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UNCERTAINTY OF THE LONG-TERM RESUSPENSION FACTOR

EVGENII K. GARGER,* F. OWEN HOFFMAN†‡ and KATHLEEN M. THIESSEN†

*Institute of Radioecology UAAS, 14 Tolstoy Street, Kiev 33, Ukraine; and †SENES Oak Ridge, Inc., Center for Risk Analysis, 102 Donner Drive, Oak Ridge, TN 37830, U.S.A.

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Abstract—Resuspension of contaminated soil into the atmosphere is one of the key processes that must be considered in the estimation of inhalation doses to humans. Data for air and soil contamination collected in Ukraine over several years since the Chernobyl accident have permitted analysis of resuspension in terms of the underlying mechanisms. Various empirical models for the resuspension factor as a function of time (e.g. Linsley, Garland, Anspaugh, etc.) are compared to the observed resuspension factors over time (9 yr) at two sites; in general, these models give overestimates for the resuspension factor as a function of time. The observed values of the resuspension factor range from greater than 10^{-5} m^{-1} at early time points to around 10^{-10} m^{-1} at later points. The uncertainty in the resuspension factor is decreased to within 1 order of magnitude if annual averaging of the experimental data is used and if the resuspension factor is determined as a function of time and of the predominant regional conditions of vegetative cover and climate. © 1997 Elsevier Science Ltd. All rights reserved.

Key word index: Airborne contamination, Chernobyl, models, resuspension factor, uncertainty.

INTRODUCTION

The resuspension of contaminants deposited on land surfaces is an important process that must be considered in the estimation of human exposures. Several different reviews have been devoted to the description of the general concepts, mechanisms, and models for obtaining quantitative assessments of resuspension (Linsley, 1978; Sehmel, 1984; Smith *et al.*, 1982; Nicholson, 1988; Makhonko, 1992). The resuspension process is very complicated, and acquisition of experimental data and improvements in their theoretical understanding are continuing. One of the general results of these efforts is that the resuspension factor is used most frequently for environmental assessments of exposure to humans; the resuspension factor is defined as

$$K = \frac{\bar{q}}{\bar{c}} = \frac{\text{mean airborne concentration (quantity m}^{-3})}{\text{mean surface contamination (quantity m}^{-2})}. \quad (1)$$

This factor is useful in localized situations for characterization of the relationship between surface and airborne contamination, and its use implies an equilibrium between the resuspended and deposited aerosol (Linsley, 1978).

In practice, however, there are no homogeneously contaminated surfaces, and the airborne concentration is a sum of the local resuspended contamination and contamination advected from upwind resuspension (Smith *et al.*, 1982). One deficiency in the concept of a resuspension factor is that the airborne concentration is assumed to be "related to the surface concentration on the soil at a person's feet rather than upwind. Another deficiency is that resuspension factors are applicable only for the conditions for which they were determined" (Sehmel, 1984). Nevertheless, several different models for K have been derived from different bases of information (Linsley, 1978; Anspaugh *et al.*, 1975; Garland, 1979; Makhonko, 1992), and although the resuspension factor has a limited physical definition, it is used as the universal parameter of the resuspension process. The first attempt to estimate the temporal dependence of the resuspension factor $K(t)$ was described by Garland (1979); this work was continued by Garland *et al.* (1991) for empirical models of $K(t)$ on the basis of experimental material obtained in different western countries after the Chernobyl accident.

The uncertainty of K has been reported to have a range of 2–3 orders of magnitude even in a single field experiment (Sehmel, 1984). The object of the present work is to estimate the uncertainty of the

‡Author to whom correspondence should be addressed.

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resuspension factor K on the basis of common physical reasoning and experimental data obtained inside and outside the 30 km zone surrounding the damaged Chernobyl reactor. This work was initiated in 1991, and preliminary results have been reported by Garger (1995).

DESCRIPTION OF THE RESUSPENSION FACTOR

A stricter definition of K for spatial–temporal analyses is

$$K = \frac{1/T\int q(x, y, z; r, t)\,\mathrm{d}t}{1/S\int c(x, y, d; r, t)\,\mathrm{d}s} \tag{2}$$

where T is the averaging period of the air concentration; S is the averaging area of soil samples; x, y, and z are coordinate axes; d is the soil depth; and r is the radius of aerosol particles. The functions q and c describe the airborne concentration and surface contamination, respectively; $c(x, y, d; r, t)$ represents the contaminant inventory in the soil layer at depth d. For experimental measuring, the time T is either the "internal" averaging period of a sampler ($T = T'$) or a selected averaging period for a specific task (for this, $T' < T$; for example, this estimate may be for one day, a week or ten days, or several hours, depending on the needs of the health physicists).

Essentially, T' represents the averaging time of the raw data, as dictated by the sampler or the operators of the sampler; T represents the averaging time of interest for the analysis of K, which might not be equal to T'.

