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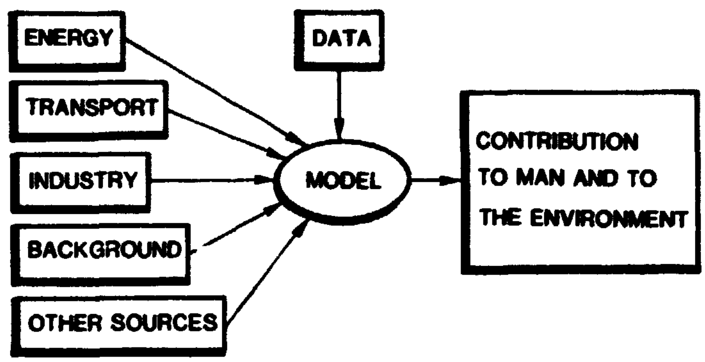

Environmental research under the Nordic Ministerial Council

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The relative importance of pollution from different sources to man and to the environment.

Risø National Laboratory, DK-4000 Roskilde, Denmark
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DRY DEPOSITION AND RESUSPENSION OF
PARITUCLATE MATTER IN CITY ENVIRONMENTS

N.O. Jensen

Abstract. The report describes, mostly in qualitative terms, the deposition and resuspension of particles and how the mechanics depend on particle size. The effect of rough surfaces is discussed. It is concluded that knowledge on the subject, at relevant large Reynolds numbers, is indeed lacking. Various methods for measurements of deposition is mentioned and further the report gives some general ideas on how a suitable full scale experiment should be laid out in order to produce some data on the problems of dry deposition to city surfaces.

INIS descriptors AEROSOLS; DEPOSITION; DUSTS; MATHEMATICAL MODELS; PARTICLE RESUSPENSION; PARTICLE SIZE; PARTICLES; REVIEW; ROUGHNESS; URBAN AREAS;

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CONTENTS

1. INTRODUCTION

In modelling of population doses of e.g. heavy metals it is, in addition to emission maps and general climatological information, necessary to have a suitable parameterization of the deposition processes.

Deposition to rural areas gives a positive contribution to the doses via foods produced here. These, of course, are distributed to city populations as well. In contrast to this, deposition in city environments may work as a reducing factor as it diminishes the air concentration and hence the respiratoric uptake.

Resuspension of this deposited material, however, may in episodes of high winds cause enhanced doses.

Most data on deposition concern vegetated surfaces. There is, however, some experimental background in supposing that deposition to surfaces consisting of smooth elements (which collectively do not have to be smooth in an aerodynamic sense) is somewhat smaller. This can be argued on the smaller "effective" area of such surfaces.

Thus in itself it is of importance to consider whatever special effect city surfaces have on dry deposition although this according to the above may not be a particularly large one. But even a small effect, on basis of the large population density, may give a large change in the total dose. Also, the suspended dust load in cities is generally high, such that a small change may have a large absolute impact.

Thus it is timely to investigate this special area. The present report deals with a review of existing knowledge in the field of dry deposition of fine particles to city surfaces. Further an experimental lay-out to improve this knowledge is discussed.

In the remaining paragraphs the mechanics of resuspension in city environments are discussed along with some experimental suggestions to improvement of knowledge about this process.

The awareness in the international research community of these problems is quite apparent. Thus in the conclusions of the proceedings of the 4th international conference on precipitation scavenging, dry deposition and resuspension it is written (Hicks and Garland, 1983):

"Our present knowledge of particle deposition derives largely from careful studies of mechanisms conducted in wind tunnels. Disagreements between this knowledge and field experience suggest the possibility that mechanisms may differ in the two situations. Several possibilities warrant investigation. Perhaps a difference in turbulent intensity or spectral distribution are among the most likely candidate explanations, and measurements of turbulence within similar canopies in the two situations may help to elucidate the difference".

Thus extrapolation of model results are considered of questionable value It is further stated that:

"Deposition in towns has received little attention. Many sources are in or near urban areas, so that concentrations there are elevated. In addition, deposition of some pollutants on houses and gardens may have greater significance for public health. Present methods probably allow an investigation of the effect of bluff buildings on the deposition to grass and crops planted between them, but field measurement of deposition to buildings may require development of new techniques".

The underlining is made by the present author.

It is thus evident that mechanisms involving deposition of particles especially to cities are largely in the unknown and severely needs investigation. In the following some aspects of this phenomenon is reviewed from a micrometeorological point is presented. In a final chapter the role of resuspension in city environments are addressed: some definitions are rehersed, but very little hard data exist on the subject, however, some methods of analysis done on general dust samples may prove to be relevant to this problem.

2. DRY DEPOSITION OF FINE PARTICLES TO CITY SURFACES

A literature study has revealed that very little, if any, data exist for the dry deposition of fine particles to city surfaces. Dry deposition to a typical large city, however, with its relatively smooth surfaces of concrete tile and asphalt, would very likely be less than to a vegetated fibrous surface. In an investigation of the deposition velocity of caesium-137 to building surfaces, Roed (1983) finds small values indeed. In making reference to model studies there certainly seems to be an effect. However, it is not at all clear how to extrapolate to full scale, i.e., what scaling factors to use. Presumably they would be combinations of physical parameters, such as: aerosol size, d; surface roughness, z_o; and turbulence, u_* (friction velocity), but lack of data prevents adequate guidance to modellers in this field.

Some work on deposition to cities has been done in the past. A study by Andersen et al. (1978) deals with comparisons of vegetation uptake and total funnel collection (including wet deposition). Fig. 1 shows isopleths of funnel collection amounts from this study and the distribution of areal use in the city of Copenhagen.

The reason for such studies to be difficult to interpret is not only due to the mix of dry and wet deposition but also due to the general unrepresentativeness of collection agent (i.e., non typical spots in the general surroundings). It depends of course on what the usage of deposition estimates are: in some respects a large deposition is a conservative estimate, in other the contrary. But in connection with aerosols and respiratory effects, it would be a wrong strategy to overestimate deposition. Hence, areally representative estimates are called for.

