should be investigated.

3.0 WIND EROSION MECHANICS

A comprehensive description of wind erosion mechanics is given by Bagnold (1943) and Chepil and Woodruff (1963). Although these are not recent articles, the same principles are used by Travis (1975), Nelson and Shepard (1978), and Utah Water Research Laboratory (1978). The literature shows that wind erosion depends on many factors, but the most important are: the surface wind velocity, the soil particle size distribution, and the surface conditions. The factors are all interrelated: when one factor changes, the effects of the other factors change.

3.1 SURFACE WIND VELOCITY

The wind structure near the ground directly influences the drag on the soil, and consequently the soil movement. Brunt (1944), using calculations involving the Reynold number, showed that an atmospheric wind speed greater than 1 m $\sec^{-1}$ causes turbulent flow. According to the wind erosion tests reviewed (Zingg 1949, 1953; Chepil 1958a), erosion only occurs at wind velocities well above 1 m $\sec^{-1}$. Therefore, the turbulent wind velocity structure must be considered when determining the effect of wind on erosion. The turbulent wind velocity above a rigid surface has been modeled by von Karman (1934) and the validity of the model has been verified by others (Bagnold 1943; Zingg 1949, 1953).

The Prandtl (Brunt 1944) and von Karman (1934) equation is:

$$u_Z = 2.5\ u_\star \ln \frac{Z}{Z_o} \tag{3.1}$$

where

u_Z = wind speed at height Z (m $\sec^{-1}$)
$u_\star$ = shear velocity (m $\sec^{-1}$)
Z = height above the surface (m)
Z_o = height of the zero velocity level above ground (m).

The wind velocity above an eroding surface depends on the erodibility of the soil. Bagnold has experimentally determined a modified version of Equation (3.1) that models the wind velocity over eroding soil. Bagnold's equation was verified by other experiments (Chepil and Woodruff 1963), but Zingg (1953) recommends a slightly different constant. Bagnold's equation is:

$$u_Z = 2.5\ u_\star \ln \frac{Z}{Z'_o} + u_t \tag{3.2}$$

The zero velocity height (Z_o) in Equation (3.1) is changed to the focal point height (Z'_o) and the velocity at the focal point (u_t) is added to Bagnold's equation. The focal point is a position near the surface where all wind velocity profiles converge to a single non-zero value. The focal point height varies for different types of soil.

The wind exerts pressure on the soil particles in three ways, two of which can be combined into a drag force (Chepil 1965). The drag acts in the general direction of the wind. The other pressure results from the aerodynamic shape of the particle and results in a lift, which is smaller than the drag and decreases rapidly with particle height above the surface (Chepil 1958b, 1961). When the combined forces of the lift and drag overcome the forces holding the particles to the surface, the particles jump almost vertically into the air (Bagnold 1943; Zingg 1953). The vertical jump is caused not only by the lift on the particle but also by the reactive forces of the neighboring particles. Once in the air, the particle's horizontal velocity increases because of the drag caused by the wind. The additional energy received by the particle is transmitted to other ground particles when it lands, which gives a few more particles enough energy to leave the ground. When the deposition of one particle causes more than one particle to rise, an avalanching effect occurs. On a uniform surface, the avalanching stops when the surface velocity of the wind is lowered. As more particles are suspended, the surface velocity is lowered because the particles use the wind energy for movement. An equilibrium is reached between the number of particles suspended and the surface velocity required for suspension.

3.2 PARTICLE SIZE

The particle size determines if and how the particle can be moved by the wind. Various researchers (Bagnold 1943; Chepil 1958a) have observed three types of particle motion: saltation, suspension, and surface creep. The size of the particles that move by each type of motion overlap and vary with windspeed; thus, no absolute size ranges can be given. General limits for the soil-particle diameter for the three types of transport are (Travis 1975):

● saltation	50 to 1000 μm
● suspension	<50 μm
● surface creep	>1000 μm

A brief description of each type of movement is given below. For a more complete description, refer to Chepil and Woodruff (1963), Bagnold (1943), Woodruff (1966), Zingg (1953), and Chepil (1958a).

Saltating particles are large enough to protrude above the layer of laminar flow close to the surface and their weight is small enough so that wind forces can overcome the force of gravity. The initial motion of a saltating particle is essentially vertical because of the position of the adjacent particles and the lift. The height a saltating particle reaches is seldom greater than 1 foot and it travels less than 10 feet. Upon depositing, the particles can rebound or they can transfer their energy to the particles they contact. The contacted particles may jump away from the surface, creep along the surface, or remain stationary. The saltating particles are the ones that cause the avalanching effect mentioned earlier. Also, the saltating particles make up 50 to 75% of the eroding mass and are believed to cause the other types of motion.

The particles that move in suspension are commonly called dust; wind forces alone cannot cause them to leave the ground. A smooth surface of dust particles has been shown to be very stable under high winds if there are no saltating particles present (Bagnold 1943). This happens because the dust particles do not extend above the layer of laminar flow; thus, they do not cause turbulence, and are more cohesive than larger particles. The wind velocity that the dust particles experience is very small and thus cannot entrain the dust. The dust particles get suspended when a saltating particle hits some dust particles, giving them enough energy to leave the ground. Once in the air, the dust particles travel for great distances and climb to great heights because their settling velocities are small compared to the upward eddy currents of the air. A dust cloud is the most noticeable phenomenon of wind erosion, but the dust only contributes 3 to 4% of the eroding mass.

