Development of a Computer Model for Calculation of Radioactive Materials into the Atmosphere After an Accident

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**Development of a computer model for calculation of resuspension of
radioactive materials into the atmosphere after an accident**

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INTRODUCTION

Secondary atmospheric contamination with radioactive dust and chemical species deposited on the ground and resuspended by wind occur very widely. This process is particularly pronounced in case of extensive contamination of soil and under extreme weather conditions, for example, during dust storms.

The mechanism of wind dust generation consists in the following. At low wind speed $U=2-3$ m/s, which is most common in midlatitude, small radioactive dust particles (diameter of hundredth of a micron to $10\div 20$ microns) are lifted from soil surface due to turbulent vortexes. Under the gravitational force the particles of 1-2 micron diameter practically do not settle. Larger dust particles cannot remain in the air for a long time: they are lifted by turbulent vortexes and settle, their motion in the wind flow is jumpwise and the interaction of particles with the flow is called saltation /1/. Saltation is the main mechanism of dust generation up to the wind velocity at which wind erosion starts. The size of dust particles can be as large as $100\text{ }\mu\text{m}$. When dropping they can be ricocheting from ground or pass the impulse to other particles which begin rolling over and jumping up. The process of dust transport by wind can be compared to a chain reaction. At the velocity of 10 m/s large particles of about $500\text{ }\mu\text{m}$ stop skipping and roll over only, while particles of more than 1 mm remain stationary. Thus, the fine fraction is blown out from the polydispersed soil particles.

The intensity of wind resuspension of radioactive dust from the ground is characterized either by a resuspension factor or a resuspension rate.

The resuspension factor /2/ is determined as a ratio of radionuclides concentration in the air at a reference level (usually 1m) and surface contamination density measured in m^{-1} .

$$R = \frac{q_1}{A}, \text{ m}^{-1} \quad (1.1)$$

where $q_1, \text{ Bq/m}^3$ is the average radionuclide concentration in the air at height 1 m;

$A, \text{ Bq/m}^2$ is the surface contamination density.

The resuspension rate /2/ is found as a fraction of contaminating species, in particular radionuclides, on the ground which is lifted into the air in time unit either under the wind action only or under mechanical action on the surface

$$\alpha = \frac{Q}{A}, \text{ s}^{-1} \quad (1.2)$$

where Q , [Bq/(m²·s)] is the turbulent radionuclides flow near the ground.

1. Resuspension factor

The main advantage of this coefficient is its simplicity and the fact that most measurements of resuspension are expressed in this form /2,3/. The disadvantage is that the formulae are empirical, which makes difficult extrapolation of results with generalization, ignoring spatial distribution of contamination and size of contaminated area.

The analysis of the first experimental data using the resuspension factor for dust contaminated by *Pu* has shown that under mechanical disturbances it lies in the range $2 \cdot 10^{-6}$ - $7 \cdot 10^{-5} \text{ m}^{-1}$. Given no mechanical disturbances and for a relatively fresh deposited material, the resuspension factor was measured to be within 10^{-8} - $2 \cdot 10^{-6} \text{ m}^{-1}$ and for the aged species - within $6 \cdot 10^{-10}$ - 10^{-13} m^{-1} /2/.

The data on plutonium fixation in soil in the climatic conditions of the Nevada testing grounds (semi-desert) have permitted describing the change in the resuspension factor with time as /3/

$$R(t) = R(0) \exp(-0,15 t^{1/2}) + 10^{-9}, \quad (1.3)$$

where t is time in days. The initial value $R(0)$ is taken to be 10^{-4} m^{-1} .

With the same material /4/ the following empirical expression was derived

$$R(t) = 10^{-5} \exp[(-1,46 \cdot 10^{-7} - 2,2 \cdot 10^{-10} - \lambda) t] + 10^{-3} \exp[(-2,2 \cdot 10^{-10} - \lambda) t], \quad (1.4)$$

where t is given in days, λ is the radioactive decay constant.

On the one hand, formula (1.4) is preferable to (1.3) as the resuspension factor $R(t)$ tends to zero with time, which matches the physical meaning of the process. On the other hand, the radioactive decay constant λ is incorporated in (1.4) formally. It is clear that with a phase-type contamination the resuspension factor R cannot depend on λ , as the radionuclide in the air and soil decays at equal rate.

In subsequent studies related to reactor safety and environmental behaviour of radionuclides /5/ the following expressions for $R(t)$ were used

$$R(t) = 10^{-5} \exp(-0,0139 t) + 10^{-9}, \quad (1.5)$$

$$R(t) = 10^{-5} \exp(-0,00185 t) + 10^{-9}, \quad (1.6)$$

where t is time since the contamination, day.

A simple formula for $R(t)$ was proposed in /5/ for the wet climate conditions of UK:

$$R(t) = 10^{-6} \exp(-0,01 t) + 10^{-9}, \quad (1.7)$$

t is given in days.

In /6/ based on data about the post Chernobyl contamination and using experimental estimation and numerical modelling the following equation for the resuspension factor was derived which does not include the background value:

$$R(t) = 1,2 \cdot 10^{-6} \cdot t^{-1}, \quad (1.8)$$

where t is time in days

Based on monitoring of ^{137}Cs concentration in the air and contamination density of the upper 1cm soil layer near Noirburg from mid May 1986 to the end 1987 /7/ and from June 1986 to the end 1990 /8/ the following expressions for $R(t)$ have been derived /8/:

$$R(t) = 3,4 \cdot 10^{-6} \exp(-0,152 t) + 18,4 \cdot 10^{-9} \exp(-0,03 t) \quad (1.9)$$

$$R(t) = 2,67 \cdot 10^{-6} t^{-1,07}, \quad (1.10)$$

where t is time, days.

According to expressions (3)-(8) the resuspension factor in the first 10 days after the accident varies within $10^{-6} \div 10^{-4}$. The values of the resuspension factor determined experimentally or calculated /5-9/ are shown in Table 1.1. Table 1.1 also includes the upper and lower bounds and average values of $R(t)$ and ratio of calculated and experimental values /9/. The data cover the period of 1986-1991 and the difference between the upper and the lower bounds of $R(t)$ can be as large as an order of magnitude. On a whole, the calculated data are in agreement with the experimental ones obtained in Chernobyl after 20 May 1986 and in 1987-1991.

Table 1.1

Mean annual resuspension factor measured in 1986 (after 20 May) in Chernobyl
and calculated by /9/

Year	Lower bound of R (10^{-7} m^{-1})	Mean value of R (10^{-7} m^{-1})	Upper bound of R (10^{-7} m^{-1})	R_{Gar} (10^{-7} m^{-1})	R_{Hoet} (10^{-7} m^{-1})	R_{Lin} (10^{-7} m^{-1})	$\frac{R_{\text{Gar}}}{R_{\text{exp}}}$	$\frac{R_{\text{Hoet}}}{R_{\text{exp}}}$	$\frac{R_{\text{Lin}}}{R_{\text{exp}}}$
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

R_{Gar} is calculated by /6/

R_{Hoet} is calculated by /8/

R_{Lin} is calculated by /5/

R_{exp} is measured in Chernobyl in 1986-1991 /9/

It should be noted that the resuspension factor calculated based on the experimental data from the vicinity of Noirburg after the Chernobyl accident /8/ is in a better agreement than others with the Chernobyl measurements /9/. The data of /6/ are systematically lower the experimental, the data of /5/ differ significantly from the experimental ones for the first two years after the accident.

Table 1.2 shows $R(t)$ calculated by /5-9/) and measured in the 30 km zone around the Chernobyl NPP in 1986 and 1991. The values of $R(t)$ calculated by /6,8/ differ by an order of magnitude from the experimental ones /9/ and /5/ for $t=117$ days and the discrepancy in $R(t)$ is decreasing with time.

Table 1.2

Comparison of calculated and measured resuspension factors

Data source	$R \text{ (m}^{-1}\text{)}$ $t = 117 \text{ day.}$ (14-17 Sept. 1986)	$R \text{ (m}^{-1}\text{)}$ $t = 1957 \text{ day.}$ (25 Sept. 1991)
/5/	31×10^{-8}	10×10^{-10}
/6/	$1,1 \times 10^{-8}$	$6,1 \times 10^{-10}$
/8/	$1,6 \times 10^{-8}$	$8,0 \times 10^{-10}$
Experimental data /9/	$^{137}\text{Cs}^a: (17 \pm 19) \times 10^{-8}$ $^{106}\text{Ru}: (23 \pm 16) \times 10^{-8}$ $^{144}\text{Ce}: (19 \pm 24) \times 10^{-8}$ $^{95}\text{Zr}: (20 \pm 23) \times 10^{-8}$	First point: $^{137}\text{Cs}: (4,3 \pm 2,2) \times 10^{-10}$ Second point: $^{137}\text{Cs}^b: (2,4 \pm 1,0) \times 10^{-10}$

^a is average over 10 points and three days

^b is mean over six cases of R measurements during one day.

In /10/ based on measurements in Haunover during the first fifteen days after the primary contamination as a result of the Chernobyl accident the following values of the resuspension factor as a function of wind velocity were derived ($R=2 \cdot 10^{-6} \div 2 \cdot 10^{-5} \text{ m}^{-1}$). In /11/ the data obtained in Haunover during 12-22 days after the accident and data of measurements in Chernobyl conducted during a longer period from June 1986 to ~15008 day after the accident were generalized which permitted writing the following equation for $R(t)$ /11/

$$R(t) = 2,09 \cdot 10^{-4} (t)^{-1,67}, \quad (1.11)$$

t is time after the accident in days. In the view of the authors of /11/, the exponent (-1.67) is most suitable, considering that the reduction in radionuclides concentration in the surface soil layer is proportional to $t^{-0.5}$ and the uplift of fine particles in the eddy flow according to /12/ is proportional to $t^{-1.07}$.

In work /13/ based on the semi-empirical equation an explicit relation between the resuspension factor and parameters of radionuclides migration in soil was derived.

Based on the data on wind resuspension of a tracer of submicron size (calcium molybdate) /2/ which was dispersed on an experimental plot using several impactors adjusted to work at different wind velocities, an attempt was made to establish a dependence of the resuspension factor on wind speed. In particular, it is established that at the height of 1,8 m the resuspension factor was increasing in proportion to wind speed with exponent 6.5. It was also noticed that during 3 years the wind resuspension of the tracer was decreasing.