Ideally, the values of time averaging and spatial averaging should be compatible. In practice, the period for measuring radioactivity is protracted over many hours or several days. The surface concentration is usually averaged over the space in the vicinity of the air sampler. The air path (trajectory) for typical values of T (1–3 d) may be hundreds of kilometers. Therefore, the magnitude of the uncertainty of an empirical resuspension factor will be dependent on the spatial heterogeneity of surface contamination. Garger *et al.* (1990) have shown that the advection effect from a highly contaminated upwind area may increase K values by two to three orders of magnitude for distances up to about 14 km from the epicenter of the contaminated area.

The function $q(x, y, z; r, t)$ for the airborne concentration is highly variable in time due to the great mobility of the atmosphere and the high variability of the vertical turbulent flux of radioactivity. In addition, the function is influenced by the change of synoptic processes over this area and the change of meteorological processes with seasons. Knowledge about the aerosol characteristics of the airborne samplers is also important, as the value of K depends directly on the integrated airborne concentrations both over time and over the distribution of particle sizes. Strictly speaking, only a portion of the full distribution of aerosol particles will be sampled by typical sampling equipment. In practice, the upper bound on the size of particles is not well known, and absence of this information may lead to different results of $q(x, y, z; r, t)$ measured in the same time and place by a factor of two to three (Garger, 1995).

The time dependence of the contaminant inventory in soil $c(x, y, d; r, t)$ is weaker than that of the airborne concentration. However, this function has several characteristic temporal periods connected with the interaction of the surface deposit with soil and subsequent processes affecting the migration of this material. These processes are important for long-term estimation of K (Sehmel, 1984; Makhonko, 1992).

In practice, the radioactivity in the soil is usually measured in terms of the total inventory. In the first period (0–1 month) after an accident, this practice does not cause problems for the estimation of the resuspension factor, as the majority of the deposited material is on the soil surface. After this initial period, it is necessary to determine $c(x, y, d; r, t)$ for the uppermost layer of soil, because an estimate of K based on the total inventory may be biased low. This bias will be most pronounced for light or dusty soil, for which determination of the total inventory may require measurement to a greater soil depth (e.g. 30–40 cm).

From examination of the various experimental measurements, and noting conditions for which there are a lack of measurements, the uncertainty in K is expected to vary from a factor of 2–3 up to 2–3 orders of magnitude.

PHYSICAL BASIS FOR EVALUATION OF THE RESUSPENSION FACTOR

To examine the physical basis for evaluation of the resuspension factor, it is sufficient to consider two idealized conditions: that is, (1) a homogeneous and stable turbulent flow over an infinite plane source of the deposited material, and (2) a constant point surface source for the stationary surface layer of the atmosphere.

The first case includes conditions corresponding to a very large spot of contamination or to global deposition; this can be written using the Monin–Obuchov theory (Monin and Yaglom, 1970; Byzova *et al.*, 1991):

$$\bar{q}(z_2) - \bar{q}(z_1) = -\frac{J}{\chi u_*}\left[\ln\frac{z_2}{z_1} + F\left(\frac{z_2 - z_1}{L_{\mathrm{MO}}}\right)\right] \tag{3}$$

where J is the nongravitational vertical flux of the deposited material, u_* is the friction velocity, χ is the von Karman constant (≈ 0.4), z_2 and z_1 refer to different measurement heights, L_{MO} is the Monin–Obuchov length, and F is the universal function of similarity in the theory of Monin and Obuchov. For simplicity, the character of the turbulent transport of matter is considered to be no different from the character of the turbulent transport of the momentum.

and use of the usual data about the inventory of the contamination in soil is appropriate. Later on, consideration of migration processes is necessary. Apparently, the first analytical attempt for taking migration into consideration for the estimation of K was done by Makhonko (1984a), using

$$K = \frac{q_m e^{-\lambda t}}{\rho \Gamma(1 + v^+)(v_D t)^{1+v} \times L} \int_0^L x^v e^{-x/v_D t} dx \quad (9)$$

where q_m is the mass concentration of dust, ρ is the density of the superficial layer of soil, $v^+ = v/v_D$ is the ratio of the convection velocity of the radionuclide to its diffusion velocity, λ is the radioactive decay constant, $\Gamma(1 + v^+)$ is a gamma function, and L is the effective thickness of the superficial dust layer of the soil. A linear dependence of the diffusion factor with depth in the superficial layer of soil was proposed. For light soil (Makhonko, 1984b), v is set equal to L, and the resuspension factor takes the form

$$K = \frac{q_m e^{-\lambda t}}{\rho \cdot L}\left[1 - \left(1 + \frac{L}{v_D t}\right) e^{-L/v_D t}\right]. \quad (10)$$

For heavy soil or in the absence of precipitation, $v = 0$ and K is expressed as

$$K = \frac{q_m e^{-\lambda t}}{\rho \cdot L}(1 - e^{-L/v_D t}). \quad (11)$$

This approach is attractive, since it gives definite possibilities for the connection of the resuspension process with the migration processes in soil. The approach assumes the same form of the distribution of radioactivity with particle size in both the soil and air. The validity of this assumption is difficult to estimate at present. Our preliminary experimental estimation shows that the distribution of radioactivity with particle size in air is weighted toward small particles as compared to the distribution in soil (European Commission, 1996). This difference is not large, and its weight can be estimated only with detailed experimental data.