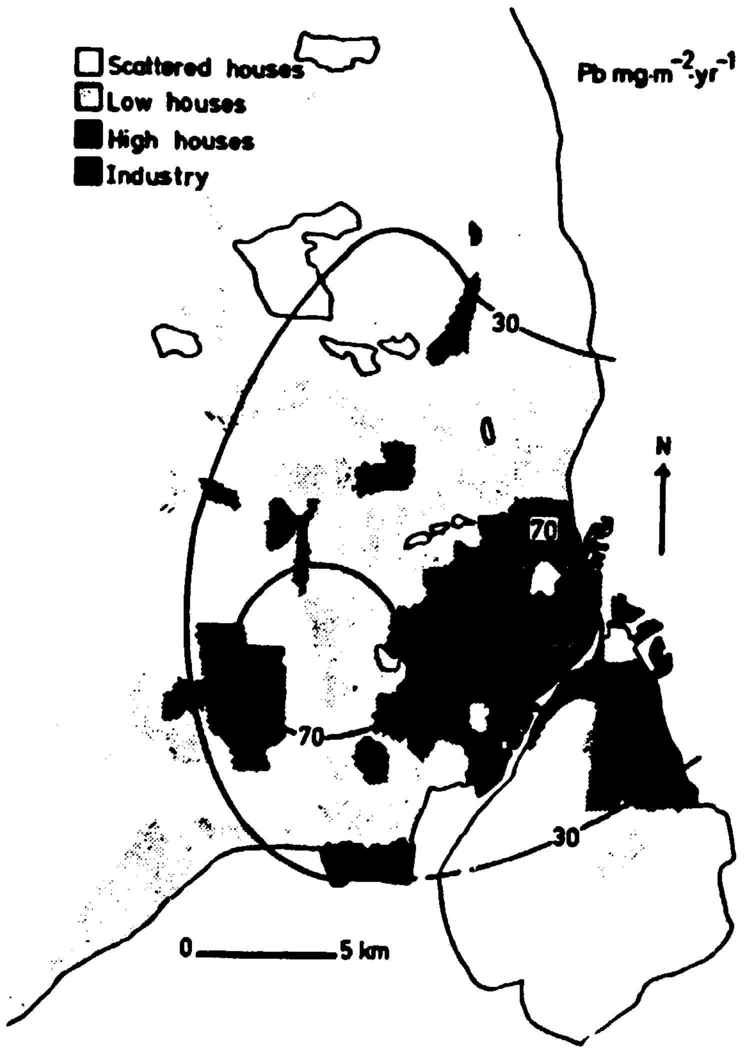


Fig. 1. Total (dry and wet) funnel collection results for Pb in the Copenhagen area.

2.1. Particles in the urban atmosphere

Figs. 2 and 3 show the size distribution of Lead and Calcium particles from measurements in Copenhagen area (Flyger et al., 1976). The suspended load of these two components are seen to be about the same in this case (~ 0.3 μg/m^3) but the shapes of the distribution are very different.

Thus for Pb, about 50% of the mass fall in the smallest category (cascade impactor range corresponding to diameters, d≤ 0.3 μm). The origin of these particles is thought to be automobile exhaust from engines burning leaded petrol. The three stages of the impactor collecting particles up to about 1.7 μm account for ~ 90% of the mass. For a "fresh" aerosol, however, where agglomeration has not yet had much chance to occur, the aerosol is even smaller.

Thus Whitby et al. (1975) find that 30 m from a freeway the aerosol is predominantly below 0.15 μm and exhibits a strong combustion mode at about 0.02 μm. With winds from the sampling station towards the freeway the aerosol was rather larger (~ 0.2 μm) in agreement with the above and with findings from other cities, e.g. St. Louis (Stampfer and Andersen, 1975; Alkezweeny, 1978).

Fig 3, however, which deals with Calcium shows a quite different and more even distribution with about 50% of the mass associated with particles larger than 2 μm. This is explained by the expectation that Calcium derives from wind blow dust.

Thus the total aerosol distribution in a city is not likely to be monotonic or describable with a simple mathemathical espression as Junge's equation (Jaenicke and Davies, 19769), but may rather appear as double peaked function.

Although, as will be mentioned below, the 1 μm size particles may be the least depositing, they may be the least abundant in the city atmosphere anyway, since the main production occurs on

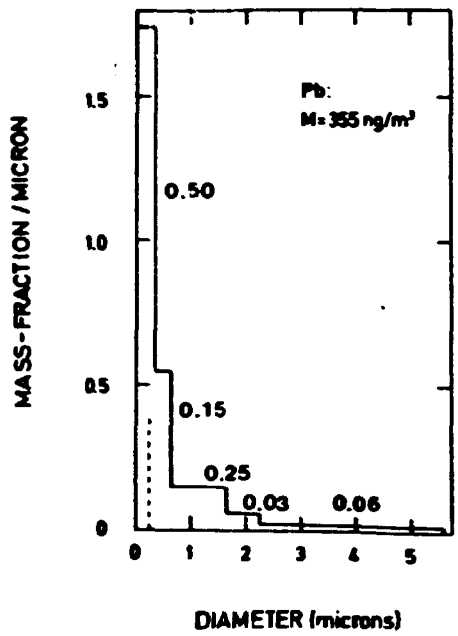


Fig. 2. Size distribution of Pb in a 2-hour cascade impactor sample from Copenhagen (from Flyger et al., 1976). The relative mass fractions are noted on the figure. The dotted line marks the mass median diameter.

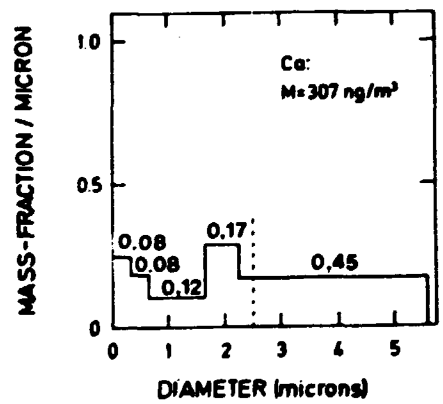


Fig. 3. As fig. 2 but for Ca.

