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Towards Understanding Resuspension

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1. Measuring Resuspension

The lofting of aerosols that have settled onto the surface back into the air is called resuspension. Particles may be resuspended into the air by wind gusts and by mechanical disturbances (e.g., walking, vehicular traffic, digging and excavation). Typically, the amount of resuspension has been reported in the literature as a resuspension factor or as a resuspension rate. The former is easier to measure, while the latter is easier to utilize in transport and dispersion models. Below, we define both quantities and discuss the limitations with each approach and the difficulties in making these measurements based on the reviews of Sehmel (1984), Nicholson (1988) and Loosmore (2003) [1-3].

Resuspension Factor (RF or K)

K [m^{-1}] = Airborne Concentration [g/m^3] / Surface Concentration [g/m^2]

The resuspension factor is the ratio of the airborne concentration of the particulate of interest to the mass of the particulate per unit area on the surface. One might surmise that if the surface concentration is higher, the airborne concentration should be higher. Though this is sometimes the case, it is not always, as the ratio depends on many other confounding factors (e.g., the wind speed, the roughness of the surface, the surface moisture, the particle size, particle attraction forces, the chemical reactivity of the particle, the depth of penetration of the particle into the soil, soil properties, the size of the area contaminated).

Resuspension Rate (Λ)

Λ [s^{-1}] = Mass Flux from Surface [g/(s·m^2)] / Surface Concentration [g/m^2]

The resuspension rate is the ratio of the mass of the particles emitted per unit time from a specific surface area to the mass of the particles per unit area on that surface. The resuspension rate can be thought of as the fraction of particles on the surface that are resuspended into the air per unit time. Thus, a resuspension rate of 0.01 means that 1% of the deposited mass is removed from the surface per second. Like the resuspension factor K, the resuspension rate Λ is a function of the wind speed, surface roughness, surface moisture, particle size, particle attraction forces, soil properties and many other variables. The resuspension rate is a necessary input for transport and dispersion modeling purposes as it along with an estimate of the surface concentration defines the source term (the emission rate of particles from the surface). The resuspension rate, however, is very difficult to directly measure.

a) How to Measure the Resuspension Factor

In theory, measurement of the airborne particle concentration is straightforward. However, specialized instrumentation may be needed to differentiate from other aerosols in the air depending on the specific contaminant of concern (e.g., a specific pollutant, radiological particle, a biological agent) and whether or not specific particle sizes are of concern (e.g., respirable particles less than 10 μm). In addition, time resolved measurements may be difficult (or more expensive) to obtain, especially for specific contaminants.

Measuring the surface concentration can be more difficult (or at least more tedious) depending on whether the surface is a solid or a soil, the porosity of the surface, the inhomogeneity of the surface properties, and whether the surface has vegetation or not. In controlled experiments, the surface may be contaminated with a known amount of particulates, so that the initial estimate of the surface concentration is fairly certain. In other cases, soil samples need to be taken or particulates may need to be extracted from solid surfaces using a wash and analyzed in a laboratory environment. It is clear that some uncertainty will be introduced due to extraction efficiency, sample size, and laboratory instrument limitations. If size-specific particle information is required from surface samples, this introduces another level of complexity that in some cases may not be possible without degrading or altering the sample.

In addition to the above mentioned difficulties, the measurement and interpretation of the resuspension factor is fraught with several ambiguities:

1) At what height should the airborne particulate concentration be measured?

In early descriptions of the resuspension factor, the height at which to measure the airborne concentration was not always specified. Since the concentration immediately above a surface source will decrease exponentially with height, K will change its value depending on the measurement height. As part of the Maralinga trials, for example, Stewart (1967) reported that the K factor for Uranium particles measured at 0.3 m was a factor of thirty larger than that measured at 0.6 m [4].

As shown in Fig. 1.1, plume model calculations show that the rate of change of particle concentration is greatest near the ground and decreases with height. For both stable (night time, clear sky, low wind) and unstable (day time, high solar insolation, low wind) atmospheric conditions a measurement at 0.5 m is about twice that at 2.5 m, for example.

The measurement height is especially important if one is concerned with particles 50 μm in diameter or greater, as these will have a significant settling velocity and tend to migrate towards the surface. Although these larger particles will redeposit to the surface, they still contribute to higher concentrations near the ground. For example, plume calculations identical to those above for A-B stability but using 50 micron particles, indicate the ratio between the dosage at 0.5 m and 2.5 m is almost a factor of five. In summary, if K factors are reported, it is important to note the height of the airborne concentration measurement.
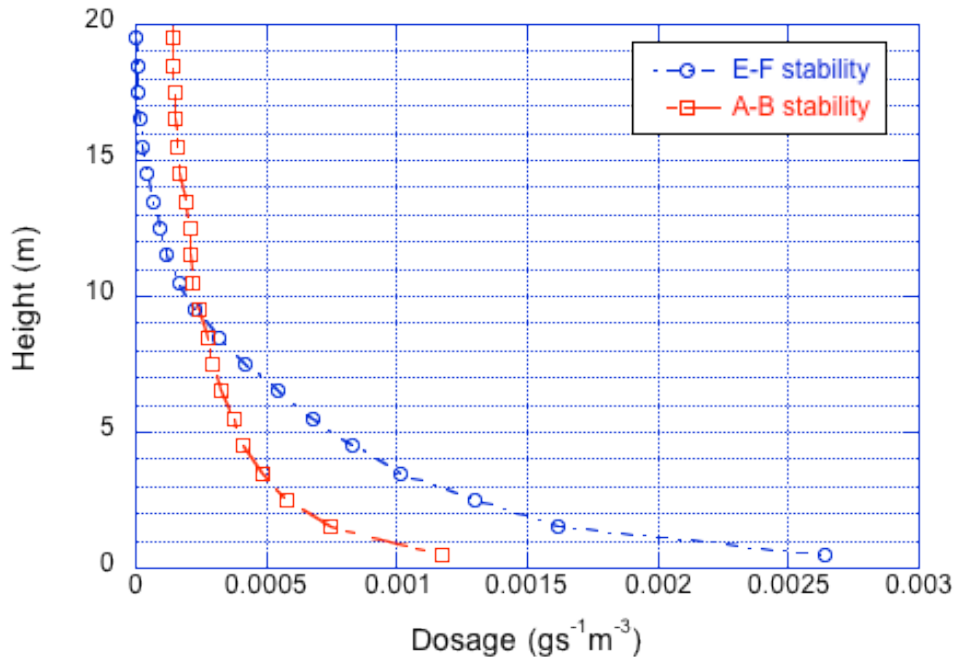
Figure 1.1 *Concentration vs. height on the downwind edge of a 600 m x 600 m plot of resuspended 1 µm aerosols for stable (E-F stability class) and unstable (A-B stability class) atmospheric conditions. Plume modeling performed using the QUIC random-walk particle dispersion code.*

2a) To what depth should the mass of the contaminant be measured in the soil?

For particulates that penetrate over time into the soil, determining the contaminant mass on the "surface" can become tricky. In theory, one should measure the particle mass in only the layer of soil that has the potential to be resuspended into the air, but how does one determine this *a priori*? Sehmel (1984) indicates that there has been no general consensus among experimentalists and states that "surface concentration … can mean anything from the pollutant in the first millimeter … to that in first several centimeter depth [1]." He further notes that if one samples too deep (i.e., deep relative to the depth of the soil that will be resuspended) one will obtain very different resuspension factors for the case where the particulate of interest is primarily near the top versus uniformly distributed throughout the depth of the soil sample. For example, for a case in which the contaminant is uniformly distributed through a soil depth of 1 cm, the sample depth is 1 cm, and 1 mm depth of soil is resuspended during a wind event, the mass available for resuspension will be overestimated by a factor of ten and thus K will be underestimated by a factor of ten. To address this issue, one could divide the soil sample into several depths and attempt to define the amount of contaminant in several layers, e.g., the first mm and the remaining cm. However, if one finds a uniform distribution, one would then need to evaluate to what depth the soil was resuspended to obtain an accurate surface concentration. This measurement may be difficult due to soil originating upwind being transported and deposited into the region of interest.