Surface creep consists of the intermittent rolling or sliding motion of particles on the surface caused by the impact of saltating particles. The external forces acting on the particles are not sufficient to exceed the gravitational and adhesive forces acting on the particles. Therefore, they do not leave the surface at any time. If saltating particles are available, they can maintain a surface creep of particles that are too large to be moved by the direct action of the wind.

3.3 SOIL CONDITIONS

One factor that is difficult to quantify is the soil condition, which includes soil moisture, organic residue, and soil cloddiness. Soil conditions also vary with the time of the year; thus, applying annual values is not realistic.

Increasing the soil moisture reduces erosion because the moisture increases the attractive forces between the particles (Chepil 1958a). Rainfall not only provides moisture to the soil, but also forms a surface crust resulting from the impacts of raindrops on the surface. If the soil contained only finely dispersed, water-soluble material, this crusting of the surface would be very stable. Usually, however, coarser particles remain on the top of the soil, abrade the surface when moved by the wind, and thus destroy the surface crust.

Soil aggregates (collections of individual soil particles bound together by soil cement) form clods that are too large to be entrained by the wind. The strength of the soil cement depends on the soil moisture and the soil composition (Chepil 1958a). Tests have shown that aggregates on the surface decrease wind erosion. However, the aggregates are broken into erodible fractions by frost, sunlight, and the abrasion of saltating particles, so the decrease in erosion is not permanent. Soil aggregates that have formed under the surface are continually brought to the surface by wind erosion. Thus, the rate of destruction and replacement of surface aggregates, as well as the wind velocity and the number of erodible particles in the soil, influences the rate of erosion.

3.4 SURFACE ROUGHNESS

Surface roughness can decrease or increase erosion, depending on the size and type of roughness elements. A rough surface lowers the surface wind velocity more than does a flat surface; however, the roughness increases the turbulence, causing rough surfaces to be exposed to higher wind speeds than are smooth surfaces (Bagnold 1943; Armbrust, Chepil and Siddoway 1964). The literature indicates that an increase in surface roughness causes an overall decrease in erosion, except where the roughness elements are highly erodible (e.g., ridges of sand). The roughness elements considered in most of the literature pertain to soil aggregates, furrows, and large windbreaks.

Plowing produces furrows that increase the surface roughness. The furrow stability depends on the strength of the aggregates that form the peaks. Tests show that the most effective height of a plowed ridge for controlling erosion is between 5 and 10 cm (Armbrust, Chepil and Siddoway 1964). Soil ridges above 10 cm cause the wind erosion to increase because of the added turbulence caused by the ridge and the added drag on top of the ridge. Nonerodible ridges or walls, called windbreaks, continually decrease erosion with height (Woodruff and Zingg 1958; Hagen and Skidmore 1971; Woodruff 1955). Besides height, the shape and porosity of a windbreak affect its ability to decrease erosion. Some windbreaks trap saltating particles; this stops avalanching and assists the decrease in erosion caused by the wind velocity reduction.

Surface roughness depends on the height, length, density, orientation, and quality of the vegetative cover (if present). To determine surface roughness by measuring these surface obstructions is extremely difficult. A ridge roughness factor (Travis 1975) has been devised using standard photographs as a guide for visual estimation of the factor. Visual estimates of the vegetative residue can also be made from these standard photographs.

3.5 TAILINGS CONFIGURATIONS

The length of a tailings pile, especially along the prevailing wind erosion direction, influences the erosion. The rate of soil movement is zero on the windward side of a field and increases with distance downwind. If the field is large enough, the maximum soil flow that wind can carry will be attained. The distance required for soil flow to reach the maximum varies inversely with erodibility. Thus, reducing the erodibility of the tailings pile with windbreaks or vegetative cover helps prevent wind erosion.

If the tailings pile is elevated above the existing terrain, the slope at the edges influences the erosion. The steeper the slopes, the more erodible the surface becomes. Also, any gradual slope over the entire pile, especially along the prevailing wind erosion direction, must be accounted for when calculating the erosion.

The prevailing wind erosion direction is not necessarily the same as the prevailing wind direction. The speed of the wind is an important factor when determining erosion; therefore, that direction from which higher-speed winds flow must be considered when calculating wind erosion. If the tailings pile is rectangular in shape the shorter side should be oriented in the direction of the prevailing wind erosion direction.

4.0 WIND EROSION MODELS

The rate of soil flow (i.e., the mass of soil moving through a plane, either vertical or horizontal) has been modeled in several ways. The amount of soil moved is estimated in terms of a horizontal or vertical flux of soil particles. Most of the factors important in wind erosion are considered by the wind erosion equation developed by Chepil (Skidmore 1974). This model is discussed below. Also, a more recent model which describes wind erosion in terms of stochastic aerodynamics is described.

4.1 WIND EROSION EQUATION

The wind erosion equation was developed by W. C. Chepil and is based on wind tunnel and agricultural field measurements. It is the result of nearly 30 years of research to determine the primary variables or factors that influence the erosion of soil by wind. The equation has the following form:

$$E = f(I,K,C,L,V) \tag{4.1}$$

where

E = soil loss by wind in tons/acre/year
I = soil erodibility factor
K = soil surface roughness factor
C = local climatic factor
L = equivalent field length
V = vegetative cover factor.