2.2 Deposition of particles in general

An often used analogy is to consider the deposition velocity v_d as the inverse of a resistance (the larger the resistance, the smaller the deposition) and then sum the various individual physical processes limiting the deposition as a series of resistances. If the total resistance, or inverse transport capacity, consists of:

r_a = the resistance in connection with the turbulent boundary layer in general

r_B = the resistance in connection with transport through the laminar (or molecular diffusive) boundary layer near surfaces

r_s = the resistance in connection with the very process of surface uptake

then

$$1/v_d = r_a + r_B + r_s \ . \qquad (1)$$

The inertia of sub-micron particles is so small that they behave like a gas. There is little tendency for these particles to rebound at a surface. Once they touch the surface their small momentum is overcome by intermolecular forces. Thus any surface is an efficient sink, and the surface resistance r_s is practically zero (Garland, 1980).

The laminar sublayer resistance, r_B, determined by Brownian diffusion is dependent on particle size. This particle diffusivity,

$$D_p = \frac{kT}{\mu d} \ , \qquad (2)$$

where k is the Boltzman constant, T is the absolute temperature, μ is the viscosity of air and d is the particle diameter, is much less than diffusivities of gases. Consequently r_B is larger for particles than for gases. Thus while r_s in addition to the aerodynamic resistance is the limiting factor for deposition of gases, this role is in the case of particles played by r_B. The smaller the particles the larger the diffusivity (see Eq. (2))

and therefore the deposition increases with decreasing particle size.

For larger particles ($d \gtrsim 1$ µm) the inertia becomes significant: these particles are mostly deposited by interception and impaction. The larger the particles the more pronounced are these effects.

Particles of a few microns may be captured largely by interception. Thus the fine structure of vegetation consists of hairs and microscopic roughness elements, and particles following the flow and passing within one particle radius of these elements will be captured. Of course the efficiency of this process depends on the details of the surface. For still larger particles the mechanism may chiefly be impaction: When stream lines curve around macroscopic details of the surface these particles continue straight forward and may coast through the laminar sublayer (i.e., shortcut r_B). Also pure gravitational settling is an increasing function of particle size (increases with d^2) but is only significant for fairly large particles (for $d \sim 3$ µm the settling velocity is $\sim 3 \cdot 10^{-2}$ cm/s) in situations where v_d is fairly small for other reasons.

In the range ~ 0.1 to ~ 1 µm neither diffusion nor interception/impaction are particularly efficient. Thus depositon is at a minimum for these particles.

For all sizes, the deposition is also dependent on the turbulence in the flow at distance from the surface elements. In Eq. (1) this is represented by r_a. Thus the stronger the turbulence (represented by the friction velocity u_*) the more deposition will occur - except for very large particles which may show a reversed effect due to bounce-off after impact, this being more likely the larger the impaction velocity is.

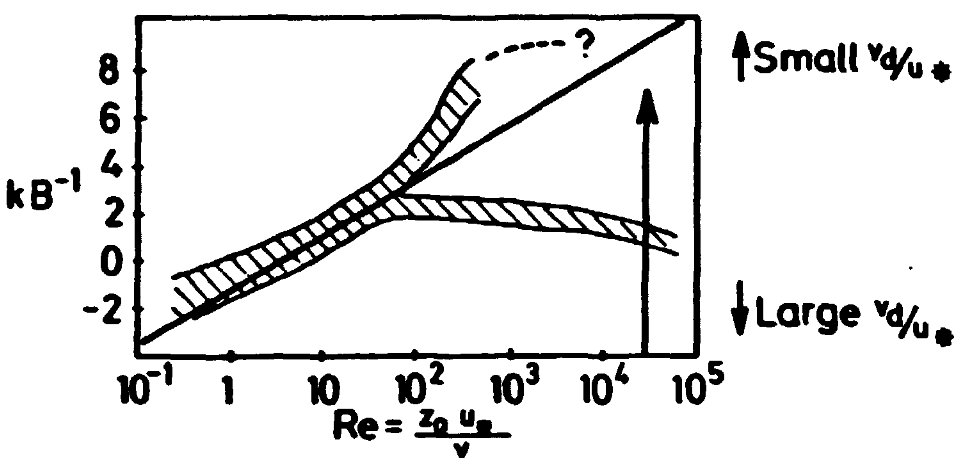


Fig. 4. The overall behaviour of kB^{-1} (defined in the text) in diffusion of water vapour to various surfaces. *Lower branch:* Fibrous elements. Upper branch: Smooth rougness elements (from Garratt and Hicks, 1973). The large vertical arrow denotes a typical Reynolds number for a large city.

2.3 Deposition to rough surfaces in general

The aerodynamic part, r_a, in Eq. (1) can be expressed as $u(z)/u_*^2$, where u is the wind speed at height z. It sets the maximum possible value for v_d (when $r_B = r_s = 0$). For $r_b + r_s$, Chamberlain (1966) has introduced the definition $(Bu_*)^{-1}$ where B may be recognized as the dimensionless sublayer Stanton number of Owen and Thomson (1963). Thus for $r_B + r_s >> r_a$, i.e. for a low affinity between the surface and the depositing material, we have

$$v_d \approx Bu_* , \qquad (3)$$

and the discussion of deposition can then concentrate on the size of B for various surfaces.

For a range of different surfaces characterized by the aerodynamic surface roughness z_0 relative to the laminar sublayer thickness ν/u_* (ν is the kinematic viscosity of air) which would exist over a smooth surface under the same flux conditions, diffusion results for various gases, mainly water vapour, have been used to obtain values of B (Garratt and Hicks, 1973). The results are shown in Fig. 4. Above Re $\equiv z_o/(\nu/u_*) \approx 10^2$, the data seem to split according to surface texture: deposition to fibrous surfaces tends towards saturation (independent of Re), whereas B for deposition to surfaces consisting of smooth, regular roughness elements continues to decrease with increasing Re. This implies a decreasing deposition with increasing roughness for surfaces of the latter type, in which category we may put cities. Results at the relevant Re-number do not exist, however, so application will require extrapolation.