2b) Over what area should soil samples be obtained?

Nicholson (1988) and Sehmel (1984) note that surface concentrations can vary significantly spatially [2], [1]. This may be due to distance from a source, or result from spatial variability of surface roughness and soil properties (resulting in enhanced or reduced deposition, particle migration via saltation and creep, or particle migration down into the soil), or the natural variability in the original dispersal process due to turbulence. Both authors indicate that some of the variability in K amongst different experiments could be a result of the spatial variation in soil sample concentrations. This is easily solved by taking more soil samples, but of course this may be cost prohibitive.

3) For solid surfaces, how does one determine extraction efficiencies?

For cases where hard surfaces (e.g., concrete, wood, metal, asphalt, plant leaves, rocks, gravel) are not carefully seeded with known amounts of particulate, one must figure out ways of estimating the amount of surface deposition. If the particles are fluorescently-tagged or radioactive, surface concentration measurements can be more easily obtained. For other particle types, the solid object may need to be washed off and particles extracted from the surface in a liquid sample. The extraction efficiency may depend on surface roughness, surface porosity, particle size, whether the particle is hydrophobic or not, as well as other particle and surface characteristics.   It is not clear if the extraction efficiency can be quantified, and thus some underestimate of the surface concentration may occur.

4a) The airborne concentration and the surface concentration immediately below are not necessarily correlated.

By defining the resuspension factor K as the airborne concentration divided by the surface concentration immediately below, there is an implied assumption that a high surface concentration means there will be high airborne concentrations when conditions are conducive to particle resuspension. But, generally speaking, the surface concentration and the airborne concentration immediately above are not correlated. This is because the particle concentration above a surface depends on the resuspended particles that originate upwind of the measurement location.   This is a result of the time it takes for the particles originating near the surface to travel (i.e., mix) a finite vertical distance up to the height of the sampler, and during this time interval the mean horizontal wind has transported the particles downwind (see Fig. 1.2). For large horizontally homogeneous particle reservoirs, the airborne concentration will scale with the surface concentration. However, if there are spatial gradients in the surface concentration, then the magnitude of the airborne concentration does not scale with the surface concentration immediately below it and the significance of K is ambiguous without other information.
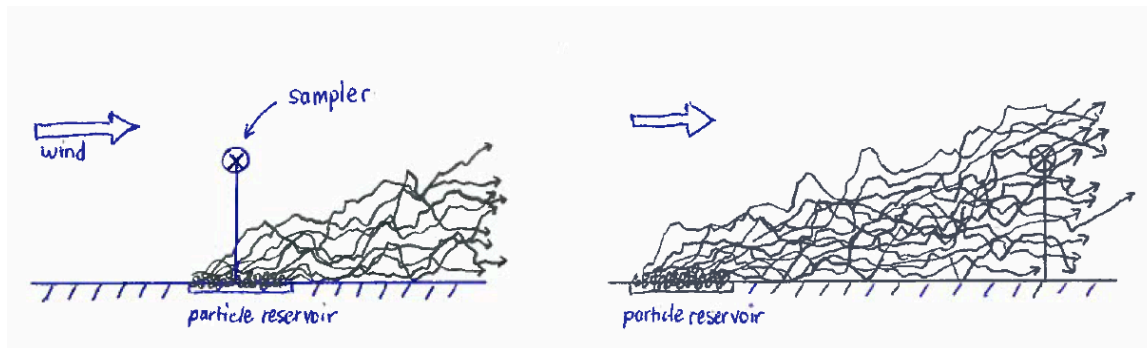
Figure 1.2. *Explanation for why the measured airborne concentration and the surface concentration immediately below are not necessarily correlated: (left) particles resuspended from the ground immediately below an air sampler will have a low probability of being measured by the sampler if there is good cross wind; (right) resuspended particles that intercept the air sampler originate upwind, implying the airborne concentration measured at the sampler depends on the upwind particle reservoir, i.e., the upwind surface concentration.*

4b) The K factor is difficult to use to define a source term.

A common complaint regarding the K factor from the transport and dispersion modeling community is that it can't be directly used in plume models to define the source term (note that we will show below that the resuspension rate – which can be used in plume models – is often derived in practice from the resuspension factor K, however). This is in part due to the lack of correlation between the surface concentration and airborne concentration referenced above in section 4a. But even if the surface concentration were to be spatially homogeneous over a large area, the airborne concentration will still change as a result of wind speed, turbulence intensity (the latter being a function of atmospheric stability), and particle size (due to size dependent gravitational settling). That is, a K value for a specific location and an airborne concentration measured for that particular location do not provide enough information to produce a unique value for the surface concentration. Hence, to utilize or correctly interpret the significance of a K value, one should know the spatial distribution of the surface concentration, the spatial extent of the surface contamination, the height of the sampler, the wind speed and direction, the atmospheric stability, and the particle size(s) of interest.

5) When were K factor measurements obtained?

As mentioned in Loosmore (2003), Nicholson (1988) and Sehmel (1984), many of the resuspension measurements were taken to investigate radioactively contaminated sites [1-3]. These measurements were obtained a week, a month, or even years after the original contamination event occurred. There is concern that these measurements and associated resuspension factors are representative of "aged" particulate sources and will lead to underestimates of resuspension for "fresh" sources. Loosmore (2003) and Nicholson (1988) show experimental evidence from time-resolved measurements that the majority of deposited particulates are resuspended in the first wind gust and that the resuspension

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flux drops off linearly with time thereafter [2, 3]. Hence, when interpreting K values, one should also consider the amount of time that has elapsed since the original event.

b) How to Measure the Resuspension Rate

In addition to all the problems associated with measuring the surface concentration described above for the resuspension factor K, the resuspension rate Λ has the additional complexity of needing a measurement of the resuspension flux. Measuring the mass or number of particles emitted per unit surface area per unit interval time near the ground is a very difficult measurement to make. Even if instrumentation is available to provide a number count of particles near the surface, it will be nearly impossible to discern between particles that originated from the ground and those that are already in the air being transported from upwind sources. It is made even more difficult if only a subset of the resuspended particles are of interest (either a specific pollutant, or only radioactive particles, or a specific biological agent particle, or particles of specific sizes) as one needs to somehow discriminate between these particles and "background" aerosols.

Due to the difficulties of directly measuring the resuspension flux $[g/(s \cdot m^2)]$, several methods have been devised to indirectly measure or approximate it. All are directly related through use of mass balance or mass conservation arguments, but each has different levels of approximations and applies to different problem types.

Source Depletion/Mass Balance. If one can accurately measure the mass of particles deposited on a surface and do this at different time intervals, the resuspension flux can be backed out by mass conservation:

$$\text{Resuspension Flux} \cong [\text{Mass}_{Sfc}(t_1) - \text{Mass}_{Sfc}(t_2)]/[\text{Area}_{Sfc} \cdot (t_2 - t_1)] ,$$

i.e., the resuspension flux for the time interval between time t_1 and time t_2 is the difference of the mass on the surface measured at the beginning and end of the time interval divided by the area of the surface with the deposited mass divided by the time interval.

