EPA-600/4-77-037
July 1977

Environmental Monitoring Series

RESUSPENSION OF PLUTONIUM FROM CONTAMINATED LAND SURFACES: Meteorological Factors

Environmental Monitoring and Support Laboratory
Office of Research and Development
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RESUSPENSION OF PLUTONIUM FROM CONTAMINATED LAND SURFACES: Meteorological Factors

by

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FOREWORD

Protection of the environment requires effective regulatory actions which are based on sound technical and scientific information. This information must include the quantitative description and linking of pollutant sources, transport mechanisms, interactions, and resulting effects on man and his environment. Because of the complexities involved, assessment of specific pollutants in the environment requires a total systems approach which transcends the media of air, water, and land. The Environmental Monitoring and Support Laboratory-Las Vegas contributes to the formation and enhancement of a sound integrated monitoring data base through multidisciplinary, multimedia programs designed to:

- develop and optimize systems and strategies for monitoring pollutants and their impact on the environment

- demonstrate new monitoring systems and technologies by applying them to fulfill special monitoring needs of the Agency's operating programs

This report presents a brief overview of studies of the resuspension of material into the air. Particular attention was directed to meteorological factors that affect the resuspension of plutonium from contaminated land surfaces. This review can serve as a concise introduction to resuspension studies for the new researchers in this field. The Monitoring Systems Design and Analysis Staff at the EMSL-LV may be contacted for further information on the subject.

George B. Morgan
Director
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ABSTRACT

A literature review is presented in a discussion of the relevance of meteorological factors on the resuspension of plutonium from contaminated land surfaces. The physical processes of resuspension based on soil erosion work are described. Some of the models developed to simulate the resuspension of materials for predicting airborne concentrations are reviewed. The significance of some of the parameters used in the different models is also disucssed. The interplay of meteorological factors measured, discussed, or implied in the literature reviewed as related to the resuspension process is discussed in the final section.

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I. INTRODUCTION

Plutonium contaminants in the environment have been introduced primarily from three types of sources: the atmospheric testing of nuclear weapons, the controlled releases from facilities handling plutonium, and the unintentional releases resulting from accidents. Of these three source types, the largest contribution has been from past atmospheric nuclear tests which introduced an estimated 300 kilocuries (kCi) of plutonium-239 based on world-wide deposition of strontium-90 and estimated strontium to plutonium production ratios (Harley, 1971). The plutonium-238 deposition is estimated to be about 3 percent of this plutonium-239 deposition.

Controlled releases of plutonium total well below that released in atmospheric nuclear tests. As an example, controlled releases from the Rocky Flats Plant in Colorado as of 1970 were at upper limit estimates of 41 millicuries (mCi) for airborne effluents and 91 mCi for liquid effluents (Hammond, 1971).

Unintentional plutonium releases, although limited, have occurred in several types of accidents. Plutonium from nuclear weapons was dispersed in two separate incidents: one near Palomares, Spain, and the other near Thule, Greenland. Both accident sites were cleaned up by the physical removal of almost all of the debris (Jordan, 1971). Uncontrolled releases have also occurred in and around plutonium facilities. Such releases from the Rocky Flats Plant were estimated by Krey and Hardy (1970) to be 2.6 curies (Ci) over an area defined by a minimum reliable measurement contour of 3 millicuries per square meters (mCi/m^2) of plutonium-239. The plutonium-239 deposited outside this measured area has a greater uncertainty and is estimated to be 3.2 Ci, attributable to releases from the Rocky Flats Plant, based on cumulative fallout estimates from soil samples collected at a nearby location. A refinement of this value is reported by Krey (1976) to be 3.4 ± 0.9 Ci of plutonium-239 and plutonium-240 from the Rocky Flats Plant which was deposited on public and private lands.

The destruction of a SNAP-9A (System for Nuclear Auxiliary Power) during atmospheric reentry was the source of an uncontrolled release of plutonium-238 from a power generator. This resulted in a world-wide distribution of an estimated 17 kCi of plutonium-238 (Harley, 1971), rather than in a concentrated ground deposit.

The objective of this paper is to discuss the relevance of meteorological factors on the resuspension of plutonium from contaminated land surfaces. The material reviewed is presented first in a description of the physical processes of resuspension. A discussion follows on some of the models developed to simulate resuspension, with the intent of using these models as predictive aids. Critical parameters used in various models are also discussed. Because meteorology plays a major role in the resuspension process, most of the discussions found in the literature, whether dealing specifically with plutonium or with some other erodible material, contain some reference to the meteorological conditions under which observations were made. The interplay of meteorological factors measured, discussed, or implied in the literature reviewed as related to the resuspension process is discussed in the final section.

A substantial contribution to the plutonium literature has emerged from the work of the Nevada Applied Ecology Group (NAEG) of the U.S. Atomic Energy Commission (AEC), predecessor to the U.S. Energy Research and Development Administration (ERDA). The work of this group is centerd around the several areas contaminated by plutonium and other transuranics in a desert environment at the Nevada Test Site. The studies are well documented in the ERDA reports (U.S. AEC, 1974, and U.S. ERDA, 1975). Reports of work in these documents related to the resuspension processes were considered in this current review.

II. PHYSICAL ASPECTS OF PARTICLE MOVEMENT

In order to gain some understanding of the complexities of the movement of particles through the air, several topics are treated in this section about the physics of the problem. Some of the influencing factors illustrating this complexity are listed in Table 1. Chepil (1975a) lists these factors as associated with air, ground, and soil. With a different emphasis, Hilst and Nickola (1959) developed a list of parameters describing soil conditions and meteorological factors and a list of secondary or derivative parameters characterizing their interaction. These considerations are also listed in Table 1.

