

dry deposition  
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DRY DEPOSITION PARAMETERISATION IN  
LONG RANGE TRANSPORT MODELS\*

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## ABSTRACT

Methods for the computation of surface deposition velocities of sulphur and nitrogen dioxide and also sulphate and nitrate particles are derived. These methods may be used in studies of long range (mesoscale and regional-scale) transport of pollutants. The influence of friction velocity and stability of the atmosphere on the aerodynamic resistance is discussed. The "standard" deposition velocities which consist of the surface resistance and resistance of the laminar sublayer adjacent to the surface, are estimated from the literature. Mean values of dry deposition velocities for some terrain categories, useful in long range transport models, are proposed.

## NOTATION

$C(z)$	airborne concentration of a pollutant ( $\text{mol m}^{-3}$ )
$F$	vertical flux density for pollutant ( $\text{mol m}^{-2} \text{s}^{-1}$ )
$k$	Von Karman's constant
$K(z)$	vertical turbulent diffusion coefficient ( $\text{m}^2 \text{s}^{-1}$ )
$L$	Obukhov stability length (m)
$r_a$	aerodynamic resistance ( $\text{s m}^{-1}$ )
$r_c$	canopy stomatal resistance ( $\text{s m}^{-1}$ )
$r_s$	surface resistance ( $\text{s m}^{-1}$ )
$r_t$	total resistance ( $\text{s m}^{-1}$ )
$u_*$	friction velocity ( $\text{m s}^{-1}$ )
$v$	"standard" deposition velocity at 1 m ( $\text{m s}^{-1}$ )
$V(z)$	real deposition velocity ( $\text{m s}^{-1}$ )
$z$	height above ground level (m)
$z_o$	aerodynamic surface roughness length (m)
$\lambda_d$	dry deposition decay rate ( $\text{s}^{-1}$ )

## 1. INTRODUCTION

The long range transport models of air pollution contain the mesoscale models which deal with spatial scales of about 500 km and regional models with a spatial scale of about 5000 km. In both scales physical and chemical processes are important (Kulig, 1981). These models can be used for (i) evaluation of concentrations and deposition of pollutants in short time periods in the order of a few hours duration to a few days (episode models) and (ii) evaluation of deposition (usually also concentrations) in long time periods (season or year). These goals demand different approaches to physical and chemical processes in the atmospheric boundary layer (or mixing layer) and a different degree of sophistication. The long range transport models require the description of physical processes as e.g. vertical or cross-wind dispersion and chemistry such as e.g. homogeneous oxidation of pollutant. Dry deposition has both physical and chemical aspects. It belongs to the essential mechanisms of the atmospheric "self-cleaning". Even in the simple air quality models this mechanism is taken into account (Fisher, 1983).

The flux  $F$  of pollutant, both gas and small particles, through the atmospheric boundary layer to the deposition surface (for instance water, soil or vegetation) is assumed proportional to the turbulent fluxes of heat or water vapour. It is also proportional to the gradient of airborne concentration,  $\partial C/\partial z$ . In some long range transport models it is usually assumed that the atmospheric boundary layer consists of a well-mixed layer with constant concentration ( $\frac{\partial C}{\partial z} = 0$ ) and a surface layer where the profile of pollution concentration varies according to the surface similarity laws (Businger et al., 1971). The equation for the surface layer with the vertical turbulent transport is

$$F = \overline{wc} = - K(z) \frac{\partial C}{\partial z} \quad (1)$$

where  $w$  and  $c$  indicate the momentaneous vertical wind speed and concentration respectively. The proportionality constant  $K(z)$  is the gas-phase eddy diffusivity coefficient, which is assumed identical to heat transfer. The flux to the surface or dry deposition of pollutant is in fact the lower boundary condition. Integrating equation (1) with respect to height between the surface,  $z = 0$  and  $z$ , also assuming that the surface concentration  $C(0)$  is equal zero, yields

$$C(z) = F \int_0^z K(z')^{-1} dz'. \quad (2)$$

The integral in right part of equation (2) expresses the total resistance  $r_t(z)$  to pollution transfer between a height  $z$  and surface. In the general case the  $r_t(z)$  can be expressed as the sum of the aerodynamic resistance  $r_a(z)$  and the surface resistance  $r_s$ .

$$r_t(z) = r_a(z) + r_s. \quad (3)$$

The reciprocal of the total resistance is identical to the real deposition velocity  $V(z)$ , defined first by Chamberlain and Chadwick (1953) as the ratio of the deposition flux mass  $F$  to the airborne concentration  $C(z)$  at some reference height.

$$V(z) = r_t(z)^{-1} = \frac{F}{C(z)}. \quad (4)$$

The dry deposition velocity from equation (4) depends on meteorological conditions, surface parameters and properties of the depositing pollutant (Sehmel, 1980). Since the concentration varies with height and  $F$  is constant in the surface layer, it is a function of height too.

## 2. DESCRIPTION OF THE AERODYNAMIC RESISTANCE

The aerodynamic resistance  $r_a(z)$  in the surface boundary layer is dependent on the height of observation  $z$ , the aerodynamic surface roughness, wind speed and the atmospheric stability. It is convenient to use the friction velocity as a velocity scale in the surface layer. The friction velocity  $u_*$  includes surface roughness and wind speed. It is defined as the square root of the kinematic surface shearing stress. The values of the atmospheric resistance in surface layer for different pollutants (e.g.  $\text{SO}_2$ ,  $\text{SO}_4^{2-}$  or  $\text{NO}_x$ ) are just the same. The differences of the values of the real deposition velocity are due to different surface resistance  $r_s$ . It is possible to predict value of  $r_a(z)$  from the well-established framework of micrometeorology. The concentration profile has the strongest gradient near ground level as a result of the decrease of the turbulent diffusion (characterized by  $K(z)$ ). The aerodynamic resistance between  $z_0$  and  $z$  is expressed by the equation

$$r_a(z) = \int_{z_0}^z K(z)^{-1} dz. \quad (5)$$

The roughness length parameter  $z_0$  is fixed by the requirement  $K(z_0) = 0$ . The height  $z$  extends up to the top of the surface friction layer and usually amounts to about 50 m.

The  $r_a(z)$  profile is given from flux-profile relationships in the atmospheric surface layer

$$r_a(z) = \frac{a}{k u_*} \left\{ \ln\left(\frac{z}{z_0}\right) - \Psi\left(\frac{z}{L}\right) + \Psi\left(\frac{z_0}{L}\right) \right\}. \quad (6)$$

The value of the coefficient  $a$  depends on form of adopted profile formulas. Van Dop et al. (1982) used in their mesoscale air pollution model an empirically determined function (Businger et al., 1971) of atmospheric stability

$$\begin{aligned} \Psi &= 2 \ln\left(\frac{1+d}{2}\right), \quad d = \left(1 - 9 \frac{z}{L}\right)^{\frac{1}{2}} && \text{for unstable conditions } (L < 0) \\ \Psi &= -6.4 \frac{z}{L} && \text{for stable conditions } (L > 0) \end{aligned} \quad (7)$$

They used  $a = 0.74$  and assumed that a considerable part of aerodynamic resistance is in the layer above 1 m. The residual part of atmospheric

resistance is counted as surface resistance.

Wesely and Hicks (1977, see also Van Egmond and Kesseboom, 1983) used

$$\Psi = \exp \left\{ 0.598 + 0.39 \ln \left( -\frac{z}{L} \right) - 0.09 \left[ \ln \left( -\frac{z}{L} \right) \right]^2 \right\}, \quad \text{for } L < 0$$

$$\Psi = -5 \frac{z}{L}, \quad \text{for } L > 0$$
(8)

They took  $a = 1$  and neglected value of the function  $\Psi$  for  $\frac{z_0}{L}$  (for  $z_0/L \rightarrow 0$  also  $\Psi \rightarrow 0$ ).