The soil erodibility factor, or index (I) was developed from wind tunnel and field measurements of erodibility. Clods larger than 0.84 mm in diameter were nonerodible in the tests. Thus, the nonerodible soil fractions greater than 0.84 mm, as determined by dry sieving, have been used to indicate erodibility of soil by wind.

The soil surface roughness factor (K) is a function of soil ridge roughness, which is the natural or artificial roughness of the soil surface in the form of ridges or small undulations. The roughness factor for a smooth surface has a value of 1.0. The value decreases to a minimum value of approximately 0.5 for soil roughness heights of 3 to 4 inches and then slowly increases with increasing soil roughness height.

The local climatic factor (C) was developed from the relationship stating that the rate of soil flow varies directly as the cube of the windspeed and inversely as the square of the effective moisture. Effective moisture of the surface soil particles was assumed to vary as indicated by the Thornthwaite P-E index (Thornthwaite 1931), developed to evaluate precipitation effectiveness.

The equivalent field length (L) is the unsheltered distance across the field along the prevailing wind erosion direction. The rate of soil movement is zero on the windward side of a field and increases with distance downwind. If the field is large enough, the maximum soil flow that a wind can carry will be attained. The equivalent field length adjusts for this variation in soil flow over the length of the field. The preponderance of wind erosion forces in the prevailing wind erosion direction is incorporated into the equivalent field length term. For example, a preponderance value of 2.0 indicates a prevailing wind erosion direction with wind erosion forces that are twice as great parallel as perpendicular to the prevailing wind erosion direction.

The vegetative cover factor (V) is determined from the quantity of vegetative cover, the kind of vegetative cover, and the orientation of vegetative cover. Graphs (Woodruff and Siddoway 1965) have been developed for various types of crops, at different stages of their development. Also, Chepil and Woodruff (1959) have developed a set of standard photographs for estimating the surface roughness factor together with the vegetative residue for farm fields. A brief review of the literature pertaining to the vegetative factor is given by Skidmore (1974). Much work has been done in quantifying the specific properties of vegetative covers. In general: 1) on a weight basis, fine-textured residues are more effective than coarse-textured residues; 2) any orientation of residue, except flattened, decreases wind erosion; and 3) fine-leafed crops, like grasses and cereals, provide a high degree of erosion control per unit weight.

The charts and graphs for obtaining values of the various factors have appeared in several reports (Woodruff and Siddoway 1965; Nelson and Shepard 1978; Israelsen et al. 1980). Relationships among variables are complex, and a single equation that expresses E as a function of the dependent variables has not been devised. The equation can be solved in a stepwise procedure involving graphical solutions. To facilitate the use of the wind erosion equation to predict soil loss more effectively, the equation has been computerized in the program WEROS (Fisher and Skidmore 1970). Besides solving the equation quickly and accurately, the computer program allows the user to visualize the problem in reverse; that is, the user can specify the tolerable limits of soil erosion, and the program then can determine conditions for controlling soil loss within those limits.

4.2 HORIZONTAL AND VERTICAL FLUX OF SOIL PARTICLES

The wind erosion equation presented in Section 4.1 gives the soil loss in terms of a flux of soil (i.e., mass per unit surface area per unit time). Gillette (1973) conducted field experiments of soil wind erosion and measured the vertical flux of particulate matter. He stated his results through the parameter of a threshold erosion wind speed, which is the wind speed at which the extrapolated vertical flux is the same for all the soils tested. This relation can be written as:

$$F_v \propto \left(\frac{u_\star}{u_{\star t}}\right)^\gamma \tag{4.2}$$

where

F_v = vertical flux gm m^{-2} sec $^{-1}$)
$u_\star$ = shear velocity (m sec^{-1})
$u_{\star t}$ = threshold shear velocity (m sec^{-1})
γ = exponent.

Gillette obtained values of γ ranging from 5.1 to 9.7, depending on the type of soil.

Vertical fluxes can also be calculated using the concept of a resuspension rate. The resuspension rate cannot be predicted accurately. Experimental studies report values ranging from 10^{-12} to 10^{-4} sec^{-1} for wind-induced resuspension (Sehmel 1980a).

Gillete (1973) also obtained measurements of the horizontal flux of soil particles. Gillette based his models on the work of Bagnold (1943), who found that the horizontal flux varied directly as the cube of the surface shear velocity:

$$F_h = C_h \, u_\star^3 \tag{4.3}$$

where

F_h = horizontal flux (gm m^{-1} sec^{-1})
C_h = empirical constant (gm sec^2 m^{-4})
$u_\star$ = shear velocity (m sec^{-1}).

A modified relationship, as proposed by Lettau, was used by Gillette (1973):

$$F_h = C_h u_\star^2 \, (u_\star - u_{\star t}) \tag{4.4}$$

This relationship incorporates the fact that erosion occurs above a certain threshold wind velocity.

An analytical solution of the equations describing the saltation process was derived by Owen (1964). The same relationship was also obtained by Kind (1976). It has the following form:

$$F_h = \alpha \frac{\rho}{g} u_\star (u_\star + u_{\star t}) \, (u_\star - u_{\star t}) \tag{4.5}$$

where

α = empirical parameter
ρ = density of air (gm m^{-3})

g = gravitational acceleration (m sec^{-2})

F_h, u_*, and u_{*t} as defined previously.