Two mechanisms are associated with the initiation of particle movement. Direct action of air moving past a particle may exert enough force to accelerate the particle, causing it to roll along the surface or to be lifted up and moved in the air stream. A second means of initiating particle movement is through the impact of airborne particles with particles on the ground. If the surface consists of fine, uniform, and similar particles, the binding forces are cohesive and are usually highly resistant to disturbance by air movements. Particles on a solid surface which have chemical and physical properties different from the base material have adhesive contact. For the resuspension of particles to occur, the force on the particle must be equal to or greater than the force holding the particle to the surface. This applies to both cohesive and adhesive bonding. Corn and Stein (1967), in their study of the mechanisms of dust resuspension, identified several factors that are known to influence particle cohesion and adhesion. The strength of these bonds depends on particle material, size, and shape, surface roughness, relative humidity of the ambient air, the presence of electrostatic charge, and the nature and physical characteristics of the substrate (in the case of adhesive bonds).

Particles that are dislodged from the surface can move in three ways: suspension, saltation and surface creep. Particles move in suspension when upward wind eddies counteract free fall, allowing transport at the average forward speed of the wind. These particles are generally less than 0.1 millimeter (mm) in diameter and are redeposited via rainout or gravity after the wind subsides. Particles between approximately 0.1 mm and 0.5 mm in diameter

TABLE 1. FACTORS INFLUENCING WIND EROSION

AIR RELATED FACTORS [1]	METEOROLOGICAL FACTORS [2]
Velocity	Wind velocity distribution in the surface layer
Turbulence	Mean wind speed
Density affected by	Wind direction
Temperature	Frequency, period, and intensity of gusts
Pressure	Verticle turbulence exchange
Humidity	Moisture content on ground surface
Viscosity	Precipitation
	Dew and frost
	Drying action of the air
GROUND FEATURES [1]	SURFACE PROPERTIES [2]
Structure affected by	Large-scale surface roughness
Organic matter	Mechanical turbulence
Lime content	Overall sheltering
Texture	Small-scale surface roughness
Specific gravity	Sheltering of individual particles
Moisture	Area of erodible surface
	Vegetative cover
	Live vegetation
	Plant residue
	Cohesiveness of individual particles
	Moisture of surface
	Binding action of organic materials
SOIL CHARACTERISTICS [1]	PARTICLE PROPERTIES [2]
Roughness	Particle-size frequency distribution
Cover	Ratio of erodible to nonerodible fractions
Obstructions	Particle density
Temperature	Particle shape
Topographic features	

[1] Chepil (1945a).

[2] Hilst and Nickola (1959).

move by a series of short bounces called saltation. Larger particles from about 0.5 mm to 2 or 3 mm in diameter can roll and/or slide along the surface in what is called surface creep. Bagnold (1941) notes that with average dune sand, the suspension flow, even under a relatively strong wind, does not exceed one twentieth of the flow in saltation and surface creep. In sand flow, saltation accounts for three quarters of the movement. Chepil's 1945 studies with various soils also showed that the greatest portion of the movement was by particles in saltation. The relative proportion of each type of movement varied greatly for different soils. Of the four soil types studied (Sceptre heavy clay, Haverhill loam, Hatton fine sandy loam, and fine dune sand), between 55 and 72 percent of the weight of the soil was carried in saltation, 3 to 38 percent was carried in suspension, and 7 to 25 percent was carried in surface creep.

DYNAMICS OF PARTICLE MOVEMENT NEAR THE GROUND SURFACE

Because particle movement occurs mainly by saltation, much knowledge has been accumulated by studying this phenomenon. Saltation data were mainly collected in soil erosion studies.

Field and laboratory measurements of the concentration of windborne particles made by Chepil (1945 a-e, 1950 a,b, 1951 a,b) indicate that with saltation movement, soil was carried at a height of less than 1 meter (m) above the ground. For the several soil types investigated, more than 90 percent of the soil was transported below the height of 30 centimeters (cm). Individual particles which have been set into motion will strike other stationary particles and either rise almost vertically in the initial stage of the movement in saltation, or eject other particles upward. These upward-moving particles are drawn into the air stream and are carried along at the same horizontal velocity while they begin to descend. Upon impact, they either rebound and continue saltation movement, or they transfer their momentum to other particles which are ejected and carried in the air stream in saltation or bounce along in surface creep. The continued saltation movement is sustained by this impact-ejection mechanism and not necessarily by the force of the airstream. Bagnold (1941) concludes this on the basis of momentum transfer from the airstream to the ejected particles. The equivalent of a steady counterforce or drag which resists the flow of air, causes the wind velocity near the surface to diminish to a level below the fluid threshold velocity, preventing further pickup by the direct action of the wind.

Particles fine enough to be moved in suspension are usually undisturbed by wind forces while they are on the ground. Chepil (1945a) found that quartz particles less than 0.05 mm in diameter could not be moved by wind velocities as high as 16.5 m/s (37 miles per hour) passing over the surface at a 15 cm (6 inches) height. However, when coarser grains ranging up to 0.5 mm in diameter were included as a mixture, the smaller particles easily moved into suspension. The larger particles in the mix are subject to wind forces and moved in saltation, which in turn initiated the movement of the finer particles into suspension. In a similar manner, grains in surface creep, which are too heavy to be moved by direct air currents, are moved during impact with smaller grains moving in saltation.

Newly deposited material behaves differently from the surface soil layer in its reaction to wind forces. However, as the surface is subjected to weathering and aging, the deposited material becomes an integral part of the surface soil and this surface behaves according to the concepts developed for soil erosion.

Relationships among some of the factors associated with soil erosion have been developed empirically. The surface soil layer consists of a mixture of particle sizes and a minimum wind speed is required to initiate soil movement. This minimum speed is associated with a predominant particle size range and was found to be unaffected by surface roughness (Chepil, 1945b). The rate of soil flow, however, varies inversely with surface roughness. The erodibility, as gauged by different measures, varied as the square-root of the apparent density of the erodible grain or aggregates. (The apparent density is the density of the removed material as opposed to the density of the soil bed). Under specified conditions of wind velocity and surface roughness, and given size and proportion of non-erodible fractions, erodibility varied inversely as the square-root of the equivalent diameter of the erodible fractions. Chepil (1951a) defined the equivalent diameter as "the diameter of an imaginary quartz grain having an apparent density of 2.65 and an erodibility equal to that of a discrete soil grain or aggregate of some particular diameter and apparent density." The cohesive force of adsorbed water films surrounding the soil particles also affect erodibility. The rate of soil movement varied with changes in the density of the air, the drag velocity, and the degree of wind gustiness.