In work /14/ the determination of the resuspension factor is based on the assumption that the radioactivity concentration in the air q is related to the measured flux of settling radionuclides S^* through the following expression:

$$q = S^* / v_d,$$

where v_d is the dry deposition velocity. On the other hand, the quantity q can be determined by density of soil radioactive contamination A and resuspension factor

$$q = R \cdot A.$$

Hence,

$$R = \frac{S^*}{v_d \cdot A}.$$

According to the data of /14/ $A = 125 \text{ Ci/km}^2$, $S^* = 9.4 \text{ Bq m}^2 \text{ s}^{-1}$, then $R = 3 \cdot 10^{-9} \text{ m}^{-1}$, the dry deposition velocity is taken to be $v_d = 0.008 \text{ m/s}$. The resulting R agrees with the value of the resuspension factor calculated by direct measurements in the first days and months after the Chernobyl accident

$$R = 10 \cdot 10^{-9} \text{ m}^{-1} \quad /15/$$

$$R = (0,6 \div 200) 10^{-9} \text{ m}^{-1} \quad /16, 17/$$

In conclusion, we present data on the resuspension factor determined from measurements in the area of Chernobyl in August-September 1986 /17/. Table 1.3 contains resuspension factors for some radionuclides estimated from the data of 14-17 September 1986 in separate points of the 30 km zone around the Chernobyl NPP. Table 1.4 shows mean resuspension factors derived based on data of August-September 1986 for the population point of Zapolie.

Table 1.3

Wind resuspension factor on 14-17 September 1986

Point	Resuspension factor $\times 10^{-8} \text{ (m}^{-1}\text{)}$							
	^{144}Ce	^{141}Ce	^{103}Ru	^{106}Ru	^{137}Cs	^{134}Cs	^{95}Zr	^{95}Nb
Pripyat	9,7	10,0	11,0	7,6	7,7	0,9	8,7	8,5
Kopachi	85,0	72,0	60,0	59,0	59,0	58,0	64,0	88,0
Lelev	16,0	322,0	15,0	26,0	5,2	42,0	9,0	18,0
Zapolie	11,0	9,0	3,0	0,6	5,3	10,0	6,0	6,5
Zalesye	10,0	11,0	10,0	21,0	6,8	17,0	55,0	9,2
Korogod	10,0	23,0	10,0	28,0	4,2	11,0	11,0	9,91
Opachichi	9,0	7,0	5,6	21,0	13,0	21,0	4,0	6,7
Yampol	3,3	7,5	5,5	26,0	5,9	16,0	4,1	2,8
Zimovichi	18,0	10,0	22,0	30,0	42,0	120,0	-	-
Chernobyl	15,0	18,0	19,0	10,0	20,0	15,0	17,0	23,0
Mean	18,7 $\pm$ 7,8	48,9 32,6	16,1 $\pm 5,4$	22,9 $\pm 5,3$	16,9 $\pm 6,2$	31,1 $\pm 11,8$	19,7 $\pm 8,1$	18,1 $\pm 9,3$

Table 1.4

Mean wind resuspension factors (Zapolie August/September 1986)

Resuspension factor $\times 10^{-8} \text{ (m}^{-1}\text{)}$						
^{144}Ce	^{141}Ce	^{103}Ru	^{134}Cs	^{137}Cs	^{95}Zr	^{95}Nb
7,7 $\pm$ 3,9	4,4 $\pm$ 2,1	9,9 $\pm$ 7,5	6,3 $\pm$ 1,3	7,7 $\pm$ 2,1	5,4 $\pm$ 3,6	5,5 $\pm$ 3,7

An attempt to study the dependence of the resuspension factor on particle diameter was made in /18/ based on measurements of 1992-1993 in the population points of Novozybkov, Mikulichi, Kovaly, Zapolie and on the bank of the Pripyat' river. In general, the resuspension factor has been found to increase with the growth of particle diameter.

In conclusion it is worth noting that today data are available on wind resuspension factor which have been obtained from measurements. The wind resuspension factor of ^{137}Cs in August-September 1986, on the average, was $(6.3 \pm 1.3) \cdot 10^{-8} \text{ m}^{-1}$ and $0.8 \cdot 10^{-9} \text{ m}^{-1}$ in 1991, with the lower and upper bounds of the value differing from the average by as much as an order of magnitude.

Approximation expressions describing the changes in the resuspension factor with time have been obtained. Among them, the expression (1.11) derived in (11) should be pointed out. Its advantage is that it has been derived based on experimental data received in Chernobyl for more than 4 years starting from 1986 and in Haunover during 12-22 days after the accident.

Data are available on dependence of the resuspension factor on the diameter of migrating particles. The resuspension factor has been shown to grow with the increase in particles diameter.

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2. Resuspension rate

Physically, the resuspension rate α is a rising flow of material from the ground, the contamination of which is unity, i.e. the proportion of radionuclides resuspended by wind from the ground surface in unit time. In a general case for a plane source with non-uniform surface and surface contamination density the radionuclides resuspension rate is a function of surface characteristics and meteorological conditions.

The studies on resuspension rate α of radioactive species from contaminated areas were initiated when nuclear testing grounds started to be used and the first results became known in 1958 /1/. The authors of /1/ investigated the process of scattering of fluorescent particles poured on the ground at a low wind speed. Later on more and more researchers became interested in the radionuclides resuspension rate. In Russia the works on radionuclides resuspension from the underlying surface were initiated after the radiation accident at “Mayak” plant in Southern Urals which resulted in formation of a contaminated area (radioactive trace). The data obtained by different authors prior to the Chernobyl accident in 1986 are included in Table 2.1

Table 2.1

Data on resuspension rate received prior to 1986

Location	Radionuclide/ tracer	Resuspension rate (s^{-1})	Comments
Nevada desert	in soil	$2.7 \times 10^{-12} \div 4.8 \times 10^{-10}$	Aged deposit /2/
South Carolina	in soil	4.3×10^{-12}	Aged deposit /3/
Nevada desert	<i>Pu</i>	$10^{-8} \div 10^{-12}$	Review of data /4/
Hanford	tracer	$5 \times 10^{-9} \div 6 \times 10^{-8}$	Deposit on grass. Wind speed 1 m/s /4/
South Urals	<i>Sr</i>	$4.3 \times 10^{-12} \div 1.3 \times 10^{-9}$	Contamination of soil in 1957÷1960 /5/

After the Chernobyl accident in April 1986 the resuspension studies have been carried out systematically by many researchers.

2.1. Methods of estimating resuspension rate.

Estimation of α can be done by several ways:

1) direct measurements of vertical turbulent flows of radionuclides above uniform and stationary sources;

2) gradient measurements of average wind speed, average air temperature and average radionuclides concentration in the near-surface atmospheric layer, which makes possible assessment of the vertical turbulent flow of radionuclides from a plane uniform stationary source;

3) measurements of radionuclides concentration in the air at a fixed height outside a limited source or directly above the source;

4) measurements of depositions on a collector at a certain height. This method is based on the assumption about equality of two steady-state flows of radioactive dust: the one directed from the underlying surface to the atmosphere and that from the atmosphere to the underlying surface.

The first method has not been used widely as for its implementation unique equipment is required. The second and the third methods call for using diffusion models of varying complexity and measurements of meteorological parameters, soil contamination density and atmospheric concentration of radionuclides /6-12/.

In addition to the above methods it has been proposed in /12/ to estimate the value of town-averaged α by dust advection, i.e. as a ratio of horizontal dust flux from this source obtained by measurement of radionuclides concentration profile to the height at which the concentration is zero and density of deposited contamination.

2.2. Experimental and calculation data on resuspension rate.

After the Chernobyl accident in 1986 wind migration of radionuclides has been studied by numerical modelling and direct measurements in the contaminated areas of Russia (Bryansk region), Ukraine and Belarus.

Practically all researchers indicate a decrease in the resuspension rate with time which is explicable by radionuclides migration down the soil profile.

The results of ^{137}Cs measurements in the atmosphere in March-April 1987-1989 allowed establishing a dependence of radioactive dust resuspension rate from the ground on time /13/:

$$\alpha = \alpha_0 \exp(-2.1 t), \quad (2.1)$$

where t is given in years, α is the value in September 1986. The obtained exponent in /2.1/ is in good agreement with the value 1.9 derived earlier in /6/ based on the measurements in spring-summer 1958-1961 in the area affected by the accident at “Mayak” in Southern Urals in 1957. It

should be noted that the time dependence of α cited in /6/ was derived for a limited time interval ($t \leq 3$ years). This limitation also applies to equation (2.1).

The resuspension rate α varies in a wide range during a year, its value depending on meteorological conditions, condition of the underlying surface and migrating radionuclide. The vegetation cover is also an important factor influencing the resuspension rate. The vegetation cover equivalent includes the amount of vegetation in the equation of air-dried biomass matter, total frontal vegetation cross-section area, and vegetation orientation. The erect vegetation tends to reduce the wind speed near the ground and lower the resuspension rate. In /14/ empirical dependencies of resuspension rate α on vegetation height h and mass m of air-dried hay collected from unit soil surface in water have been derived

$$\alpha = \frac{2.5 \cdot 10^{-9}}{h^{1.4}}, \text{ s}^{-1}, \quad (2.2)$$

$$\alpha = \frac{2.9 \cdot 10^{-8}}{m^{1.4}}, \text{ s}^{-1}, \quad (2.3)$$

where h is expressed in cm, m in g/m². The same work /14/ includes an empirical expression of dependence of α on roughness length z_0 of the underlying surface

$$\alpha = \frac{2.0 \cdot 10^{-10}}{z_0^{1.4}}, \text{ s}^{-1}, \quad (2.4)$$

where z_0 is given in cm.

The presented empirical expressions have been derived for a plane (forest steppe piedmont of Southern Urals) under usual weather conditions of the central part of Russia for the average wind speed at the vane level of 2÷6 m/s based on observational results in the radioactive trace in 1957 after the accident at “Mayak”. In /13/ the similarity in curves $\alpha(t)$ for resuspension of fresh radioactive species from soil surface in piedmont of Southern Urals and Northern Ukraine have been noted. There is a good correlation between α and the degree of development of vegetation inhibiting resuspension.