All the horizontal flux relations given above vary with the cube of the surface shear velocity.

To include the effects of moisture in the flux relationships, Belly (1964) developed the following equation for the threshold shear velocity:

$$u_{*t} = A \sqrt{\frac{\rho_s - \rho}{\rho} gd} \ (1.8 + 0.6 \log_{10} W) \qquad (4.6)$$

where:

A = a dimensionless coefficient of 0.1 in value

ρ_s = density of sand particle (gm m^{-3})

d = diameter of sand particle (m)

W = water content expressed in weight by percent

ρ and u_{*t} as defined previously.

Using a range of particle diameters from 0.015 cm to 0.084 cm and W from 0.1 to 1.3 results in a range of u_{*t} from 0.2 m sec^{-1} to 0.7 m sec^{-1}. The increase in moisture reflected by $u_{*t} = 0.7$ m sec^{-1} has a pronounced influence on the horizontal flux, because no flux is obtained until the velocity at a height of 10 meters exceeds 12 m sec^{-1}.

Iverson et al. (1976) have reported several other horizontal flux relations, similar in form to Gillette's and Owen's. The empirical constant, which appears in all the formulations, can be evaluated for different soil properties.

Because vertical fluxes are never observed without horizontal fluxes, Travis (1975) assumed F_v is directly proportional to F_h and obtained the following ratio for the two fluxes:

$$\frac{F_v}{F_h} = \frac{C_v}{C_h} \frac{1}{u_{*t}^{\,3}} \left[\left(\frac{u_*}{u_{*t}} \right)^{(p/3)} -1 \right] \qquad (4.7)$$

where

C_v = empirical constant (gm m^{-2} sec^{-1})

p = particle mass percentage less than 20 μm diameter.

The exponent $p/3$ was obtained using the data of Gillette (1973). This ratio goes to zero for the two limiting cases: 1) no flux for the surface shear velocity equal to the threshold value, and 2) no flux for the suspendible particle mass percentage, p, equal to zero. The shear velocity, u_*, in all the equations in this section is implied to be greater than or equal to the threshold shear velocity, u_{*t}.

4.3 SURFACE RENEWAL

The turbulent wind velocity structure, as modeled by Prandtl, von Karman, or Zingg, treats the turbulence in an average sense by use of the shear velocity. A more realistic model, referred to as a "surface-renewal" model, describes turbulent flow near a solid boundary as a random or stochastic "renewing" of the fluid near the surface by a fluid with the properties of the bulk flow. In other words, this model stipulates that fluid exchange intermittently occurs between the region immediately adjacent to the surface, the viscous flow region, and the turbulent flow region.

The particle motion of the saltation process is described as initially having a vertical displacement. An instantaneous lift force great enough to cause the vertical displacement can be associated with the turbulent breakup of the viscous sublayer, as described by the surface renewal model. Bisal and Nielsen (1962) and Lyles (1970), observing sand grains on a surface exposed to wind, found that grains seemed to vibrate and then were ejected away from the surface. Disrud and Fan (1974) reviewed various "surface renewal" models and developed a model applicable to transport processes associated with wind erosion events.

The shear stress at the soil surface is one of the parameters used to estimate the flux of particles from the surface. In terms of a statistical distribution function $\phi(t,\theta)$, which represents the fraction of fluid elements having a contact time with the surface between θ and $\theta + d\theta$, the mean shear stress at time t can be written:

$$\tau(t) = \int_0^t \phi(t,\theta)\, \tau_i(\theta)\, d\theta \tag{4.8}$$

where

$\tau_i(\theta)$ = instantaneous shear stress at the surface for contact time θ.

A surface renewal model formulated by Thomas (1980), which was called surface rejuvenation by him, is based on the simple diffusion equation. He obtains exact solutions for the velocity and temperature distributions using random variables in the analysis. Hicks and Slinn (1982) point out that this analysis cannot be applied to rough surfaces because the pressure gradient has been assumed to be negligible. The surface renewal model shows promise in describing wind erosion; however, more theoretical development and experimental verification are needed.

5.0 SOIL DEPOSITION

The previous sections have been concerned with the removal of soil particles as a result of wind stresses. The reverse, however, could occur: the deposition of soil particles. The removal of soil from a uranium mill tailings cover is obviously detrimental; it allows the mill tailings to be more exposed to the environment. However, the addition of soil through deposition may or may not be beneficial. Deposition could reconfigure the tailings pile to an undesirable shape, or it could promote the growth of vegetation, which, in turn, can be helpful or harmful. Only the mechanics of deposition will be presented here, not the aspect of its desirability.

5.1 DEPOSITION VELOCITY

The removal of particles from the atmosphere can be described by the use of a deposition velocity. The amount deposited, or downward flux of particles, is obtained by multiplying the air concentration at some reference height by a deposition velocity. Because experimentally determined deposition velocities vary from 10^{-6} to 10^{-1} m sec^{-1} (Sehmel 1980b) and because the air concentration is measured at arbitrary reference heights, a realistic value for deposition is difficult to obtain. As pointed out by Hicks and Slinn (1982), the mathematical problem is how to specify the boundary conditions at the interface between the air and surface.