2.4 Deposition of particles onto rough surfaces

In scaling of model results (e.g. Sehmel, 1973) as well as in theoretical developments (e.g. Owen, 1969, Wood, 1981) the depostion velocity is often expressed in terms of particle diameter, relative to viscous sublayer thickness:

$$\frac{v_d}{u_*} = f_1 \left(\frac{d}{\nu/u_*}\right) \quad , \qquad (4)$$

which seems to appear regardless of whether a stopping length hypothesis is involved or not. For geophysical flows, this is however not likely to be a workable proposition, since in the developments leading to Eq. (4) it is always assumed that z_o is of the order of ν/u_* or less (Re $\leq$ 1).

It is quite likely that a proper scaling in very rough flows, where $z_o \gg \nu/u_*$ (large Reynolds number) would involve a correlation of the sort described in the previous paragraph, where for gases

$$\frac{v_d}{u_*} = f_2 \left(\frac{z_o}{\nu/u_*}\right) \quad . \qquad (5)$$

But it is also likely that an equivalent expression for particle deposition woul· have to show an additional dependence on d. For small particles, a proposition would be the following.

Consider a layer of thickness δ over which a concentration difference $\Delta\chi = \chi - \chi_o$ exists. By the flux-gradient hypothesis (Fick's law) we have that flux equals $\kappa(\Delta\chi/\delta)$. Assuming, that $\chi_o << \chi$ (relevant for particles where $r_s \sim 0$) we get by direct definition

$$v_d = \kappa/\delta \quad , \tag{6}$$

where κ is the appropriate diffusivity. Further, having a viscous (sub-) sublayer developiong along each roughness element of scale z_o, its thickness will be $\delta \sim \sqrt{\nu t} \sim \sqrt{\nu z_o/u_*}$ where the advective time of development is estimated as z_o/u_* (u_* being a relevant velocity in the roughness flow layer) whereby Eq. (6) may be written as

$$\frac{v_d}{u_*} = \frac{\kappa}{\nu}\left(\frac{z_o}{\nu/u_*}\right)^{-1/2} , \tag{7}$$

in accordance with Eq. (5). The structure of Eq. (7) is similar to the formula given by Owen and Thomson (1963) for gases and later confirmed by Chamberlain (1968) whereby κ/ν is given to the power 1.25 and the Reynolds number $z_o u_*/\nu$ to the power - 0.45. Using Eq. (7) with κ substituted for the particle diffusivity according to Eq. (2) results in

$$v_d \propto \sqrt{u_*/z_o}/d \tag{8}$$

where the proportionality factor contains all the physical constants. This formula combines Eqs. (4) and (5) in the case of sub-micron particles. For large particles in the impaction range we have presently no theoretical proposition.

Knowledge regarding the deposition of particles is indeed very meager. Of course, in agreement with the above development, very fine particles can always be postulated to behave as gases, but the argument is not really appropriate for particles of size > 1μm. Thus, deposition of the latter particles will probably not scale as simply as the deposition of gases but rather be dependent on the surface geometry itself (i.e. whether surfaces with the same aerodynamic z_0 consist of densely packed or more spread elements): thus there will be less diffusion of small particles to a surface of less area which presumably means that the roughness elements are widely spread and of simple geometry, but more impaction of large particles to the protrusions of a surface with such widely spread elements). Very little guidance regarding parameterization of this problem can presently be given.

2.5 Methods of measurements of dry deposition

In addition to the methods mentioned in the introduction, i.e. analyzing the amount of material present on artificial or natural samples with the related question of areal representativeness (besides collecting wet deposits, moss is hardly representative of the major part of a city surface in regard to dry deposition) a number of micrometeorological alternatives exists which directly or indirectly measure the downward flux of material in question in the air above the surface.

One such method is the gradient method in which the flux, F, of material is determined from

$$F = K \frac{\partial \chi}{\partial z} , \qquad (9)$$

where K is an eddy diffusivity in the turbulent flow which may be assumed proportional to $u_* z$, and $\partial\chi/\partial z$ is the gradient of particle concentration. Thus measurements of profiles of wind and concentration are needed.

Another method, the socalled eddy correlation method, measures the flux directly. Defining χ' as the instantaneous deviation from the average concentration and w' as the instantaneous vertical velocity (the mean may be taken as zero)

$$F = \overline{\chi' w'} , \qquad (10)$$

where the overbar means an average over a suitable length of time (e.g. 10 min). Compared to the previous method, the latter requires very fast responding concentration measuring equipment (measurements of w' is no problem). A few suitable instruments exist for this, based on various techniques in connection with light scattering off a continuously flowing aerosol sample.

A special version of the eddy correlation method is the so-called eddy accumulation technique (Desjardins, 1977) where sampling during occasions with upward respectively downward velocity fluctuations is done separately. The outstanding feature of this method, which has not been emphasized much in the contemporary literature, is that the sampling can be made onto filters, which later in the laboratory can be analyzed for any chemical element by usual, slow instrumentation.

Use of both of the above methods in a city would require spatial averaging (over several house blocks) as well, which conveniently might only be obtained by flying the instruments from an aircraft.

Indirectly deposition can be obtained by using some sort of a budget method which again for the present problem would require aircraft concentration sampling. An exception is in case of a well mixed boundary layer with a capping inversion, where a few tower measurements from moderate height would suffice. In this case great precision of the concentration measuring equipment is required (Williams, 1982).

The main problem with traditional micrometeorological methods, however, is that local sources and horizontal gradients in the concentration field in general contaminate the measurements.

2.6 Suggestion for an experimental lay out

The problem of the overall horizontal gradient over a city could be overcome by flying cross-wind, but the presence of local sources makes the fluxes spurious no matter what measurement technique is used including upwind/downwind budget methods. The only alternative seems to be the use of an artificial or tracer aerosol, which can be destinguished from the background. It should be of a well defined particle size; it should be possible to produce in various size ranges in order to investigate deposition over the relevant spectrum and above all it should be non toxic as it probably must be applied in a sizeable dose to enable significant pick-up. Only a few laboratories in the world are probably able to taylor such a tracer. Their interest and cooperation is hoped for.