A second source of uncertainty is the value of the effective thickness of the superficial dust layer of soil. Makhonko (1984b) does not give a description of the definition of L as a function of time. It is clear that the thickness of the dust layer is a complicated function of many factors, and this complexity is especially apparent under damp climatic conditions. Values of L can be determined with an accuracy of about one order of magnitude when the surface deposit is located within the top centimeter of the soil.

A third source of possible uncertainty is the choice of the mass concentration of dust. It is desirable that this dust concentration be averaged not only over the first observation period (0–1 month) but also over the area of the surface deposition. Presently there are no direct estimates of the dependency of K on different characteristics of soil, but it is clear that the magnitude of this dependency should be large.

A more complicated case exists for the determination of the emission rate from surface sources for small aerosol particles, as there is not a generally accepted theory about the mechanisms of lift-up of small particles from the soil surface into the atmospheric surface layer. The first and classic studies explain the process for the removal of soil particles as flows whose velocity exceeds some threshold value when the saltation process is beginning (Sehmel, 1984). The process is continued over time; however, the process may be episodic in places with lightly eroded soil. The resuspension process goes on continually, even in places with a damp climate, as is the case in the Ukrainian Polessie.

A new alternative approach recognizes the influence of turbulent energy transferred to a particle from the resuspending flow (Reeks *et al.*, 1988; Hall and Reed, 1989). This energy maintains the particle in motion on the surface within a surface adhesive potential well. The particle is detached from the surface when it has accumulated enough vibrational energy to escape from the well. The analogy is seen with a vibrating spring where the resonant frequency can have an effect on the amplitude of vibration, as particles can be resuspended at much lower threshold flow velocities than those velocities calculated only on the basis of a balance of aerodynamic and adhesive forces. The very important result for application of this theory is that for long-term resuspension, the resuspension rate varies almost inversely with the time of exposure. This theory is an excellent addition to the older theories for the explanation of real geophysical processes in different places of the world.

PRACTICAL APPROACHES TO ESTIMATION OF THE RESUSPENSION FACTOR

It is important to examine various practical approaches for the empirical estimation of the resuspension factor. One of the first empirical models describes the time dependency of K as a simple expression

$$K(t) = K(0)\, e^{-\lambda t} \quad (12)$$

where λ is the effective half-life and $K(0)$ is a constant representing the initial value of the resuspension factor (Langham, 1971). Anspaugh *et al.* (1975) noted that such a formulation appears to simulate the available observations reasonably well for time periods up to several weeks after the deposition. This simple model is an approximation for the following:

$$K(t) = K(0) e^{(-\lambda\sqrt{t})} + 10^{-9} \quad (13)$$

where the second term of equation (13) is based on 17 years of data for observations of plutonium in air, and where the initial value of $K(0)$ is equal to $10^{-4}\ m^{-1}$.

Linsley (1978) gives formulas for K that were used for the U.S. Liquid Metal Fast Breeder Reactor and the Reactor Safety Study. In addition, Linsley

From equation (3), the difference between concentrations is seen to be a function of two groups of integrated parameters: (a) pure micro-meteorological parameters (u_* and L) and (b) the vertical turbulent flux of the surface deposit Q; the latter is the result of the interaction of the surface adhesive forces and the different lift forces induced by turbulent flow. It is clear that the assumption of constancy of these sources is correct only within the limits of a time period comparable to the integral of the scale of small-scale turbulence in the atmospheric surface layer. The values of the friction velocity and the Monin–Obuchov length have clear diurnal variations; the value of the friction velocity depends on the seasonal (one-half year period) variations of the roughness length of the ground surface. Obviously, the short temporal scale of the variations for the first period (ten days to two weeks) after an accident should be considered. A short temporal scale must also be considered in the case of very high contamination, when it is necessary to obtain high temporal resolution to determine the fluctuation in the air concentration; the fluctuation may have large amplitudes and periods.