Eliassen and Saltbones (1983) assumed in a receptor-oriented one-layer trajectory model for some model experiments a logarithmic concentration profile in surface layer. They considered in fact the case of neutral stratification. They obtained from equation (6)

$$r_a(50) = \frac{1}{k u_*} \ln \frac{50}{z_0}. \quad (9)$$

The meteorological input as function of space and time for long range transport models should be based on the routine meteorological data. Obukhov length and friction velocity are derived from measured spatial average 10-m wind velocity and estimated heat flux (Van Dop et al., 1982). During daytime the sensible heat flux may be assumed to be proportional to the measured solar radiation and a linear function of albedo (Van Egmond and Kesseboom, 1983). During the night the determination of  $L$  is based on Venkatram's (1980) empirical relation  $L = 1100u_*^2$ .

The comparison between atmospheric resistance values obtained from equations (6) and (7) or (6) and (8) show that differences are about 20% and in practice not substantial. Only equation (9) gives a more considerable deviation in unstable or stable conditions (see Table 1). Calculations are made for  $u_*$  equal 0.1 and 0.6  $\text{ms}^{-1}$  and  $k = 0.40$ .

Figures 1, 2, 3 and 4 display in what way the atmospheric resistance depends on friction velocity and stability conditions respectively for roughness length 1.0, 0.1, 0.010 and 0.001 m. In Table 2 values of surface roughness length are given for some terrain categories from fundamental investigations and applications. The original literature is indicated. It shows  $z_0$  ranges over five orders of magnitude. The friction velocity varies over a wide range. Usually  $u_*$  ranges from 0.1 to 0.6  $\text{m s}^{-1}$ . The  $z/L$  values range from -0.12 to 0.08  $\text{m}^{-1}$ , which cover all Pasquill stability classes (A-F)



for  $0.001 < z_0 < 1.0$  m (Golder, 1972; Holtslag, 1984). According to these figures it follows that during unstable conditions ( $L < 0$ ) or large friction velocity (strong wind) the resistance to transfer of pollutants is low (some tens of seconds per meter). During stable conditions ( $L > 0$ ) the aerodynamic resistance distinctly increases.

Considerable difference in dry deposition during day- and nighttime may be generally expected because of the different meteorological conditions. The aerodynamic resistance in the boundary layer is lower in a well-developed mixing layer during daytime. During nighttime the aerodynamic resistance under stable circumstances is higher and as a consequence the deposition velocity decreases.

The aerodynamic resistance increases as a result of the decrease of surface roughness length. This relation is more complicated in the real atmosphere because a small value of  $z_0$  induces a higher mean wind velocity in the surface layer at the same time but the value of  $u_*$  decreases too. Areas with varying surface structure also contribute to the roughness (Van Dop, 1983). The numerical value of the Von Karman's constant is most often taken as 0.40 but it may vary from 0.36 to 0.44 (Tennekes, 1982). These differences are not important for  $r_a(z)$  calculations. They caused a divergence of values of about 10%. It is shown in Figures 5 and 6 that those divergences for dry deposition velocities for the surface resistance  $1000 \text{ s m}^{-1}$  ( $v_1 = 0.1 \text{ cm s}^{-1}$ ) and  $100 \text{ s m}^{-1}$  ( $v_1 = 1.0 \text{ cm s}^{-1}$ ) respectively are considerably smaller.

The influence of the atmospheric resistance on the real deposition velocity is substantial in particular during stable conditions. This is shown in Figure 7 for  $r_s = 125 \text{ s m}^{-1}$ .

### 3. PARAMETERISATION OF THE SURFACE RESISTANCE

The surface resistance  $r_s$  depends on surface characteristics (physical, chemical and biological properties of settling surface) and usually includes resistance in the laminar sublayer adjacent to the surface. Values of  $r_s$  are rather obtained on the basis of experimental results.

The surface resistance for a vegetation may be computed as a sum of the laminar sublayer resistance and canopy stomatal resistance  $r_c$  (Van Egmond and Kesseboom, 1983; Fowler, 1978; Wesely and Hicks, 1977)

$$r_s = \frac{2.6}{k \cdot u_*} + r_c \quad (10)$$

The stomatal resistance depends on the kind of pollutant and season. The values of  $r_c$  are shown in Table 3 (see also De Leeuw et al., 1985).

Over a water surface the surface resistance for gaseous pollutants may be computed from

$$r_s = \frac{1}{k u_*} \ln \frac{z_o k u_*}{D_c} \quad (11)$$

Here,  $D_c$  indicates the kinematic molecular diffusivity of the pollutant (see Table 4). The roughness length of a water surface is a function of friction velocity (Sheih et al., 1979)

$$z_o = \frac{0.11 \cdot \nu}{u_*} + \frac{0.016 \cdot u_*^2}{g} \quad (12)$$

where:  $\nu$  - kinematic viscosity of air ( $\text{m}^2 \text{s}^{-1}$ )

$g$  - acceleration due to gravity,  $9.81 \text{ m s}^{-2}$ .

The values of  $\nu$  for two temperatures also are given in Table 4.

The roughness length calculated from equation (12) has values in range  $0.00003 - 0.0006 \text{ m}$  which is in agreement with the data of Table 2. The surface resistance from equation (11) has a maximum value of  $10 \text{ s m}^{-1}$  for these  $z_o$  values. In comparison with the surface resistance for vegetation ( $70 - 1000 \text{ s m}^{-1}$ ) this resistance may be neglected. Therefore, the surface resistance for  $\text{SO}_2$  and  $\text{NO}_2$  over a water surface and wet surfaces of vegetation is counted as zero.

The reciprocal of  $r_s$  is the "standard" deposition velocity  $v$ , which is characteristic for every pollutant. It varies from  $0.3$  to  $1.4 \text{ cm s}^{-1}$  for  $\text{SO}_2$ ,

0.3 to 0.5  $\text{cm s}^{-1}$  for  $\text{NO}_2$  and 0.1-0.2  $\text{cm s}^{-1}$  for aerosol over vegetation (equation (10) and Table 3). It is estimated close to the surface, usually at a height of 1.0-1.5 m. Below this level only surface resistance is particularly important since residual aerodynamic resistance is relatively small. Measurement of dry deposition velocities of sulphur and nitrogen compounds in the field is usually carried out by the gradient method but also some other methods may be used (e.g. the correlation method, tracer methods and mass balance methods) (Van Aalst and Bergsma, 1981).

The values of the "standard" deposition velocity from measurements for one kind of pollutant may vary even over two orders of magnitude. On the basis of 14 references, Sehmel (1980) established that this partition mutability for sulphur dioxide is from 0.04 to 7.5  $\text{cm s}^{-1}$ . Garland (1978) reported that deposition velocities for  $\text{SO}_2$  normally lie in the range between 0.3 and 2.2  $\text{cm s}^{-1}$  with an average value of about 0.8  $\text{cm s}^{-1}$ , which is applicable for large areas of Europe. The same rate of dry deposition for sulphur dioxide is used in the EMEP model (Eliassen and Saltbones, 1982, 1983 and Izrael, 1983). Fowler (1978) estimated the dry deposition velocity for agricultural areas of Britain as 0.6  $\text{cm s}^{-1}$ , Smith and Jeffrey (1975) suggested 0.8  $\text{cm s}^{-1}$  as the mean deposition velocity for whole Britain.

