FSTC-HT-23-627-68

U.S. ARMY FOREIGN SCIENCE AND TECHNOLOGY CENTER

INERTIAL MECHANISM OF SETTLING OF COARSELY DISPERSED AEROSOL ON TERRESTRIAL VEGETATION

COUNTRY: USSR

TECHNICAL TRANSLATION

Distribution of this document is unlimited. It may be released to the Clearinghouse, Depc ıment of Commerce, for sale to the general public.

DISCLAIMER NOTICE

THIS DOCUMENT IS BEST QUALITY PRACTICABLE. THE COPY FURNISHED TO DTIC CONTAINED A SIGNIFICANT NUMBER OF PAGES WHICH DO NOT REPRODUCE LEGIBLY.

TECHNICAL TRANSLATION

FSTC-HT-23-627-68

INERTIAL MECHANISM OF SETTLING OF COARSELY DISPERSED AEROSOL ON TERRESTRIAL VEGETATION

by

V. F. Dunskiy

Source: VOPROSY ATMOSFERNOY DIFFUZII I ZAGRYAZNENIYA VOZDUKHUATRUDY GLAVNY GEOFIZICHESKOY OBSTERVATORII
Transaction of the Main Geophysical Observatory
Imeni A. I. Voyeykova, Issue 172, Leningrad, 1965
USSR

Translated for FSTC by Techtran Corporation

INERTIAL MECHANISM OF SETTLING OF COARSELY DISPERSED AEROSOL ON TERRESTRIAL VEGETATION

The modern theory of diffusion of a heavy additive considers only gravitational settling, i.e., it actually deals with the settling of particles on a smooth horizontal surface. The fact is that there is really no ideally flat place on the Earth's surface; the latter is always rough and a large portion of it is covered by vegetation.

The settling of fine particles on a rough surface in the presence of a wind cannot be governed by the force of gravity alone. The rate w of gravitational settling of the particles is usually tens and hundreds of times less than the wind speed u; therefore, the particles do not fall to Earth vertically at all, but move above the ground on what is usually a sloping trajectory. Along with the gravitational settling, there must also be a settling of the particles on plants and other obstacles under the influence of the forces of inertia; under certain conditions, it can also result from the action of electrostatic forces, radiometric forces of Brownian motion, etc. In the case of coarsely dispersed aerosols, we are interested primarily in the inertial mechanism of settling, in addition to the gravitational mechanism.

This can be supported by experimental data. In an experimental study of the propagation of liquid, coarsely dispersed aerosols [1], 20 wind-vane collectors were set out on the experimental area, at different distances from the aerosol source, to evaluate the role of inertial settling. Each of these collectors was equipped with a horizontal glass plate and a vertical glass slide. The wind vane turned constantly under the influence of the wind and the vertical slide always faced into the wind. A horizontal glass slide was placed on the ground beside each collector. It was assumed that above the horizontal slide in the wind vane, as well as above the glass slide located on the ground, a laminar boundary layer is formed, from which the drops fall onto the surface of the glass by gravitation with a velocity w, and that the deposition on the windward side of the vertical slide occurs under the influence of inertia. The slides in the wind-vane collector were located near the upper limit of a relatively sparse growth of vegetation, with an average plant height h = 30 cm. For each fraction, we determined the average value of the ratio n_v/n_h for 20 points, on the basis of the results of a microscopic analysis of the slides; in this ratio n_v is the average number of drops of a given fraction which land on a unit area of the windward side of the vertical slide, while n_h is the same value for the top of the horizontal slide.

The results are shown in Table 1 in the form of the ratio $n_v/n_h = f(d)$, where d is the average diameter of the drops of a given fraction.