Quantification of the vertical flux of deposited matter J is complicated, as J is a function of several parameters of the soil which must be examined separately. Dividing equation (3) by the value of the surface contamination, we obtain

$$\frac{\bar{q}(z_2)}{\bar{c}(d)} - \frac{\bar{q}(z_1)}{\bar{c}(d)} = K(z_2) - K(z_1)$$

$$= -\frac{\alpha}{\chi u_*}\left[\ln\frac{z_2}{z_1} + F\left(\frac{z_2 - z_1}{L_{MO}}\right)\right] \quad (4)$$

where $\alpha = J/c$ is the resuspension rate (Sehmel, 1984) and the terms on the left-hand side of the equation formally represent the resuspension factors at different heights. In other words, the difference $[K(z_2) - K(z_1)]$ may be a universal function only in the case of an idealized situation of a uniformly contaminated plane surface. From equation (4) it follows that for a constant friction velocity and Monin–Obuchov length, the resuspension factor will be directly connected only with the temporal function of the resuspension rate. From equation (4) it is easy to determine the ratio between α and K (for this idealized situation)

$$\frac{\alpha}{K} = \chi u_*\left[\ln\frac{z_2}{z_1} + F\left(\frac{z_2 - z_1}{L_{MO}}\right)\right]^{-1}\left[1 - \frac{\bar{q}(z_2)}{\bar{q}(z_1)}\right] \quad (5)$$

where $K = \bar{q}(z_1)/\bar{c}$ and $[1 - \bar{q}(z_2)/\bar{q}(z_1)] < 1$ for wind-driven resuspension. For neutral conditions when $L_{MO} = \pm\infty$ m, and for selection of z_1 or z_2 equal to the roughness length z_0, the ratio α/K will have a magnitude near 0.1 u_* m s^{-1}. The expression $\chi u_*\{\ln z_1/z_0 + F[(z_1 - z_0)/L_{MO})]\}^{-1}$ for that case is the turbulent vertical resuspension velocity of the deposited material for this idealized situation.

This analysis shows that the dispersion part of the resuspension process will have only one factor of long-term variation, namely seasonal variability, which controls the long-term time dependence of the resuspension rate.

The second case, a contaminated point source (or a small spot), will be relevant for neutral thermal stratification and a receptor that is far removed from the source. The simple asymptotic expression for the air contamination at ground level is

$$q(x,0,0) \approx \frac{Q}{u_*^3\tau^2\ln(c_1 u_*\tau/z_0)} \quad (6)$$

where Q is the emission rate of radioactivity from the point source, τ is the diffusion time, and c_1 is an empirical universal thermal constant equal to 0.2 (Garger, 1982). In this equation, τ must be determined through x for $x = \bar{x}$, where $\bar{x}$ is the abscissa of the center of gravity of the particle cloud

$$\bar{x} = \frac{u_*\tau}{\chi}\left(\ln\frac{c_1 u_*\tau}{z_0} - 1\right). \quad (7)$$

For further thermal stratification, a more complicated function is used based on the dimensionless argument $\bar{z}/L_{MO}$, where $\bar{z}$ is the height of the center of gravity of the particle cloud.

As distinguished from the first case, the air concentration is dependent on the diffusion time, or the distance from the center of gravity of the particle cloud to the point source. The ratio $J/c(x, y, d)$ will be a function of distance or diffusion time for this simple case.

Thus, if the conditions differ from the idealized case of a uniformly contaminated plane surface, an uncertainty for K of several orders of magnitude may be expected (Garger, 1994). Large uncertainties also exist for cases with contaminated spots, where the ratio of the horizontal scale of a spot X to the characteristic height of the atmospheric surface layer h (where there is equilibrium between concentrations in the atmosphere and the underlying surface) will be small. That is, the necessary condition (Vozzhennikov and Nesterov, 1988)

$$\frac{X}{h} \geqslant \frac{T_x}{\max\left(\frac{h}{u_*}, \frac{h}{v_s}\right)} \gg 1 \quad (8)$$

will not be met. T_x is the characteristic time of the horizontal transport of the surface deposited material, v_s is the dry deposition velocity, h/v_s is the characteristic time of the establishment of equilibrium between the atmosphere and the underlying surface, and h/u_* is the characteristic time of the vertical intermixing.

SOURCES OF UNCERTAINTY IN THE SURFACE CONTAMINATION

For short times after an accident, changes of the surface contamination $c(x, y, d; r, t)$ will be negligible,

proposed the formula

$$K(t) = 10^{-6}\,e^{-0.01t} + 10^{-9} \qquad (14)$$

where the initial value of K was selected for the relatively damp climate of England. The background value of K is reached after two years with this formula. Thus, these expressions are empirical interpolation formulas describing the transition process from an initial high level of K to a background level.