This approach is most amenable to controlled experiments in which a small surface is seeded with specific particles of a known amount and the surrounding area is free of these specific particles (so that resuspension of these same particles from nearby regions will not be transported and deposited on the seeded surface, resulting in a mass gain). Hence, this approach is more difficult to apply to large contaminated regions because it would then be difficult to distinguish between the loss of mass due to resuspension and the gain of mass due to deposition of resuspended particles from the surroundings.

Nicholson and Branson (1990) used the source depletion/mass balance approach by fluorescently tagging porous silica particles and depositing them on a small section of roadway [5]. They used a UV lamp and a photomultiplier to measure the fluorescence, the magnitude of the signal being proportional to the number of particles on the surface. They measured fluorescence over time and could thus estimate the particle loss from the surface.

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This approach may not work well for soil surfaces in which particles may migrate into the soil or for surfaces with significant roughness that can obstruct the view of the particle.

Resuspension Factor K. In order to investigate particle resuspension, Nicholson (1993) performed a controlled outdoor wind tunnel experiment in which a known quantity of mono-disperse particles were deposited on the upwind section of the wind tunnel floor (on grass for some experiments and on concrete for others), [6]. In this paper, the resuspension rate Λ is given as a function of the resuspension factor K:

$$\Lambda[s^{-1}] = K [m^{-1}] \cdot Area_{Cross}[m^2] \cdot WS[m/s] / Area_{Sfc}[m^2]$$

where $Area_{Cross}$ is the wind tunnel cross section, WS is the average wind speed in the tunnel, and $Area_{Sfc}$ the area of the contaminated surface.

The derivation of the equation is not given in the paper, but can be derived from simple mass balance arguments. Nicholson approximated the airborne particle mass leaving the tunnel, by placing an array of eight particle air samplers in a single vertical plane across the tunnel near exit and just downwind of the contaminated surface [6]. The horizontal mass flow rate of particles in the air at the wind tunnel exit can then be approximated by:

Horizontal Mass Flow Rate in Air [g/s] = $Conc_{Air}$ [g/m³] $\cdot Area_{Cross}$ [m²] $\cdot$ WS[m/s]

where $Conc_{Air}$ is the average airborne particle concentration across the downwind exit plane based on eight sampler measurements [g/m³].

From mass conservation, the mass of particles flowing out of the tunnel is equivalent to the mass of particles resuspended into the air from the contaminated surface (note: it's not perfectly equivalent because some of the resuspended particles redeposit onto the ground before leaving the tunnel, however, for the small particles used in this study, deposition should not be a major issue), i.e.,

Mass Flow Rate from Surface [g/s] = Horizontal Mass Flow Rate in Air [g/s]

= $Conc_{Air}$ [g/m³] $\cdot Area_{Cross}$ [m²] $\cdot$ WS[m/s]

Dividing through by the area of the contaminated surface $Area_{Sfc}$, the resuspension mass flux from the surface is obtained:

Mass Flux$_{Sfc}$[g/(s·m²)] = {$Conc_{Air}$ [g/m³] $\cdot Area_{Cross}$ [m²] $\cdot$ WS[m/s]} / $Area_{Sfc}$[m²]

Substituting into the original definition for the resuspension rate, rearranging, and then utilizing the definition of the resuspension factor K, we can now obtain the equation proposed by Nicholson:

$$\Lambda [s^{-1}] = \text{Mass Flux}_{Sfc}[g/(s·m^2)] / Conc_{Sfc} [g/m^2]$$

$$= (\text{Conc}_{Air} / \text{Conc}_{Sfc}) \;\; \cdot \text{Area}_{Cross} \cdot \text{WS} / \text{Area}_{Sfc}$$

$$= \text{K} \cdot \text{Area}_{Cross} \cdot \text{WS} / \text{Area}_{Sfc}$$

The assumptions and approximations that went into the derivation of the resuspension rate equation are consistent with the limitations mentioned earlier in regards to the resuspension factor K. There is an implied assumption that the deposited mass is uniformly distributed. If it's not, then either the computed resuspension rate would need to be thought of as an area average and not be applicable to specific surface areas or concentration measurements would have to be made in other vertical planes (perpendicular to the wind) to quantify the resuspension rate for different regions. Even with multiple planes of measurements, this is difficult because it is not clear what surfaces upwind are "contributing" to the concentration measurement. This is why many prefer to use a combination of measurements and plume modeling for inhomogeneous surfaces.

A few simplifying assumptions were made that are also not correct and may lead to significant errors in the horizontal mass flow rate calculation. For a surface release, as shown in Fig. 1, the concentration near the ground will be significantly higher than that further up in the air. In addition, the wind speed also varies rapidly near the ground, being very small near the surface and initially increasing rapidly with height but then becoming more uniform at higher heights. When the horizontal mass flow rate is computed, it is not correct to simply use the average wind speed and the average concentration, rather the wind speed and the concentration at each height and spaced laterally across the plume should be used in a piece-wise summation over the vertical plane of interest.

Airborne Concentration Measurements. Nicholson's utilization of the resuspension factor K to determine the resuspension rate Λ is in reality a method that utilizes concentration measurements from air samplers and mass balance arguments [6]. It is worthwhile to delve into the problems associated with this approach for outdoor applications.

A critical step in the Nicholson method is the determination of the horizontal particle mass flow rate in the air. Nicholson was helped immensely by the fact that the experiment was conducted in a wind tunnel so that the downwind airborne particle plume was confined by the walls of the tunnel. He was therefore able to use the cross sectional area of the tunnel to help estimate the flux of material out of the tunnel [6]. In the outdoor environment, however, the airborne plume keeps expanding, both laterally and vertically as it travels downwind. In order to determine the horizontal airborne mass flux, one would need towers of concentration analyzers spaced across the plume to fully sample the plume across its width and depth in order to estimate the cross sectional area (see Fig. 1.3).

As alluded to earlier, the main concern that makes computing resuspension rates from airborne sampler concentrations problematic is if the surface concentration is spatially inhomogeneous. Since most particle dispersal – deposition applications will result in spatial variability in the surface concentration, we are stuck with this problem. In the next section, we discuss how one can use both plume models and measurements to estimate
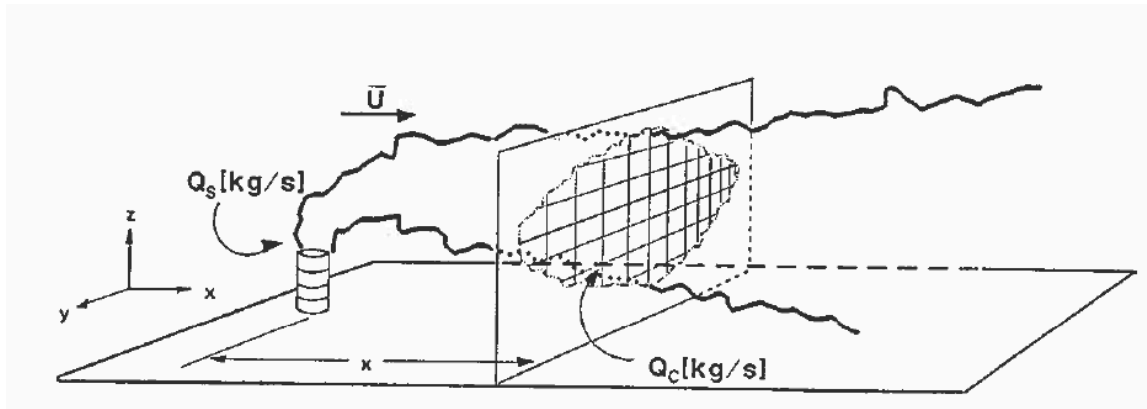
Figure 1.3. *If one can estimate the mass flux Qc [mass per unit time] through the plane as illustrated above, then one can determine the source strength Qs. This is the idea behind using mass balance arguments to estimate the amount of material resuspended from the surface. However, to estimate Qc is no trivial matter, as one needs to sum up the concentration multiplied by the wind velocity measured in each little box in the downwind plane. Many concentration samplers and wind sensors on multiple towers spaced along the plane would be required to obtain a reasonable estimate of the mass flux as the wind velocity varies with height and the concentration varies with height and distance across the plume.*

resuspension rates for inhomogeneous releases or for cases where there are few concentration air samplers.