Table 1

Average Values of n_v/n_h for Various Aerosol Fraction, Obtained in Experiments [1] With the Aid of Wind Vane Collectors

Number of Experiment [1]	Diameter d of drops, in microns											$u(h)$ m/sec.
	13	25	42	58	75	92	108	133	167	217	293	
2	0,84	2,8	4,8	4,4	4,5	4,3	4,1	3,6	2,5	2,1	2,2	1,8
3	4,6	8,3	7,1	7,5	5,0	3,2	2,4	3,0	3,1	2,9	4,1	3,6
7	2,6	5,2	6,1	5,6	5,5	4,4	3,2	2,4	3,5	1,2	0,76	1,6
Deposition rate of drops, w, m/sec	0,00550	0,0208	0,0620	0,112	0,173	0,284	0,338	0,487	0,620	0,953	0,25	—

Note: $u(h)$ is the mean wind speed at the upper limit of the vegetation with h = 30 cm.

It is clear from Table 1 that the values of $n_v/n_h \gg 1$, i.e., on the vertical slides (which can be viewed as crude models of leaves), the density of the drops of a given type was several times greater than on the horizontal ones.

These results are a direct indication that inertial settling of aerosols on vegetation may under certain conditions prevail over gravitational settling.

Having adopted this point of view, let us consider the propagation of a monodisperse aerosol, formed by a constant linear source.

Above a covering of vegetaion with height h, i.e., in the region $0 < x < \infty$, $h < z < \infty$ (with source coordinates $x = 0$, $z = H$), the propagation of the aerosol is determined by the equation of convective diffusion:

$$u(z)\frac{\partial q(x, z)}{\partial x} - w\frac{\partial q(x, z)}{\partial z} = \frac{\partial}{\partial z}\left[k(z)\frac{\partial q(x, z)}{\partial z}\right], \qquad (1)$$

where q is the concentration of the additive and k is the coefficient of turbulent diffusion.

Turbulent transfer of the additive takes place both within the cover of vegetation and above it. The particles settle on the plants by inertia and under the influence of gravity. The corresponding decrease of additive within the cover of vegetation can be thought of as a current which is constantly flowing through the plant layer.

The inertial current of particles against the system of obstacles around which the aerosol flows is

$$g_0 = \alpha\beta u q, \qquad (2)$$

where $\alpha = f(stk)$ is the coefficient of entrapment.

Stokes' criterion is

$$stk = \frac{\rho_p u d^2}{18\mu_a x}, \qquad (3)$$

where ρ_p is the density of the substance of the particles, d is their diameter, μ_a is the viscosity of the air, x is the characteristic size of the obstacles, β is the specific (i.e., relative to a unit volume) area of the projection of the obstacles on a plane, normal to the speed vector $\vec{u}$.

The gravitational current of the additive against the obstacles is

$$g_0 = \alpha\beta w q, \qquad (4)$$

where β_h is the specific area of the horizontal projection of the obstacles.

In accordance with this, the equation of turbulent diffusion for the region inside the cover of vegetation ($z \leq h$) is written as follows:[1]

$$u(z)\frac{\partial q(x, z)}{\partial x} - w\frac{\partial q(x, z)}{\partial z} = \frac{\partial}{\partial z}\left[k(z)\frac{\partial q(x, z)}{\partial z}\right] - \\ - [\alpha(z)\beta(z)u(z) + \beta_h(z)w]\, q(x, z). \tag{5}$$

We must add to Equations (1) and (5), the boundary conditions which determine the material balance of the additive, the conditions on the ground ($z = 0$), both at infinity and contained in the plane $z = h$.

To solve this two-layer problem, we must know the microclimatic and geometrical characteristics of a given cover of vegetation: $\alpha(z) = f_1[stk(z)]$, $\beta(z) = f_2(z)$, $\beta_h(z) = f_3(z)$, $u(z) = f_4(z, \mathrm{Ri})$, $k(z) = f(z, \mathrm{Ri})$ in the region $0 < z < h$, where Ri is Richardson's criterion. At the present time, these characteristics are still unknown[2], so that a solution of the two-layer problem does not appear to be possible as yet. Other approaches to a solution must be sought.