In contrast to equations (12)–(14), the expression given by Garland *et al.* (1991) does not have a low background level for K and is obtained empirically from experiments conducted over grass-covered soil in a wind tunnel:

$$K(t) = (1.2 \times 10^{-6})t^{-1}. \qquad (15)$$

Empirical equations have been published by Hoetzl *et al.* (1989, 1992) for the concentration of ^{137}Cs in air over time at Neuherberg (near Munich, Germany) from mid-May 1986 to the end of 1988 and from June 1986 to the end of 1990. Normalizing these equations for the density of contamination of ^{137}Cs in the 0–1 cm soil layer (Hoetzl *et al.*, 1992), we have

$$K(t) = (2.67 \times 10^{-6})t^{-1.07}. \qquad (16)$$

SOURCES OF UNCERTAINTY IN EQUATIONS FOR THE RESUSPENSION FACTOR

From equations (13)–(16), the first general source of uncertainty in K is seen to be the selection of the initial value of the resuspension factor $K(0)$, which may vary from 10^{-6} to $10^{-4}\,m^{-1}$. The second source of uncertainty is connected with the rate of decrease of K with time, which is determined by the value of λ in equations (13) and (14); this source of uncertainty may produce changes of 2–3 orders of magnitude. The background term may cause errors in the estimates of K using equation (14) at a very long time after the initial starting point, as this equation is designed to describe the relaxation of the primary disturbance and a constant situation after its attenuation. The common defect of these models is that they do not account for the fact that the real processes have both a deterministic and a stochastic component, and it is therefore not possible to use the models to obtain recommendations for the selection of averaging time in practice.

METHOD AND CONDITIONS OF MEASUREMENTS

Following the accident at Unit 4 of the Chernobyl Nuclear Power Plant (NPP), stationary air samplers were operated at towns of Chernobyl and Baryshevka, 16 and 150 km, respectively, from the site of the accident (UKRUGMS 1987; 1991). Other air samplers were operated simultaneously, but intermittently, at points within the 30 km zone, at distances of 4–25 km from the Chernobyl NPP (Garger, 1994). The samplers, designed by SPA "Typhoon", Russia, were operated at a flow rate of 100,000–120,000 $m^3\,d^{-1}$ at sampling heights of about 1.5 m. The filter used was of the Russian type (Petryanov cloth FPP-15-1.5), with an area of 1.05 m^2. The exposed filters were pressed into tablets, ashed at 300–400°C, and then analyzed by gamma-ray spectrometry. The exposure time for each filter was normally about 24 h. Data from the stationary samplers were averaged for either one day or one month; data from the intermittent samplers were averaged for three days in 1986 and for 4 h in 1991, using the same procedures for sample preparation and measurement by gamma-ray spectrometry.

ANALYSIS OF EXPERIMENTAL DATA

Temporal motion of the airborne concentrations

The change in monthly air concentration with time was examined for the period 20 May 1986 through August 1994 (Fig. 1). The relative behaviors of the air concentration in Chernobyl (within the 30 km zone) and in Baryshevka (150 km southeast of the Chernobyl NPP) are the same for the first 4 yr and somewhat different after about 4 1/2 yr. The general tendency is a sharp decrease in the concentrations during the first two months and a slower decrease after that. The presence of long-period fluctuations of a different nature is easily seen between the two sites. The amplitude of the monthly oscillations can reach one order of magnitude as shown in Fig. 2 (in effect, the resuspension factor shown in the graph is the air concentration normalized for the ground contamination). This gives us the first estimate of uncertainty for the fluctuation of the air concentration after the period of initial deposition. Data supporting the observed magnitude of variation have also been obtained for Budapest and Paks for resuspension occurring during

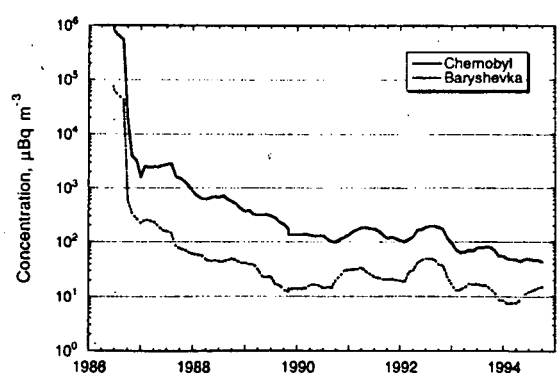

Fig. 1. Monthly mean concentrations of ^{137}Cs in air for Chernobyl and Baryshevka. Data have been smoothed by averaging over overlapping 7-month segments to show the seasonal variability.

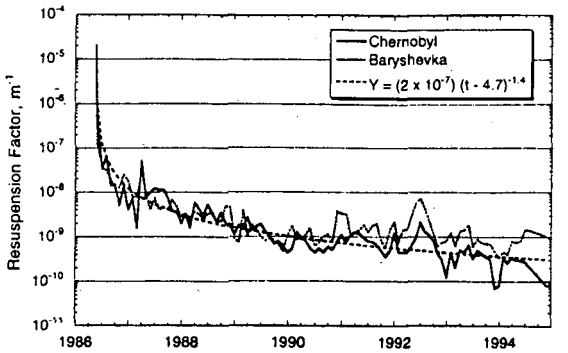

Fig. 2. Observed resuspension factors over time for ^{137}Cs at Chernobyl and Baryshevka. The data can also be viewed as the air concentrations normalized for the ground contamination. For the equation, t = time in months.

the 365 days following the Chernobyl accident (Feher, 1988).