Two models developed to describe deposition from a plume originating from a point source are the source depletion model and the surface depletion model. Both incorporate the deposition velocity. The source depletion model (Van der Hoven 1968) accounts for the loss of airborne material through deposition by reducing the source strength of a Gaussian plume as a function of downwind distance. Thus, the effect of the deposition is distributed throughout the entire vertical extent of the plume. A more physically realistic approach to deposition is provided by the surface depletion model (Horst 1977). In this model, particles are deposited from that part of the plume close to the surface, thus causing the plume to become non-Gaussian in shape close to the surface. The review by Sehmel (1980b) lists other models that include deposition velocity.

5.2 DEPOSITION ENHANCEMENT

The use of vegetation or riprap has been suggested as a means of reducing soil erosion of a tailings pile cover. Both of these methods would also promote deposition by increasing the surface roughness. The amount deposited would reach some equilibrium condition, that is, the amount resuspended would equal the amount deposited over some time period, for example, in one year, if a sufficient source of depositing particles is available. In 1963 and 1964, Smith and Twiss (1965) measured the deposition of "dust" at several sites in the United States. They reported relatively similar rates of deposition for a number of months when the atmosphere appeared free of dust. Thus, some basal rate of influx of dust particles appears to exist. Because deposition on a tailings pile would occur over time spans on the order of hundreds of years, an equilibrium condition should be reached.

6.0 APPLICATION OF MODELS TO TAILINGS PILES

As pointed out in Section 4.0, the wind erosion equation incorporates many of the factors needed to quantify wind erosion from a tailings pile. In this section, a sample tailings pile, in particular a pile at Grand Junction, Colorado, is analyzed for the factors that enter into the wind erosion equation. Because the parameters that are used in calculating deposition vary by orders of magnitude, only a qualitative description will be given for this process.

6.1 EROSION

Grand Junction is located on the Colorado Plateau in western Colorado. The soil in this region is a Billings silty clay loam. Soil surveys taken by the U.S. Government indicate that 95 to 100% of the soil particles in this type of soil are less than 0.42 mm in diameter (passing through a 40-mesh screen). The tables of soil erodibility index (Woodruff and Siddoway 1965) are tabulated as a function of the percent of dry soil not passing a 20-mesh screen (0.84 mm particle diameter). The assumption will be made that 2.5% of the soil is greater than 0.84 mm in diameter. From the tables in Woodruff and Siddoway (1965), the soil erodibility factor, I, is 235 tons $\text{acre}^{-1}\text{yr}^{-1}$.

Another parameter that is part of this factor is the amount of slope of the pile. A typical slope assumed in some model site studies (Nelson and Shepard 1978) is a 2% maximum grade. This amount of slope would increase the erodibility by a factor of 1.5. Thus, the erodibility factor, I, becomes approximately 350 tons $\text{acre}^{-1}\ \text{yr}^{-1}$.

The soil surface roughness factor can vary from 0.5 to 1.0. A value of 1.0 is for a smooth surface. This parameter will be varied over its range, providing an upper and lower bound for this parameter.

Using the figures in Skidmore and Woodruff (1968), the wind erosion climatic factor, C, varies roughly from 40% to 80%, depending on the month of the year. An annual average of 60% will be assumed.

Because most tailings piles are of substantial size (greater than 1000 m in any length measure) the maximum soil flow that a wind of a given velocity can carry is assumed to always occur. This is especially true for this site, because the soil erodibility index is large and the distance required for soil flow to reach its maximum varies inversely with erodibility. Therefore, the equivalent field length parameter, L, does not affect the soil loss.

The vegetation currently existing on the Grand Junction tailings pile has not been quantified; thus, a range of values for the vegetative cover factor will be assumed. This range will provide a measure of how effective different types of vegetative covers would be if applied to the Grand Junction pile. The range of values considered for the equivalent vegetative cover is 0 pound acre^{-1} to 15,000 pound acre^{-1}.

Figure 6.1 shows the soil loss in inches per year versus equivalent vegetative cover. The curves for the two surface roughness factors, K = 0.5 and K = 1.0, show the upper and lower bounds of soil erosion for this factor.

Bander (1980) compared the soil loss resulting from wind erosion for three different erosion models. Figure 6.2 compares the soil loss versus wind speed for the three models. In this comparison, no vegetative cover is assumed and the local climatic factor and soil roughness for the wind erosion equation (WEE) are incorporated implicitly in the threshold shear velocity, u_{*t}. The curve labeled GILLETTE is based on Equation (4.4) and the curve