The increase in the resuspension rate with wind speed has been noted by many researchers /15,17/. In the studies of tracer resuspension with the use of submicron particles of calcium molybdate scattered on a sparsely vegetated area with roughness length $z_0=3.4$ cm a

relation between resuspension rate α and wind speed u measured at height 2,1 m has been derived /15/:

$$\alpha = 1,96 \cdot 10^{-13} u^{4,82}, \quad (2.5)$$

u is given in m/s. Assuming that the observations were made under neutral stratification, (2.5) can be written as /15/

$$\alpha = 2 \cdot 10^{-16} u_*^{4,82},$$

where u_* is friction velocity.

Expression (2.5) has been derived by processing data at wind velocities 8-10 m/s and for wind velocities 1-6 m/s the following expression has been proposed /15,16/

$$\alpha = 0,74 \cdot 10^{-10} u^{1,94}. \quad (2.6)$$

In /17/ the dependence of resuspension rate on wind speed has been studied using the diffusion model and field measurements. The values of α were determined for different wind speeds by measuring 3-hour ^{137}Cs concentrations in the air and deposition flux and using model calculations of α . The measurements were conducted in Novozybkov in 1992-1993. Using the derived values of α approximation expressions for α dependence on wind speed at the vane level were found:

$$\begin{aligned} \alpha &= 10^{-10} u^{1,2} & \text{at } u &= 1 \div 3 \text{ m/s;} \\ \alpha &= 0,3 \cdot 10^{-10} u^{2,9} & \text{at } u &= 4 \div 6 \text{ m/s;} \\ (2.7) \\ \alpha &= 0,02 \cdot 10^{-11} u^5 & \text{at } u &= 8 \div 10 \text{ m/s.} \end{aligned}$$

This is, in fact, all the information available regarding the relations of the resuspension rate and relevant parameters which influence it. In addition to the above expressions there are numerous experimental data which were used to determine the value of α by different ways at different time after the Chernobyl accident in different areas, yet these are for the atmospheric conditions close to neutral stratification.

In [12] based on the measurements made in 1986 on the western edge of Chernobyl the values were derived in three ways: by gradient measurements, by dust advection from the source and by measurements of the deposition flux. The data of [12] are shown in Table 2.2.

The underlying surface was partly a field with grass of 30-40 cm height and partly an area with rare bushes, trees and barns. The measurements were conducted during 3 days, in the first day the soil was wet and in the following two days- dry; the wind speed at the height of 1 m did not exceed 2.1 m/s. On the average, according to [12] in July 1986 the resuspension rate was $2 \cdot 10^{-8} \text{ s}^{-1}$ for coarse dust (*Ce-134*, *Zr-95*, *Nb-96*); $4 \cdot 10^{-8} \text{ s}^{-1}$ for fine dust (*Ru-103*, *Cs-137*) and $4 \cdot 10^{-6} \text{ s}^{-1}$ for *I-131* [12].

Table 2.2

Method of determination	Resuspension rate, $\alpha \cdot 10^{-9} \text{ s}^{-1}$						Time of measurements
	<i>Ce-144</i>	<i>Zr-95</i>	<i>Nb-95</i>	<i>Ru-103</i>	<i>Cs-137</i>	<i>J-131</i>	
Gradient measurements	15,5	26	24	42	44	4200	11-13.06 (<i>Ru-103</i> -11.06)
Estimation of horizontal dust flux	-	1,6	1,2	4	10	-	11.06
By deposition flux	3,8	5,9	6,4	5,8	6,0	-	8-14.06

In /8/ the gradient method was used to measure the flux of radioactive dust and simultaneously wind speed at heights 4,0 and 15,0 m. The measurements were made in July-August 1992 in the area of Verbeby (about 10 km south-west of Novozybkov) in the ^{137}Cs contaminated field under rye. The values of α calculated by the measured data are in the range $(1.2 \div 1.5) 10^{-9} \text{ s}^{-1}$ and $(7 \div 8.6) 10^{-11} \text{ s}^{-1}$, given the contamination density is calculated by ^{137}Cs inventory in the upper 1 cm and 20 cm layer, respectively. The average wind speed was 2.2-2.8 m/s at the height of 15 m, the soil remained dry during the measurements.

In /19/ in numerical experiments using measurements of meteoroparameters and ^{137}Cs contamination density the resuspension rate in July 1992 was $2.24 - 2.4 \cdot 10^{-10} \text{ s}^{-1}$.

In /20/ a method has been proposed to determine the resuspension rate from concentration measurements at one level (in one point) which is the extension of the gradient method. This method is based on the fact that for a limited size of a dust-generating surface there is a height at which the concentration turns into zero, if the hypothesis on the finite velocity of turbulent scattering of material is adopted. The proposed method has been applied to estimate the resuspension rate and resuspension factor using measurements of concentration in the area of Novozybkov in April-May 1992. The radioactive aerosols were sampled on a gauze collector and a filter manufactured in "Typhoon". The average parameters of resuspension calculated by these data are $R=10^{-10} \text{ m}^{-1}$, $\alpha = 10^{-11} \text{ s}^{-1}$.

Extensive data on resuspension have been obtained by the authors of /1, 9, 10, 21, 22/ using ten-years observational series in the contaminated areas formed after the Chernobyl accident in 1986. Most of the experimental data were obtained by the gradient method. Table 2.3 /9, 10/ contains the resuspension rates obtained in September-October 1986 for different types of the

underlying surface: former arable field covered by grass, young pine forest with average tree height 5-6m, and the sandy bank of the Pripyt' river.

Table 2.3

Resuspension rate as a function of type of the underlying surface /9, 10/

Type of surface	Resuspension rate $\times 10^{-9}$ (s ⁻¹)		
	¹⁴⁴ Nd	¹³⁷ Cs	⁹⁵ Zr + ⁹⁵ Nb
Field	0.3 $\pm$ 0.1	1.0 $\pm$ 0.7	0.4 $\pm$ 0.2
Forest	2.1 $\pm$ 0.9	2.1 $\pm$ 0.8	3.7 $\pm$ 0.9
Pripyat bank	2.2	3.7	2.4

The data of table 2.3 show a systematic difference in the values of α for field, forest and beach. The values of α for forest are higher those for field by a factor of 2 to 9. The high values of resuspension rate is most probably attributed to the fact that the radionuclides depositions were fresh and did not migrate down the soil profile, it is also due to the fact that the dust-generating area is greater than in the forest which has a considerable canopy. The difference in the resuspension rate for field and beach is explained by the difference in the roughness length, which is lower in the latter case. The data were obtained for dry underlying surface, the average wind speed being ~ 2 m/s at the height of 1 m.

Table 2.4 and 2.5 /21,22/ include data on resuspension rate for 1992-94. The data were obtained for different anthropogenic activities, and mobility of people and using different methods of measuring airborne concentration of radioactive dust. It has been pointed out in /21/ that intense agricultural activities and movement of people can lead to a change in the resuspension rate by 1-2 orders of magnitude. This can be seen from the data for Zapolie (0.605.93÷10.05.93) and on the bank of the Pripyt (14.07.92 ÷16.07.92).

Table 2.4

 ^{137}Cs or $[\text{Pu}]$ resuspension rate

Site	Resuspension rate, s^{-1}
Zapolie 1992	1.1×10^{-13}
Beach Pripyat	1.1×10^{-11}
Zapolie 1993	1.7×10^{-12} [3.1×10^{-12}]
Novozybkov	4.4×10^{-13}
Kovali	1.3×10^{-11}

The data of Table 2.5 show that the magnitude of resuspension rate depends on measuring equipment, and the difference in data may be as large as several orders of magnitudes.

Table 2.5

Resuspension rate for ^{137}Cs

Site	Date	Means $\alpha \cdot 10^{-10}, \text{s}^{-1}$			
		Cone	impactor+AI10 GRAD	aspiration devices	gauze collector
Zapolie	13.05.92÷11.08.92	4.20±0.16	0.8±0.7	0.0011	0.44
Beach Pripyat	14.07.92÷11.08.92	0.08±0.07		0.11	
Zapolie	06.05.93÷01.06.92	1.60±1.20		0.017	
Kopachi	28.07.93÷03.08.93				
Novozybkov	17.05.94÷24.05.94			0.0044	
Mikulichi	13.07.94÷29.07.94			0.13	

On a whole, the resuspension rate from the underlying surface covered by grass according to data of /9, 10, 21, 22/ has decreased from $1 \cdot 10^{-9} \text{ s}^{-1}$ to $1.6 \cdot 10^{-10}$ (see Table 2.3, 2.4 and 2.5).

The works on resuspension rate suggest the dependence of this process on soil moisture. The attempts to estimate this dependence are made in /13, 23/. In /13/ the coefficients accounting for the effect on concentration of mineral dust in the air, the soil surface state, wind gradation and anthropogenic activity were obtained experimentally. The data are shown in Table 2.6.

Table 2.6

Coefficients of effects of mineral dust in the air on concentration

Soil surface			Wind			Anthropogenic activity		
dry	moist	wet	weak	moderate	strong	work days	week end	intense agricultural works
1.0	0.55	0.45	1.0	1.3	1.5	1.0	0.75	1.7

In [23] based on the physico-statistical analysis of data of systematic observations of radioactive contamination of the near-surface atmosphere, meteorological conditions in the summer-autumn period of 1992-1993 in Novozybkov and its vicinity, a scheme has been proposed for prediction of ^{137}Cs concentration in the air from data of standard agricultural and meteorological observations. The governing parameters for a specific area in the warm time of the year at regular speeds were the water content of the upper soil layer with allowance for precipitation, increased anthropogenic activity and mean daily wind direction. The latter is because the territory around Novozybkov from where radioactive dust can be transported is contaminated non-uniformly from $4 \cdot 10^4$ to above $1,40 \cdot 10^6$ Bq/m². The relation of the radioactive dust concentration q_n and the above parameters is proposed to be

$$q_n = (q/C)_m \cdot C_0 \cdot K_e \cdot K_p \cdot K_x \cdot K_v,$$

where q , C is ^{137}Cs and dust concentration in the air, respectively; $(q/C)_m$ is specific mean activity of ^{137}Cs in the air-born dust in the observational period, C_0 is mean concentration of the air-born mineral component in dust; K_e is coefficient accounting for water content of soil; K_p is coefficient accounting for anthropogenic activity, K_x is coefficient accounting for agricultural works; K_v is wind direction.