The data were smoothed by averaging over overlapping 7-month segments to permit the seasonal variability the resuspension process to be distinguished from possible long-period tendencies (Fig. 1). Two general phases of the decrease of the airborne concentrations can be more clearly seen (a sharp, short decrease followed by a slow decrease), and this trend can be compared to the seasonal variation of resuspension. An increase in the annual concentration was observed in 1991 and 1992 in Chernobyl and Baryshevka, followed by a fairly sharp decrease (Fig. 1); this decrease is especially evident in Chernobyl (see also Table 1). The decrease in air concentrations is explained by the decrease in anthropogenic activity at that time, connected with economic difficulties. In 1992, an increase in the concentrations is explained by a very hot and dry summer accompanied by forest fires that occurred in the 30 km zone and its vicinity.

The results presented in Table 1 demonstrate the difference between the estimates of the standard deviations and coefficients of variation from daily as opposed to monthly data. The coefficient of variation for daily concentration averaging is more than 2.5 to 3.0 times that for monthly data, that is, the uncertainty of the daily averaged air concentrations is high. Furthermore, the uncertainty in daily averaged concentrations can be approximated using monthly averaged observations and the formula quoted in Table 1.

Temporal variability of K

Normalization of the data presented above makes it possible to trace the temporal variability of the monthly values of the resuspension factors in Chernobyl and Baryshevka (Fig. 2). In spite of the different positions of these places relative to the epicenter of the accident and the different levels of contamination surrounding these points, a similar behavior of K is seen for these places. The largest discrepancies are with the change in observed air concentrations when

Table 1. Long-term characteristics of the activity concentration of ^{137}Cs in the atmospheric surface at Chernobyl

Year	1986[a]	1987	1987[c]	1988	1989	1990	1991	1992	1993	1994	Total
Annual concentration q (μBq m^{-3})	19,600	1980	1490	570	248	117	137	176	66.5	40.8	
Standard deviation σ_q from daily data (μBq m^{-3})	101,000[b]	6060[b]	1640	620	357	150	184	323	89	61	
Standard deviation σ_q from monthly data (μBq m^{-3})	40,400	2420	710	255	110	46	52	96	32	22	
Exponent (m)	0.27[d]	0.27[d]	0.27	0.25	0.34	0.37	0.32	0.24	0.30	0.30	0.30 ± 0.05

[a] Data from 1 June 1986 to 31 December 1986.
[b] Calculated values using the power function $\sigma(T_2) = \sigma(T_1)[T_2/T_1]^{-m}$ (Garger et al., 1994).
[c] Daily data from 1 July 1987 to 31 December 1987.
[d] Values used for calculating the daily standard deviation for the month from averaged data.

Table 2. Annual mean resuspension factors (K) for ^{137}Cs measured at Chernobyl city in 1986 (after May 20) and 1987–1991, compared with model calculations[a]

Year	Lower limit of K ($m^{-1} \times 10^7$)	Mean value of K ($m^{-1} \times 10^7$)	Upper limit of K ($m^{-1} \times 10^7$)	K_{Gar} ($m^{-1} \times 10^7$)	K_{Hoet} ($m^{-1} \times 10^7$)	K_{Lin} ($m^{-1} \times 10^7$)	$\frac{K_{Gar}}{K_{exp}}$	$\frac{K_{Hoet}}{K_{exp}}$	$\frac{K_{Lin}}{K_{exp}}$
1986	0.053	0.330	0.830	0.270	0.510	3.90	0.82	1.54	11.8
1987	0.013	0.082	0.170	0.030	0.042	0.27	0.36	0.51	3.30
1988	0.004	0.032	0.070	0.014	0.021	0.016	0.44	0.66	0.50
1989	0.002	0.014	0.034	0.010	0.014	0.010	0.71	1.00	0.71
1990	0.0008	0.006	0.015	0.008	0.010	0.010	1.33	1.66	1.66
1991	0.001	0.008	0.018	0.006	0.008	0.010	0.75	1.00	1.25

[a] K_{Gar}—calculated according to Garland *et al.* (1991).
K_{Hoet}—calculated according to Hoetzl *et al.* (1992).
K_{Lin}—calculated according to Linsley (1978).
K_{exp}—derived from experimental measurements.

anthropogenic activities ceased in the city of Chernobyl.