Airborne Concentration Measurements and Modeling. Horst (1978) indicates dispersion modeling and air concentration measurements can be used to deduce the horizontal mass flow rate (and by extension the resuspension rate, as described above) [7]. Plume models can be used to help define resuspension rates even for cases with spatially inhomogeneous surface concentrations and for cases where only one or a handful of airborne concentration analyzers are available. However, the following are critical for making this work:

a) a good estimate of the spatial distribution of the surface deposition pattern and surface deposition concentrations must be obtained (this might be obtained from direct measurement, but could also be approximated by a well-validated transport and dispersion model with good particle-size dependency capabilities);

b) an estimate of the atmospheric stability during the period of airborne concentration analyzer collection must be known; and

c) a good measurement of the wind speed and wind direction (and to a lesser extent its variation with height) during the period of airborne concentration analyzer collection must be known.

Information on the particle sizes that are expected to be re-aerosolized is also important. This may be difficult to determine, however, especially for cases where the particles of

interest may attach to larger soil particles, or for biological slurry releases where individual spores will likely clump together as the droplet evaporates, with the final clump size dependent on the initial droplet size. Particle size information isn't crucial if the airborne concentration samplers are only measuring particles in the respirable size range, as these typically have small gravitational settling velocities (note: the resuspension rate is particle size dependent; Nicholson (1993) has shown that 20 micron particles are much more readily resuspendible from a surface as compared to 4 micron particles, for example) [6].

For short sampling time durations, i.e., an hour or less, or for longer sampling periods over which the winds and atmospheric stability do not change dramatically, the plume model can be run using a spatially-varying polygonal surface area source release (set to match the initial deposition pattern). Using the measured winds and stability for this time period, the transport and dispersion model can be run to create a 3D plume and the release rate (g/s) can be adjusted to best match the measured airborne concentrations.

I can hear the groans from folks that say a dispersion model isn't good enough to do this. And you are right, there will be errors. No dispersion model is perfect, but they are bound by reality, i.e., by physical approximations and principles such as mass conservation and diffusion equations and wind profiles and stability, and to a first order can provide a worthwhile estimate of the plume transport and dispersion. If a semi-accurate method for estimating source depletion directly is not available, then the alternative is to use a limited number of airborne samplers and the techniques described in earlier sections. The techniques described earlier require very drastic simplifying assumptions (e.g., homogeneous surface deposition, non-spatially varying concentration, a constant wind speed, neglect of deposition processes) which do not reflect reality.

By using a well-vetted transport and dispersion model to help determine the resuspension rate, the model is implicitly taking into account missing measurements that are needed (e.g., the plume width and depth that is required in the calculation of the plume cross sectional area $Area_{Cross}$); it is summing up the horizontal mass flux correctly using a 3D spatially-varying field of concentrations and winds; and it is accounting for a spatially-varying source term, for particle-size dependent gravitational settling, deposition of particles, and stability impacts on vertical and lateral mixing. Given the several order of magnitude uncertainty quoted in Sehmel (1984) and others in the resuspension rates [1], the factor of two uncertainty typically quoted for transport and dispersion models may not be so bad and still allow for useful estimates of resuspension rates.

c) Typical values of the Resuspension Factor and the Resuspension Rate

Owing to the simplicity of measuring resuspension factors, many references for K are found in the literature. In a review of by Sehmel (1980), he reports that K ranges from about

1×10^{-10} to 4×10^{-4} m^{-1} for resuspension due to wind

and

1×10^{-10} to 4×10^{-2} m^{-1} for resuspension due to mechanical disturbances

Sehmel indicates that the majority of the mechanical resuspension factors in the 10^{-2} to 10^{-3} range are for indoor cases, where there is no wind to carry away the particles, thus airborne concentrations can climb (hence it is unlikely that such high K factors will be measured outdoors) [8].

Sehmel's review lists considerably fewer resuspension rates owing to the difficulty of measuring it. Wind induced resuspension rates are shown to vary from 10^{-4} to 10^{-6} s^{-1} (for pollen on corn leaves) to 3×10^{-6} to 10^{-12} s^{-1} for primarily radiological particles originating on soil surfaces. As a frame of reference, Sehmel notes that if the resuspension occurred at a constant rate of 1×10^{-8} s^{-1} over an entire year, only 27% of the surface source would be resuspended at the end of the year. For a constant resuspension rate of 1×10^{-5} s^{-1}, 58% of the surface source would be resuspended in a day [8].

It should be noted that many of the early resuspension factor and rate measurements were reported for wind erosion purposes or for resuspension of radiologically-contaminated soils from fallout and accidental releases. Soil erosion factors typically include all particle sizes, and thus might be misleading for cases where only respirable particles are of interest. Radiologically-contaminated soil resuspension measurements are often long-term averages (e.g., seasonal or monthly) and may underestimate the resuspension of freshly deposited material. As outlined in Loosmore (2003), controlled wind tunnel experimental results of fresh particle deposits on different surfaces show that wind-induced resuspension rates from 10^{-4} to 10^{-2} s^{-1} are possible immediately after deposition [3].

Experiments of resuspension from vehicles passing over roads show resuspension rates ranging from 10^{-5} to 10^{-2} s^{-1} per vehicle pass depending on vehicle speed and weight, e.g. [1]. Nicholson and Branson (1990) show that the amount of particulate resuspended after a single pass depends on the particle size as well ranging from 20% resuspended for 4 µm particles and up to 60% for 12 µm particles at a speed of 40 mph [5]. They also showed that the fraction of particles resuspended did not increase much after a few vehicle passes.

2. Factors that Influence Resuspension

There are hundreds of factors that are thought to affect the resuspension of particles from surfaces, but how they affect resuspension is poorly understood. As a starting point, the variables Sehmel (1980) listed are provided in Table 2.1 with several additional variables that may be of importance or are related specifically to biological agent resuspension [8].

Before discussing the reasons for the importance of a subset of the variables above, it is advantageous to consider how current resuspension models relate the resuspension rate to properties of the particle, surface, and atmosphere. The developers of these models have had to make pragmatic decisions on what parameters are most important to include in their model equations. Two classes of models are discussed, those involving wind-induced resuspension and those involving vehicle-induced resuspension. Note that nearly all the models are empirically based, rather than developed from first principles.