Ranges of dry deposition velocities for sulphur dioxide and different terrain categories obtained from original investigations and applications are collected in Table 5 together with the original literature references. The values vary usually about one order of magnitude for one deposition surface. These variations might be partially due to different properties of the surface and variable atmospheric conditions during experiments. Other potential sources of variability are the experimental uncertainties (e.g. in the concentration gradient method the large errors may occur in difference values of two concentrations measured at two elevations which are usually at a distance of only a few meters apart (Davis and Wright, 1985). The measurements referring to deposition velocities of  $\text{SO}_2$  on grass are most frequently reported (see Table 3) and generally they give values in the range of 0.5-1.0  $\text{ms}^{-1}$ . Fowler (1978) reported that "standard" dry deposition velocity for  $\text{SO}_2$  over wheat varied between 0.1 and 1.5  $\text{cm s}^{-1}$  and is controlled primarily by surface processes. He counted that the surface resistance generally contributes 70% of the reciprocal  $v$ . When the crops or foliar system is wet due to rainfall or dew and provided that the pH is higher than 3.5, the surface resistance is negligible and "standard" deposition velocity is

controlled by atmospheric resistance only (may exceed  $1.0 \text{ cm s}^{-1}$ ).

It is not clear yet to what degree forests are effective in removing  $\text{SO}_2$  under different conditions. Measurement and interpretation of deposition velocities over a tall forest is more difficult than over a surface with much shorter surface elements. Various values of the deposition velocity over forest are reported ( $0.1\text{--}0.6 \text{ cm s}^{-1}$  Garland, 1978;  $1.0 \text{ cm s}^{-1}$  Belot et al., 1976;  $2.0 \text{ cm s}^{-1}$  Garland et al., 1974).

The other major pollutants in long-range transport are nitrogen oxides, mainly because of the acidification phenomenon. The knowledge about the dry deposition of  $\text{NO}_x$  is unfortunately rather limited and the data are sometimes contradictory. Nevertheless current estimates indicate that dry deposition especially of  $\text{NO}_2$  (because the concentrations are 2-8 times higher than  $\text{NO}$ ) may have a significant contribution to the removal of  $\text{NO}_x$  from the lower atmosphere.

The solubility of  $\text{NO}$  in water (Henry's law constant  $H=21.1$ ) is low in comparison with  $\text{NO}_2$  ( $H=1.0$ ) and  $\text{SO}_2$  ( $H=0.03$ ) (Durham et al. 1981). Therefore the  $\text{NO}$  uptake by water may be neglected. Available information about  $\text{NO}_x$  dry deposition together with original literature is given in Table 6.

The dry deposition of sulphate and nitrate particles is small in comparison to the wet deposition. Deposition of particles strongly depends on their size. Particulate sulphate and nitrate aerosol diameters lie in the range from  $0.1$  to  $1.0 \mu\text{m}$ , for which dry deposition processes are least efficient (Fowler, 1980). The deposition velocities for these particles are generally about  $0.1 \text{ cm s}^{-1}$  (Garland, 1978) but also larger values are reported, e.g.  $0.2$  to  $0.5 \text{ cm s}^{-1}$  (Rodhe, 1978).

In the WMO report (Izrael, 1983) the dry deposition of sulphur compounds was computed based on the rate of dry deposition for sulphates and sulphuric acid estimated to be  $0.1 \text{ cm s}^{-1}$ . Sehmel (1980) presented dry deposition velocities for  $\text{SO}_4^{2-}$  particles diameter  $3\text{--}7 \mu\text{m}$  (and  $u_* = 0.08\text{--}0.34 \text{ m s}^{-1}$ ) on soil between  $0.01$  and  $0.05 \text{ cm s}^{-1}$  and for grass between  $0.015$  and  $0.15 \text{ cm s}^{-1}$ .

Information about the deposition velocity of  $\text{NO}_3^-$  is insufficient. Therefore the numerical values are reported indirect from the sizes of aerosol particles and suitable deposition velocities. The dry deposition velocity of sulphate and nitrate particles for different terrain categories are presented in Table 7. The dry deposition on soil depends on its humidity (dry or wet) and pH. A seasonal variation with minimum values when the vegetation is dry is also observed. A mid-day maximum in dry deposition velocity is frequently

observed, reflecting diurnal maxima in stomatal opening and in turbulent transport. The average daily particulate sulphur deposition velocity over green grass 0.3-0.5 m tall at the DDIEs (Dry Deposition Intercomparison Experiments - Champaign, Illinois 1981-82) appears to be approximately  $0.22 \pm 0.06 \text{ cm s}^{-1}$  at a height near 6 m. Day-to-day natural variations of  $v$  are at least 50% and maximum values greater than  $0.5 \text{ cm s}^{-1}$  occur in the windy afternoon conditions (Wesely et al., 1985). However, in this case the aerodynamic resistance was partly influencing the results. The deposition velocity range for forest (Table 7) varies significantly because the lower values are given for tall leafless deciduous forest in winter season and higher values are obtained from similar measurements performed over a pine forest in the summer season.

#### 4. DISCUSSION AND CONCLUSIONS

The present long range transport models contain only a few layers, (surface and mixing layer or reservoir layer). The number of layers partly depends on available input data. It depends also on the goal of the model. A current review of long range transport modelling was made by Fisher (1983). Especially long period averaged models are shown.

The dry deposition velocity of sulphur dioxide used in numerical models is sometimes assumed to be equal to the "standard" deposition velocity (about  $0.8-1.0 \text{ cm s}^{-1}$ ) (Bolin and Persson, 1975; Eliassen and Saltbones, 1983). In practice this approach neglects the dependence of deposition velocity on the height above the surface and also ignores the frequent large variations of surface characteristics and atmospheric conditions. In this case the choice of average values  $v$  is very substantial. For this kind of models (one layer models) it is assumed that the decay rate as a consequence of dry deposition is determined by

$$\lambda_d = \frac{v}{H}, \quad (11)$$

where  $H$  is the height of the mixed layer. With a typical height of 1000 m and deposition velocity of  $0.8 \text{ cm s}^{-1}$ ,  $\lambda_d = 8 \cdot 10^{-6} \text{ s}^{-1}$  which corresponds to a turn-over time of roughly 35 h ( $\sim 1.5$  day).

In episodic models the dry deposition should be at least a simple function of atmospheric conditions and surface characteristics. Changes in the atmospheric stability and surface properties (such as roughness and resistance) to uptake can have a strong effect on the deposition velocity (see Fig. 1 and Tables 1, 5, 6 and 7). The dry deposition velocity is expressed as

$$V(z) = [ r_a(z) + v^{-1} ]^{-1} = \frac{v}{v \cdot r_a(z) + 1} \quad (12)$$

The values of  $v$  are given in Table 8 (as the weighted average) for some terrain categories, which may be sufficient to use in long range transport models. Sulphur dioxide, nitrogen dioxide and sulphate and nitrate particles are specified together. The nitrogen oxide is omitted because the combined effect of two competitive processes of uptake and release cause that the net fluxes are near naught.

The "standard" deposition velocities given in Table 8 in fact are about 50% of

mean values in the partition mutability from Tables 5, 6 and 7. From Table 8 follows that dry deposition of sulphur dioxide is more defined by terrain category than in case of nitrogen dioxide or aerosols. The correlation coefficient among roughness length and dry deposition velocity for the same terrain category is equal to 0.85, 0.35 and -0.17 for SO<sub>2</sub>, NO<sub>2</sub> and aerosols respectively. This fact can be partly explained by physical, chemical and biological processes on the absorbed surface.