With this goal in mind, let us consider the material balance of the additive for an element of the cover of vegetation, whose length is dx, whose width is equal to unity, and whose height is h.

With a stationary regime (continuous source), the equation of material balance of the additive in this element is written thus:

$$\int_S q(x, z)\, u_n\, dS + \int_S N(x, z)\, dS + \int_V p(x, z)\, dV = 0, \tag{6}$$

where $u_n(z)$ is the component of the rate of turbulent transfer which is normal to the surface S, $N(x,z)$ is the component of the diffusion current of the additive which is normal to the surface S, and

$$p(x, z) = -[\alpha(z)\beta(z)u(z) + \beta_h(z)w]\, q(x, z)$$

---

1 Settling under the influence of other forces can be considered similarly.
2 There are several papers dealing with the wind profile within the cover of vegetation; in particular, data for corn stalks is given in [2].

is the rate of decrease of the additive within the cover of vegetation due to inertial and gravitational settling; S and V are the surface and volume of the element, respectively.

Let us carry out the integration, averaging over z and disregarding the small higher orders:

$$\int_S q(x, z)\, u_n(z)\, dS = \left\{ w\,[q(x, h) - q(x, 0)] - h\bar{u}\frac{\partial \bar{q}}{\partial x} \right\} dx,$$

$$\int_S N(x, z)\, dS = k(h)\frac{\partial q(x, h)}{\partial z}\, dx$$

(considering $k(0) = 0$ when disregarding horizontal diffusion):

$$\int_V p(x, z)\, dV = -\int_0^h [\alpha(z)\beta(z)u(z) + \beta_r(z)w]\, q(x, z)\, dx\, dz = -(\bar{\alpha}\bar{\beta}\bar{u}h + \beta_h wh)\bar{q}\, dx.$$

Substituting these expressions into (6), we will have

$$w\,[q(x, h) - q(x, 0)] - h\bar{u}\frac{\partial \bar{q}}{\partial x} + k(h)\frac{\partial q(x, h)}{\partial z} - (\bar{\alpha}\bar{\beta}\bar{u}h + \bar{\beta}_h wh)\bar{q} = 0. \tag{7}$$

Let us replace the values of q, ∂_q/∂_x, and u, averaged over z, by their values at the upper limit of the cover of vegetation. We will likewise change the values α, β, and β_h, calling these new values $\bar{\alpha}$, $\bar{\beta}$, and $\bar{\beta}_h$. Carrying out the indicated substitutions in (7), we will have

$$\frac{\partial q(x, h)}{\partial z} = \frac{\left[h\alpha\beta u(h) + w\left\{h\beta_h - 1 + \frac{q(x, 0)}{q(x, h)}\right\}\right]}{K(h)}\, q(x, h) + \frac{hu(h)\, k_1 k_2}{k(h)}\frac{\partial q(x, h)}{\partial x},$$

where

$$k_1 = \frac{\overline{u}}{u(h)}, \quad k_2 = \frac{\dfrac{\partial \overline{q}}{\partial x}}{\dfrac{\partial q(x, h)}{\partial x}}.$$

Disregarding the horizontal gradients q in relation to the vertical ones, we finally obtain the following boundary conditions at the upper limit of the cover of vegetation:

$$\frac{\partial q(x, h)}{\partial z} = aq(x, h), \tag{8}$$

where

$$a = \frac{h\alpha\beta u(h) + w(h\beta_h - 1 + \xi)}{k(h)}, \qquad \xi = \frac{q(x, 0)}{q(x, h)}. \tag{9}$$

Hence, the problem of the propagation and settling of an additive with consideration of both gravitational and inertial settling leads to a solution of the equation of turbulent diffusion (1) with boundary condition (8) on the subjacent surface[3] for the value a determined by Equation (9).