PARTICLE-SIZE DISTRIBUTION

Trevino (1972) notes that among the parameters which most influence the motion of soil by wind are the space and time variation of the soil particle-size distribution. The soil particle-size distribution also influences the particle-size distribution of the particles removed by various processes such as resuspension, as reported by Slinn (1973a). He stresses the importance of reporting simultaneous measurements of both size distributions (airborne and surface soil) in future resuspension studies.

Gillette et al. (1972) similarly concluded that the size distribution of aerosols resuspended from a ground deposit of soil is very similar to the size distribution of the soil itself. For a variety of erosive field conditions for particles in the size range of 0.3 to 0.6 mm, a common power law was suggested for both the aerosol particle-size distribution and the size distribution of the soil.

In considering particles of plutonium, some caution must be exercised. Although it is currently unknown what fraction of the plutonium in resuspension consists of unattached tracer particles and what fraction is attached to host soil particles, it is suspected that a large portion of plutonium material can be attached to resuspended soil particles. In a particle-size study using impactor samplers, Sehmel (1975c) found plutonium on individual soil particles to be much smaller than the impactor size diameter of the fraction collected. The plutonium present, assumed to be PuO_2, had particle diameters of less than 0.25 mm.

III. RESUSPENSION MODELS

There have been many studies on the resuspension of material previously deposited on a natural surface. Some of the works have provided the basis for the development of empirical models used for estimating the average concentration of airborne material. Other models have been developed from theoretical considerations of the movement process.

Sehmel and others (Sehmel and Orgill, 1973; Sehmel and Lloyd, 1974b and 1975b) have reported work directed towards developing general models for predicting particle resuspension from different environments. Based on field measurements and data from other investigators, and on reported monitoring program data, Sehmel et al., assembled information applicable to resuspension models for the environment surrounding the Rocky Flats Plant in Colorado. As a first approximation, plutonium resuspension was assumed to be similar to the physics of soil erosion. In soil erosion, the amount of material removed is proportional to the cube of the air velocity when the air velocity is above a threshold velocity. In the case of plutonium resuspension, it is postulated that the amount of material resuspended is a function of the air velocity to some unknown power when the air velocity is above some unknown threshold velocity. Using data collected at a specific sampling station during the 6-month period of July 1970 to January 1971, the wind-caused plutonium resuspension in femtocuries per cubic meter (fCi/m^3) was found to be:

$$\chi = 0.45(\bar{u})^{2.1}$$

In the preceding formula, $\bar{u}$ is the air velocity in miles per hour averaged over a 1-hour period. The average airborne concentration for a 1-hour period is a function of the dominant winds -- in this case, westerly and southwesterly. The constants were determined by a least squares analysis of the predicted and measured weekly average concentrations. Sehmel et al., note that although theoretical predictions suggest airborne concentration to be proportional to $(\bar{u})^{2.0}$ compared to the experimental $(\bar{u})^{2.1}$, modeling for other time periods and sampling areas is required before any model generalization of this exponent is warranted. It is also noted that this model predicted higher average concentrations than the measured weekly average concentrations.

The majority of measurements of airborne resuspended material reported in the literature has been normalized by surface measurements which are presumed to be the source of the resuspended material. This normalization is expressed as a resuspension factor:

$$K = \frac{\text{resuspended air concentration (activity/m}^3\text{)}}{\text{surface deposition (activity/m}^2\text{)}}$$

Values of K reported in the literature were tabulated in reports by Mishima (1964) and Stewart (1967). These values show a range of several orders of magnitude. Anspaugh et al., (1974) have suggested a model for predicting the airborne concentrations of resuspended contaminants over long periods of time by making the resuspension factor a function of time. A time-dependent resuspension factor was first formulated by Kathrens (1968), and again by Langham (1971), as follows:

$$K(t) = K_o \exp(-\lambda t)$$

For this expression, Kathrens' value of half-time ($1/\lambda$) was 45 days and Langham's estimate was 35 days. Anspaugh et al., (1974) point out that for several weeks after deposition, the above expressions adequately agreed with observations. For aged deposits, the predicted concentrations of resuspended materials were seriously underestimated. Accordingly, Anspaugh et al., have proposed an alternate expression for a time-dependent resuspension factor which should be applicable to reentrainment processes around aged sources. The following constraints were imposed on the formulation:

1. The apparent half-time of decrease during the first 10 weeks should approximate a value of 5 weeks and should nearly double during the next 30 weeks.

2. The initial resuspension factor should be $10^{-4} m^{-1}$.

3. The resuspension factor 17 years after the contaminating event should approximate $10^{-9} m^{-1}$ (based on the longest period of post-deposition measurements of plutonium resuspension).

The Anspaugh et al., model is as follows:

$$K(t) = 10^{-4} \exp(-0.15 \text{ days}^{-1/2} \sqrt{t}) + 10^{-9} [m^{-1}]$$

In the above, t = time in days. Note that this model was derived to simulate experimental measurements, and, as Anspaugh et al., point out, the model contains no fundamental understanding of the resuspension process. It was derived for the prediction of long-term averages of airborne concentrations, but has an initial value which is sufficiently high (10^{-4}) to account for unusual disturbances. Anspaugh et al., point out that the model assumes resuspension to be a local phenomenon with the air concentration dropping off rapidly downwind of the deposited source. This is consistent with experimental observations.

The time-dependent resuspension factor is used to determine the integrated air activity over some specified time period. The formula is written as follows:

$$A = vA_o \int K(t)dt$$

The deposition velocity is v (normally written as v_d) and A_o is the initial integrated air activity measured in activity-time per volume. The product vA_o is the ground deposition.