Table 2.1 Variables Influencing Resuspension

Particle Properties	Surface Properties		Particle-Surface Interaction	Meteorology	Mechanical Forces
Density	General/All:	Soils:	Attraction Forces:	Atmospheric Stability	Mechanical:
Diameter	Aggregation Potential	Composition[1]	Capillary Forces	Dew Amount	Type[2]
Dissemination Method	Charge	Erodible Fraction	Chemical Binding	Humidity	Vehicle Size
Electrostatic Charge	Density	Particle Size Distribution	Electrostatic	Precipitation	Vehicle Speed
Hydrophobicity	Moisture Content	Percent Obstacles	Impingement	Turbulence	
Hydrophylicity	Particle Loading	Scouring Susceptibility	Magnetic	Friction Velocity	
Particle Aggregation	Porosity	Vegetation:	Van der Waals	Reynolds stress	
Particle Coating	Roughness	Height Above Ground	Slurry Viscosity	Wind Gusts	
Reactivity	Texture	Leaf type	Orientation	Wind Velocity	
Shape	Manmade:	Stickiness/Cilia	Penetration Depth		
Size Distribution	Material	Wind "Shakeability"	Saltation Potential		
Slurry Preparation	Adhesion		Sheltering		
Surface Roughness	Soil Loading		Time of Contact		
	Silt Content				

[1] Silt, clay, sand, organic, non-organic, etc.
[2] Foot traffic, digging, construction, etc.
Variables that are underlined are commonly applied in resuspension models

a) Wind-induced resuspension.

Three primary types of models have been developed in the air quality community for wind-induced particle resuspension: those used for wind erosion and dust applications, those derived from "aged" deposits of radioactive particles from fallout, and those based on resuspension of "fresh" particles deposited onto specific surface types. We will look at each of the three model types to see what they include as important factors for resuspension.

Dust Resuspension. Although wind erosion and dust transport models may not seem relevant to homeland security applications, they are of interest because it is suspected that biological and radiological agent particles attach to larger soil particles [9]. Wind erosion and dust researchers have been studying resuspension for over 70 years; thus their models are more mature and generally account for more factors. Shaw (2008) has developed the following vertical dust flux equation based on Gillette and Passi's (1988) evaluation of a large amount of experimental data from different soil types under different conditions:

$$G = \alpha \cdot C \cdot u_*^4 \left(1 - f_w \frac{u_{*t}}{u_*} \right) \quad \text{for } u_* > u_{*t}$$

$$= 0 \quad \text{otherwise}$$

G is the vertical dust flux of all particles sizes[g/s cm²], α is a coefficient for vegetative cover [non-dimensional] ranging from 0 (complete vegetation) to 1 (no vegetation), C is a constant based on a fit to experimental data and equals 1e-14 g/(cm⁶s³), the friction velocity u_* [cm/s] is a measure of the atmospheric turbulence, f_w is a soil moisture function ranging from one (dry soil) to larger than one (wet soil), and u_{*t} is a threshold friction velocity below which dust emission does not occur [10, 11].

From the equation it is seen that dust flux is strongly dependent on the friction velocity. Shao (2000) indicates that experimentalists have reported the exponent as ranging

anywhere between 2 and 5 [12]. Almost all resuspension models utilize u_* or its surrogate, the mean wind velocity. Below a minimum friction velocity u_{*t}, soil resuspension does not occur. According to Shaw et al. (2008) its value is 0.2 m/s, although it would seem that the threshold value should depend on the characteristics of the soil [11].   As we will see below, an important difference with resuspension models for particles that are deposited on surfaces (e.g., radiological particles from fallout, biological particles from a terrorist attack) is the lack of time dependence in the above equations. This is because of the assumption of an infinite reservoir in the case of soil resuspension, whereas for the fallout and terrorist attack cases there are a finite number of particles deposited onto a surface and with time resuspension will act to spread out and dilute the material.

The α coefficient accounts for the sheltering effect of obstacles (in this case, vegetation), i.e., resuspension of soil particles is reduced in regions where there is vegetation because vegetation slows the wind down and reduces the turbulence.   Note that this applies only to the soil particles in the soil layer. If there are particulates on the leaves of the vegetated surfaces, there is some evidence that resuspension of particles from the leaf surfaces would be much greater as compared to resuspension of those same particles from a ground surface [1]. The equation also indicates that any soil moisture reduces the vertical dust flux. The soil moisture function f_w depends on the gravimetric soil moisture and the maximum amount of moisture the soil can hold, the latter dependent on the amount of clay in the soil.

Resuspension of Aged Deposits. Many of the resuspension measurements performed over the past several decades have stemmed from the need to understand the health impacts due to resuspension of particles from the fallout due to nuclear testing and nuclear accidents (e.g., Chernobyl). As discussed in Loosmore (2002), the majority of these experiments were performed weeks, months, or years after the events occurred. This means that much of the radiological particles will have migrated into the soil and possibly have bound to other soil particles and thus represent an "aged" deposit.

The National Council on Radiation Protection developed a simple model for estimating the resuspension factor K for resuspension of radiological particles [13]. Loosmore (2002) converted the resuspension factor equation into one for resuspension rate:

$$\Lambda\left[s^{-1}\right] = u_* \cdot 10^{-7}[m^{-1}] \quad \text{for t < 1 day}$$

$$= u_* \cdot \frac{10^{-7}[days/m]}{t} \quad \text{for t > 1 day and t < 1000 days}$$

where u_* is a long term average friction velocity [m/s], the constant has dimensions as indicated, and t is in days since the particles were deposited [14].

What is of note is how simple the equation is, only depending on the friction velocity. Loosmore indicates the formula behaves very poorly for times less than one day, severely underestimating the resuspension rate [14]. However, it is tantalizing to wonder if such a simple equation could be used to estimate biological agent resuspension several days after

a wide area attack. This author doubts that would be the case, especially given that the review by Sehmel (1984) indicates the resuspension factor K for radiological particles at numerous sites ranges five orders of magnitude (10^{-5} to 10^{-10} m^{-1}) [1]. This suggests the above equation is a best fit to a data set with several orders of magnitude on either side.

Resuspension of Fresh Deposits. Loosmore analyzed several wind-tunnel experiments involving time-resolved resuspension of seeded particles on concrete, bare soil, and grass surfaces and obtained a best-fit equation for particle resuspension rate:

$$\Lambda\left[s^{-1}\right] = 0.42\frac{u_*^{2.13}d_p^{0.17}}{t^{0.92}z_0^{0.32}\rho_p^{0.76}},$$

where the resuspension rate Λ is the mass flux of particles resuspended (g/s m^2) divided by the surface concentration of particles (g/m^2); the friction velocity u_* [m/s] is a measure of the turbulence in the atmosphere; d_p [μm] is the particle diameter; t [s] is the time since the winds started blowing; the roughness length z_0 is a measure of how rough or smooth the surface is; and ρ_p [kg/m3] is the density of the particle [14].

The most important contribution of the Loosmore study was to emphasize the importance of the early time resuspension, i.e., the inverse dependence of resuspension rate on time [14].   The experimental measurements indicate that the majority of the mass flux occurs in the first wind and turbulent gusts immediately after the particles are deposited. One can imagine that the first wind gust will remove the particles that are easily loftable leaving behind those that are sheltered within the roughness and thereby making it harder for each subsequent wind gust to loft particles into the air.

The equation makes qualitative sense. A larger friction velocity u_* implies a larger wind speed and the force imparted by the wind is what acts on the particle to overcome particle adhesion, gravity and any other "sticking" forces to loft the particle into the air.   As shown in Fig. 2.1, the Loosmore equation indicates that the fraction of the deposited material resuspended into the air is strongly dependent on the friction velocity u_*.

The Loosmore equation also implies that bigger particles, although heavier, are still more likely to be re-aerosolized than smaller particles of equal density (see Fig. 2.2). This is because larger particles stick up higher above the surface and thus are more likely to be buffeted by the wind and lofted into the air. There is, of course, a point at which particles become large enough that they will quickly settle back to the surface (according to Gillette et al. (1974) this is when the particle diameter is roughly 100 microns or larger [15]).

The reduction in resuspension rate as a function of increasing surface roughness can be explained by the roughness elements shielding the particles from the wind (Fig. 2.3). That is, particles can settle in the crevices between roughness elements and be more difficult to loft into the air as the wind will have difficulty penetrating down into the crevice.