If inertial settling prevails over gravitational settling (fine particles in a strong wind, tall vegetation through which the wind blows readily), then $\alpha\beta u(h) \gg \beta_h w$, $\xi < 1$, and we can use the following expression for a:

$$a = \frac{h\alpha\beta u(h)}{k(h)}. \tag{10}$$

Having solved the diffusion equation with a new boundary condition, we can show that consideration of inertial settling by the root method changes the picture of the process.

The density of a deposit of the additive on the ground below the vegetation, produced by a constant source during 1 second (the gravitational flow of the additive to the ground below the plants), is

$$g_0 = \xi w q(x, h), \tag{11}$$

---

[3] Boundary condition (8) was proposed in its general form by Monin [3]. We gave it a concrete form in applying it to the inertial settling mechanism.

where, according to (9), $\xi = \frac{q(x,\ 0)}{q(x,\ h)}$.

The density of a deposit of the additive on the vegetation, relative to a unit area of ground, produced by a constant source during 1 second (the sum of the inertial and gravitational flows of the additive onto the vegetation), is

$$gh = g_0 + g_h = [kha + w(1 - \xi)]q(x, h). \tag{12}$$

For practical calculations, it is necessary to know how to determine the new dimensionless characteristic of the vegetation which enters into (9), the effective coefficient of entrapment, $\alpha\beta h = f(stk)$.

It is easy to see that the direct experimental determination of this characteristic for an actual growth of vegetation, for example by direct measurement of the additive deposit on the leaves, involves considerable difficulty. Therefore, let us use the indirect method of determining $\alpha\beta h$ on the basis of the material balance of the additive:

$$G = G_0 + Gh,$$

where G is the output of the source,

$$G_0 = w\xi \int_0^\infty q(x,\ h)\,dx$$

is the gravitational flow of the additive onto the ground beneath the vegetation, and

$$G_h = h\,[\alpha\beta u(h) + \beta_h w] \int_0^\infty q(x,\ h)\,dx$$

is the sum of the inertial and gravitational flows of the additive onto the vegetation. Then

$$\frac{Gh}{G_0} = \frac{G - G_0}{G_0} = \frac{\alpha\beta h u(h) + \beta_h w h}{\xi w},$$

whence

$$\alpha\beta h = \frac{w}{u(h)}\left[\xi\left(\frac{G}{G_0} - 1\right) - \beta H^i\right]$$

or in the case of predominance of inertial settling,

$$\alpha\beta h = \frac{\xi w}{u(h)}\left(\frac{G}{G_0} - 1\right). \qquad (13)$$

The values which enter into the right-hand side of (13) can be determined by means of field tests of the same type as described in [1], while the value w is calculated in the usual manner [6]. In particular, the values were determined in the experiments described in [1] with the aid of wind-vane collectors as described above. It was assumed that $\xi = \frac{n_h}{n_{h_0}}$, where n_h is the average number of drops of a given fraction which fall on a unit area of the horizontal slide in the collector; n_{h_0} is the same value for the horizontal slide on the ground. The value G can be determined in field tests only for an area of specified dimensions, i.e., it is assumed that $w\xi\int_0^L q(x, h)dx \approx$ $\approx w\xi\int_0^\infty q(x,h)\,dx,$ where L is the width of the area. For the experiments in [1], which were carried out with the source at a height of 1.6 meters and an area 500 meters wide, this assumption evidently was justified for all aerosol fractions except perhaps the very finest ones, since the degree of settling ε, calculated with the aid of the Rounds formula (i.e., without considering inertial settling) was close to 100% for the majority of fractions; in Experiment No. 1, for example, ε = 68.4% for fraction d = 50 microns, 96.0% for d = 83 microns, etc.

This method of determining the characteristic $\alpha\beta h$ opens up the possibility of using the inertial theory for practical calculations.