The coefficients K_m at $m=e, p, x$ are determined as a ratio of sample averaged concentrations $\bar{q}$ or $\bar{C}$ and corresponding value of concentration in the most frequent cases ($m=m_0$).

The comparison of the calculated and observed concentrations of ^{137}Cs in the air has shown good agreement.

2.3. Resuspension of radioactive dust particles in the air due to anthropogenic activities.

The resuspension associated with mechanical disturbances of the underlying surface which is hereinafter referred to as mechanical resuspension in accordance with [10] depends on the magnitude of the force applied, its nature, the depth of the layer to which the action is exerted and wind speed. The first experiments on mechanical resuspension of tracer ZnS (see [15]) during

walking of a man along an asphalt road 3 m wide and 15 m long covered with the tracer have shown that the values of mechanical resuspension rate vary significantly and may be higher the wind resuspension rate by a factor of 100. The results of the analysis of air samples collected when working the field contaminated with *Pu* and used for calculation of wind resuspension rates have shown that the wind resuspension rate during the agricultural operations depend on the type of the operation, field area and meteorological conditions and vary in a wide range 10^{-6} – 10^{-8} s⁻¹ during sowing and with vegetation removed; $4 \cdot 10^{-8}$ - $6 \cdot 10^{-8}$ s⁻¹ with disking and $3 \cdot 10^{-9}$ - $4 \cdot 10^{-7}$ s⁻¹ with harrowing.

In [21, 22] the wind resuspension rate during agricultural works in the fields contaminated after the Chernobyl accident was estimated with experimental data and numerical modelling. The starting data for modelling were specific measured values of surface contamination density 1.2; 0.45; 0.56 mBq/m² near Novozybkov, Mikulichi and Kovali, respectively and the meteorological characteristics obtained in 1994. The results of numerical modelling as airborne concentrations of radionuclides *q*, fluxes of radioactive particles of diameters less than 10 µm and more than 15 µm from the unit surface and wind resuspension rate calculated by these fluxes and emission rates of the particles are presented in Table 2.7.

Table 2.7

Radionuclides concentration in the air (q), flux of radioactive dust (Q),
mechanical resuspension (α).

Site and date of experimental data	q (mBq m ⁻³)	Q (< 10 μ m) (mBq s ⁻¹ m ⁻²)	Q (> 15 μ m) (mBq s ⁻¹ m ⁻²)	α (s ⁻¹)
Novozybkov 13.5	19.3	-	8.1	$6.8 \cdot 10^{-9}$
14.5	43.5	-	20.4	$1.7 \cdot 10^{-8}$
14.5	39.9	-	16.3	$1.4 \cdot 10^{-8}$
17.5	11.7	-	5.3	$4.4 \cdot 10^{-8}$
Mikulichi 30.7	25.6	0.2	5.5	$1.4 \cdot 10^{-8}$
31.7	8.7	0.4	1.2	$3.8 \cdot 10^{-8}$
01.8	30.7	1.6	4.7	$1.5 \cdot 10^{-8}$
02.8	127.0	0.9	20.6	$5.1 \cdot 10^{-8}$
Kovali 06.8	5.6	0.3	0.8	$2.0 \cdot 10^{-9}$

The mean mechanical resuspension rate in this case is $\sim(1.5 \pm 0.6) \cdot 10^{-8} \text{ s}^{-1}$ which is several orders of magnitude higher the wind resuspension rate. The data in Table 2.7 show that the flux from the soil of particles of diameter (d) more than 15 μ m is much larger than the flux of smaller particles, i.e. the derived mechanical resuspension rate should rather be referred to resuspension of particles with $d > 15 \mu$ m. Work /21/ indicates that the flux of radionuclides from unit length in Zapolie (10 km from Chernobyl) in the spring 1993 was 11 Bq/m⁻¹ s⁻¹ and 35 Bq/m⁻¹ s⁻¹ for the lifting particles with diameters $d < 10 \mu$ m and $d < 15 \mu$ m, respectively. During the same time period data on emission rate of soil particles with use of different kinds of machinery were obtained. These data are presented in Table 2.8.

It has been shown in /21/ that the particles emission rate is higher the mechanical resuspension rate by three orders of magnitude. It has also been noted that land band of 200 m between the zone of active mechanical working of soil and the rest of the area ensured a reduction in the air-born ¹³⁷Cs by two orders of magnitude.

Table 2.8

Soil particles emission rate with use of different kinds of machinery.
(Zapolie, 1993)

Date	Type of vehicle	Emission rate, 10^{-6} s^{-1}	Emission rate of particles with $d \leq 12 \mu\text{m}$, 10^{-6} s^{-1}
12.05.93 morning	IÖZ-82 (tractor)	0.027	0.004
13.05.93 morning	Ò-150 - “ -	1.5	0.16
13.05.93 afternoon	Ò-150 - “ -	2.0	0.20
22.05.93 morning	ZIL-131 car	1.0	0.09
22.05.93 afternoon	ZIL-131 - “ -	1.4	0.13
24.05.93 afternoon	ZIL-131 and ZIL-130	0.48	0.09

2.4. Doses due to wind and mechanical resuspension of radioactive dust.

Estimates of doses due to mechanical resuspension of radioactive dust during agricultural works on the contaminated areas according to data of 1994 are presented in /21/. The inhalation dose received by a tractor driver in 832 hours of work per year has been estimated to be 0.07 mSv for lungs and the effective dose is 0.02 mSv.

The annual inhalation dose due to wind resuspension does not exceed 0.003 mSv /21/ for lungs and the effective dose is 0.0006 mSv.

The calculation of average effective dose due to wind resuspension received in 50 years in the area affected by radioactive contamination as a result of the accident at the Siberian chemical plant in Tomsk-7 on 06.04.93 suggests that the atmospheric contamination will be insignificant and does not pose any threat to the population. The density of soil contamination with gamma- and beta- irradiating radionuclides was 5 Ci/km^2 .

By the standards of radiation safety of Russian Federation there are no restrictions on living and anthropogenic activity in the area in which the annual effective dose does not exceed 1 m Sv. So, the doses formed due to wind resuspension and mechanical resuspension do not present hazard for the population with time after the accident or at low level of soil contamination.

In conclusion of this section it should be said that since 1986 the works on wind resuspension rate α have been conducted on a regular basis.

By now the relationship between the wind resuspension rate and wind speed has been studied and analytical expressions to approximate this relationship have been derived.

The relationship of wind resuspension rate on roughness length, vegetation height and amount of vegetation in the form of air-dried biomass matter has been established.

Based on experimental data estimates of wind resuspension rate have been made.

The analysis of data obtained by different authors has shown that in 1986 the value of α was estimated at $(1 \div 10)10^{-9} \text{ s}^{-1}$ and in 1992 the values of α varied in the range $(1.1 \cdot 10^{-13} \div 2.4 \cdot 10^{-10}) \text{ s}^{-1}$ with the exception of data of /18/ where $\alpha (1.2 \div 1.5)10^{-9} \text{ s}^{-1}$ obtained in estimation of surface contamination density from ^{137}Cs content in the upper 1 cm soil layer.

It has been noted that the value of wind resuspension rate can vary by two orders of magnitude depending on the thickness of the upper soil from which the contamination density of the underlying surface is estimated.

The mean mechanical resuspension rate derived from data of 1994 corresponding to the situation in the population points Novozybkov, Mikulichi and Kovali is $1,4 \cdot 10^{-8} \text{ s}^{-1}$ which is several orders of magnitude higher the wind resuspension rate.

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3. Mass load.

When estimating the concentration of a contaminant in the air through determination of mass load detailed characteristics of soil during wind resuspension can be ignored and relation can be established between measurements of contaminant concentration in soil and air by the concentration of soil particles in the air. That is to say, the contaminant concentration in the air is expressed as a product of its concentration in the soil and concentration of soil particles in the air. If the number of soil particles in the air is known from some considerations, then theoretically for estimating contaminant concentration in the air, it is enough to measure concentration of contaminants in the soil. In a general case this can be written as

$$q = A_s \cdot C_d,$$

where q is concentration of contaminants in the air, A_s is specific concentration of contaminants in the upper soil layer, C_d is dust concentration in the air.

For such estimation two parameters are required: dust concentration in the atmosphere and contaminant concentration in the soil. By data obtained in UK in 1966 from the national air monitoring network, the average dust concentrations for urban stations are in the range 33-254 $\mu\text{g}/\text{m}^3$ and for rural - 9-79 $\mu\text{g}/\text{m}^3$ /5/. By the data of the national service of atmospheric monitoring the background air contamination levels /1, 2/ and air contamination levels averaged over a year for cities of the former USSR /3/ are 0.02-0,03 mg/m^3 and 0.20 mg/m^3 , respectively.

By data of /4/ obtained in July-August 1992 in the vicinity of Novozybkov the dust concentration varied from 30 to 170 $\mu\text{g}/\text{m}^3$ and the average value was equal to 95 $\mu\text{g}/\text{m}^3$.

The verification of the mass load method was conducted in /5/. Concentrations of some radionuclides in the air were measured and compared to concentrations calculated by the radionuclides concentration in the soil under the assumption of the air dust concentration of 100 $\mu\text{g}/\text{m}^3$. The results of comparison have shown the workability of the method. In /4/ the experimental values of ^{137}Cs concentration in the air above a cultivated field at the height 1.3 m (July-August 1992 in the vicinity of Novozybkov) were compared to the values calculated from measurements in the same period for counting dust concentrations in the air and specific activity of soil fractions. It has been estimated that the average over this period value of experimental concentrations is higher the average calculated concentrations of ^{137}Cs in the air by a factor of 1.4, which suggests that the method can be successfully used.

The difficulties in using the mass load method are related to estimation of dust concentration in the air. It should be noted that using data of air monitoring network can bring

in some uncertainties associated with the fact that the collected particles may include part of particles of industrial origin and therefore the results may be overestimation. Besides, samplers are not always placed in the zones of human inhalation.