The data presented show that for short times after the accident, up to about ten days, the resuspension factor exceeds the value 10^{-5} m^{-1}; for the following days the value of K was on the order of 10^{-6} m^{-1} in Chernobyl, and after three months, near 10^{-8} m^{-1}. An exception during this later time period was for locations of high anthropogenic activity near the Chernobyl NPP and in the vicinity of major roads frequented by vehicular traffic, where values of K were 10^{-6}–10^{-7} m^{-1}. These major roads were frequently washed by special equipment (Garger *et al.*, 1994; Bondarenko *et al.*, 1993). The estimation of K for the same time period (after three months) in the vicinity of roads in the town of Chernobyl was equal to 10^{-4}–10^{-6} m^{-1} in July–August 1986 (Bondarenko *et al.*, 1993). It is important to note that stabilization (leveling off) of the values of K did not happen in the town of Chernobyl over the time period considered (Fig. 2), as human activity has not stayed constant: there has been a significant decrease in activity recently as compared to 3–4 yr after the accident. After 8 yr the values of K are approximately 10^{-10} m^{-1}.

Comparison of model predictions with empirical data

For comparison of model predictions with empirical data, the correspondence of the time or space averaging of the calculated and measured values of K must be considered. Because the model values of K assume homogeneity of external conditions (soil contamination, character of the underlying surface) and stable average meteorological conditions for the measuring period, the empirical data averaged for the whole year were used. The annual means of the resuspension factor, determined experimentally and calculated by models, are shown in Table 2. This table presents the lower and upper limit of K from 1986 to 1991 and the ratio of the calculated values of K to the experimental values.

The Hoetzl *et al.* model (1992) agrees best with the data. This model was derived from empirical data measured in Munich, Germany, after the Chernobyl accident. The Garland *et al.* model (1991) agrees well also, but systematically gave results lower than experimental values. The calculated values of K from the Linsley model (1978) are very conservative for the first two years and much closer to the observations for later years. If the calculated values are compared with the upper limits of observed values, the predictions of the models by Garland and Hoetzl are seen to be lower by a factor of two to three. Note that the lower and upper limits are obtained on the monthly mean resuspension factors. The ratio of the predicted to observed values for K for the daily data will be larger.

Air concentrations and surface deposition of eight radionuclides were measured at 10 points during the same time period on 14–17 September 1986 (Garger, 1994; Table 3). The calculated resuspension factors ranged from 6×10^{-9} to 3×10^{-6} m^{-1}. Data on the spatial means of K are presented in Table 3 for time periods in 1986 and 1991; also shown are the calculated values according to the models of Linsley (1978), Garland (1991), and Hoetzl *et al.* (1992). The experimental data and the calculated results differ by as much as one order of magnitude or more. The high range of the resuspension factors reflects the different underlying surface soil and the effects of anthropogenic actions in the 30 km zone. Anthropogenic activities were especially important for places which were situated near the nuclear power plant or to general roads. The advection effect from upwind sources was illustrated by Garland (1991) and Garger (1994). For specific locations, however, the K values may be higher than estimated by the models of Garland and Hoetzl by two to three orders of magnitude.

The models for K were compared with the experimental monthly data and with each other as the normalized resuspension factor $K(t)/K(0)$ with respect to time (Fig. 3). The Chernobyl and Baryshevka data are shown, along with five model equations and a new equation derived from the experimental data: $K(t)/K(0) = t^{-1.4}$. This equation was selected after study of the value of the power function for the entire

Table 3. Comparison of calculated resuspension factors (K) with those experimentally determined following the Chernobyl accident

Model/data	$K(m^{-1})$ $t = 117$ d (14–17 September 1986)	K (m^{-1}) $t = 1957$ d (25 September 1991)
Linsley (1978)	31×10^{-8}	10×10^{-10}
Garland *et al.* (1991)	1.1×10^{-8}	6.1×10^{-10}
Hoetzl *et al.* (1992)	1.6×10^{-8}	8.0×10^{-10}
Experimental	$^{137}Cs^{a}$: $(17 \pm 19) \times 10^{-8}$	First Point:
	^{106}Ru: $(23 \pm 16) \times 10^{-8}$	^{137}Cs: $(4.3 \pm 2.2) \times 10^{-10}$
	^{144}Ce: $(19 \pm 24) \times 10^{-8}$	Second Point:
	^{95}Zr: $(20 \pm 23) \times 10^{-8}$	$^{137}Cs^{b}$: $(2.4 \pm 1.0) \times 10^{-10}$

[a] Mean over 10 points and three days.
[b] Mean of six values of K measured during one day.