Table 2

Covering of Vegetation	Roughness Parameter z_0 cm.	ξ	h cm	$\alpha\beta h$	x cm
Sparse grass, 3-10 cm high [7].	0,52	1,0	5	0,0015	—
Sparse grass, 5-15 cm high [7].	0,66	1,0	8	0,006	—
Wild plants, 1959 [1]	1,8	1,0	20	0,14	0,20
Wild plants, 1960.	2,7	1,0	30	0,055	0,38
Winter wheat in blossom, 50-80 plants/m^2	—	0,38	60	0,20	0,30

Table 2 lists the values for the parameters ξ, h and $\alpha\beta h$ which were found in field tests [1, 7] and in additional experiments conducted in 1961 on wheat sprouts. As we know, the coefficient of entrapment $\alpha = f(stk)$ approaches unity asymptotically at $stk \to \infty$. Table 2 shows values of $\alpha\beta h$ which have been assumed constant for the sake of approximation and correspond to values of $stk > 8$; the value of stk was calculated by (3), while the values used for the characteristic size of the vegetation x are shown in Table 2. With $stk < 8$, i.e., for very fine drops or a weak wind, the values of $\alpha\beta h$ must be made smaller than those shown in the Table, for example, by multiplying the values in the Table by the factor $stk/8$.

From the standpoint of practical calculations, an important advantage of the new method (especially for agricultural applications) is the possibility of calculating separately the flow of the additive to the ground below the plants (loss of chemicals) and the flow of the additive directly onto the vegetation (chemicals usefully employed).

For practical approximate calculations, we can use the known solutions of the diffusion equation (1) $q_0(x, y, 0)$, obtained without consideration of inertial settling (for example, in the case of a direct linear source, the Rounds formula [4] can be used), but the additive flow must be divided into the two parts of interest to us, using relationships (1) and (2):

$$g_h + g_0 \approx w q_0(x, 0) \approx h[\alpha\beta u(h) + \beta_h w]\, q(x, h) + \\ + w(x, 0) = \{h[\alpha\beta(h) + \beta_h w] + \xi w\}\, q(x, h),$$

from which we obtain the actual concentration of the additive at the upper limit of the covering of vegetation:

$$q(x, h) \approx \frac{q_0(x, 0)}{h\left[\frac{\alpha\beta u(h)}{w} + \beta\gamma_h\right] + \varepsilon}.$$

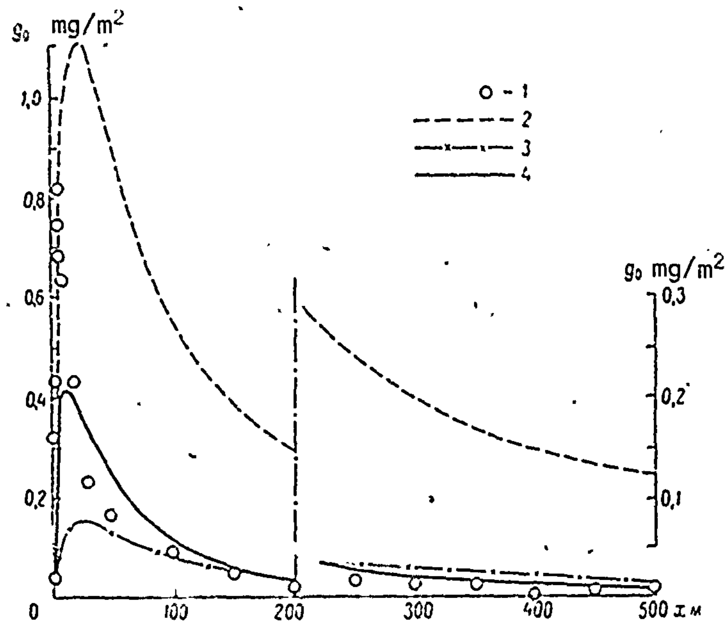

Figure 1. Density values for deposits of an additive on the ground beneath vegetation, $g_0 = f(x)$. Experiment No. 1 [1], d = 25 mm.
1 - Experimental data; 2 - Exact solution of diffusion equation without consideration of inertial settling (Rounds formula); 3 - Rounds formula with "inertial" coefficient; 4 - According to (15).