Another issue is the dust origin. Fine particles in the air can be transported over long distances and as most of the contaminated areas are rather limited in size it can be assumed that only part of the dust originates from these areas and hence, the background dust can be assumed to be uncontaminated and finely-dispersed, i.e. the large particles deposit in the vicinity of the dust-forming source.

An important point is contaminant concentration in the soil. Soil particles entrained in resuspension have a small size, while the large ones deposit quickly. Therefore, if the concentration of contaminant in the soil fraction containing fine particles differs considerably from the concentration in other size fractions, then a low concentration can be expected which is predicted by mass load using the total soil concentration. In /2/ it was proposed to use the enrichment coefficient defined as a sum of products of q which are the ratio of proportion of total activity in the increment of the i -th size and the total mass of this fraction and f -proportion of mass of each increment of aerosol particle size. For soil particles with known distribution /5/ the calculated enrichment coefficient is 1.5.

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4. Calculation formulae for characteristics of wind resuspension of radioactive dust.

4.1. Formulae to calculate resuspension wind and resuspension factor.

The analysis of the available data on resuspension characteristics has shown that data are available and approximations have been derived for dependence of resuspension rate on wind speed [1, 2, 3], roughness length, height of grass cover and bush and phytomass [4]. Yet, resuspension rate has not been related to time in case of a long term period, i.e. for intervals more than 3 years, while for the wind resuspension factor there are many time-dependent approximations, but the dependence on other parameters has not been studied. It should be noted in this respect that all of the derived dependencies are empirical in character.

Therefore, we consider both the resuspension rate and resuspension factor and first establish the relation between these two characteristics. To pass from α to R we use the notion of characteristic rate in the near-surface layer $\bar{u}$,

$$\alpha = \bar{u} R,$$

or the effective rate of radioactive dust resuspension from the underlying surface v_α [6]

$$\alpha = v_\alpha \cdot R.$$

For the climatic conditions characteristic of the central part of Russia the effective rate is 2÷5 cm/s, for the nuclear testing ground in Nevada (USA) $v_\alpha = 5$ cm/s [6].

We use the approach to establishing the relation between the two characteristics of wind resuspension R and α proposed in [7, 8]. According to the Monin-Obukhov theory the expression for the difference in concentrations in the thermally stratified near-surface atmospheric layer is written as

$$q(z_2) - q(z_1) = \frac{Q}{\rho_1 u_*} \left[\ln \frac{z_2}{z_1} - \Phi\left(\frac{z_2}{L}\right) + \Phi\left(\frac{z_1}{L}\right) \right], \quad (4.1)$$

where q is radionuclide concentration in the air;

Q is vertical flux of radionuclides;

u_* is friction velocity;

L is the Monin Obukhov length scale of the atmospheric stability;

$\Phi\left(\frac{z}{L}\right)$ are universal similarity functions in the Monin-Obukhov theory;

$$\alpha_1 = \alpha / \text{Pr} ;$$

$\alpha=0.4$ is the von Karman constant;

$\text{Pr}=0.85$ is Prandtl number;

z_1, z_2 are fixed heights in the atmospheric surface layer.

Formula (4.1) is the basis for using the gradient method mentioned above.

If as z_2 we take the height δ at which $q(\delta)=0$, then

$$\alpha_1 = \frac{Q}{\alpha_1 u_*} \left[\ln \frac{\delta}{z_1} - \Phi\left(\frac{\delta}{L}\right) + \Phi\left(\frac{z_1}{L}\right) \right], \quad (4.2)$$

If for some considerations the value of δ is known then assuming $Q_s = \alpha C$ we get

$$\alpha = \frac{\alpha_1 u_* R}{\left[\ln \frac{\delta}{z_1} - \Phi\left(\frac{\delta}{L}\right) + \Phi\left(\frac{z_1}{L}\right) \right]}. \quad (4.3)$$

As the height δ as shown in /8/ we can take the surface layer height H , then

$$\alpha = \frac{\alpha_1 u_* R}{\left[\ln \frac{H}{z_1} - \Phi\left(\frac{H}{L}\right) + \Phi\left(\frac{z_1}{L}\right) \right]}, \quad (4.4)$$

or

$$R = f(H, z_1) \cdot \alpha, \quad (4.5)$$

where

$$f(H, z_1) = \frac{\left[\ln \frac{H}{z_1} - \Phi\left(\frac{H}{L}\right) + \Phi\left(\frac{z_1}{L}\right) \right]}{\alpha_1 u_*}. \quad (4.6)$$

Considering that the experimental data have been obtained in the conditions close to neutral stratification, we get

$$f(H, z_1) = \ln(H / z_1) / \alpha_1 u_*. \quad (4.7)$$

The measurements used for determining of resuspension characteristics are carried out at different heights from the underlying surface. Therefore, it is useful to introduce the height averaged resuspension factor as

$$\overline{R} = R(z) / \ln \delta / z, \quad (4.8)$$

or

$$\overline{R} = R(z) / \ln H / z$$

Then,

$$\alpha = \overline{R} \cdot \varpi u. \quad (4.9)$$

Using $\overline{R}$ for interpretation of measurements is preferable, as this factor does not depend on measurement height and hence is a more universal characteristic. Further, the consideration is based on the assumption that the wind speed is measured at the vane height (9 m), unless it is specified otherwise.

As noted above, that there are approximations for dependencies of resuspension rate on wind speed. These expressions, however, have been derived either for non-osculating speed intervals /1, 2/ or at the bounds of speed intervals resuspension rates change jumpwise /3/.

Analysing the available experimental data derived at different wind speeds and using the approximation formulae, two expressions for dependency of resuspension rate on wind speed have been derived

$$\alpha = 7,7 \cdot 10^{-9} u^{2,25}, \quad (4.10)$$

$$\alpha = 10^{-11} u^2 (0,012 u^3 - 0,65 u + 8,0), \quad (4.11)$$

for $0 \leq u \leq 15$ m/s.

Expressions (4.10), (4.11) combine the approximations derived earlier. Formula (4.10) is rather simple, but describes the available experimental data satisfactorily.

We will be using these two expressions. The values of α calculated by (4.10) and (4.11) are shown in Fig 4.1.

The expressions for $\overline{R}$ and R take the form

$$\overline{R} = \alpha / (\varpi \cdot u.),$$

$$R = \frac{\alpha \cdot \ln H / z}{\varpi u.}.$$

Assuming that the dependence R on time is written as (1.11), considering (4.10), (4.11) and substituting data $\varpi = 0,47$, $u. = c_d^{1/2} \cdot u$, $c_d^{1/2} = 0,07$, we get

$$R = 5,3 \cdot 10^{-5} u^{1,25} t^{-1,67}$$

$$R = 1,1 \cdot 10^{-5} t^{-1,67} u (0,012 u^3 - 0,65 u + 8,0)$$

where t is time after the accident in days. The expressions for resuspension rate will then be written as

$$\alpha = 5,1 \cdot 10^{-7} u^{2,25} t^{-1,67} .$$

$$\alpha = 1,05 \cdot 10^{-7} t^{-1,67} u^2 (0,012 u^3 - 0,65 u + 8,0)$$

Expression (1.11) has been chosen for describing the dependence of the resuspension factor on time because it has been derived with a fairly large volume of experimental data obtained in Chernobyl during a long observational period (more than 4 years) and in Haunover during 12-22 days after the accident.

For deriving the dependence of wind resuspension rate on the underlying surface characteristic such as roughness length works /1, 2, 4/ were analysed. In /4/ the dependence of α on z_0 has been obtained, the wind speeds varying in the range 2÷6 m/s. The data show that for wind speed in this range the relation between α and z_0 in the bilogarithmic scale is satisfactorily described by a straight line. Since the slope angle of this line is weakly dependent on the wind speed it can be assumed that such a dependence of α on z_0 is valid for a wider range of wind speeds. Taking into account that the experimental data /1, 2/ have been derived for $z_0=3,4$ cm and the relation α and z_0 is established for mean monthly wind speeds 2÷6m/s at height 10 m and assuming that all the data have been obtained in the atmospheric conditions close to neutral stratification, we get

$$R = \frac{2,8 \cdot 10^4 u^{1,25} t^{-1,67}}{z_0^{1,4}}, \quad (4.12)$$

$$a = \frac{2,7 \cdot 10^6 u^{2,25} t^{-1,67}}{z_0^{1,4}}, \quad (4.13)$$

$$R = \frac{6,1 \cdot 10^5 t^{-1,67} u (0,12 u^3 - 0,65 u + 8,0)}{z_0^{1,4}}, \quad (4.14)$$

$$\alpha = \frac{5,9 \cdot 10^7 t^{-1,67} u^2 (0,12 u^3 - 0,65 u + 8,0)}{z_0^{1,4}} \quad (4.15)$$

where z_0 is given in cm.

For the water surface $R, \alpha=0$ as the water surface is absorbing and radionuclides can be resuspended to the atmosphere only due to evaporation.

In the winter time when the soil is covered with snow no dust resuspension from the soil surface occurs, and therefore, R, α can be taken to be 0.

For the territories covered by forest there are few data on resuspension rate. It is known /3, 9, 10/ that α for forest, given fresh depositions of radionuclides, is 2÷9 times higher the resuspension rate for radioactive dust from the field. Results of numerical experiments, the starting data for which were observations of 1992-93 in Novozybkov, suggest that the resuspension rate α for forest is lower the corresponding α for meadow and arable land. Thus, in (4.12)-(4.15) in calculation of the averaged resuspension factor and resuspension rate R , α the empirical coefficient K_f is introduced for forest. As the comparison with experimental data has shown

$$\hat{E}_f = \begin{cases} 5, & \text{for the first year after the accident and forest as underlying surface;} \\ 1, & \text{for subsequent years and other types of underlying surfaces in the first year.} \end{cases}$$

The dependence of resuspension rate on moisture content of the upper soil layer has been already discussed above. This dependence can be taken into account by introducing a dimensionless factor K_m in (4.13). The dependence of this factor on the moisture content in the upper soil layer was obtained by analysis of field experiment /11/ and expert judgements /13/. Table 4.1 includes the values of K_m factor as a function of quality (visual) evaluation of moisture content of the upper soil layer using methodology /12/.