Horst et al., (1974, 1975) have suggested concepts of a resuspension model where there is a separation of the actual resuspension from the atmospheric dilution and transport of the airborne material. Attention is given to the total ground concentration components consisting of a portion available for resuspension and one that becomes unavailable through soil fixation. Figure 1, redrawn from Horst et al., (1974), is a schematic diagram of these concepts. Resuspension and soil fixation are assumed to be proportional to the concentration of available material on the ground through a resuspension rate λ and a fixation rate α while the deposition velocity v_d relates the deposition of material to the primary air concentration. An initial time-independent resuspension factor K_o can be defined in terms of the available concentrations. The available ground concentration G and the total ground concentration S are derived to be as follows:

$$G = G_o \exp(v_d K_o - \lambda - \alpha) t$$

and

$$S = \frac{S_o}{(v_d K_o - \lambda - \alpha)} [\alpha + (\lambda - v_d K_o) \exp (v_d K_o - \lambda - \alpha) t]$$

At t = o, the time of initial surface contamination, the available ground concentration is the total ground concentration (i.e., $G_o = S_o$).

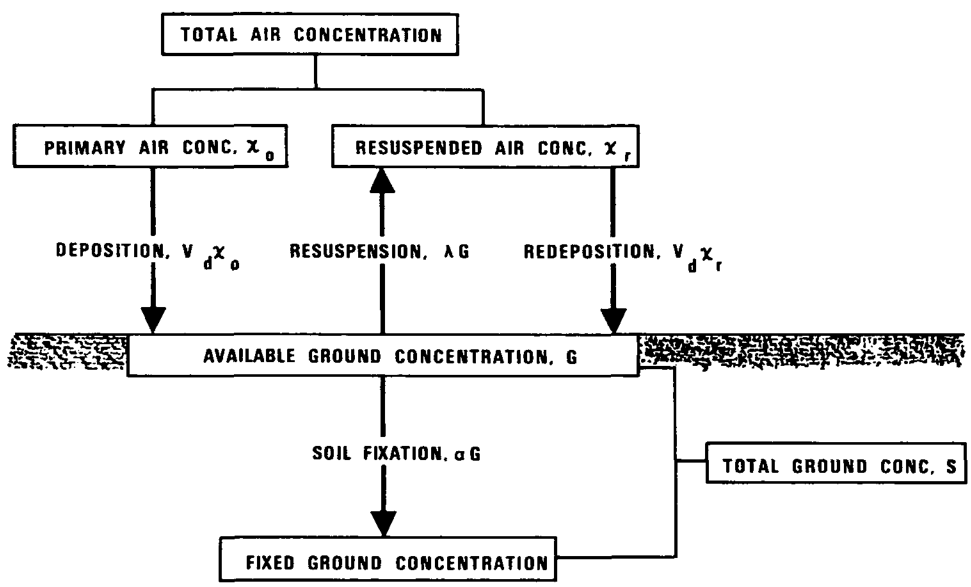

Figure 1. Schematic diagram of resuspension model concepts, redrawn from Horst, Droppo, and Elderkin (1974).

Horst et al., noted the consistency of their formulation with observations. For example, the exponential decay of the available ground concentration depends on the sum of the resuspension and fixation rates less the redeposition rate.

Two situations were considered in this formulation. The first situation applies to soils showing small total ground concentration losses. In the second situation, the material is distributed uniformly over an area beyond the transport distance of the surface-air exchange process and resuspension must balance redeposition.

It has been shown for the first situation that less than 10 percent of the material was lost by resuspension based on observations at a particular site over an extended period. When a uniform primary air concentration χ_o is produced by a continuous trace level release of material to the atmosphere, Horst et al., found that after several half-lives of decay of the available ground concentration, the ratio of the resuspended air concentration χ_r to the primary air concentration was as follows:

$$\frac{\chi_r}{\chi_o} = v_d K_o / \alpha$$

This ratio could range from 5 to 5 × 10^4.

In the case where resuspension balances redeposition, the ratio of resuspended air concentration to primary air concentration becomes:

$$\frac{\chi_r}{\chi_o} = \lambda / \alpha$$

The measured range of this ratio is between 0.05 and 0.5.

In a later report, Horst and Elderkin (1975) extended the model to account for radioactive decay of the hazardous material and allowed a lower limit for the resuspension factor. After testing this revised model, Horst and Elderkin concluded that the evaluation of the hazard of environmental plutonium release is affected only by a source which emits continuously for an extremely long period.

Some preliminary efforts by Slinn (1973a) to develop initial resuspension models were made from two standpoints. The vertical transport of materials dislodged was first described using the convective diffusion equation. An expression was then derived, which is subject to several assumptions and boundary conditions, for the number of particles per unit volume of some radius r located at some heights as follows:

$$f(r,z) = f_o(z/z_o) v_s(r)/Cu_*$$

In the preceding formula, v_s is the magnitude of the particle-setting velocity, u_* is the friction velocity, and C is an unknown parameter. Slinn notes several limitations of this approach and points out the poor predictive ability of the formula when compared with plotted data from the literature. In a later report, Slinn (1975) suggests that the best available procedure for obtaining the vertical flow of particles is the use of experimental data to estimate the horizontal flux as a function of altitude. He cites as an example Chepil's work which shows how the weight of dust in a unit volume of air varies with height.

Slinn's 1973a report also examines resuspension from a statistical approach, but concluded that this approach was even less valuable than via the convective diffusion equation. One of the major difficulties is that many of the statistical properties are unknown. However, even if these properties were better known, Slinn acknowledges that the statistical analysis approach is not without serious difficulties.

From another strictly theoretical viewpoint, Trevino (1972) uses power-spectral analysis of random wind-speed fluctuations to develop a mathematical model of wind-induced motion of ground deposits. Spectral analysis is concerned with the splitting of a time series into different frequency components, and, as applied to the wind, allows an inclusion of its effects on the resuspension process.