Eddy correlation measurements of this tracer would probably be difficult as fast instruments concentration measurements are not specific to chemical composition. However, one could use a version of the eddy-accumulation technique where samples were collected on filters for later conventional laboratory analysis.

However, if a second non depositing tracer (e.g. SF_6) is released and sampled simultaneously with the particle tracer, such that measurements of relative concentration is enabled,. budget estimates can be made more readily. Thus it is no longer necessary to care for inhomogeneous areal influence or representativeness of measurement points as the technique directly gives the integrated effect of the surface in question.

We may then make the following budget considerations: Assume that the concentration χ is well mixed in the boundary layer of height z_i, and denote the conditions at the reference cross section by suoscript o and by subscript L at a distance L further downwind, then

$$V_o \chi_o = V_L \chi_L + v_d < \chi \sigma L > \quad (11)$$

where brackets denote a horizontal average over the concentration times the plume with σ, and where V denotes a volume flux $= \sigma z_i u$. If the deposition is quite small eq. (11) can be approximated by

$$V_O \chi_O = V_L \chi_L + v_d (V_O \chi_O / z_i u) L \tag{12}$$

or

$$\frac{V_L \chi_L}{V_O \chi_O} = 1 - \frac{v_d L}{u_* z_i} \quad . \tag{13}$$

Denoting that for a non-depositing tracer of concentration χ' the product $V\chi'$ is a conserved quantity, we obtain

$$\frac{V_L}{V_O} = \frac{\chi_O'}{\chi_L'} \quad . \tag{14}$$

Thus a simultaneously released inert tracer may then be used to determine the "diffusion function" in the experiment. Defining R as the ratio of depositing tracer to non-depositing tracer, χ/χ', we finally obtain

$$\frac{R_L}{R_O} = 1 - \frac{v_d}{u_*} \frac{L}{z_i} \quad . \tag{15}$$

Thus it is not necessary to measure absolute concentrations but only relative changes. However, since v_d is expected to be small in cities, and the fetch L is limited, it will be necessary to seek experimental conditions where z_i and u are rather small in order to obtain a large enough "signal".

A particularity simple lay out for an experiment then emerges where everything is sampled at ground level as average concentrations over suitable lengths of time. For a full answer, comparison experiments would have to be conducted over agricultural land, however. The advantage of using an aircraft that remains is that much more sampling flexibility can be obtained relative to a given upwind release; further that it might be possible to conduct the comparison measurements at the same time during that release; and lastly that some advantage may be obtained by letting the aircraft release the agents in a suitable configuration upwind (e.g. crosswind or more realistically in an alongwind direction simulating a continuous elevated source) which will lead to a complete independence of wind direction vagaries.

3. RESUSPENSION IN CITY ENVIRONMENTS

A literature search on this subject has not been very revealing. Only the symposium on Atmosphere-Surface Exchange of Particulate and Gaseous Pollutants has been found to address the problem (Harrison et al., Rahn and Harrison, Sehmel, 1976). Thus, it appears that very little work has been done on this particular subject. We are therefore mostly limited to comments on the principles.

In addition to studies of mono-disperse particles on smooth flows in wind tunnels (e.g. Fairchild and Tillery, 1982) the problem has mostly been addressed in terms of resuspension of soils. These latter works concentrate mostly on the complicated influences of soil texture, composition and crustiness (Gillette, 1977; Gillette et al., 1982) and are thus not relevant in the present context.

3.1 Resuspension definitions

Depending on the availability of resuspensible particles, the resuspension flux may or may not be constant with time for given meteorological conditions. Thus, at a given time, "crusted" surfaces may have a limited amount of resuspensible material while soft soils and sandy surfaces may sustain a steady flux.

Two different concepts are usually applied: The <u>resuspension factor</u>

$$K = \frac{\chi}{C} \; , \; [\frac{1}{m}] \; , \qquad (16)$$

where χ is the air concentration of resuspended material [kg/m^3] and C is the surface concentration of resuspensible material [kg/m^2], is directly dependent on the wind speed and the extent of the resuspending area as we will see below. The other concept, the <u>resuspension rate</u>

$$R = \frac{F}{C} \; , \; [\frac{1}{s}] \; , \qquad (17)$$

where F is the surface flux [$kg/s/m^2$], concentrates more on local conditions and is also more independent of the surface concentration C.

3.2 Resuspension by wind

In this case the energy required to dislodge the particles comes from the wind and thus is a function of wind speed. Fig. 5 shows the dependence of the above defined resuspension measures on the wind speed for that particular resuspension situation (as already mentioned the resuspension factor is dependent on the size of the upwind resuspension area).

The particle size of the resuspended material is not given but it is probable that the deposited tracer is attached to larger host particles or dislodged by the movements of these larger host particles.

The threshold wind speed for introducing motion of these larger particles is determined experimentally in the classic work of Bagnold (1941). Fig. 6 shows that this threshold (represented by the friction velocity u_*) depends on the particle size.

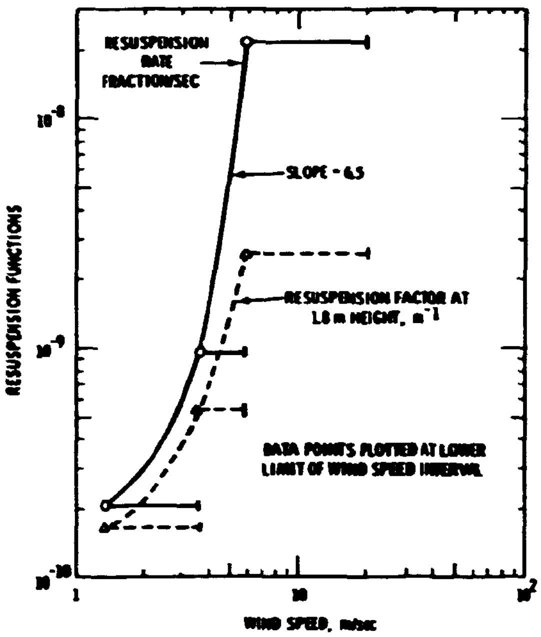


Fig. 5. Resuspension rates and factors of submicron calcium molybdate from a slightly vegetated natural surface as a function of the wind speed at a height of 2 m. From Sehmel and Lloyd (1976).