The flow of additive onto the vegetation is

$$g_h \approx \frac{wq_0(x, 0)}{1+\frac{\xi}{h\left[\frac{\alpha\beta u(h)}{w}+\beta_h\right]}} \approx \frac{wq_0(x, 0)}{1+\frac{w\xi}{\alpha\beta h u(h)}} \tag{14}$$

and the flow of additive onto the ground beneath the vegetation is

$$g_0 \approx \frac{\xi w q_0(x, 0)}{h\left[\frac{\alpha\beta u(h)}{w}+\beta_h\right]+\xi} \approx \frac{\xi w q_0(x, 0)}{\frac{\alpha\beta h u(h)}{w}+\xi}. \tag{15}$$

For the sake of an example, we have plotted in Figures 1 and 2 the results of determining g_0 by the Rounds formula and by the approximate formula (15), together with a determination of $q_0(x, 0)$ by the Rounds formula. The following values for the parameters were used in the calculations: (1) Figure 1, [1], Experiment No. 1, fractions 17-33 microns, d = 25 microns, G = 802 mg/m, H = 1.6 m, h = 0.2 m, k = 0.166 m/sec, w = 0.0208 m/sec, q = 0.281, u_0 = 4.12 m/sec, ξ = 1.0, $\alpha\beta h$ = 0.0486, $u(h)$ = 2.62 m/sec, $k(h)$ = 0.0332 m^2/sec, β_h = 0. (2) Figure 2, [1], Experiment No. 3, fractions 67-82 microns, d = 75 microns, G = 3680 mg/m, H = 1.6 m, h = 0.3 m, k = 0.234 m/sec, w = 0.173 m/sec, q = 0.312, u_0 = 5.17 m/sec, ξ = 1.0, $\alpha\beta h$ = 0.055, $u(h)$ = 3.59 m/sec, $k(h)$ = 0.0702 m^2/sec, β_h = 0.

We have also listed here the corresponding experimental values for g_0, obtained in experiments [1] with liquid aerosols.

Obviously, the approximate solution is significantly closer to the experimental data than is Rounds' solution.

The high experimental values of g_0 near the source ($x \leqslant$ 15 m) can probably be explained by the influence of the aerodynamic shadow of the automatic device on which the aerosol generator was mounted [1].

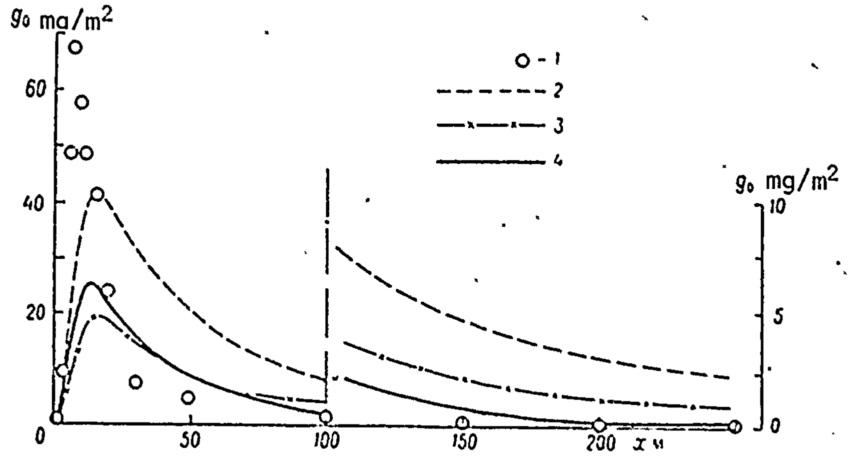

Figure 2. Density values for admixture deposits on the ground beneath vegetation, $g_0 = f(x)$. Experiment No. 3 [1], d = 75 microns. For key to symbols, see Figure 1.