Trevino's (1972) formulation of the total loss at any coordinate at any time is as follows:

$$P_i(t) = \int_0^t h_i(t,t')f(t')dt'$$

The variable $h_i(t,t')$ defines the infinitesimal loss at the time by some removal process P_i (saltation or suspension) due to a unit impulse or gust of wind applied at time t'. The wind which initiates the corresponding P_i motion is f. Trevino observes that since f is a random function of time and as such has an indeterminate form, the integral equation above cannot be solved in its present form. Trevino applies the method of power-spectral analysis to rewrite the equation in a form amenable to solution as:

$$\overline{P_i(t)} = \frac{1}{(2\pi)^2}\int |H_i(t,\omega)|^2 \phi_f(\omega)d\omega$$

$\overline{P_i}$ is understood to be the total mean-square contamination loss and ϕ_f is the frequency spectrum of the wind. $|H_i(t,\omega)|$ is the absolute value of the contamination loss at the time t by P_i due to a sinusoidal wind of frequency ω. Some known methods of determining H and ϕ_f are described by Trevino. Note that Trevino's model accounts for the random nature of the wind, and furthermore, the system under consideration is time-dependent.

Another theoretical model was developed by Amato (1971, 1976) which mathematically describes the prediction of long-range, time and space redistribution of surface contamination by wind in a one-dimensional flow pattern. By considering a series of continuous intervals, Amato writes a first-order differential equation to describe the contamination concentration as a function of time within each interval. A Sutton-Chamberlain diffusion model was used for air concentration computations. In Amato's 1976 report, the model was extended and theoretical resuspension ratios were calculated. According to Amato, the calculated ratios indicate "the steady state effects of a continuous source on the relative amount of downwind air concentrations moving directly, or by means of resuspension."

In Travis' (1976) development of the redistribution of deposited material, he assumes contaminants and host material have the same properties. Horizontal flux formulation is based on soil erosion work of Bagnold and Chepil and the vertical flux component is based on Gillette's work which Travis referenced. Vertical emissions are discrete and periodic; they diffuse downwind and are characterized by a three-dimensional Gaussian diffusion model. The potential hazard from wind-eroding toxic materials is determined through application of the model.

IV. DISCUSSION OF IMPORTANT PARAMETERS

Many parameters used in developing characterizations of materials movement in the atmosphere are critical in the resuspension model developments. Some of these parameters are discussed here in more detail relative to their importance, limitations, and measurability.

RESUSPENSION FACTOR

In proposing a time dependent resuspension factor for calculating airborne concentrations of resuspended material, Anspaugh et al., (1974) were aware of the limitations of this parameter. For example, relating air activity measured over a certain area to ground deposition measurements at the same point is not entirely justified when data show resuspension factors in low deposition areas are greater than in areas of relatively higher deposition. Furthermore, the resuspension factor neglects many important variables such as wind velocity, surface roughness, the physical and chemical characteristics of the soil surface, and vegetation cover.

Measured values of the resuspension factor range from 10^{-2} to $10^{-13} m^{-1}$. The large values were measured for indoor air above mechanically disturbed fine material on a newly painted concrete floor, while the lower range was from measurements of natural turbulence of aged plutonium on desert soil. Although this wide range may limit the value of the resuspension factor as a predictive aid, Horst et al., (1974), Anspaugh (1974), and others point out that this approach does compensate for one important source of variability in measured air concentrations by normalizing these to the potential source strength. However, Sehmel and Lloyd (1975a), Mishima (1964), Stewart (1967), and others state that the amount of airborne material would tend to depend upon the extent and level of contamination upwind rather than upon local surface contamination.

It is observed that despite the shortcomings of the resuspension factor, investigators continue to report results in terms of this parameter. One way to improve this parameter, as reported by Slinn (1975), is to relate soil erodibility to the resuspension factor. Chepil (1950a,b), Woodruff and Siddoway (1965), and others, have worked to develop a general functional relationship which defines the rate of soil loss in terms of influencing variables. Slinn transforms this formulation with the aid of a Gaussian plume model evaluated at a distance downwind of the field so that the product $\sigma_y \sigma_z$ approximates the area of the contaminated area to yield the resuspension factor. This is stated as follows:

$$K = \frac{3.5 \times 10^{-9} \text{ cm-s}^{-1}}{1 \text{ ton acre}^{-1}\text{mo}^{-1}} \; \frac{rE}{(2\pi \bar{u}\delta)}$$

E is the erodibility or soil removal rate. Slinn identifies the parameter r as the fraction of the horizontal flux which travels at the height of the sampler.

The mean wind speed at the sampler height is $\bar{u}$ and δ is the depth of penetration of the contamination into the soil.

RESUSPENSION RATE

The resuspension model concepts of Horst et al., (1974) show the flux of material from the ground to the air to be proportional to the available ground concentration through a resuspension rate $\lambda(s^{-1})$. However, only a few field measurements of this parameter have been reported in the literature. Sehmel and Lloyd (1974a, 1975a) have conducted several field experiments to determine resuspension rates using tracer particles. For ZnS particles on asphalt, the range of values was reported on the order of 5×10^{-9} to 60×10^{-9} fraction removal per second in wind speeds of 0.9 to 4 m/s (2 to 9 mph). Calcium molybdate deposited on sandy soil had resuspension rates on the order of $2 \times 10^{-10} s^{-1}$ in the wind range of 1.3 to 3.6 m/s (3 to 8 mph), and upwards to $220 \times 10^{-10} s^{-1}$ in 5.8 to 20 m/s winds (13 to 45 mph). A summary of measurements by Sehmel et al., is presented in Table 2.

The significance of the resuspension rate is that it accounts for how rapidly material is removed from the surface and transported downwind. Sehmel et al., (1974) found this parameter to increase rapidly with wind speed. Above 3.6 m/s, the resuspension rate was estimated to increase with wind speed to the 6.5 power.