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TABLE 1. Comparison of different methods for atmospheric resistance  $r_a$  (50) evaluation

$1/L$ ( $m^{-1}$ )	$Z_0$ (m)	$u_* = 0.1 \text{ m s}^{-1}$			$u_* = 0.6 \text{ m s}^{-1}$		
		eq. (6) and (7)	eq. (6) and (8)	eq. (9)	eq. (6) and (7)	eq. (6) and (8)	eq. (9)
-0.12	0.01	105	145	215	15	25	35
	0.10	60	85	155	10	15	25
	1.00	25	30	100	5	5	15
-0.08	0.01	110	145	215	20	25	35
	0.10	70	90	155	10	15	25
	1.00	30	30	100	5	5	15
-0.04	0.01	120	155	215	20	25	35
	0.10	80	100	155	15	15	25
	1.00	40	40	100	5	5	15
0.00	0.01	160	215	215	25	35	35
	0.10	115	155	155	20	25	25
	1.00	70	100	100	10	15	15
0.04	0.01	395	465	215	65	75	35
	0.10	350	405	155	60	70	25
	1.00	305	350	100	50	60	15
0.08	0.01	630	715	215	105	120	35
	0.10	590	655	155	100	110	25
	1.00	535	600	100	90	100	15

TABLE 2. Surface roughness length  $z_0$  for different terrain categories

TERRAIN CATEGORY	$z_0$ [m]	REFERENCE
smooth mud flats, ice	0.00001	Counihan (1975), Sehmel (1980)
smooth snow on short grass	0.00005	Sehmel (1980)
smooth open sea	0.0002	Counihan (1975), Nieuwstadt (1984), Sehmel (1980), Wieringa (1980)
level desert	0.0003	Sehmel (1980)
water surface	0.001	Van Dop (1983)
snow surface, lawn to 1 cm	0.001	Counihan (1975), Eliassen and Saltbones (1983), Sehmel (1980)
mud flats, snow; no vegetation, no obstacles	0.005	Counihan (1975), Dorland and Eliassen (1976), Wieringa (1980)
open flat terrain; grass, few isolated obstacles	0.03	Counihan (1975), Van Dop (1983), Eliassen and Saltbones (1983), Nieuwstadt (1984), Sehmel (1980), Wesely et al. (1985), Wieringa (1980)
low crops, occasional large obstacles $l_0/h_0 > 20$	0.01	Counihan (1975), Sehmel (1980), Wieringa (1980)
open field with scattered trees and hedges, high crops, scattered obstacles $15 < l_0/h_0 < 20$	0.25	Van Dop (1983), Eliassen and Saltbones (1983), Nieuwstadt (1984), Wieringa (1980)
roads, railways, parkland, bushes, numerous obstacles $l_0/h_0 \sim 10$	0.50	Van Dop (1983), Wieringa (1980)
regular large obstacle coverage (suburb, forest)	1.00	Counihan (1975), Van Dop (1983), Eliassen and Saltbones (1983), Nieuwstadt (1984), Wieringa (1980)
city, buildings	2.00	Counihan (1975), Van Dop (1983)

Note: Here  $l_0$  is a typical upwind obstacle distance and  $h_0$  is the height of the corresponding mayor obstacles.

TABLE 3. Stomatal resistance  $r_o$  values for  $\text{SO}_2$ ,  $\text{NO}_2$  and aerosols

COMPOUND	stomatal resistance ( $\text{s m}^{-1}$ )	
	summer	winter
$\text{SO}_2$	70	200
$\text{NO}_2$	200	200
$\text{SO}_4^{2-}$ , $\text{NO}_3^-$	650	900

TABLE 4. Kinematic molecular diffusivity and kinematic viscosity values for two temperatures ( $\text{m}^2 \text{s}^{-1}$ )

PARAMETER	T = 273 K	T = 298 K
$D_c$ for $\text{SO}_2$	$0.98 \cdot 10^{-5}$	$1.36 \cdot 10^{-5}$
$D_c$ for $\text{NO}_2$	$1.19 \cdot 10^{-5}$	$1.79 \cdot 10^{-5}$
$\nu$ for air	$1.32 \cdot 10^{-5}$	$1.33 \cdot 10^{-5}$



TABLE 5. Dry deposition velocity ranges of sulphur dioxide for different terrain categories

TERRAIN CATEGORY	$v [10^{-3} \text{ m s}^{-1}]$	REFERENCE
ice, roads, railways	0.4 - 1.7	Garland (1976), Sehmel (1980)
snow	0.7 - 3.8	Barrie and Walmsley (1978), Dovland and Eliassen (1976), Izrael (1983)
water surface	1.6 - 22.0	Van Dop (1983), Fowler (1980), Garland (1978), Izrael (1983), Sehmel (1980), Spedding (1972), Whelpdale and Shaw (1974)
soil (sandy, calcareous)	1.0 - 12.0	Fowler (1980), Garland (1978), Izrael (1983), Judeikis and Stewart (1976)
grass, alfalfa, crops, open field with scattered trees and hedges, countryside	1.0 - 49.0	Van Dop (1983), Fowler (1978, 1980), Fowler and Unsworth (1974), Garland (1978), Garland et al. (1973, 1974), Izrael (1983), Owers and Powell (1974), Sehmel (1980), Shepherd (1974), Smith and Hunt (1978)
forest	1.0 - 20.0	Belot et al. (1976), Fowler (1980), Garland (1978), Garland and Branson (1976), Garland et al. (1974), Sehmel (1980)
buildings	8.6 - 75.0	Van Dop (1983), Judeikis and Stewart (1976), Sehmel (1980)

TABLE 6. Dry deposition velocity ranges of nitrogen oxides for different terrain categories

TERRAIN CATEGORY	SPECIES	$v [10^{-3} \text{ m s}^{-1}]$	REFERENCE
snow	NO	0.3	Granat and Johansson (1983)
	NO <sub>2</sub>	0.3	Granat and Johansson (1983)
water surface	NO	~ 0	Van Aalst (1982)
	NO <sub>2</sub>	0.1 - 0.2	Van Aalst (1982), Van Aalst and Bergsma (1981)
soil (sandy, calcareous)	NO	negative - 8.0	Van Aalst and Bergsma (1981), Judeikis and Wren (1978)
	NO <sub>2</sub>	0.1 - 8.0	Van Aalst and Bergsma (1981), Judeikis and Wren (1978)
grass, countryside	NO	negative - 9.0	Van Aalst (1982), Fowler (1980), Hill (1971), Sehmel (1980)
	NO <sub>2</sub>	0.1 - 19.0	Van Aalst (1982), Van Aalst and Bergsma (1981), Fowler (1980), Hill (1971), Sehmel (1980), Wesely et al. (1982)
forest	NO	~ 0	Van Aalst (1982)
	NO <sub>2</sub>	0.3 - 3.0	Van Aalst (1982), Granat and Johansson (1983)
buildings	NO	2.1	Judeikis and Wren (1978)
	NO <sub>2</sub>	3.2	Judeikis and Wren (1978)

TABLE 7. Dry deposition velocity ranges of sulphate and nitrate particles for different terrain categories

TERRAIN CATEGORY	$v [10^{-3} \text{ m s}^{-1}]$	REFERENCE
snow	0.4 - 29.0	Dorland and Eliassen (1976), Fowler (1980), Ibrahim et al. (1983)
water surface	4.0	Prahm et al. (1976)
soil	negative - 0.5	Sehmel (1980), Wesely et al. (1985)
grass, pasture	negative - 6.0	Van Aalst (1982), Van Aalst et al. (1983), Fowler (1980), McMahon and Denison (1979), Sehmel (1980), Wesely et al. (1985)
forest (deciduous and coniferous)	negative - 10.0	Hicks et al. (1982), McMahon and Denison (1979), Wesely et al. (1983)