Table 4.1

Soil moisture class	Quality characterization of moisture in the upper soil layer	Soil-hydrological constant	Factor value K_m
1, 2	wet soil, puddles, surface layer is flowing or sticky	saturated soil	0.13
3	very moistened soil, soft	field specific retention	0.26
4	weakly moistened soil, hard	wilting point content	0.52
5	dry soil, loose	maximum hygroscopicity	1

The quality characterization of moisture content in the upper soil layer may be related to soil-hydrological constants. Table 4.1 shows the relation between the soil moisture classes and soil hydrological constants.

Coefficient K_m is incorporated in (4.12), (4.13) as a factor, as is the empirical coefficient K_f .

The anthropogenic activity influences the concentration of mineral dust in the air as well as radionuclides. In /2, 10, 13/ empirical coefficients for increase in radioactive dust concentration in the air due to anthropogenic and agricultural activities have been derived. Considering that the experimental data used for deriving the resuspension rate and resuspension factor have been obtained in field, meadow or forest where anthropogenic activity is insignificant, if any, and combining the data of /11, 12/ we get the values of anthropogenic coefficient K_a : on working days $K_a = 1.3$ for settlements and cities; $K_a = 1$ on weekend. K_a is included in (4.12) and (4.13) as a factor. It should be noted that here we do not include field agricultural works in anthropogenic activity and this will be considered separately.

We shall consider two other types of underlying surface: bog and soil partly covered with snow. In the first case, the radionuclide resuspension can occur from vegetation and hillocks. To estimate wind resuspension from the surface which is not dust-forming partially, the coefficient $K_w = S_r / S_t$ where S_r / S_t is ratio of areas of dust-forming and entire area.

So, based on the introduced factors, the resuspension factor and resuspension rate will take the form:

$$R = \frac{2,9 \cdot 10^4 u^{1,25} t^{-1,67} K_f \cdot K_m \cdot K_a (1 - K_w)}{Z_0^{1,4}}, \quad (4.16)$$

$$\alpha = \frac{2,8 \cdot 10^6 u^{2,25} t^{-1,67} K_f \cdot K_m \cdot K_a \cdot (1 - K_w)}{Z_0^{1,4}} \quad (4.17)$$

$$R = \frac{6,1 \cdot 10^5 t^{-1,67} u(0,12u^3 - 0,65u + 8,0) K_f \cdot K_m \cdot K_a \cdot (1 - K_w)}{Z_0^{1,4}} \quad (4.18)$$

$$\alpha = \frac{5,8 \cdot 10^7 t^{-1,67} u^2 (0,12u^3 - 0,65u + 8,0) K_f \cdot K_m \cdot K_a \cdot (1 - K_w)}{Z_0^{1,4}} \quad (4.19)$$

In (4.16)-(4.19) t is time since the accident in days.

4.2. Estimation of mechanical resuspension rate.

This section deals with description of areas of field agricultural works. As mentioned in 2.3, the radius of the zone is about ~200 m, and the ground band of approximately the same width serves to reduce the radionuclide concentration in the air by a factor of 2.

To estimate the mechanical resuspension, data of /9, 10/ are used. Summarizing results presented in these works we get that the rate of mechanical resuspension of particles α_m of all sizes $\sim (1.5 \pm 0.6) \cdot 10^{-8} \text{ s}^{-1}$. Considering the data of Table 2.7 this value rather applies to wind resuspension of particles with diameter more than 15 μm . Estimation of rate of mechanical

resuspension of respirable particles of smaller diameter ($d < 12\mu\text{m}$) by their emission rate from soil has shown that $\alpha_m \approx 0.11 \cdot 10^{-9} \text{ s}^{-1}$. For some kinds of agricultural machinery the mechanical resuspension rate was estimated by data of /9/ and the derived data are presented in Table 4.2.

Table 4.2

Mechanical resuspension rate with operation of some kinds of machinery

Kind of machinery	Mechanical resuspension rate α_m , 10^{-9} s^{-1}	
	particles with $d > 12 \text{ }\mu\text{m}$	particles with $d < 12 \text{ }\mu\text{m}$
Tractor MTZ-82	0,03	0,004
Tractor T-150	1,8	0,18
Vehicle ZIL-131	1,2	0,11

4.3. Comparison of calculated values α and R with experimental.

For comparison we take published experimental data. The main criterion for selection of data was availability of description of natural-climatic conditions of an experiment: wind speed, type of underlying surface, height and location of obstruction and soil moisture. The experiments on determination of parameters of wind resuspension of radioactive dust are usually conducted under conditions of neutral stratification of the atmosphere or close to them and therefore, it was assumed in the calculations that the profile of wind speed changes with height by the logarithmic law.

The resuspension factors R were calculated by (4.16) and (4.18) for time 15,117 days after the accident for September 1987-1991 and end May 1992. The wind speed and roughness length were taken to be equal to averaged-climatic values 3 m/s and 3.4 cm, respectively. The calculations were compared to experimental /8, 9/ averaged over separate years. As the calculations by (4.16) and (4.18) are close (see Table 4.3) fig.4.2 shows only one calculated curve derived by (4.16). Table 4.3 shows all resuspension factors R calculated by (4.16), (4.18) and corresponding experimental results /8,9/. The presented data show that the calculated and experimental values of R are in good agreement; the correlation factor estimated with these data is 0.9.

Table 4.4 includes starting data for calculations of resuspension rate α , the date of measurements, characteristics of the underlying surface, wind speed and height at which it was measured, source of information. The dashes in the table mean that the data are not available. These data were used to estimate parameters required for calculating resuspension rate α with formulae (4.17), (4.19). Table 4.5 includes the values of parameters, resuspension rates α calculated by (4.17) and (4.19) and those received empirically by the authors of works indicated in Table 4.4.

Table 4.3

Calculated and experimental wind resuspension factors R , s^{-1}

Time after accident day	R , s^{-1} (4.16)	R , s^{-1} (4.18)	R , s^{-1} /9/
15,0	$0,216 \cdot 10^{-5}$	$0,228 \cdot 10^{-5}$	$3,0 \cdot 10^{-6}$
117,0	$0,701 \cdot 10^{-7}$	$0,739 \cdot 10^{-7}$	$3,3 \cdot 10^{-8}$
482,0	$0,659 \cdot 10^{-8}$	$0,695 \cdot 10^{-8}$	$8,2 \cdot 10^{-9}$
847,0	$0,257 \cdot 10^{-8}$	$0,271 \cdot 10^{-8}$	$3,2 \cdot 10^{-9}$
1212,0	$0,141 \cdot 10^{-8}$	$0,149 \cdot 10^{-8}$	$1,4 \cdot 10^{-9}$
1577,0	$0,910 \cdot 10^{-9}$	$0,960 \cdot 10^{-9}$	$6,0 \cdot 10^{-10}$
1942,0	$0,643 \cdot 10^{-9}$	$0,678 \cdot 10^{-9}$	$8,0 \cdot 10^{-10}$

Table 4.5

Resuspension rate α calculated by (4.17) and (4.18) and calculation parameters

1	Time since accident	Roughness length	$\hat{E}_m$	$\hat{E}_f$	Wind speed at 9 m m/s	α , s ⁻¹ by (4.17), (4.18)	α_{exp} , s ⁻¹ , source
1.1	30	7	0,52	1	3,8	$6,36 \cdot 10^{-9}$, $6,14 \cdot 10^{-9}$	10^{-8} /15/
1.2	32	7	1	1	3,8	$1,10 \cdot 10^{-8}$, $1,06 \cdot 10^{-8}$	$4 \cdot 10^{-8}$ /15/
2.1	157	2	1	1	3,9	$4,72 \cdot 10^{-9}$, $4,52 \cdot 10^{-9}$	$1,0 \cdot 10^{-9}$ /9/
2.2	157	0,6	0,52	1	3,6	$1,11 \cdot 10^{-8}$, $1,09 \cdot 10^{-8}$	$2,1 \cdot 10^{-9}$ /9/
2.3	157	50	1	5	10,4	$2,37 \cdot 10^{-9}$, $4,23 \cdot 10^{-9}$	$3,7 \cdot 10^{-9}$ /9/
3.1	1855	0,7	1	1	2	$7,39 \cdot 10^{-11}$, $9,20 \cdot 10^{-11}$	$1,0 \cdot 10^{-10}$ /8/
3.2	1860	2,4	0,52	1	3	$1,70 \cdot 10^{-11}$, $1,79 \cdot 10^{-11}$	$1,4 \cdot 10^{-11}$ /8/
3,2,1	1865	3	1	1	2	$9,55 \cdot 10^{-12}$, $1,19 \cdot 10^{-11}$	$3,3 \cdot 10^{-11}$ /8/
4	2240	5	1	1	3,4	$1,13 \cdot 10^{-11}$, $1,14 \cdot 10^{-11}$	$7,8 \cdot 10^{-11}$ /16/

Table 4.4.

Starting data for calculating the resuspension rate

1	Underlying surface	Obstruction height and location	Experiment date	Soil moisture	Wind speed	Wind speed measurement height	Authors
1.1.	200 m - field covered by grass 100 m - bush, structures	30 - 40 cm, sparse individual	11.06.86	wet	2,1 m/s	1 m	Belyaev S.P. Surnin V.A. /15/
1.2.	200 m - field covered by grass 100 m - bush, structures	30 - 40 cm, sparse individual	13.06.86	dry	2,1 m/s	1 m	
2.1.	Cultivated field	-	September - october 1986	-	2,5 m/s	1 m	Hallander W. Garger E. /9/
2.2.	Beach Pripyat	-		-			
2.3.	Young pine forest	5 - 6 ì		-			
3.1.	Meadow arable land	-	22 - 27 May 1992	dry	1 - 2 m/s	9 m	Voszhennikov O.I. /8/
3.2.	Meadow arable land	-	1 - 10 June 1992	wet			
4.	Rye field		July-august 1992	dry	2,9 m/s	4 m	Naidenov A.V. Lukoyanov N.F. /16/

Results derived with (4.17), (4.19) and experimental data /13, 15-17/ are also presented in Fig 4.3. The experimental data are along the abscissa axis and results calculated by (4.17) and (4.19) are along the ordinate axis. The distance of signs from the regression line (the signs represent calculations) show the deviation of the experimental data from the calculated ones. The analysis of data of Tables 4.5 and 4.3 shows that formulae (4.17), (4.19) satisfactorily approximate the experimental data. The greatest deviation (almost an order of magnitude) occurs in the resuspension rate for the Pripyat river bank (2.2 Table 4.5). This difference is caused by the difference in the value of roughness length $z_0=0.6$ cm in the calculations and $z_0=2\div 6$ cm in /9/.