Loosmore Resupension Model

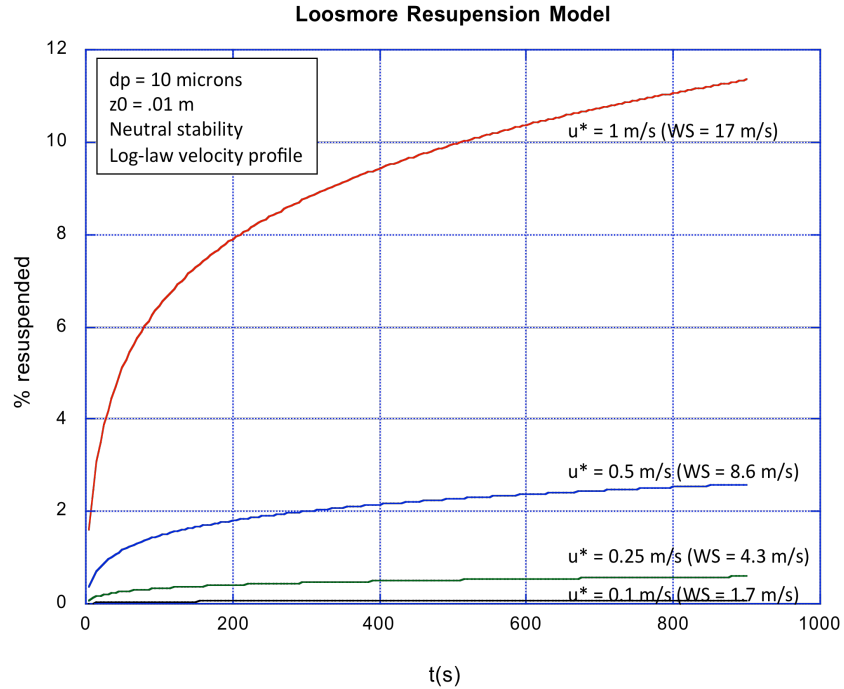**Fig. 2.1.** *The percentage of deposited 10 micron spherical particles resuspended from a semi-rough surface as a function of the friction velocity u∗ based on the Loosmore best-fit equation.*
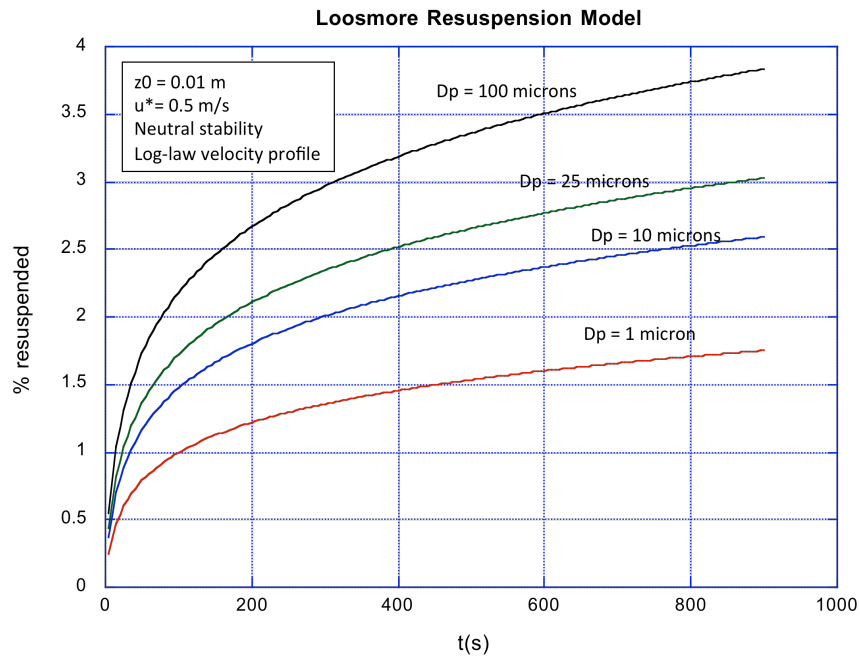
Loosmore Resuspension Model

Fig. 2.2. *The percentage of deposited particles resuspended from a semi-rough surface as a function of the particle diameter based on the Loosmore best-fit equation.*
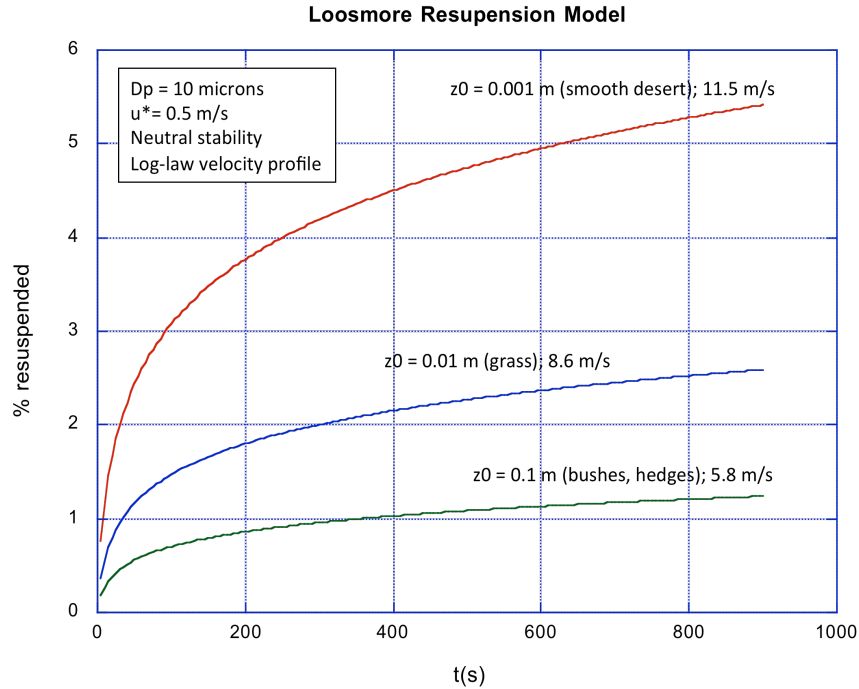
Fig. 2.3. *The percentage of deposited 10 micron particles resuspended from different surfaces based on the Loosmore best-fit equation.*

It should be emphasized that the Loosmore equation was derived from only a handful of experiments in which particle sizes varied between 0.5 and 22 microns, the friction velocity ranged from 0.1 to 1.4 m/s, the roughness varied between 0.3 mm to 30 mm, and only two particle densities were used (1000 and 7160 kg/m^3) so the use of the equation outside this range may not be warranted.   Furthermore, not all combinations of parameters were measured and different methods were used by each of the experimentalists to infer the resuspension rate as well as several of the parameters (e.g, u_* and z_0).

b) Vehicle-induced resuspension

Vehicle-induced resuspension typically results in more particles resuspended in comparison to wind-induced resuspension. Empirically-based models have been developed for paved and unpaved roads. For unpaved roads, Gillies et al. (2005) found that the particulate emissions for particles of ten microns and less could be expressed as:

$$E_{PM10} = 0.003 \; x \; W \; x \; S,$$

where E_{PM10} is the mass of dust emitted by the vehicle per kilometer traveled [g/km], W is the weight of the car [kg], and S is the speed [km/h] [16].