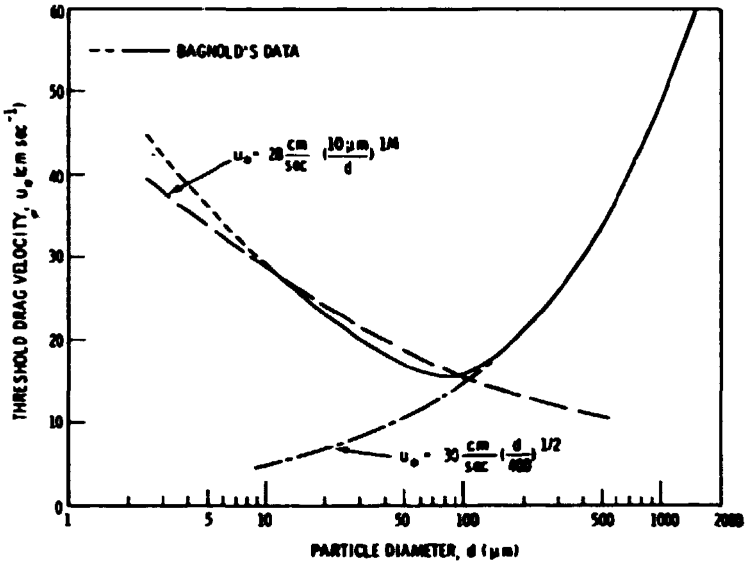
The behaviour of the curve for particles larger than 100 μm can be explained by relating the air force on the particle to the gravitational pull. Thus the particle will move if

$$\tau d^2 > \rho_p d^3 g \qquad (18)$$

where we have forgotten π's and other small factors on both sides, and where τ is the frictional stress ($= u_*^2 \rho_{air}$) exerted by the air. The threshold friction velocity u_{*t} is thus approximately

$$u_{*t} \sim \left(\frac{\rho_p}{\rho_{air}} g d\right)^{1/2} \quad . \qquad (19)$$

The dependence of u_{*t} on $d^{1/2}$ for large particles fit Bagnold's data quite well.



<u>Fig. 6</u>. Minimum friction velocity required to induce motion of particles and comparison with theory. After Slinn (1976).

For small particles, however, the threshold speed is seen to increase with decreasing particle size. This has been explained by Slinn (1976) as being the result of such smaller particles being embedded in the laminar sublayer on the surface, hence experiencing smaller turbulent drag forces. Thus, if the velocity profile here is linear, a characteristic "drag velocity" u is

$$u \sim \frac{d}{\delta} u_* \qquad (20)$$

where δ is the laminar sublayer thickness $\sim \nu/u_*$. By then applying a turbulent drag coefficient c_D (i.e. a constant), the aerodynamic force on the particle should be

$$F = \frac{1}{2} \rho_{air} \left(\frac{d}{\nu} u_*^2\right)^2 c_D d^2 \qquad (21)$$

which again by comparing to the gravitational pull gives a threshold for u_*:

$$u_{*t} \sim \left(c \frac{\rho_p}{\rho_{air}} g d^{-1}\right)^{1/4} \quad (22)$$

where c is $\sim v^2/c_D$. It should thus be demonstrated that u_{*t} increases as the particle diameter decreases (as $d^{-1/4}$). However, to assume a turbulent drag coefficient in a laminar sublayer seems strange. By assuming instead a consistent $c_D \propto d^{-1}$ behaviour the threshold velocity would precisely become independent of particle size.

A more likely explanation on the small particle behaviour of u_{*t} is to be sought in the action of cohesive forces (Iversen, 1976).

It thus appears that there is an absolute minimum wind speed which is able to move particles in an optimal size range about 80 μm. These particles will not go into suspension. This can be seen by comparing their terminal velocity

$$v_t \sim \frac{\rho_p}{\rho_{air}} g d^2/v \quad , \quad (23)$$

with the velocity they would have if leaving the surface. Assuming that this equals u_{*t} as given by eq. (19) for large particles, one obtains that only particles with diameter

$$d < \left[\frac{v^2}{g(\rho_p/\rho_{air})}\right]^{1/3} \quad (24)$$

will get into suspension. These are particles less than about 30 μm. The larger particles will only move in a shallow layer along the surface in a mode called saltation. The depth h of this layer can be estimated by equating particle kinetic energy after dislodgment ($1/2\ m\ u_*^2$) and obtainable potential energy (mgh), whereby

$$h \sim \frac{u_*^2}{g} \tag{25}$$

In wind profile investigations over surfaces with saltating material this quantity is also found to be proportional to the aerodynamic roughness of the surface (Chamberlain, 1983).

The individual particles move in staccato. During the airborne period, spins of the particles in connection with the wind shear play a role in providing lift (Owen, 1969) which is quickly diminished as they rise above the sublayer. On impact they loose their acquired horizontal momentum by kicking of other particles. The flux of material in the saltation layer per unit width of the flow Q[(kg/s)/m] is proportional to the flow speed (~ u_*), depth (eq. (25)) and particle density. Hence,

$$Q \propto \rho_p \frac{u_*^3}{g} \quad . \tag{26}$$

The fraction of that flux actually going into suspension is sometimes simply assumed to be some fixed percentage - but in general it must depend on the fractions of "small" and "large" particles on the surface.

3.3 Resuspension by traffic

In addition to resuspension by wind action, particles can also be dislodged and become airborne by stresses from mechanical action. Here we shall refer to some experimental results by Sehmel (1976) on resuspension from an asphalt road caused by car and truck traffic.

Particle resuspension by moving vehicles is caused by the air turbulence in their wakes as well as the direct mechanical forces of the tires. Both mechanisms must be assumed to contribute to the measured air concentrations in the experiment referred to, but the relative contributions cannot be sorted out directly.