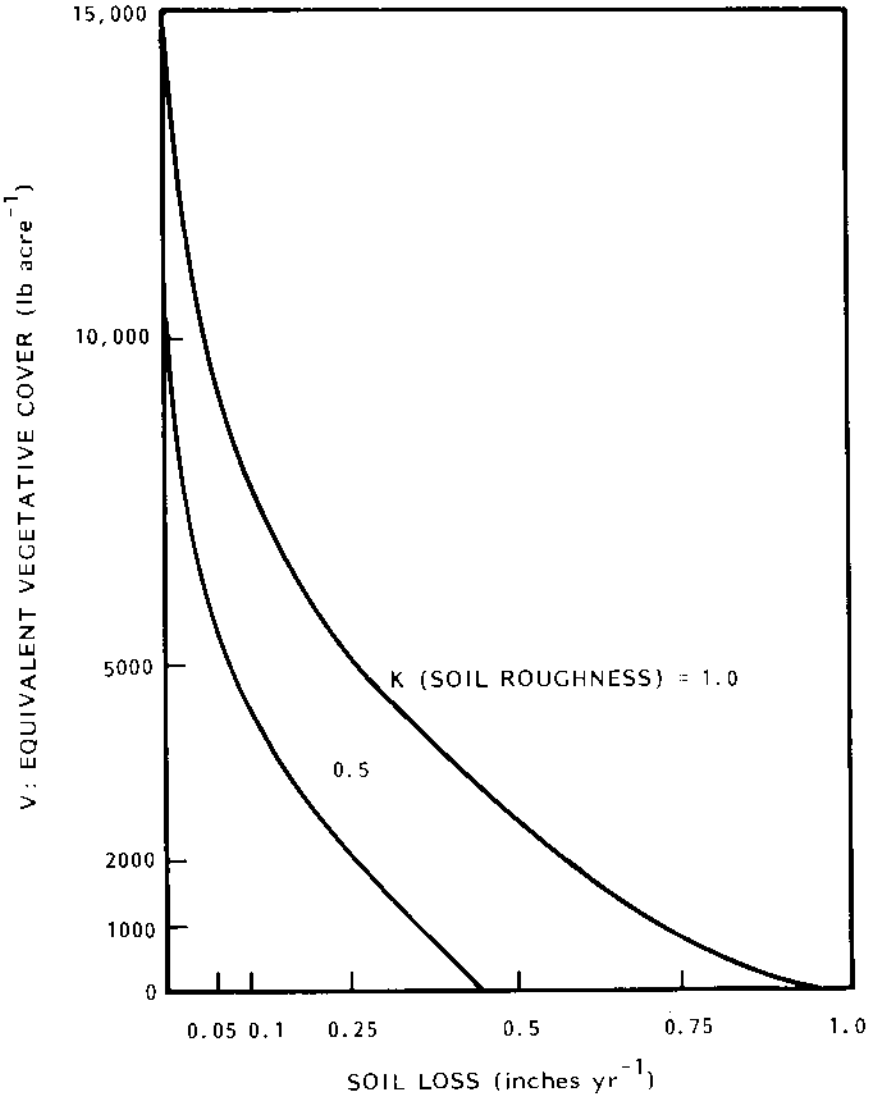

FIGURE 6.1. Soil Loss Versus Vegetative Cover as a Function of Roughness Factor, K

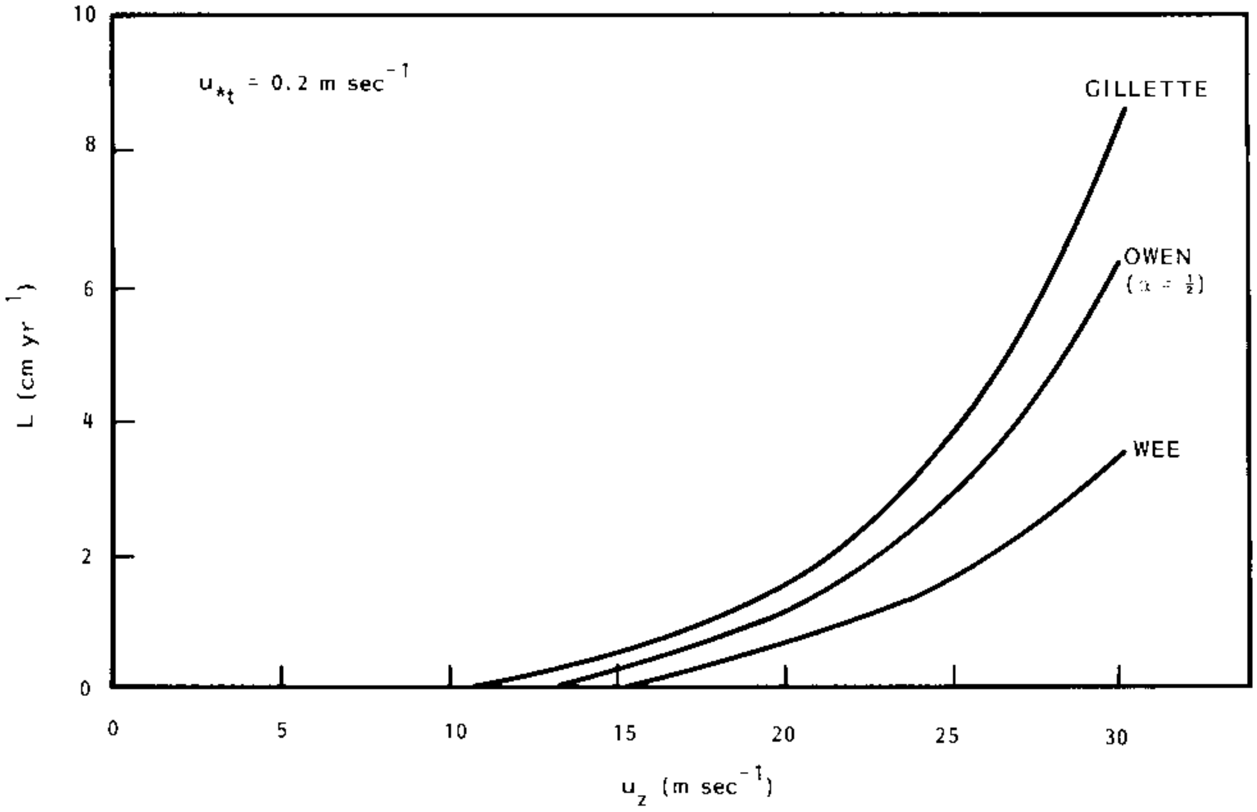

FIGURE 6.2. Loss of Soil, L, Versus Wind Speed, u_z (10 m)