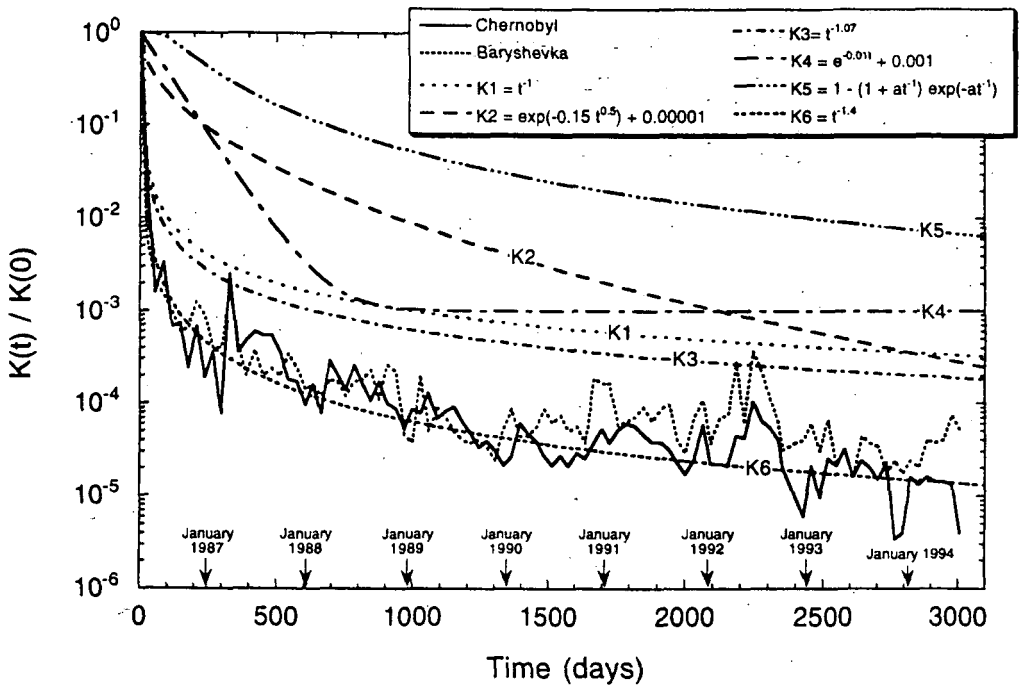

Fig. 3. Comparison of observed and predicted resuspension factors over time, normalized for the initial resuspension factor $K(0)$. $K1$, model of Garland; $K2$, model of Anspaugh; $K3$, model of Hoetzl; $K4$, model of Linsley; $K5$, model of Makhonko; $K6$, empirical dependence described in this paper. For all equations, t = time in days.

time series of measurements at Chernobyl (Fig. 4); it provides the best fit to the experimental data and shows that the process of stabilization is going more rapidly, with stabilization of the experiment occurring near 1200 d. The processes of migration in soil are probably appreciable by this time. Presentation of the model predictions as $K(t)$ normalized for $K(0)$ permits comparison of the form of the dependence of K on time without the effect of differences in the initial value of K. The value of $K(0)$ is dependent on a substantial amount of subjective estimation.

The similar character of the inverse curves with powers from 1.0 to 1.4 is easily seen (Fig. 3). The models of Linsley (1978) and Anspaugh *et al.* (1975) exceed the experimental data in the first 1000 days by two to three orders of magnitude. The curve by Makhonko (1992), developed for long-term resuspension after the deposition of radionuclides from the stratosphere, describes the resuspension factor controlled by the process of soil migration [equations (10) and (11)] for the stationary atmospheric conditions of the middle strip of Russia; it differs sharply in value from

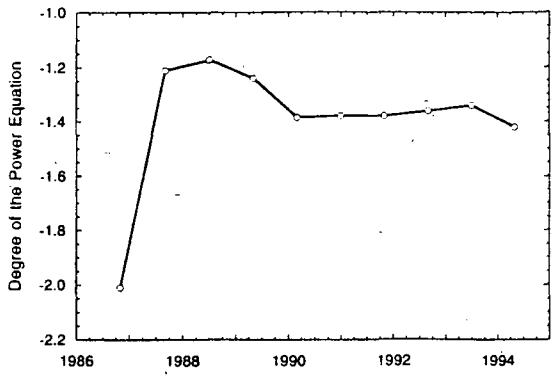

Fig. 4 Observed degree (a) over time for the power function $K(t)/K(0) = t^{-a}$, based on measurements of K made at Chernobyl.

the other curves in Fig. 3. In spite of the inverse dependence with a predicted power near 1.1 (Hall and Reed, 1989), the decrease of the resuspension ("the decrease in the power of the spring and the capacity of the well") is more rapid than predicted. This is explained by the downward migration processes of radiocesium initially deposited on the soil surface.

CONCLUSIONS

The resuspension factor is one of the key parameters necessary for calculation of the inhalation dose to humans; therefore accurate estimation is necessary in order to perform reliable post-accident evaluations of health risk. Uncertainty in K may reach 2–3 orders of magnitude if the definition of K as a function of its controlling variables is disregarded. The value of K averaged over large regions may differ from calculated values by more than one order of magnitude; however, uncertainties in the estimates of K are decreased to within one order of magnitude if annual averaging of the experimental data is used and K is determined as a function of time and predominant regional conditions of vegetative cover and climate.

Comparison of empirical data for long-term K-factors with model estimates shows that models based on the inverse power function best reflect reality. These models have a clearer physical basis for territories with damp climates and moderate conditions of wind. Continued progress in this area is expected, based on new experimental and theoretical data.

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