Although there are only a few measurements of resuspension rates reported in the literature, the measurements of Sehmel et al., summarized in Table 2, indicate some apparent relationships between resuspension rates and resuspension factors. Sehmel cautions, however, that there are insufficient data to draw general conclusions on these relationships and the data only suggest a comparability of resuspension factors between 10^{-10} and $10^{-9} m^{-1}$ to resuspension rates between 10^{-10} and 10^{-8} fraction resuspended per second.

Further efforts to understand the limitations of the resuspension rate parameter is reported to Sehmel (1975a) via some laboratory experiments using 10 μm diameter monodisperse uranine particles. The resuspension rate from a smooth surface was measured under varying conditions. As a function of time, the parameter decreased non-exponentially at a constant friction velocity. At increasing air flow rates, the parameter increased. The values ranged from 10^{-6} to 10^{-3} fraction resuspended per second. Sehmel's comparison with field data obtained elsewhere suggests a decrease in resuspension rates with increasing surface roughness.

RESUSPENSION RATIO

Another approach to evaluating the relative significance of resuspended material was introduced by Amato (1976) in calculations of theoretical resuspension ratios. As described previously, Amato's derivation is based on a number of simplifying assumptions and considers the transport mechanism of material into and out of a series of continuous intervals. The resuspension ratio for each interval is calculated as the ratio of the portion of the air concentration attributed to resuspension upwind to the portion of the air concentration due to contaminants arriving at the interval directly from the source. Within a specified range of values for the dependent parameters,

TABLE 2. RESUSPENSION RATES

Particles	Particle Data	Surface	Wind Speed m/s (mph)	Average Resuspension Rate Range--fraction removed/second	Reference
ZnS	Not given	Asphalt	0.9- 4 (2-9)	5×10^{-9} to 6×10^{-8}	2
ZnS	Not given	Asphalt (Disturbed surface by walk through)	1.3- 6.2 (3-14)	1×10^{-5} to 7×10^{-4}	2
ZnS	*TD = 4.1 g/cc MMD = 5 μm NMD = 2 μm	Asphalt (Disturbed surface by vehicular traffic)	Not given Vehicle speed ranged from 2.2-22 (5-50)	10^{-5} to 10^{-2}	1
$CaMo_4$	Not given	Sandy soil (lightly vegetated)	1.3- 3.6 (3-8)	2.0×10^{-10}	4
$CaMo_4$	Not given	Sandy soil (lightly vegetated)	5.8-20 (13-45)	2.2×10^{-8}	4
Uranine	10 m diameter	Smooth surface (laboratory experiment)	16.5-18.3 (37-41)	10^{-6} to 10^{-3}	3

*TD = Theoretical Diameter; MMD = Mass Median Diameter; NMD = Number Median Diameter.

1. Sehmel (1972a).
2. Sehmel (1972c).
3. Sehmel and Lloyd (1974a).
4. Sehmel and Lloyd (1975a).

Amato's calculations show the following behavior:

> "(1) The steady-state surface contamination decreases with both increasing distance from the source and increasing wind speed.
>
> (2) The largest values of the resuspension ratio, R, occur near ground level during low wind speeds and stable meteorological conditions, and when the effects of weathering are minimal.
>
> (3) The resuspension ratio increases with increasing distance from the source."

These observations applied to downwind distances up to 700 meters.

Horst (1975a) made some extended calculations on resuspension ratios using a surface flux model. In Amato's calculations, the Sutton-Chamberlain equation accounts for dry deposition by substituting the original source-term with an effective depleted source-term. Horst's formulation diminishes only the portion of the plume adjacent to the surface. Estimates of surface air concentrations and, hence, the deposition flux are lower by factors of 2 to 4 for moderately strong deposition by assuming surface depletion rather than source depletion. The resuspension ratio derived by Horst is a function only of the ratio of deposition velocity to wind velocity. Horst's resuspension ratios concur with Amato's calculations and were calculated out to 10^5 meters downwind.

DEPOSITION VELOCITY

The removal rate of airborne material is an important factor in modeling the resuspension process. Several of the models described earlier make some assumptions of the value of this removal rate which is expressed as a deposition velocity. The ratio of the amount deposited per cm^2 of surface per second to the airborne particle concentration per cm^3 at 1 meter above the surface has units of length divided by time for the deposition velocity. One of the difficulties in specifying the value of this parameter is that the value will vary depending on particle characteristics, surface characteristics, wind speed, and other meteorological conditions.

Van der Hoven (1968) summarized from the literature results of field experiments for the determination of deposition velocities for ^{131}I. These were found to range over one order of magnitude. The summarized data suggest that chemically active materials are deposited more readily than inactive materials, and that the presence of vegetation increases removal rates. Sehmel and Schwendiman (1971a,b) suggest that this latter effect is caused by particle interception by rough surfaces and by increased eddy diffusivity. Their studies, using uranine particles, indicate dependence of deposition velocity on the type of deposition surface, the particle diameter (2 to 28 μm used in their experiments), and the friction velocity (11 to 44 cm/s). Controlled laboratory measurements for the deposition velocity ranged from 0.06 to 12 cm/s for two different surfaces. These measurements also indicated no correlation between the deposition velocity and the average air velocity.

In a later study, Sehmel, Sutter, and Dana (1973) found that the deposition velocity increased with air velocity for a constant particle diameter. A minimum deposition velocity is associated with a particle diameter in the range of 0.1 μm caused by a shift in the importance of eddy diffusivity and Brownian diffusion in the transport process. Measurements by Sehmel and Horst (1972) show that the minimum deposition velocities are nearly independent of atmospheric stability.

In these several controlled laboratory studies, the measured deposition velocities are directed toward predicting other values which can be used in atmospheric transport models. There is good evidence from the above studies that data obtained from wind tunnel studies can be applied to atmospheric calculations.

To determine deposition velocities of resuspended particles, Sehmel (1972a,b,c) conducted field experiments using ZnS particles deposited on asphalt surfaces. The range of values were a minimum of 0.4 cm/s to a maximum of 17 cm/s. The particle size characteristics in relation to the deposition velocity were not determined.