labeled OWEN is based on Equation (4.5). To obtain the annual loss at a specific site, the annual frequency of occurrence of wind speeds is needed. Thus, the total loss would be the sum of the losses for each wind speed times the frequency of occurrence of that wind speed.

6.2 DEPOSITION

Smith and Twiss (1965) reported dust deposition rates of 20 to 100 pounds acre^{-1} month^{-1}. For these rates the amount of dust deposited would be 1 to 5×10^{-3} cm yr^{-1}. This would be for time periods when the atmosphere appeared free of dust. During a noticeably dusty period they obtained a deposition rate of 3600 pounds acre^{-1} month^{-1} at one collection site. This ratio gives a deposition of almost 0.02 cm in one month.

For a tailings pile the most likely source of depositing material is the soil adjacent to the pile. If a covering of riprap is used on the pile to reduce erosion, then deposition would be enhanced by the increased surface roughness from the riprap. To estimate the amount deposited on the pile, the suspension of the surrounding soil could be determined using the wind erosion equation (see Section 4.1). Then, the effect of the roughness elements (riprap) in depositing this suspended material should be determined. Some wind tunnel experiments would help to quantify this process. Also, if the riprap could be modeled in the wind tunnel, the equilibrium condition could be investigated for different wind speeds.

REFERENCES

Armburst, D. V., W. S. Chepil and F. H. Siddoway. 1964. "Effects of Ridges on Erosion of Soil by Wind." Soil Sci. Soc. Amer. Proc. 28(4):557-560.

Bagnold, R. A. 1943. The Physics of Blown Sand and Desert Dunes. WM. Morrow & Co., New York.

Bander, T. J. 1980. "Long Term Erosion Resistance of Unprotected Radon Suppression Earth Covers to Wind Stresses." Proceedings of the Third Uranium Mill Tailings Management Symposium, Fort Collins, Colorado.

Beedlow, P. A., M.C. McShane and L. L. Cadwell. 1982. Revegetation/Rock Cover for Stabilization of Inactive Uranium Mill Tailings Disposal Sites: A Status Report. PNL-4328, Pacific Northwest Laboratory, Richland, Washington.

Belly, P. 1964. Sand Movement by Wind. Defense Documentation Center for Scientific and Technical Information.

Bisal, F., and K. F. Nielsen. 1962. "Movement of Soil Particles in Saltation." Canad. Jour. Soil Sci. 42(1):81-86.

Brunt, D. 1944. Physical and Dynamical Meteorology. 3rd ed. Cambridge, Univ. Press, London.

Chepil, W. S. 1958a. "Soil Conditions that Influence Wind Erosion." USDA Tech. Bulletin No. 1185.

Chepil, W. S. 1958b. "The Use of Evenly Spaced Hemispheres to Evaluate Aerodynamic Forces on a Soil Surface." Trans. Amer. Geophysical Union, 39:397-404.

Chepil, W. S. 1961. "The Use of Spheres to Measure Lift and Drag on Wind-Eroded Soil Grains." Soil Sci. Soc. Amer. Proc. 25(5):343-345.

Chepil, W. S. 1965. "Transport of Soil and Snow by Wind." Meteorological Monographs, p. 123-131.

Chepil, W. S., and N. P. Woodruff. 1959. "Estimations of Wind Erodibility of Farm Fields." Prod. Res. Report No. 25, U.S. Department of Agriculture.

Chepil, W. S., and N. P. Woodruff. 1963. "The Physics of Wind Erosion and Its Control." Advances in Agronomy, 15:211-302.

Disrud, L. A., and L. T. Fan. 1974. "A Stochastic Model for Momentum Transfer in Wind Erosion--A Surface Renewal Concept." In Atmosphere-Surface Exchange of Particulate and Gaseous Pollutants. R. J. Engelmann and G. A. Sehmel (Coords.), pp. 528-539. Available as ERDA CDNF-740921 from NTIS, Springfield, Virginia.

Fisher, P. S., and E. L. Skidmore. 1970. WEROS: A Fortran IV Program to Solve the Wind-Erosion Equation. USDA, ARS 41-174.

Gillette, D. A. 1973. "On the Production of Soil Wind Erosion Aerosols Having the Potential for Long Range Transport." Special Issue of Journal de Recherches Atmospherique on the Nice Symposium on the Chemistry of Sea-Air Particulate Exchange Processes, Nice, France.

Hagen, L. J., and E. L. Skidmore. 1971. "Turbulent Velocity Fluctuations and Vertical Flow as Affected by Windbreak Porosity." Trans. Amer. Soc. Agr. Eng. 14(4):634-637.

Hicks, B. B., and W. G. N. Slinn. 1982. "Surface Fluxes of Small Particles." Fine Particles in the Atmosphere, ed. A. P. Altshuller, U.S.EPA.