TABLE 8. Comparison of surface roughness length  $z_0$  and the weighted average of dry deposition velocities  $v$  of  $\text{SO}_2$ ,  $\text{NO}_2$  and aerosols for some terrain categories

TERRAIN CATEGORY	$z_0$ [m]	$v$ [ $10^{-3} \cdot \text{m s}^{-1}$ ]		
		$\text{SO}_2$	$\text{NO}_2$	$\text{SO}_4^{2-}, \text{NO}_3^-$
water surface	0.0002	4	0.2	1.0
snow	0.001	2	0.3	3.0
open flat terrain: grass, crops	0.03	8	1.0	1.0
open field with scattered trees and hedges, countryside	0.25	8	3.0	2.5
roads, railways	0.50	1	0.0	0.0
forest	1.00	10	1.0	2.0
city	2.00	20	2.0	1.0

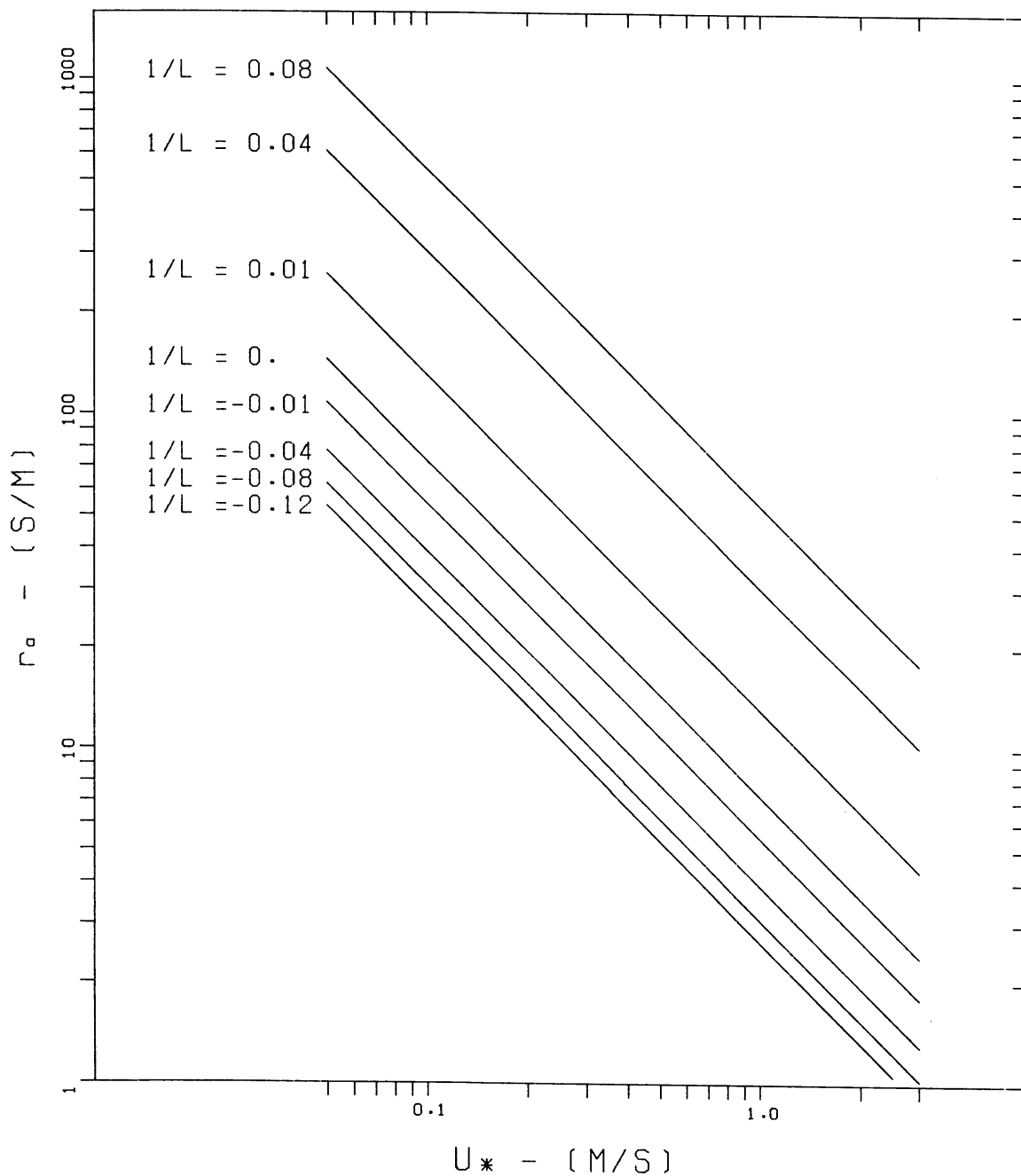


FIG. 1. AERODYNAMIC RESISTANCE  $r_a$  AS A FUNCTION OF FRICTION VELOCITY  $U_*$  AND THE MONIN-OBUKHOV STABILITY LENGTH ( $1/L$ ) FROM EQUATION (7).  $k=0.40$ ,  $Z_0=1.00\text{m}$ ,  $Z=50\text{m}$ .