V. METEOROLOGICAL CONSIDERATIONS

Meteorological factors which influence the resuspension of material from ground deposits are wind characteristics, and moisture as it affects ground surface conditions. The amount of material that can be carried in the air currents is dependent on the density, velocity, and viscosity of the air. The force exerted on the particles is directly proportional to the density and viscosity of the air and varies with the square of its velocity (Chepil, 1945c). In common natural conditions, the viscosity of the air is independent of atmospheric pressure and has a minor variation with temperature. Temperature, pressure, and humidity determine the density of the air. Moist air consists of dry air and water vapor and is shown from gas law relationships to be lighter than dry air at the same temperature and pressure. Thus, the erosive force of moist air currents is lower than that of dry wind.

Fixation of material can occur at a deposition site and it has been shown that fixed material will be dispersed in a surface layer several centimeters deep. Stewart (1967) reported on experimental results obtained in field tests which indicated continuous changes in surface layer characteristics such that a simple relationship between resuspended material and wind speed had limited validity. For example, in Healy and Fuquay's 1959 study using a zinc sulphide particulate on a variety of different surfaces, the amount of airborne material was found to be a function of the square of the wind speed. To have this simple u^2 or u^3 relationship, Stewart suggests that the contaminant must be very finely-divided submicron particles which are insoluable in water, and the surface must be in equilibrium with only a minor degree of soil movement occurring. The host material on which contaminants adhere may not have the ideal characteristics to show an obvious correlation between resuspended material and various wind parameters. In Volchok's (1971) report on elevated plutonium levels in surface air near the Rocky Flats Plant, there was a qualitative indication of some correlation between the plutonium air concentration and some wind parameters, such as mean wind speed, peak gusts, mean weekly gusts, and number of hours in the sampling period which the wind exceeded various speeds. Volchok's example of concentration versus wind speed for one week sampling periods showed reasonable correlation ($r = 0.83$) for the fall data and a poor correlation ($r = 0.18$) for the summer data. The better correlation in the fall data was suggested to be attributable to the higher average wind speeds experienced in that period and, further, suggested a threshold average wind speed above which good linear correlation is evident.

Gross measurements, such as airborne dust concentrations, have been made using different combinations of particle size and wind speed. For several of these combinations, a nonlinear relationship between airborne dust concentrations and increasing wind speed is inferred. Data from Sehmel (1975b) show these dust concentrations range in proportionality from 0.6 to 3.2 power of wind speed. For example, above 4 m/s (9 mph), a cubic relationship held. An order of magnitude increase in particle concentration is observed in different particle size ranges for increases in wind speed from 1.3 to 9 m/s (3 to 20 mph). According to Shinn et al., (1974), the dust concentration can sometimes vary with the sixth power of the wind speed.

Improvement in Trevino's (1972) model takes into account the random wind effects on particle transport and its effects on deposition and emphasizes two important meteorological dependencies: soil transport and particle deposition. Soil transport by wind is dependent on the wind velocity distribution with height, and suspended particle deposition is dependent on the time variation of the mean wind speed. Chepil (1951b) cautioned, however, that the effects of surface roughness on the velocity distribution above the ground must be known for wind velocity measurements to be meaningful. For this reason, the drag velocity is suggested as a better indicator of the force exerted by the wind at ground level. The drag velocity V_* is formulated as follows:

$$V_* = \frac{v_z}{5.75 \log(z/k)}$$

In the above formula, v_z is the wind velocity at any height z, and k is the height at which the extrapolated wind velocity is zero. If the velocity is plotted against the logarithm of height, the drag velocity determines the slope of the wind velocity distribution. A relationship of the relative amount of erosion to the drag velocity has been shown by Chepil (1951b) to be a power relationship. Chepil indicates that the power relationship is not completely uniform but varies with soil conditions and surface roughness, as well as other factors. However, in some wind tunnel and open field tests with both erosive and nonerosive soil fractions, Chepil (1945) showed that the rate of soil movement varied with the cube of the drag velocity and the degree of gustiness of the wind. He further pointed out that the thermodynamic relationship among the air parameters indicates only a minor effect of air density changes on erodibility. For example, a 10°C decrease in temperature increases air density which in turn increases the wind force, but only by a small percentage. An increase in pressure would have a similar, minor effect.

Among the several parameters which characterize the resuspension process, some correlation with meteorological factors is evident. Resuspension rates were found to increase with increasing wind speed (Sehmel and Lloyd, 1975b). For respirable particles, the resuspension rate increased from 2.0×10^{-10} fraction resuspended per second with a wind speed interval of 1.3 to 3.6 m/s to 2.2×10^{-8} for 5.8 to 20.1 m/s. The tracer material in these tests was deposited on a lightly vegetated area of about a 23-m radius. For undisturbed soils, the resuspension rate is a nonlinear function of the wind speed, increasing by the 6.5 power for wind speeds greater than 3.6 m/s. In areas where mechanical disturbances due to human activities occur, a similar increase in resuspension can be expected with a greater availability of contamination for resuspension.

Sehmel and Lloyd (1975a) also reported similar behavior of the resuspension factor. This might have been expected based on earlier work relating the resuspension factor to resuspension rates. The parallel behavior of these two parameters is illustrated by Sehmel and Lloyd (1975a) in Figure 2.