The EPA [17]has developed vehicle-induced particle emission equations for two types of unpaved roads: unpaved surfaces at industrial sites and unpaved publicly accessible roads. For the industrial site, the dust emissions equation for particles less than 10 microns is:

$$E_{PM10} = 1.5\ (s/12)^{0.9}\ (W/3)^{0.45}$$

where E_{PM10} is in lbs. per vehicle mile traveled, s is the surface material silt content [%], and W is the average vehicle weight [tons]. EPA documentation provides tables that contain typical silt content range at different kinds of industrial sites. The EPA-42 guidance also indicates that the equation holds for vehicles from 2 to 290 tons, implying that is meant for industrial-sized dump trucks and other commercial vehicles.

For publicly accessible unpaved roads, the EPA dust emissions equation is:

$$E_{PM10} = 1.8 \frac{(s/12)(S/30)^{0.5}}{(M/0.5)^{0.2}} - C$$

S is the average vehicle speed [miles/hr], M is the surface moisture content (%), and C is a correction factor to take into account the particulate emissions from vehicle exhaust, brake wear, and tire wear [0.00047 lbs. per mile traveled]. The equation was developed from experiments in which the vehicle weight was between 1.5 and 3 tons, vehicle speed between 10 and 55 mph, and surface moisture content between 0 and 13%. EPA documentation indicates the tested unpaved roads were usually hard and non-porous [17].

For publicly accessible paved roads, the 2010 draft EPA-42 guidance provides the following equations for resuspension of road surface particulates:

$$E_{PM10} = 0.015(sL/2)^{0.98}(S/30)^{0.16}(W/3)^{0.53}$$

Variables are the same as denoted above, except that sL is road surface silt content in gm^2. The equations were developed for cases with silt loading between 0.03 and 400 g/m^2, vehicle weight from 2 to 42 tons, and speeds from 1 to 55 mph. EPA documentation provides typical silt loadings for roads based on traffic amount (silt loading is reduced as traffic volume increases), as well as a multiplication factor for winter conditions. EPA also suggests adding 2 g/m^2 to account for locations where winter time anti-skid abrasives are used. They imply that if precipitation is above 0.01 inch, PM10 particulate road emissions are near zero. It is not clear to the authors why a correction term C for direct vehicle particulate emissions is not added to this equation as was done above for the unpaved road equation (it is included in the 2006 guidance, but the vehicle speed term S is not) [17].

The above equations are meant to be applied to daily, weekly, seasonal, or yearly averages using average traffic flow values. Since the equations do not have time dependence, they imply an infinite or renewable supply of particulate matter and hence are not likely to work well in the immediate hours after a "fresh" deposit.

Experiments performed by Sehmel (1973) and Nicholson and Branson (1990) looked at the resuspension of fresh particle deposits on paved roads by moving vehicles [5, 18]. Both

experiments found that a single vehicle pass can cause high amounts of particle resuspension, but what is surprising is the huge difference found in the fraction of the deposited material resuspended. Sehmel seeded an asphalt road with non-mono-disperse phosphorescent ZnS particles with a MMD of 5 microns (with an upper bound of 25 microns) and found that up to 1% could be resuspended by a single vehicle pass for a vehicle traveling at 40 mph [18]. Using mono-disperse spherical silica particles, Nicholson and Branson ran individual experiments with 4, 10, 12, and 20 micron diameters and found that for a vehicle traveling at 40 mph, a single vehicle pass resulted in 20% of the 4 micron particles being resuspended. A little less than 50% of the 10 and 12 micron particles were removed from the road, and almost 60% of the 20 micron particles were removed [5]!

No matter what numbers are "correct" (they both may be), the Sehmel (1973) and Nicholson and Branson (1990) experiments suggest that vehicles moving through a contaminated area immediately after a deposition event could have significant health consequences due to particle resuspension [5, 18]. Even keeping vehicle speeds low could still cause health impacts. At 5 mph, the Nicholson and Branson experiments show about 10% of the 12 micron particles are removed from the road in a single vehicle pass, and a little over 20% are removed after ten vehicle passes. The Sehmel experiments show a dramatic drop off for cars driven at 5 mph through the ZnS particles with only 0.02% being resuspended per vehicle pass [18]. However, a truck driven through the tracer at the same speed results in 0.25% of the particle mass being resuspended in a single pass.

Are the differences between these experiments real or is there a fundamental difference between them, or error(s) in the methodologies? Some possible explanations are:

1) The density of ZnS particles is 4000 kg/m3, while the silica particles are 1000 kg/m3. The Loosmore wind-induced resuspension equations, however, suggest that the resuspension rate would only be 3 times smaller for the ZnS particles, not enough to explain the difference.

2) Sehmel's paper states that "the vehicles were driven on a dry seasoned asphalt road that was originally laid as a ¾ minus gravel road mix and was subsequently coated with 3/8 inch to 5/8 inch clear chip gravel." Under these conditions, it is possible that a large fraction of the seeded particles ended up below and in between the gravel, sheltered from the vehicle-induced wind and turbulence. Nicholson and Branson only say that particles were deposited on a road surface, with no mention of its surface characteristics.

3) Sehmel's paper states that the vehicles were driven over the seeded particles on the "same day that the ZnS was placed on the road". Was this minutes after the seeding, hours, many hours? There is the possibility that wind gusts could have removed some of the initially seeded particles. According to the wind-tunnel experiments analyzed by Loosmore, the majority of the particles are resuspended in the first gusts, in the first minutes after deposition. Nicholson and Branson's paper does not say when the vehicles were driven over, but they do say that "the particles were allowed to settle [onto the road test section] in an enclosed volume", implying that they were concerned about wind effects.

4) The density of particle seeding should or could impact resuspension. For example, if someone dumped lots of particles in a small area, so particles piled up on other particles, one can imagine that a large fraction of particles would be aerosolized. However, Nicholson and Branson say that their seeding procedure resulted in 25% of the surface being covered in a mono-layer. It doesn't seem that this would result in particles being piled onto other particles. Sehmel writes that the particles were deposited at an average of 0.5 g/ft^2.

5) One of the major differences could be due to how the "fraction remaining" on the surface was computed. Nicholson and Branson used a direct measurement. Particles were fluorescent and they determined the amount deposited on the surface by illuminating the surface. After each vehicle pass they illuminated the surface to calculate how much material was left on the surface. They write that their detection equipment was calibrated using known masses of material and that there was a linear response.

On the other hand, Sehmel deduced the amount remaining via mass balance by measuring the concentrations on 3 downwind towers at each of 3 downwind locations (10, 20, and 30 ft from the source), wind measurements at 3 heights, and deposition at several downwind locations and then estimating the horizontal mass flux. As discussed earlier, a mass balance technique is likely to introduce errors due to trying to calculate an integral with only a few measurements. In fact, Sehmel includes tables that show some cases where the mass balance indicates a factor of 2 too much mass and other cases with a factor 2 too little.

It is possible part of the difference is because Sehmel is measuring the amount resuspended and likely not the fraction that is saltating or traveling below the 1-ft height of the lowest sensor. Nicholson and Branson, however, are in effect measuring both the resuspension and saltation component together. That is, if the particles just blow off the test section, only a few meters away, it "counts" as having left. However, it would be incorrect on our part to interpret this as particles that have been resuspended.

6) When the car drives over the florescent particles in the Nicholson and Branson experiments, could background dust be kicked up that then settles on top of the florescent particles, thus obscuring them from view and resulting in an underestimation of particles remaining on the test surface when illuminated?