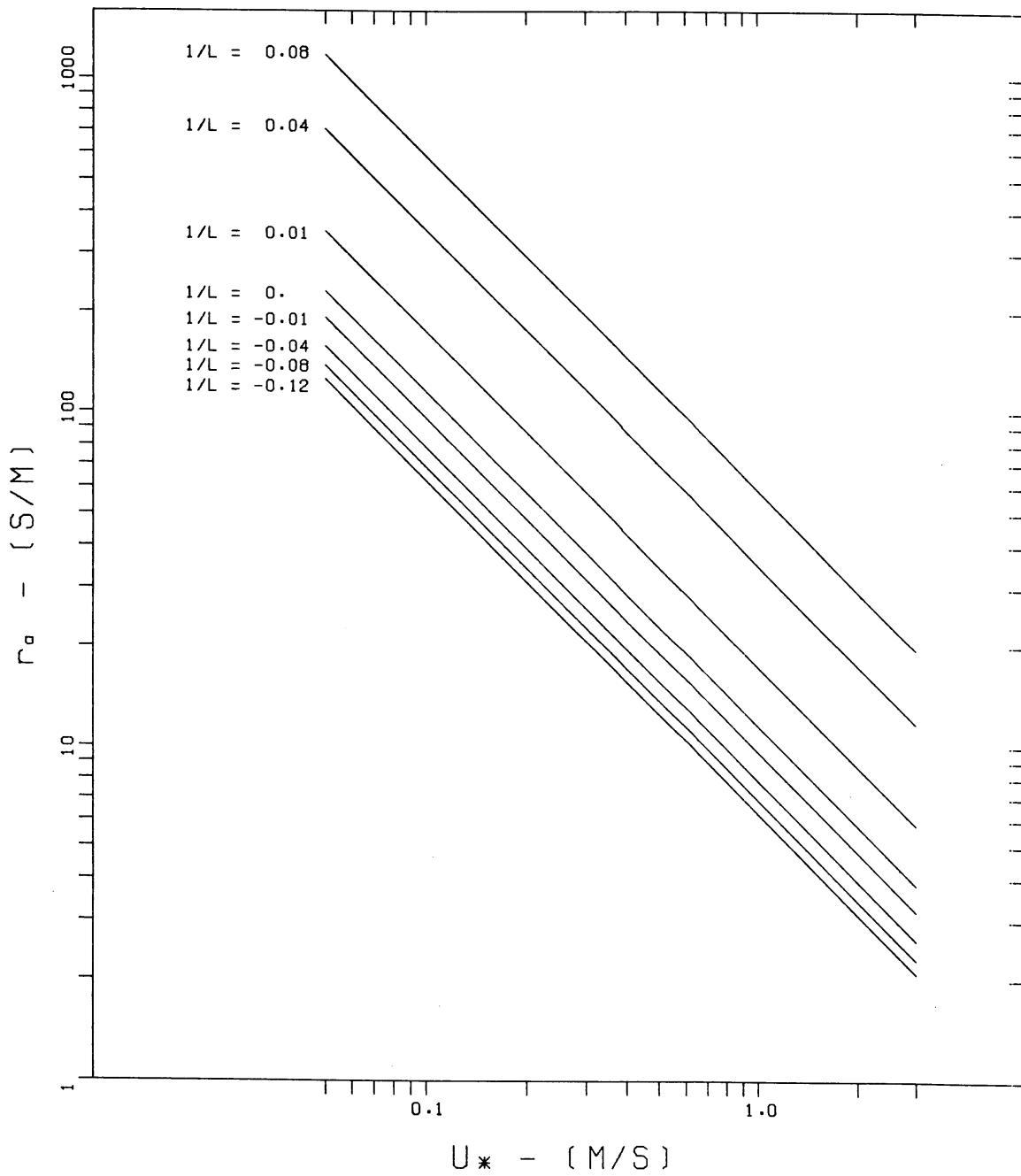


FIG. 2 .AERODYNAMIC RESISTANCE  $r_a$  AS A FUNCTION OF FRICTION VELOCITY  $U_*$  AND THE MONIN-OBUKHOV STABILITY LENGTH ( $1/L$ ) FROM EQUATION (7).  $k=0.40$ ,  $Z_0=0.10m$ ,  $Z=50m$ .

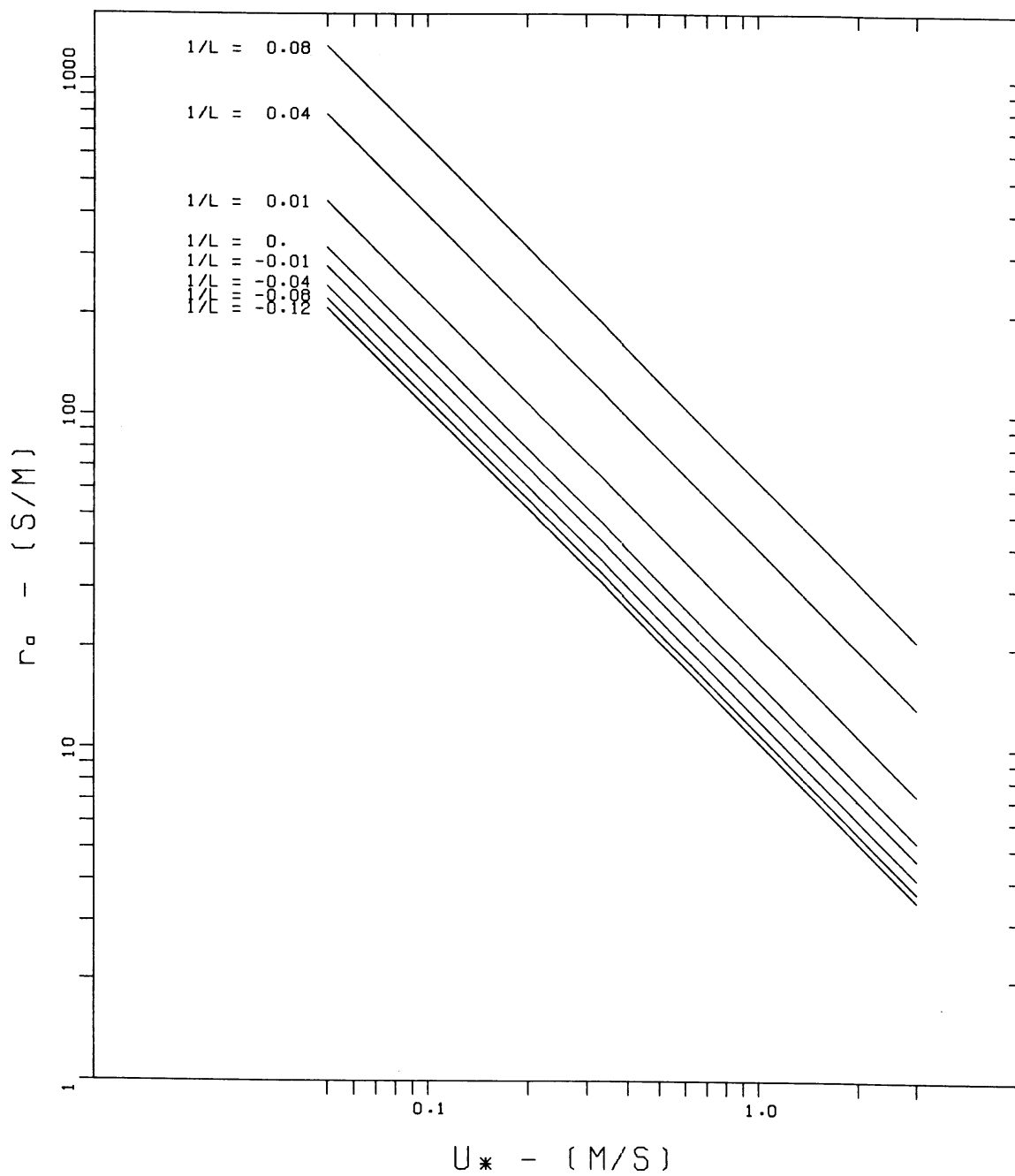


FIG. 3. AERODYNAMIC RESISTANCE  $r_a$  AS A FUNCTION OF FRICTION VELOCITY  $U_*$  AND THE MONIN-OBUKHOV STABILITY LENGTH ( $1/L$ ) FROM EQUATION (7).  $k=0.40$ ,  $Z_0=0.01m$ ,  $Z=50m$ .