The tracer used for these experiments was ZnS particles of a diameter of 2 and 5 µm in number and mass median, respectively. By a special process the "powder" was dusted on to the road surface of the test section (100 feet long, 10 feet wide) in a known quantity (approximately 0.5 gr/ft^2). Downwind of the test area air concentration as well as deposition to ground level samplers were measured. Fig. 7 shows the resulting resuspension "rates" for a range of vehicle speeds (from 5 to 50 mph).

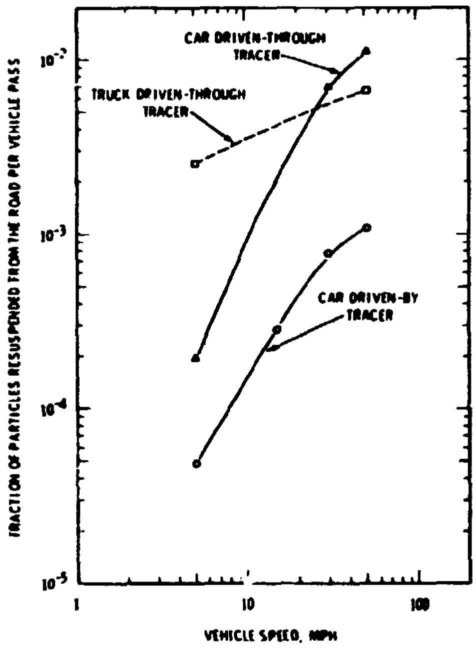


Fig. 7. Particle resuspension rates from an asphalt road caused by vehicle passage.

For the fast driving, the fraction of material resuspended per vehicle pass is about 10^{-2}. The tests were done under dry conditions. If this figure is relevant also to spray formation behind cars driving on wet roads it might be of interest to winter maintenance personnel strewing salt for ice protection that about 100 car passes are enough to reduce the amount of salt strewn to about one third, and by about 200 cars to the level of 1/10.

The effect of weathering, i.e. the process of particles becoming less readily resuspended with time since deposition, is shown in Fig. 8. After a few days the resuspension rate is reduced by an order of magnitude and after about one month by about three orders of magnitude (depending somewhat on the car speed). This effect is caused by the tracer being more firmly bond to the surface as the time goes, either chemical bonds or cohesive/ adhesive forces to the surface (or to larger, less resuspensible host particles). The slower moving cars have the largest reduction.

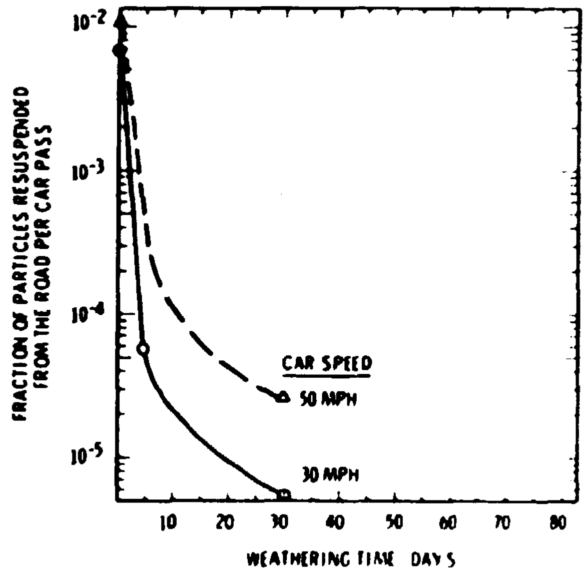


Fig. 8. Particle resuspension rates from an asphalt road as a function of weathering time (car driven through tracer).

The effect of traffic with heavier vehicles is to increase the resuspension. It is not concluded whether this is due to stronger turbulence in the wake of such vehicles (at the same speed) or it is due to the larger tire stress.

Another source of information on "dust emission factors" is provided by Cowherd (private communication), Midwest Research Institute (MRI), Kansas City, Missouri. His results are given in Table I along with emission factors for a range of other operations and processes.

A comparison with the above experimental results by Sehmel is not possible, however, as the factors in Table I assume the presence of a natural background (surface concentrations) of resuspensible material.

Table I. Dust emission factors resulting from various operations and processes, experimentally determined by Midwest Research Institute (MRI), Kansas City, Missouri. The table was kindly supplied by Dr. Cowherd.

OPEN DUST EMISSION FACTORS EXPERIMENTALLY DETERMINED BY MRI

Source Category	Measure of Extent	Emission Factor[a] (lb/unit of source extent)
1. Unpaved roads	Vehicle-miles traveled	$5.9 \left(\frac{s}{12}\right)\left(\frac{S}{30}\right)\left(\frac{W}{3}\right)^{0.7}\left(\frac{w}{4}\right)^{0.5}\left(\frac{d}{365}\right)$
2. Paved roads	Vehicle-miles traveled	$0.09\,I \left(\frac{4}{N}\right)\left(\frac{s}{10}\right)\left(\frac{L}{1{,}000}\right)\left(\frac{W}{3}\right)^{0.7}$
3. Batch load-in (e.g., front-end loader, railcar dump)	Tons of material loaded in	$0.0018 \frac{\left(\frac{s}{5}\right)\left(\frac{U}{5}\right)\left(\frac{h}{5}\right)}{\left(\frac{M}{2}\right)^{2}\left(\frac{Y}{6}\right)^{0.33}}$
4. Continuous load-in (e.g., stacker, transfer station)	Tons of material loaded in	$0.0018 \frac{\left(\frac{s}{5}\right)\left(\frac{U}{5}\right)\left(\frac{h}{10}\right)}{\left(\frac{M}{2}\right)^{2}}$
5. Active storage pile wind erosion	Acre-days of exposed storage pile surface	$1.7 \left(\frac{s}{1.5}\right)\left(\frac{d}{235}\right)\left(\frac{F}{15}\right)$
6. Batch load-out (e.g., front-end loader, railcar dump)	Tons of material loaded out	$0.0018 \frac{\left(\frac{s}{5}\right)\left(\frac{U}{5}\right)\left(\frac{h}{5}\right)}{\left(\frac{M}{2}\right)^{2}\left(\frac{Y}{6}\right)^{0.33}}$
7. Wind erosion of exposed areas	Acre-years of exposed land	$3{,}400 \frac{\left(\frac{e}{50}\right)\left(\frac{s}{15}\right)\left(\frac{f}{25}\right)}{\left(\frac{P\text{-}E}{50}\right)^{2}}$