Horst, T. W. 1977. "A Surface Depletion Model for Deposition from a Gaussian Plume." Atmospheric Environment, 11:41-46.

Israelsen, C. E., et al. 1980. Erosion Control During Highway Construction. National Research Council, Washington, DC.

Iversen, J. D., et al. 1976. "The Effect of Vertical Distortion in the Modeling of Sedimentation Phenomena: Martian Crater Wake Streaks." Journal of Geophysical Research, 81(26):4846-4856.

Kind, R. J. 1976. "A Critical Examination of the Requirements for Model Simulation of Wind-Induced Erosion/Deposition Phenomena Such as Snow Drifting." Atmospheric Environment. 10:219-227.

Lyles, L. 1970. Turbulence as Influenced by Surface Roughness in a Wind-Tunnel Boundary Layer and Subsequent Effects on Particle Motion, Ph.D. Dissertation, Dept. of Mechan. Engin., Kansas State Univ., Manhattan, Kansas.

Nelson, J. D., and T. A. Shepard. 1978. Evaluation of Long-Term Stability of Uranium Mill Tailing Disposal Alternatives. For Argonne National Laboratory, Geotechnical Engineering Program Civil Eng. Dept., No. 31-109-38-4199, Colorado State Univ., Ft. Collins, Colorado.

Owen, P. R. 1964. "Saltation of Uniform Grains in Air." J. Fluid Mech. 20(2):225-242.

Sehmel, G. A. 1980a. "Particle Resuspension: A Review." Environmental International, 4:107-127.

Sehmel, G. A. 1980b. "Particle and Gas Dry Deposition: A Review." Atmospheric Environment, 14:983-1011.

Skidmore, E. L. 1974. "A Wind Erosion Equation: Development, Application, and Limitations." In Proceedings of the Atmosphere-Surface Exchange of Particulate and Gaseous Pollutants Symposium, NITS, Springfield, Virginia.

Skidmore, E. L., and N. P. Woodruff. 1968. Wind Erosion Forces in the United States and Their Use in Predicting Soil Loss. USDA, Agriculture Handbook No. 346.

Smith, R. M., and P. C. Twiss. 1965. "Extensive Gaging of Dust Deposition Rates." Transactions of the Kansas Academy of Science, 68:311-321.

Thomas, L. C. 1980. "The Surface Rejuvenation Model of Wall Turbulence: Inner Laws for u^+ and T^+." International Journal of Heat and Mass Transfer, 23:1099-1104.

Thornthwaite, C. W. 1931. "Climates of North America According to a New Classification." Geog. Rev. 25:633-655.

Travis, J. R. 1975. "A Model for Predicting the Redistribution of Particulate Contaminants from Soil Surface." In Proceedings of the Atmosphere-Surface Exchange of Particulate and Gaseous Pollutants Symposium, NITS, Springfield, Virginia.

Utah Water Research Laboratory. 1978. Manual of Erosion Control Principles and Practices. Hydraulics and Hydrology Series Report No. H-78-002, College of Engineering, Utah State Univ., Logan, Utah.

Van der Hoven, I. 1968. "Deposition of Particles and Gases." Meteorology and Atomic Energy, 1968, ed D. Slade, USAEC, TID-24190.

von Karman, T. 1934. "Turbulence and Skin Friction." J. Aerosol Sci. 1:1-30.

Woodruff, N. P. 1955. "Barriers Reduce Wind Velocity, Evaporation, and Control Snow Drifting." J. of Soil and Water Conservation, 10:151.

Woodruff, N. P. 1966. "Wind Erosion Mechanics and Control." In Proceedings of First Pan American Congress of Soil Conservation, pp. 253-262, San Paulo, Brazil.

Woodruff, N. P., and F. H. Siddoway. 1965. "A Wind Erosion Equation." Soil Sci. Soc. Amer. Proc. 29:602-608.

Woodruff, N. P., and A. W. Zingg. 1958. "A Comparative Analysis of Wind Tunnel and Atmospheric Air Flow Patterns about Single and Successive Barriers." Trans. American Geophysical Union, 30:203-208.

Zingg, A. W. 1949. "A Study of the Movement of Surface Wind." Agricultural Engineering, 30:4-13.

Zingg, A. W. 1953. "Wind Tunnel Studies of the Movement of Sedimentary Materials." In Proceedings of the Fifth Hydraulics Conference, Bulletin No. 34, Manhattan, Kansas.

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16. ABSTRACT (200 words or less)

Pacific Northwest Laboratory (PNL) is investigating the use of a rock armoring blanket (riprap) to mitigate wind and water erosion of an earthen radon suppression cover applied to uranium mill tailings. The mechanics of wind erosion, as well as of soil deposition, are discussed in this report. Several wind erosion models are reviewed to determine if they can be used to estimate the erosion of soil from a mill tailings cover. One model, developed by W. S. Chepil, contains the most important factors that describe variables that influence wind erosion. Particular features of other models are also discussed, as well as the application of Chepil's model to a particular tailings pile. For this particular tailings pile, the estimated erosion was almost one inch per year for an unprotected tailings soil surface. Wide variability in the deposition velocity and lack of adequate deposition models preclude reliable estimates of the rate at which airborne particles are deposited.

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