The degree of settling of a given fraction within the limits of the experimental area, determined experimentally (Figure 1), was ε = 4.18%; the corresponding values according to approximate inertial formulas are 3.04%, while Rounds' formula gives 21.7%. For the experiment (Figure 2), the experimental value of ε = 36.6%, while the calculated values are 38.9 and 83.2%, respectively, i.e., when inertial settling is taken into account, the calculated values of ε are much closer to the measured values than those obtained by the Rounds formula.

Moreover, for Figure 1 g_h/g_0 = 6.73, for Figure 2 g_h/g_0 = 1.14, i.e., as in the experiments with wind-vane collectors, the calculated inertial flow of the additive onto the vegetation exceeds the gravitational flow for small (d = 25 microns) and medium (d = 75 microns) drops.

Conclusions

Direct experiments have shown that inertial settling of coarsely dispersed aerosols on a cover of vegetation can predominate over gravitational settling under certain conditions. A theory is proposed for the propagation and settling of aerosols, which takes into account both the gravitational and inertial settling of particles on vegetation covering the ground. This inertial theory makes it necessary to determine a new characteristic of such cover, the effective coefficient of entrapment. A method is proposed for determining this characteristic on the basis of field test results.

A comparison with experimental data shows that the inertial theory which is proposed agrees with experimental data much better than the generally accepted (gravitational) theory; in addition, the inertial theory makes it possible to determine the flow of the additive which is deposited directly on the vegetation, and to determine separately the flow of the additive onto the ground beneath the vegetation, which is very important for agricultural purposes.

BIBLIOGRAPHY

1. Dunskiy, V. F., I. F. Yevdokimov, V. M. Krasil'nikov, K. P. Mikulin, and Z. M. Yuzhniy. Settling of coarsely dispersed aerosol from the atmospheric layer nearest the earth to the subjacent surface of the earth, in this collection.

2. Geiger, R., Climate of the atmospheric layer nearest the earth. Foreign Language Publishing House, Moscow, 1960.

3. Monin, A. S., The boundary condition at the surface of the earth for a diffusing additive, in: Atmospheric diffusion and air pollution, Foreign Language Publishing House, Moscow, 1962.

4. Rounds, W., Solution of the two-dimensional diffusion equation, Trans. Amer. Geophys. Union, Vol. 36, p. 395, 1955.

5. Berliand, M. E., Forecasting and regulation of the thermal regime of the atmospheric layer nearest the earth, Gidrometeoizdat Press, Leningrad, 1956.

6. Fuchs, N. A., Mechanics of aerosols, Publishing House of the Academy of Sciences of the USSR, Moscow, 1955.

7. Dunskiy, V. F., Settling of aerosols, in: Aerosols and their use, Publishing House of the Ministry of Agriculture of the USSR, Moscow, 1959.

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Foreign Science and Technology Center US Army Materiel Command Department of the Army	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP

3. REPORT TITLE
Inertial Mechanism of Settling of Coarsely Dispersed Aerosol on Terrestrial Vegetation

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Translation

5. AUTHOR(S) (First name, middle initial, last name)
V. F. Dunskiy

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
	13	N/A

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO. 0503023C	FSTC-HT-23-627-68
c. 9223628 2301	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d.	ACSI Control Number (None)

10. DISTRIBUTION STATEMENT
Distribution of this document is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	US Army Foreign Science and Technology Center

13. ABSTRACT

An analysis of experimental data on the scattering of drops of liquid in the atmosphere is used as the basis for demonstrating the necessity of considering the inertial settling of aerosols on terrestrial vegetation. A method is proposed for estimating the inertial settling in a study of the atmospheric diffusion of coarsely dispersed aerosols.

DD FORM 1 NOV 65 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

UNCLASSIFIED
Security Classification

UNCLASSIFIED
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
gravitational settling						
terrestrial vegetation						
aerosol						
inertial theory						
inertial settling						

UNCLASSIFIED
Security Classification