Returning to the initial data used for deriving approximation expressions, it should be pointed out that the resuspension rate α at large wind speeds u was earlier found to be proportional to u^5 . Therefore, expressions (4.18), (4.19) are recommended to be used at large wind speeds and roughness length and in other cases - (4.16) and (4.17).

In conclusion of this section let us summarize the main results:

- formulae for the resuspension factor and resuspension rate have been derived including the dependence of these parameters on time since the accident, wind speed, roughness length, type of the underlying surface, moisture content of the soil and intensity of anthropogenic activity;
- the values of mechanical resuspension rate for a general case and when operating machinery have been presented;
- the comparison of resuspension rates derived by (4.16)-(4.19) and experimental measurements shows good agreement between the data;
- the correlation factor for calculated and experimental data for the wind resuspension is 0,9;
- it is recommended that for calculating the resuspension factor and resuspension rate formulae (4.18) and (4.19) are used at large wind speeds and roughness length, while in other cases (4.16) and (4.17) should be used.

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5. Methodology for estimating the resuspension rate and resuspension factor and the flux of radioactive dust from the underlying surface.

5.1. Input parameters required for calculation.

For calculation of resuspension rate and resuspension factor from the underlying surface the following data are required:

t , days is time in days since the accident;

u , m/s is wind speed measured at 10 m height or recalculated for this height;

z_0 , cm is roughness length;

h , cm is height of obstructions;

K_m is characteristic of soil moisture content;

K_f is characteristic of the underlying surface (water surface, forest etc.);

K_w is a part of the area under water, snow;

K_a is the coefficient of anthropogenic activity;

A , Bq/cm² is density of radioactive contamination of the underlying surface;

H is height of the surface layer;

5.2. Roughness length.

Roughness is an important parameter in deriving the speed profile. The roughness length is usually designated by z_0 . The relation between the roughness length and measured characteristics of obstructions is the subject of many studies. For example, work [4] presents relations of roughness length z_0 and the average height of roughness components h_0

$$(h_0 / z_0) = e^2 \approx 7,39,$$

for widely spaced obstructions and

$$(h_0 / z_0) = 3 e \approx 8,15$$

for closely spaced obstructions.

The values z_0 /1, 2/ for most frequently occurring surfaces are shown in Table 5.1.

Table 5.1

Roughness length for different surfaces

Surface type	z_0 , m
Grass (1 cm height, meadow)	0,1
Grass (airport)	0,45
Grass (prairie)	0,65
Grass (artificial, 7,5 cm height)	1,0
Grass (dense to 10 cm height)	2,3
Mowed grass 1,5 m height	0,2
3 m height	0,7
4,5 m height at $U = 2$ m/s	2,4
at $U = 6-8$ m/s	1,7
Grass (sparse, to 50 m)	5,0
Wheat stubble (18 m; Êansas)	2,44
High grass (60-70 m) at $U = 1,5$ m/s	9,0
at $U = 3,5$ m/s	6,1
at $U = 6,2$ m/s	3,7
Grass (with sparse bush and trees Solsbery Plane, UK)	4,0
Inhomogeneous surface with alternating sections covered by grass, bush, trees etc. by measurements at masts in Obninsk (Kaluga region) and Round Hill (South Dartmouth, Massachusetts)	~ 10
Vegetation of 1-2 m height (c. Canaveral, Florida)	20,0
Trees of 10-15 m height (c. Canaveral, Florida)	40 - 70
Young oak trees of mean height 10 m by measurements in Brukhaven (New York)	~ 100
Bush savanna (25 % - trees of 8 m height; 65 % - dry grass of 1 m height; 10 % - burnt grass and sand)	40
Urban area with high buildings, by measurements at TV masts in Leningrad and Novosibirsk	~ 100
A large city (Tokio, Japan)	165

5.3. Calculation of the resuspension factor and resuspension rate.

Using the available data on wind speed, roughness length and other parameters mentioned in 5.1 the resuspension factor and resuspension rate are calculated with the following formulae:

$$a = \frac{2,8 \cdot 10^{-6}}{Z_0^{1,4}} K_m K_f (1 - K_w) K_a u^{2,25} t^{-1,67}, \quad \text{at } u \leq 10 \text{ m/s} \quad (5.1)$$

$$a = \frac{5,8 \cdot 10^{-7}}{Z_0^{1,4}} K_m K_f (1 - K_w) K_a u^2 t^{-1,67} (0,012u^3 - 0,65u + 8,0), \quad \text{at } 10 < u \leq 15 \text{ m/s} \quad (5.2)$$

$\alpha_i = (1,5 \pm 0,6) \cdot 10^{-8} \text{ s}^{-1}$ for the area where agricultural works are conducted;

$$R = \frac{2,9 \cdot 10^{-4} u^{1,25} t^{-1,67} \cdot K_m \cdot K_f \cdot (1 - K_w) \cdot K_a}{Z_0^{1,4}}, \quad \text{at } u \leq 10 \text{ m/s}$$

(5.3)

$$R = \frac{6,1 \cdot 10^{-5} u^5 t^{-1,67} \cdot K_m \cdot K_f \cdot (1 - K_w) \cdot K_a}{Z_0^{1,4}}, (0,012u^3 - 0,65u + 8,0), \quad \text{at } 10 < u \leq 15 \text{ m/s}$$

(5.4)

5.4. Flux of radioactive dust from the underlying surface.

The flux of radioactive dust from the underlying surface Q is written as

$$Q = \alpha A$$

by substituting (5.1) for α , we get

$$Q = \frac{2,8 \cdot 10^{-6} \cdot t^{-1,67} K_f \cdot K_m \cdot K_a \cdot (1 - K_w) \cdot u^{2,25}}{Z_0^{1,4}} \times A.$$

For (5.2) the formula is derived in a similar way.

The flux of radioactive dust due to mechanical resuspension is calculated by the formula

$$Q = \alpha_i \cdot A.$$

Thus, using the measured and calculated wind speeds, roughness length, with allowance for the number of days since the accident, moisture content and type of the underlying surface we can calculate the flux of radioactive dust from the contaminated underlying surface due to wind resuspension.

5.5. Calculation of wind resuspension characteristics using the mass load method.

5.5.1. Input parameters for calculation with the mass load method.

A_s , Bq/g is specific radionuclides content of the underlying surface;

A , Bq/m² is radioactive contamination density of the underlying surface;

q_1 , Bq/m³ is radionuclides concentration in the air at height of 1 m;

C_1 , g/m³ is dust concentration in the air at height of 1 m;

u_g , m/s is friction velocity;

H , m is height of the surface layer.

5.5.2. Calculation of the resuspension factor, resuspension rate and flux of radioactive dust.

The radionuclides concentration in the air is calculated by

$$q_1 = A_s \cdot C_d.$$

Then, $R = q_1 / A$

Considering that

$$q_1 = \frac{Q}{\alpha u_*} \ln \frac{H}{z_1},$$

where $\alpha = \alpha_1 / \text{Pr}$, $\alpha_1 = 0.4$ is Karman constant, $\text{Pr} \approx 0.85$ is Prandtl turbulent number, $z_1 = 1$ m, Q is vertical flux of radionuclides, we get

$$\alpha = \frac{\alpha_1 u_* R}{\ln H / z_1}$$

$$Q = \frac{\alpha_1 \cdot u_* \cdot A_s \cdot C_d}{\ln H / z_1}.$$

The dust concentration is taken from the data of the state atmospheric monitoring service as a characteristic value or year-averaged (season or month averaged).

If q_1 is known, the resuspension rate and radionuclides flux is calculated by the above formulae.

For conservative estimation the following values of the basic quantities are used:

1) if the dust concentration in the air is not known, then it is assumed that $C_d = 100$ $\mu\text{g}/\text{m}^3$

2) if the information about A_s is not available, then

$$\dot{A}_s = \frac{A}{\rho_s \cdot \delta_s},$$

where $\rho_s = 10^{12} \text{ } \mu\text{g/m}^3$ is soil density,

$\delta_s = 0.005 \text{ m}$ is thickness of the upper soil layer;

3) ageing of radionuclides is taken into account by introducing the time factor

$$\dot{A}_s = \frac{A}{\rho_s \cdot \delta_s} \cdot t^{-1,67},$$

where $t \geq 1$ is time since the beginning of the accidental release.

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6. About estimation of atmospheric contamination with burning radioactive materials.

After the zones of radioactive contamination as a result of the Chernobyl accident were formed the radioactivity of the atmospheric surface layer in these and adjacent zones was determined primarily by the processes of wind resuspension and transport of radionuclides during strong wind and due to fires. In the course of a forest fire burning products such as soot, ash and moisture are released into the atmosphere, and the concentration of radionuclides in them can exceed the permissible concentration in the air.

The radionuclides deposited in the forest around the Chernobyl NPP are distributed as follows: about 5% occur in the stock of trees, 20÷85% in the litter and the rest in the mineral soil layer, and with time the radionuclides content increases both in the stock and in the mineral soil layer /1, 2/.

In 1991-1994 22 major and medium size forest fires occurred in the area around the Chernobyl NPP covering 3.9 thousand hectares of forest /3, 4/. The fire risk season in this area starts when the snow cover melts and lasts till rainy autumn weather or formation of snow cover. The largest number of forest fires (65%) occurs in spring, 25% - in the autumn and 10% in the summer.

Depending on the way of fire propagation in the forest the fires are divided into lower (55%) and upper (30%) level fires and others are transitional and underground. The number of major forest fires (area of more than 200 ha) was 9%, medium-size (from 100 to 150 ha) 28% and local (less than 100 ha) 63%. The number of forest fires on the territory with ^{137}Cs contamination of more than 5 Ci/km² constituted 68%, 23% of fires occurred on the territory with contamination level from 15 to 40 Ci/km² and others - on the territory with contamination level more than 100 Ci/km².