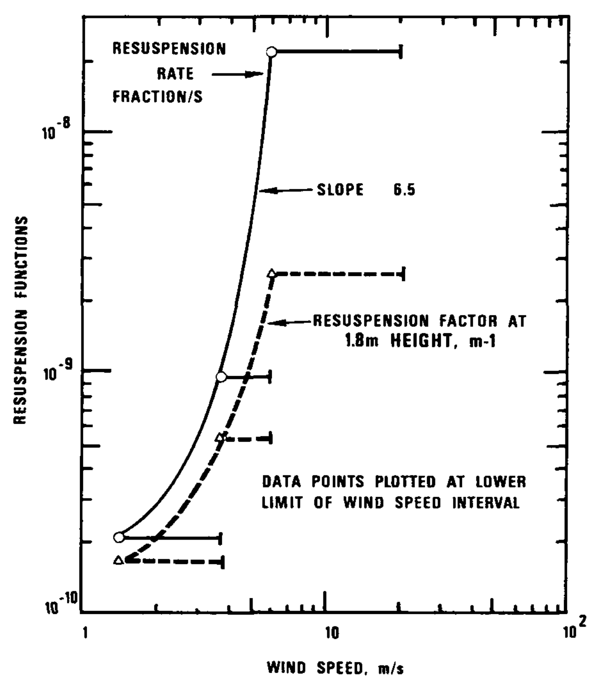

Figure 2. Resuspension rates and resuspension factors as a function of wind speed. Sehmel and Lloyd (1975a).

Amato (1976), in introducing the resuspension ratio, also presented data on the meteorological effects on this ratio. He noted that the largest values were observed near ground level during low wind speeds and under stable meteorological conditions, and when past weather least affected the surface layer.

Other meteorological parameters can affect suspended particles. Wagman et al., (1967) reported a trend toward increasing sulfate particle size with increased relative humidity at several urban areas. However, they caution that a theoretical humidity dependence for comparison with their results cannot be inferred because of certain conditions associated with their measurements. Specifically, the system studied consisted of heterogenous particles of unknown composition and structure which contained varying amounts of sulfate.

Wagman et al., (1967) further reported poor correlation of sulfate particle size with absolute humidity. However, when atmospheric sulfate concentrations were considered, good correlation was found with absolute humidity whereas poor correlation with relative humidity was evident.

In Hagen and Woodruff's 1973 work, visibility could not be correlated with various powers of wind speed. They suggested that particulate concentrations can be estimated from visibility measurements during dust storms when low humidity and particle-size distributions are relatively constant.

While it was noted that the very important parameter, deposition velocity, correlated well with friction velocity, Sehmel and Schwendiman (1971b) found that in general, the average air velocity does not correlate with the deposition velocity. In the case of a constant particle diameter, v_d does increase with air velocity. It was further noted that a minimum deposition velocity is characteristic of a given particle diameter. Sehmel and Horst (1972) concluded that the minimum deposition velocities are nearly independent of atmospheric stability.

The vertical stability of the atmosphere does determine dust devil activity, a meteorological phenomenon described by Sinclair (1969) as thermal updrafts initiated by dry convective currents and which later develop into a vortex of sufficient intensity to pick up surface debris. While dust devils may only occur in a limited geographical area, their potential for transporting toxic or hazardous materials resuspended from contaminated surfaces in these geographical areas could be a critical problem. The visible portion of the dust devil rarely exceed 600 m (2,000 feet) (Sinclair, 1969), but a thermal plume may extend upward to 5,000 to 6,000 m (15,000 to 18,000 feet) mean sea level (Sinclair, 1973). An estimated 2,700 metric tons of desert dust and sand per 100 km^2 area may be picked up and transported downwind by dust devils over an average season (based on observations by Sinclair at two 100 square miles area sites). Very fine particles may be suspended in the upper portion of the vortex and could conceivably be transported large distances by general circulation in the troposphere.

VI. SUMMARY

The resuspension of material from ground deposits is a complex process. While a considerable body of work has been reported on studies related to the resuspension process, a satisfactory mathematical formulation of the process is not evident. Deficiency is evident in some of the physical parameters which have proven to be important in the characterization of materials movement in the atmosphere. For example, only a limited number of measurements have been reported on the resuspension rate parameter.

There appears to be some understanding of the meteorological factors which influence the resuspension of material from ground deposits. The effects of wind and moisture on erodibility depend on the particle size and density of the erodible material. Some correlation with meteorological factors is evident amoung the several parameters which characterize the resuspension process. This too depends on the particle size and density of the material for which the parameter measurements were made.

Some studies have been made about the effect of diffusion of plutonium through the soil (Horst et al., 1974 and Horst and Elderkin, 1975). However, measurements are needed to better characterize this diffusion process.

While the primary focus of this review was on the meteorological factors affecting the resuspension process, some discussion on resuspension models and parameters was included. It is beyond the scope of this review to discuss the assets and liabilities of various diffusion models or to compare the advantages and/or disadvantages of and relationships among the several resuspension parameters.

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TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/4-77-037	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE RESUSPENSION OF PLUTONIUM FROM CONTAMINATED LAND SURFACES: Meteorological Factors		5. REPORT DATE July 1977
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) P. N. Lem, J. V. Behar and F. N. Buck		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Environmental Monitoring and Support Laboratory Office of Research and Development U.S. Environmental Protection Agency Las Vegas, Nevada 89114		10. PROGRAM ELEMENT NO. 1FA628
		11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS U.S. Environmental Protection Agency--Las Vegas, NV Office of Research and Development Environmental Monitoring and Support Laboratory Las Vegas, Nevada 89114		13. TYPE OF REPORT AND PERIOD COVERED Final Report
		14. SPONSORING AGENCY CODE EPA/600/07

15. SUPPLEMENTARY NOTES

16. ABSTRACT

A literature review is presented in a discussion of the relevance of meteorological factors on the resuspension of plutonium from contaminated land surfaces. The physical processes of resuspension based on soil erosion work are described. Some of the models developed to simulate the resuspension of materials for predicting airborne concentrations are reviewed. The significance of some of the parameters used in the different models is also discussed. The interplay of meteorological factors measured, discussed, or implied in the literature reviewed as related to the resuspension process is discussed in the final section.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
*Plutonium	Resuspension Process	04B
*Soil Erosion	Transport Modeling	18H
Radioactivity	Particle Dispersion	20H
Dust Particles	Meteorological Influences	
Wind Erosion		
Particle Size Distribution		

18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS *(This Report)* UNCLASSIFIED	21. NO. OF PAGES 36
	20. SECURITY CLASS *(This page)* UNCLASSIFIED	22. PRICE

EPA Form 2220-1 (9-73)