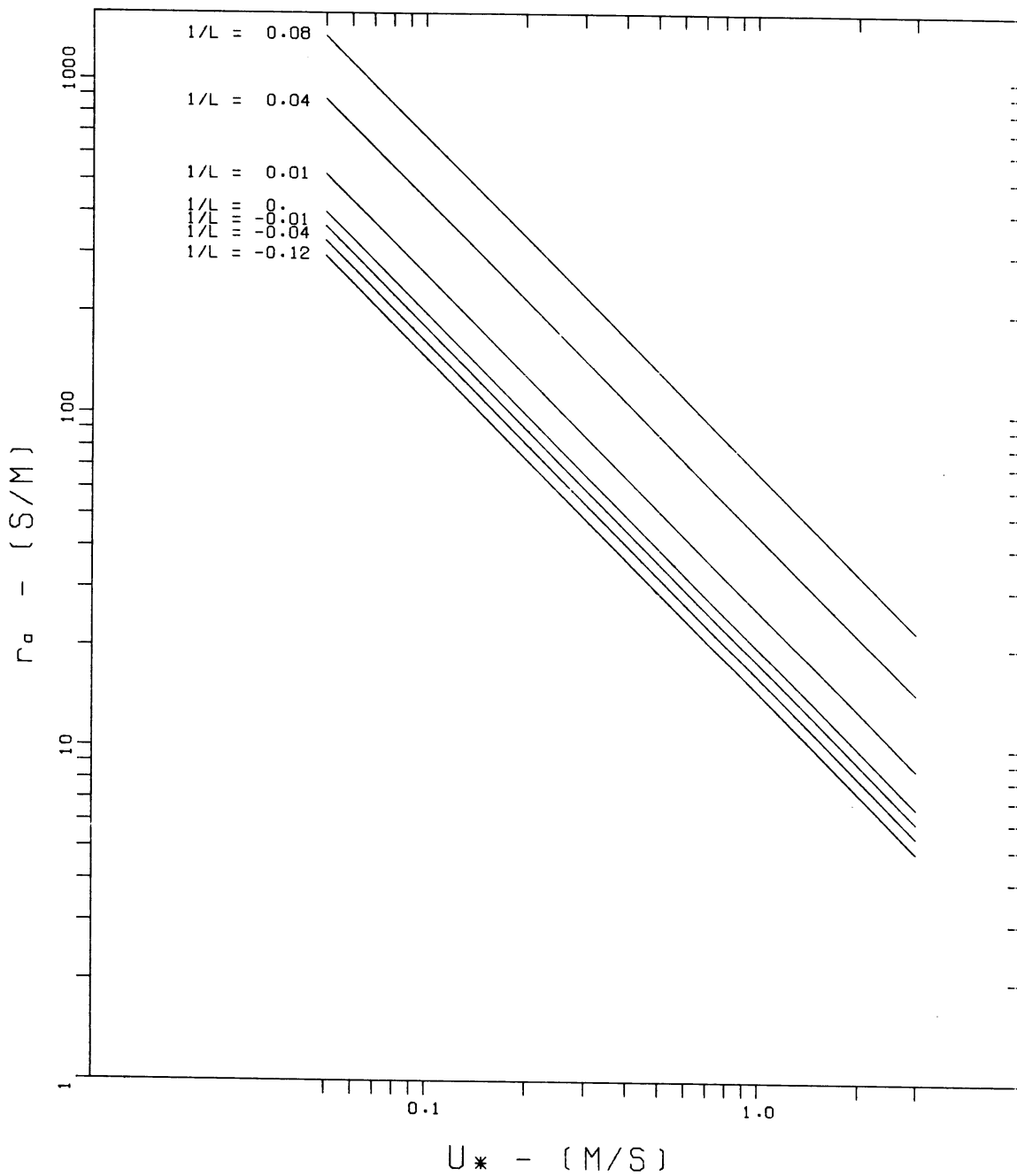


FIG. 4. AERODYNAMIC RESISTANCE  $r_a$  AS A FUNCTION OF FRICTION VELOCITY  $U_*$  AND THE MONIN-OBUKHOV STABILITY LENGTH ( $1/L$ ) FROM EQUATION (7).  $k=0.40$ ,  $Z_0=0.001m$ ,  $Z=50m$ .



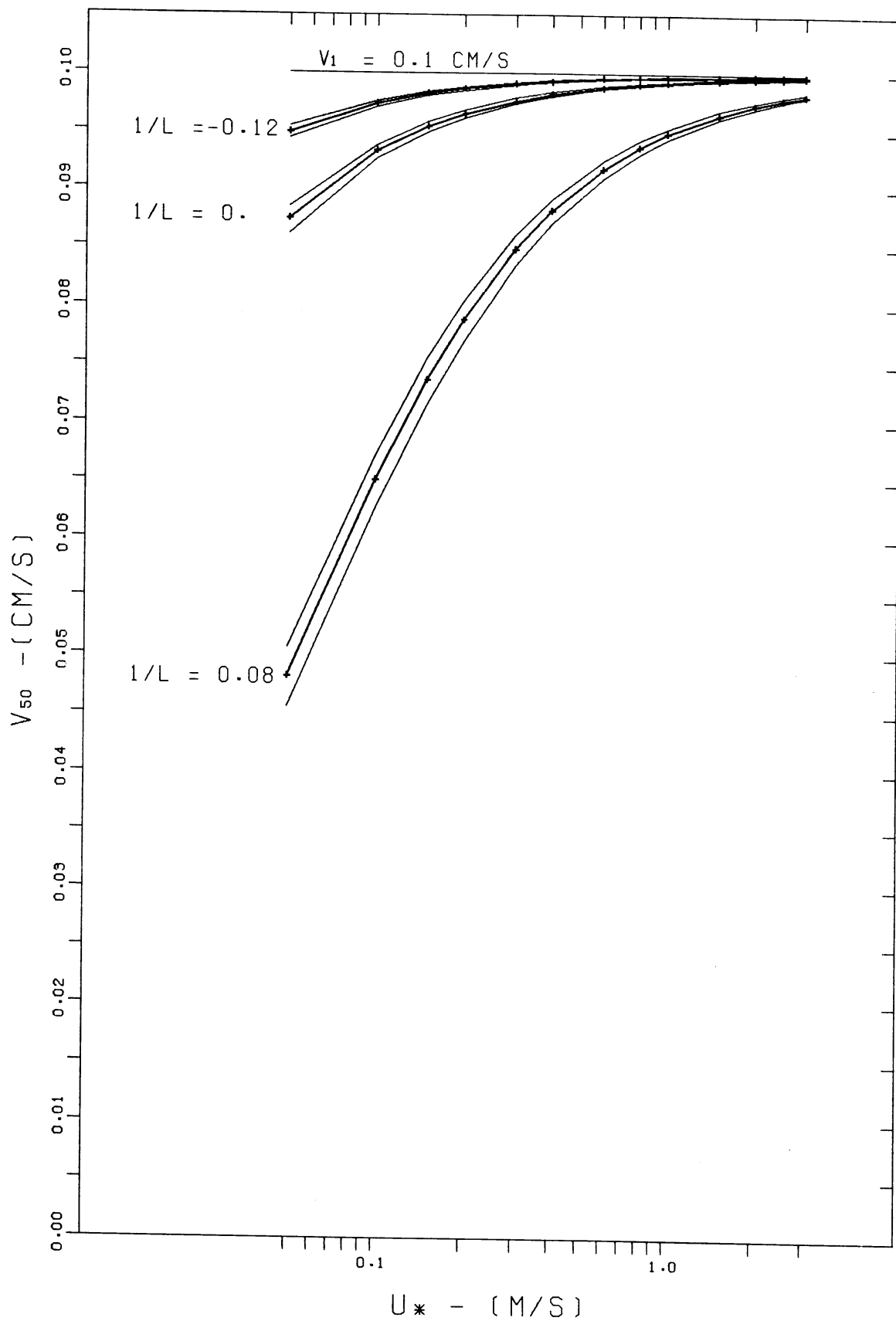


FIG. 5. DRY DEPOSITION VELOCITY FOR DIFFERENT VALUES OF VON KARMAN'S CONSTANT. Lower curve:  $k=0.36$ , central thicker curve:  $k=0.40$ , upper curve:  $k=0.44$