3. Identified Gaps & Issues Specific to Biological Agent Resuspension

a) Quantification of aggregation of soil particles and biological particles

The interaction of spores with soil particles is likely complex, dependent on soil and spore properties. It is important to understand these processes since small particles, less than 5 microns, are not as resuspendable during a wind gust as larger particles. If small spore particles, however, adhere to bigger soil particles, they could be resuspended more easily and perhaps separate during the saltation process. Chepil (1945) writes that particles less than 5 microns do not exist in soils because soil particles bind together [19]. Chinn (1996) goes onto say that bio particles in the 1-5 micron range will therefore bind to larger

particles in the soil [20]. There is very little experimental evidence, if any, to support the eventual particle size distribution of deposited *Bacillus anthracis* in soils. Hugh-Jones and Blackburn (2009) state that "Humus particles are positively charged at a neutral pH and act as chelators, collecting and holding bacteria." The exosporium of *Bacillus anthracis* is likely to carry a negative charge, meaning that the spores are more likely to form aggregates with other positively charged soil components, such as calcium and humic substances, than with each other. The pH of the soil greatly affects the persistence of the spore [9]. However, a number of other factors may influence soil particle-spore aggregation and subsequent resuspension, but have not been extensively investigated:

- Soil particle size and shape
- Soil type and texture
- Humic matter content
- Mineral content
- Moisture content
- Surface charge/coating of spore
- Impact of rain and standing water

Hugh-Jones discusses many of these factors in terms of the survival and proliferation of the spore; however, a deeper understanding of the size of the spore-soil complex is an important input for modeling resuspension.

b) Types of Wind-Induced Particle Movement: Creep vs. saltation vs. resuspension

According to Nicholson (1988) creep is when big particles (500 – 1000 microns) roll along the ground due to wind forces; saltation is when medium size particles (100-500 microns) skip and bounce along the ground due to wind forces; and resuspension is when smaller particles (<100 microns) are suspended into the wind and stay there for some time [2]. Saltation is apparently very important in erosion and sand transport and accounts for the horizontal movement of the greatest mass. Nicholson (1988) explains that saltating particles typically do not resuspend above 1 m in height. Saltation may be an important consideration from a modeling perspective since saltating particles can result in other particles saltating or rolling, induce resuspension through a "sandblasting" effect, and/or knock smaller micron sized particles from larger soil particles [2]. This was demonstrated in wind tunnel experiments: the addition of 100 and 200 µm particles upwind of ≤ 7 µm particles increased resuspension of the smaller particles [21]. Chinn(1996) states that "soil aggregates will shed bio particles … when struck by saltating particles."

Saltation may need to be addressed when modeling bio agent particulate fate. Careful studies on a number of urban surfaces showing the impact of larger saltating particles on the resuspension of smaller bio agent particles should be carried out. In addition, controlled experiments on the effect of saltating particles on soil–bio particle aggregates should be carried out to confirm whether Chinn's (1996) statement about bio particles being shed from soil particles is true.

c) Influence of spore preparation on deposited particle size distribution

Spore preparation will affect the particle size of the deposited particulates and thus impact resuspension, but more research on how spore prep impacts the particle size distribution is needed. For a wet slurry release, the droplet may evaporate completely before hitting the ground causing the spores to clump together and form larger dry agglomerates. If the droplet does not evaporate before hitting the ground, then the spores may not clump together, thus creating a very different size distribution of smaller sized spores on the ground. Sprayer type, slurry concentration, viscosity and additives such as anti-sticking agents will impact the final dry agglomerate particle size distribution and, for the latter two, particle characteristics such as electrostatic charge. Additionally, agglomerated particles may break up upon hitting the surface [22] or over time due to mechanical forces. The sizes and characteristics of the deposited dry agglomerated particles will significantly impact the resuspension flux.   Controlled deposition experiments with different sprayer types (initial droplet size distributions) and spore preps should be carried out under different met conditions (relative humidity, wind speed) with different urban surface types in order to assess the spore clumping on the surfaces using electron microscopy or other methods.   The fate of the dry agglomerates over time should be determined in relation to stresses from environmental factors (e.g., solar radiation, heating and cooling, moisture, wind, saltating particles).

Depending on the preparation, the spores of dry powder releases will be less or more likely to stick together. In comparison to slurries, it is thought that the particle sizes deposited onto the ground surfaces will be much smaller for dry releases and thus harder to resuspend. However, as discussed above, the spores may attach to larger soil particles and thus be more resuspendable. It is not clear how different aspects of the weaponization process will impact the resuspension and soil aggregation capability of the spores.

d) Impact of different urban surfaces and climactic conditions on reaerosolization

In addition to spore preparation, the deposition surface may influence the particle size distribution and subsequently, the reaerosolization potential. Droplet evaporation and dry particle accumulation will be different depending on the underlying surface (non-porous vs. porous, rough vs. smooth, etc.). Crevices from a porous surface may act as a shielding mechanism for bio-particles, while smooth surfaces (e.g. steel) may facilitate blow-off.

Tree and leaf surfaces may also be important sources of reaerosolization. According to information from the pesticides community and the soil erosion community, trees act as a sink trap for particles (i.e., a large quantity of particles deposit out onto leaf surfaces). Anecdotal evidence suggests that for an equivalent wind speed (or friction velocity) resuspension from trees is larger than from the ground. This makes sense, because winds up high at leaf level are faster than near the ground. Plus, the leaves shake and vibrate. How will resuspension differ from a high stationary source, like a roof? The difference between deposition of particles onto walls and roofs/ground surfaces needs to be studied.

The condition of the surface will also have an effect reaerosolization. Roads and other urban surfaces can accumulate soils and other particulate debris. Small particles could then latch onto these big particles and become resuspended. Knowing the soil/particulate debris accumulation on roads might be important in quantifying the resuspension flux.

A review by Birenzvige (1992) suggests that soil moisture is one of the most important parameters affecting resuspension. Soil moisture may even affect the resuspended particle size, increasing it as the soil dries [23]. Equations that incorporate moisture content into the threshold friction velocity can be performed, but a deeper understanding of the effect of climatology and meteorology on different surfaces should be addressed.

It is also not clear how spores migrate into the soil over time. Quantifying how they migrate as a function of soil type and texture, vegetation cover and root density, and on weather conditions (e.g., precipitation) has not been established. How spores migrate into concrete, asphalt, wood, painted wood, and other manmade surfaces over time is also not well understood. Will rain events push spores deeper or wash them off? It has been proposed that rain can wash soil-aggregated spores into concentrated areas, such as a low-laying pools [9], but other reports suggest spores are relatively stable in soil and large amounts of rain will not have an effect [24, 25]. Little is known about other surfaces.

e) Instantaneous vs. time-averaged view of resuspension

Most model formulations of the resuspension flux are based on time-averaged measurements of the wind and turbulence. But resuspension of particles occurs instantaneously during large wind gusts when winds and turbulence are large. To truly understand reaerosolization, experiments need to be designed where fast response particle samplers and fast response wind sensors are used simultaneously.

f) Scrutiny of results from laboratory-scale resuspension experiments

As mentioned earlier in this report, the particle resuspension rate is proportional to u_*^n, where n is somewhere between 3 and 5. Hence, the friction velocity u_* is critically important to quantify in any resuspension experiment. Since the friction velocity requires special fast response instrumentation to measure, some researchers estimate u_* from a measurement of the wind speed. For a fully turbulent boundary layer (i.e., the atmosphere, specialized meteorological wind tunnels) the friction velocity is proportional to the wind speed. However, many researchers have conducted particle resuspension experiments in non-fully turbulent boundary layers (e.g., in non-meteorological wind tunnels, in chambers or in duct work) and have inappropriately computed a friction velocity based on a measurement of the mean wind speed. The relationship between u_* and wind speed only holds for a fully turbulent boundary layer. The results from experiments without fully turbulent boundary layers need to be interpreted with caution as they are likely significantly overestimating the value of the friction velocity.

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