Correction Parameters

- s = Silt content of aggregate or road surface material (%)
- S = Average vehicle speed (mph)
- W = Average vehicle weight (tons)
- L = Surface dust loading on traveled portion of road (lb/mile)
- U = Mean wind speed at 4 m above ground (mph)
- M = Unbound moisture content of aggregate or road surface material (%)
- Y = Dumping device capacity (yd^3)
- d = Number of dry days per year
- f = Percentage of time wind speed exceeds 12 mph at 1 ft above the ground
- e = Surface erodibility (tons/acre/year)
- P-E = Thornthwaite's Precipitation-Evaporation Index
- N = Number of active travel lanes
- I = Industrial road augmentation factor[b]
- w = Average number of vehicle wheels
- h = Drop height (ft)
- F = Percentage of time unobstructed wind speed exceeds 12 mph at mean pile height

a Represents particulate smaller than 30 μm in diameter based on particle density of 2.5 g/cm^3

b • Equals 7.0 for trucks coming from unpaved to paved roads and releasing dust from vehicle underbodies,
• Equals 3.5 when 20% of the vehicles are forced to travel temporarily with one set of wheels on an unpaved road berm while passing on narrow roads.
• Equals 1.0 for traffic entirely on paved surface.

MRI

3.4 Resuspension in cities

For determination of resuspension rates in cities it is necessary to know the surface concentration of resuspensible particles as well as their size distribution. Such an investigation has been made by Rahn and Harrison (1976). Street dust was collected at 49 different sites in Chicago. In the collected dust (particles larger than 150 µm were removed) enrichment compared to the level in average crusted rock was found for certain elements. This enrichment was somewhat less than that found in the city aerosol for the same elements. The extreme variability of some of the enriched elements over the city suggests local deposition followed by mixing of street dust. It was intended to determine the mass of the various elements as a function of particle size by shaking it into a cascade impactor. When this was done, however, all the material was collected in the first stage (corresponding to a equivalent aerodynamic diameter larger than about 8 µm). Thus, the finer fractions might have been lost during the handling of the samples. On the other hand, Wiltshire and Owen (1965, 1966) used firehosing to clean paved areas. They found a decreasing effect for decreasing particle size. Even for smoothly textured surfaces they came to the conclusion that there was practically no decontamination effect for particles sizes of 10 µm or less. Corn (1961) stated that solid aerosols apparently adhere with great tenacity to solid surfaces; even vigorous blowing on a surface dislodges only few particles smaller than 10 µm.

Considering that Pb constitutes a large fraction of the city aerosol, that it derives as submicron particles from auto emission, and deposits as such, - it must then follow that the only way it can get into resuspension again is by being attached to larger host particles. These host particles may originate from the rural districts, being trapped at previous resuspension events, or from crumbling of the local city surfaces. Some deposits on the city surfaces may also go into suspension as a result of the grinding action of large saltating particles.

3.5 Suggetions for an experimental investigation

In contrast to studies of dry deposition of fine particulates to city surfaces, it may be possible to use the natural background particulate in studies of resuspension from this environment. This might even be a must, since as pointed out above, the resuspension rate of a given element is dependent on how it is attached to the "surface" and how the size of surface (host) particulate matter is distributed.

The basic background material for a resuspension study would be a cascade impacted analysis of elements in the different stages, during periods of wind speeds below the threshold for resuspension. This analysis should be performed for wind direction intervals for sites with various distinct, but well defined, upwind conditions: for example a large point source upwind of a homogeneous built-up area, or immediately off a busy traffic lane.

During resuspension situations (sorted in bins of high wind speeds) the filter samples on the various stages should then be compared to the comparable data under low winds.

For a refined estimate on the magnitude of the resuspension contribution, the subtraction of the filter samples of air concentration during low wind conditions should be reduced with the appropriate wind speed ratio since the air concentration not deriving from resuspension would be diluted accordingly (assuming that the general emission is not correlated). To illustrate this a sketch of expected air concentration as a function of wind speed is shown in Fig. 9.

To sort out what fraction of the air concentration of a given element which derives locally and what fraction which comes from far upwind sources under a resuspension event, it is necessary to do analyses of the composisiton and enrichment of elements in street dust. This might be done simply by "vacuum cleaning" streets and other city surfaces through a stage impactor.

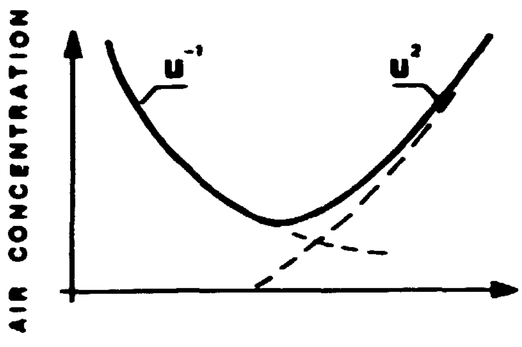


Fig. 9. For relatively low wind speeds air concentration is inversely proportional to the wind speed u (assuming constant emission). When resuspension sets in, concentration is expected to rise, ideally with the square of the wind speed (since the flux increases with the cube of u (eq. 26) and dilution (1/u) is still taking place).

To move beyond a suspension factor analysis it would be helpful to have such street dust analyses both before and immediately after a resuspension event. In connection with well defined upwind conditions this would facilitate a resuspension rate estimate.

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Dry deposition and resuspension of particulate matter in city environments N.O. Jensen	Department or group Meteorology and Wind Energy Section
36 pages + tables + illustrations	Group's own registration number(s)

Abstract

The report describes, mostly in qualitative terms, the deposition and resuspension of particles and how the mechanics depend on particle size. The effect of rough surfaces is discussed. It is concluded that knowledge on the subject, at relevant large Reynolds numbers, is indeed lacking. Various methods for measurements of deposition is mentioned and further the report gives some general ideas on how a suitable full scale experiment should be laid out in order to produce some data on the problem of dry deposition to city surfaces.

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