From 19 to 25 April 1996 in some areas of the Bryansk region including those affected by Chernobyl depositions forest fires occurred. The areas under the fires in hectares, their duration and ^{137}Cs contamination of fuel material are presented in Table.

By data of /4/ after the lower fire about 20% of the initial vegetation mass remains in the forest litter, with the upper fire - 70% and with transitional 35%. During a local forest fire the smoke plume can be as high as 0.4-1.5 km., the plume length - to 30 km and the concentration of suspended smoke particles in the air - 100 mg/m³. During the fire the mineralization of the forest

litter and organic matter in the upper part of the soil profile occurs which results in a hazard of wind erosion, acceleration of wash-off and infiltration of radioactive zone in the natural landscape.

Table

Fires in the Bryansk region, 19-25 April 1996

1	District	Area under fire ha	Mean contamination density Ci/km ²	Activity of burning products, Ci		Duration hour
				by (6.1)	by model /6/	
1	Novozybkovsky	3,4	15	0,029	0,025	5
2	Krasnogorsky	675	10	3,847	3,400	65
3	Pogarsky	20	1	0,011	0,010	11
4	Zlynkovsky	7	25	0,100	0,090	7
5	Unechsky	6,6	0,3	0,001	0,001	6
6	Trubchevsky	50	0,6	0,017	0,015	18
7	Mglinsky	6,6	0,2	0,001	0,001	6
8	Klintsovsky	12,4	0,4	0,003	0,025	9
9	Kletnyansky	22,3	0,2	0,003	0,002	12

Hence, forest fires in the area of radioactive contamination is an important factor of radioecological risk due to

- external exposure to gas-aerosol smoke cloud and a trace of burning radioactive materials on the soil;

- internal exposure due to inhalation of radioactive smoke and consumption of food contaminated by radionuclides.

For calculation of the activity of volatile fire products the following data need to be known:

type of the fire (lower, upper etc);

burning material contamination density, A_s , Bq/m²;

fire length T , hour;

coefficient accounting for the content of volatile particles in the burning products ε , %;

fire area S , m².

If the coefficient of the content of volatile particles in the burning products has not been specified, its value is taken to be $\varepsilon \approx 3.5\%$ for the forest litter burning (with moisture of 40%) and $\varepsilon \approx 5.7\%$ for burning of pine branches and needles (moisture 15%).

The release strength for volatile burning products N is determined by the formula

$$N = S \cdot \varepsilon \cdot A_s / T, \text{ Bq s}^{-1}, \quad (6.1)$$

activity of burning products:

$$A = S \cdot \varepsilon \cdot A_s, \text{ Bq}. \quad (6.2)$$

As an example, let us consider the fire forest in the Bryansk region in 1996. The data derived with (6.2) are given in Table. It also contains the activities of burning products calculated with 3-D Lagrangian model of atmospheric transport /6/.

The data in the Table, except the Klinty district, are in good agreement, which lets us recommend formula (6.2) for estimating the activity of burning products formed during forest fires.

Thus, the parameters required for estimation of activity of forest fires burning products have been derived. Estimation was made based on specific data of forest fires in the Bryansk region in April 1996. It has been shown that formula (6.2) can be used for estimating the activity of burning products.

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Conclusion

The performed analysis of the literature data on wind resuspension of radionuclides into the atmosphere from the underlying surface has demonstrated that

- data are available on the resuspension factor and resuspension rate obtained by measurements;
- approximation expressions accounting for the change in wind resuspension factor with time, and resuspension rate dependence on roughness length and wind speed have been derived;
- the average effectiveness of mechanical resuspension according to the data of 1994 is $(1,5 \pm 0.6) 10^{-8} \text{ s}^{-1}$;
- the mass load method is workable.

The results of the performed study include

- Expressions for the resuspension factor and resuspension rate have been derived including their dependence on time since the accident, wind speed, roughness length, type of the underlying surface, moisture of the soil, intensity of anthropogenic activity.
- It has been shown that the wind resuspension rates derived in this work and those based on experimental measurements are in good agreement.
- It has been found that the correlation factor for the calculated and experimental data on the wind resuspension is 0.9.
- It is recommended that equations (4.18) and (4.19) are used for calculating the resuspension factor and resuspension rate at large wind speeds and roughness length and in other cases - (4.16) and (4.17) should be used.

APPENDIX

Description of program module **RESUSP**

Program module written in FORTRAN/9000 calculates next quantities (output variables):

R is resuspension factor;

alpha is resuspension rate;

Q is flux of radioactive dust from the surface.

Input variables are subdivided into essential, which are always used in program (their definition is compulsory) and optional ones. Optional variables (friction velocity **Udyn**, height of surface layer **Hsfl**) are estimated with conventional parameterization or by default. Another optional variables (specific radionuclides content in the upper soil layer **AmSoil**, radionuclides concentration in the air **A1mAir**, dust concentration in the air **CAir**) are used only if experimental data are available direct assessment of resuspension characteristics without using of parameterizations.

Two different parameterizations are used for calculation of factor **R** (and accordingly for **alpha** and **Q**). The parametrization is changed when wind speed goes beyond the value of 10 m/s. Also there is a switch (**mach**) for choosing specific definition of **alpha** and **Q** in the region where agricultural machines operate.

Fig.4.1. Wind speed dependence of resuspension rate calculated by various approximations.

Fig.4.2. Time-dependence of the res

Fig.4.3. Resuspension rate/s.

c Program module RESUSP(R, alpha, Q)

c OUTPUT VARIABLES

c R, 1/m - resuspension factor
c alpha, 1/s - resuspension rate
c Q, Bq/(m2*s) - flux of radioactive dust from the surface.

c SPECIFICATION OF INPUT VARIABLES

c t, day - number of days after an accident (t >= 12);

c u, m/s - wind speed on height 10 m (1 <= u <= 15);
c Udyn, m/s - friction velocity (optional);

c Hsfl, m - height of the surface layer (optional);

c z0, cm - roughness length (z0 <= 0.1);
c h, cm - average height of roughness components;

c ms - parameter of moisture of soil, it has following
c values:
c 1 - near saturated soil moisture content
c 2 - field capacity
c 3 - wilting point content
c 4 - hygroscopic coefficient

c forest - a switch for accounting for occurrence of forest in
c the region (0 or 1)
c (this parameter is used only during the first year
c after an accident);

c Kw - part of the surface covered with snow or water
c (from 0 to 1);

c Ka - coefficient of anthropogenic activities
c (1 - outside and inside a town on weekends
c Sunday;
c 1.3 - inside the town on other days);
c mach - attribute of presence of agricultural machinery operation
c (=1 when such activities take place);
c AdSoil, Bq/m2 - soil surface contamination density in t days after
c accident;
c AmSoil, Bq/g - specific radionuclides content in the upper (1 sm) soil
c layer in t days after an accident (optional);
c AlmAir, Bq/m3 - radionuclides concentration in the air at height of 1 m
c in t days after an accident (optional);
c CAir, g/m3 - dust concentration in the air at height of 1 m in t days
c after an accident (optional).

subroutine RESUSP(R, alpha, Q)
real Kw, Ka, Kf, Ws(4)

```

integer forest, flag
common /Essent/ t, u, z0, h, ms, forest, Kw, Ka, AdSoil, mach
common /NEssent/ Udyn, Hsfl, AmSoil, AlmAir, CAir
data Ws/0.13, 0.26, 0.52, 1/

if(mach.ne.1) then

c default parameter definition and range limitation:
  if(t.lt.12.) t=12.
  if(u.lt.1.) u=1.
  if(u.gt.15.) u=15.
  if(Udyn.le.0.) Udyn=0.07*u
  if(Hsfl.le.0.) Hsfl=30.
  if( (z0.lt.0.1) .and. (h.lt.0.8) ) z0=5.
  if( (z0.lt.0.1) .and. (h.gt.0.8) ) z0=h/8.
  if( (ms.lt.1) .or. (ms.gt.4) ) ms=4
  if(AdSoil.le.0.) then
    R=0
    alpa=0
    Q=0
    go to 1
  endif

c including forest
  if( (t.lt.365.) .and. (forest.eq.1) ) then
    Kf=5.
  else
    Kf=1.
  end if

c Choosing of parameterization:
  flag=1
  if(u.ge.10.) flag=2

c Checking of experimental data availability
  if ( (AlmAir.le.0.) .and. (CAir.le.0.) ) then

c Calculating with use of parameterization
  xxx= t**(-1.67) * z0**(-1.4) * (1-Kw) * Ka * Kf * Ws(ms)
  select case (flag)
    case (1)
      R = 2.8e-4 * u**1.25 * xxx
    case (2)
      R = 6.1e-5 * (0.012*u**4-0.65*u**2+8.*u) * xxx
  end select

c Assessment with experimental data (using concentration
c                                     of radionuclide AlmAir)
  else
    if (AlmAir.gt.0.) then
      R = AlmAir/AdSoil
    else

c Assessment with experimental data (using dust concentration CAir)
  R = CAir*AmSoil/AdSoil

```

```

        end if
        end if
        alpha = 0.47 * Udyn * R / ALOG(Hsfl)
        else
        alpha = 1.5e-8
        endif
        Q = alpha * AdSoil
1      continue
        return
        end

```

c Example of calling module RESUSP

```

        program main
        real Kw, Ka
        integer forest
        common /Essent/ t, u, z0, h, ms, forest, Kw, Ka, AdSoil, mach
        common /NEssent/ Udyn, Hsfl, AmSoil, AlmAir, CAir

        open(unit=1,file='dat')
        read(1,*)
        read(1,*) t, u, z0, h, ms, forest, Kw, Ka
        read(1,*)
        read(1,*)
        read(1,*) AdSoil, AmSoil, AlmAir, CAir
        call RESUSP(R, alpha, Q)
        close(unit=1)

        open(unit=2,file='out.dat')
        write(2,*) ' R=', R, '      alpha=', alpha, '      Q=', Q
        close(unit=2)
        stop
        end

```

t	u	z0	h	ms	forest	Kh	Ka
1000.	3.	5.	0.	4	0	0.	1.
AdSoil	AmSoil	AlmAir	CAir				
5.e5	0.	0.	0.				

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