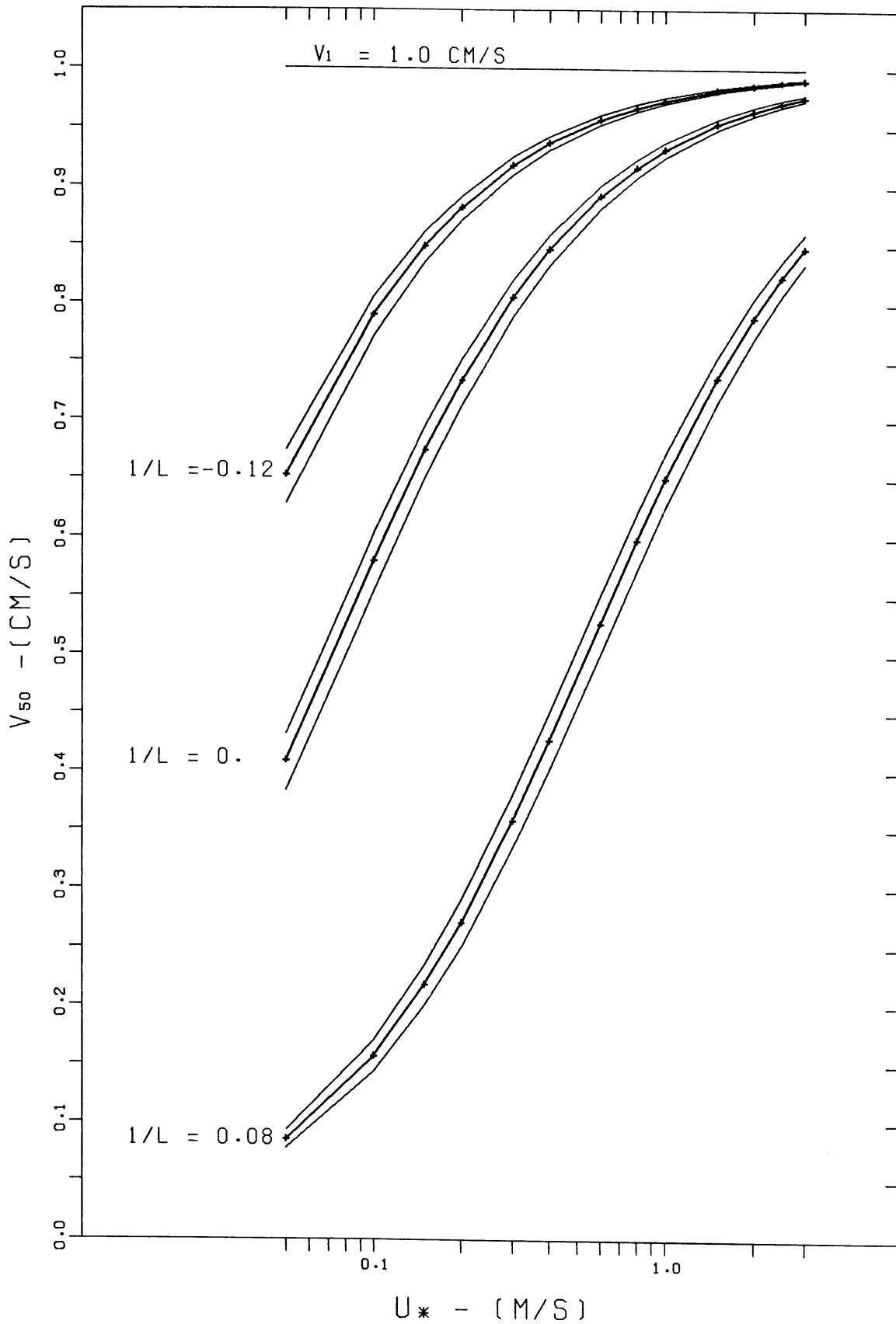


FIG. 6. DRY DEPOSITION VELOCITY FOR DIFFERENT VALUES OF VON KARMAN'S CONSTANT. Lower curve:  $k=0.36$ , central thicker curve:  $k=0.40$ , upper curve:  $k=0.44$

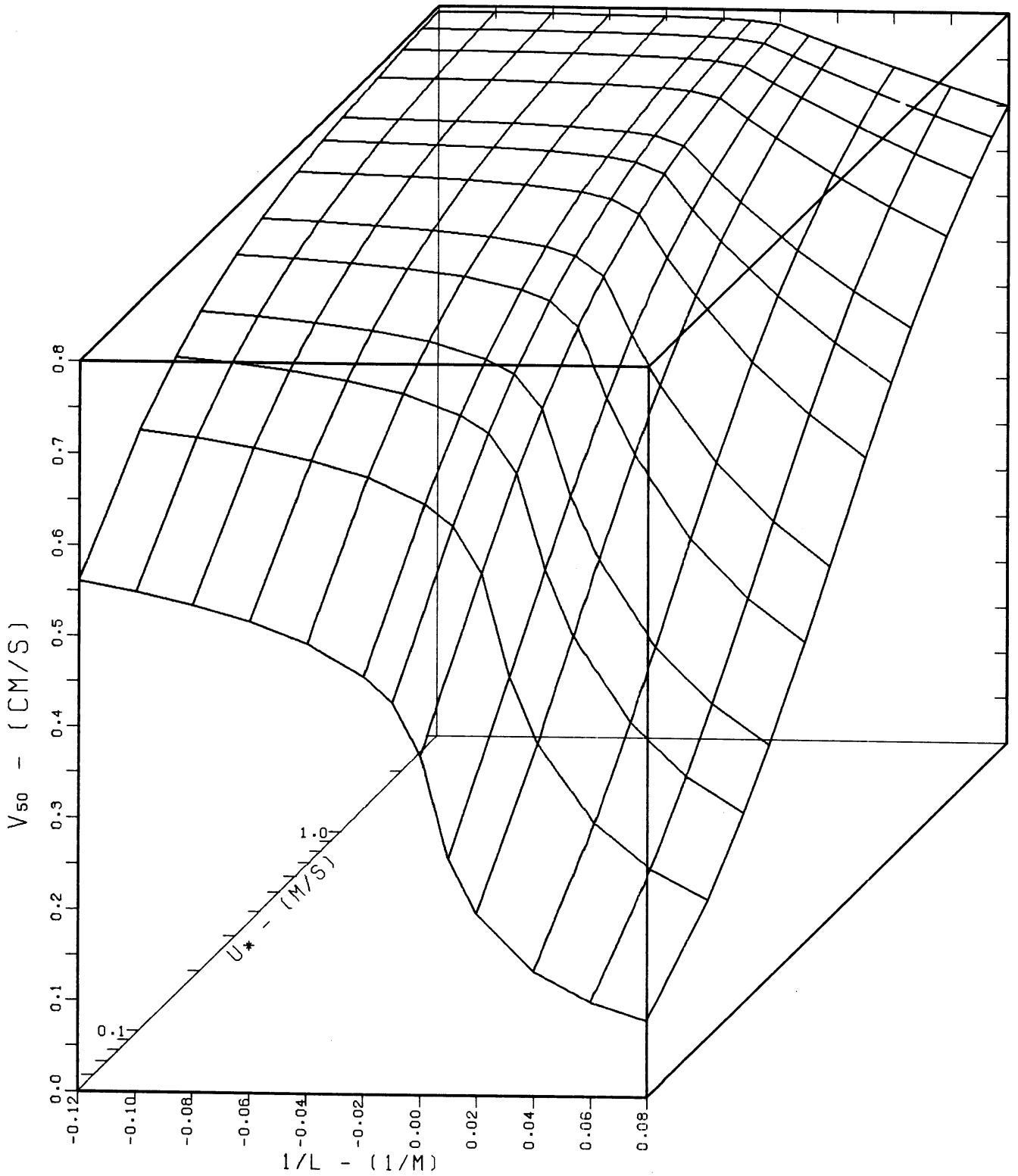


FIG. 7. DRY DEPOSITION VELOCITY  $V_{50}$  AS A FUNCTION OF FRICTION VELOCITY  $U^*$  AND THE MONIN-OBUKHOV STABILITY LENGTH ( $1/L$ ) FOR  $V_1 = 0.8 \text{ cm/s}$ ,  $k=0.40$ .