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ELEMENTS OF A UNIFIED PROGNOSTIC MODEL FOR SECONDARY AIR CONTAMINATION BY RESUSPENSION

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Abstract. Based on results of several joint experimental campaigns and an extensive literature survey, a prognostic model was constructed capable of predicting airborne activity concentrations and size distributions as well as soil surface activity concentrations as a function of time and meteorological conditions. Example scenario calculations show that agricultural practices are of lesser importance to secondary air contamination than dust storms immediately after primary deposition and forest fires.

1 INTRODUCTION

The Chernobyl accident has affected and still affects many people. Mitigation of these effects is one priority. Another priority must be to analyze and understand the behaviour of radionuclides in the environment so that in the event of a future accident, predictions can be made and remedial actions can be taken based on rational strategies.

1.1 THE IMPORTANCE OF RESUSPENSION

Once soil particles have become airborne, they will be picked up by the wind. The turbulent motion of the wind disperses the particles so that their overall concentration decreases while the dimension of the cloud increases. In addition to this process, which conserves the total airborne mass, particle deposition may take place: cloud or rain processes may scavenge particles and bring them down to the surface by this so-called *wet deposition.* In addition, particles may have a relative motion with respect to the air parcel to which they belong. Eventually, they may settle due to gravity, or impinge on flow obstacles like plants, rocks etc due to their inertia or by diffusive motion which is prevalent for small particles. All the latter processes contribute to *dry deposition.*

From the surface, they may migrate into the soil, become dissolved and carried away by groundwater, and taken up by plants. Yet there is still the possibility that nuclides already deposited on the surface may become airborne again by a process called resuspension: It is important since it provides a potential vector for secondary contamination of already decontaminated areas, and an occupational risk for people working in agriculture.

In the Experimental Collaborative Project ECP1, natural and anthropogenic nuclide resuspension was studied in the neighbourhood of Chernobyl. The general objective of ECP1 was to enhance understanding of the various mechanisms leading to resuspension and secondary contamination, and to start building up a predictive capability for airborne

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concentration (and its radiological consequences) caused by resuspension by using all available literature data.

1.2 ELEMENTS OF RESUSPENSION, ATMOSPHERIC TRANSPORT, AND DRY DEPOSITION.

The following information is required for understanding and predicting resuspension, atmospheric transport, and dry deposition:

- The soil nuclide specific activity and its depth distribution as a function of time. The most important parameter is of course the specific activity at the very surface from where resuspension actually takes place.
- The airborne mass concentration (in mg/m^3) which also depends on wind speed, soil humidity, and anthropogenic activities of different kinds
- The soil-air transfer factor which relates the specific activity of the soil surface with the specific activity of the airborne dust for a variety of soil types, and as a function of wind speed, soil humidity, and anthropogenic activities of different kinds.
- The atmospheric transport factor which takes into account atmospheric dilution as well as dry deposition. Wet deposition is not considered here since it was found that during wet weather resuspension is greatly reduced.
- Based on these data, the atmospheric nuclide concentration and the inhalation exposure of risk groups can be assessed as well as the potential speed of secondary contamination of already decontaminated areas, and the possibility of land reclamation. This requires, however, knowledge of the primary airborne particle size distribution and its temporal evolution.

2 MODELLING

The ECP1 experiments were performed in order to generalize the description of resuspension as far as possible with the goal of building up a predictive capability for secondary airborne radioactivity. Questions to be answered (preferably on the basis of data collected during ECP1) concern

- the migration of hot spots, and the recontamination of already decontaminated areas by natural as well as anthropogenic resuspension, and
- the health impact on occupationally exposed agricultural workers

Normally, there are two main steps in resuspension. First of all, through hydrodynamic (wind) stress or mechanical disturbance (like agricultural activity), particles carrying activity will be separated from the soil matrix and become airborne in a layer close to the ground. Therefore, for modelling we need source-specific activities (of soil, firewood etc), and gravimetric source strengths which depend on soil properties and the types of resuspension. Subsequent atmospheric transport has to be covered in the next step. All our own data, and many from the literature are compiled in the present chapter and parameterized so that easily airborne concentrations for a wide variety of situations can be predicted in terms of size distribution and concentration as a function of source distance. To achieve this, we need a

- source characterization module, a
- transfer module, and a
- resuspension/transport/deposition module.

Using these modules we can perform comprehensive modelling and discuss the results of selected example scenarios.

2.1 SOURCE CHARACTERIZATION MODULE

There is a variety of potential sources like wood, pollens, sea spray etc which cannot be discussed here but are dealt with in the ECP1 Final Report [1]. Focusing on soil resuspension, the single most important aspect is without a doubt the soil surface activity. Initially, the deposited nuclides rest in a very thin layer at the surface. Later on, the contamination will migrate into the soil by leaching, dissolution, and capillary effects which can be described mathematically by convective diffusion. The specific soil activity (A_s in Bq/kg) is a solution of the convection-diffusion equation fulfilling the boundary condition $\frac{\partial A_s}{\partial z}|_{z=0} = 0$ which is initially δ-distributed and is given by (with the soil density ρ)

$$A_s(z,t) = \frac{\sigma}{\sqrt{2\pi}\cdot\rho\cdot s(t)}\cdot\left\{\exp\left[-\frac{(z-u\cdot t)^2}{2s(t)^2}\right]+\exp\left[-\frac{(z+u\cdot t)^2}{2s(t)^2}\right]\right\} \tag{1}$$

The above boundary condition is approximately fulfilled if the mass transfer rate into the soil is much faster than into the air which is the case unless there is a dust storm. The dispersion s(t) is given by $s(t) = \sqrt{2Dt}$ with the diffusion coefficient D and the convective velocity u. Then, the relation between the surface contamination density σ and the specific soil activity $A_s(z,t)$ is given by $\sigma = \rho\int_0^{-\infty} A_S(z,t)dz$. Note that σ does not depend on time if radioactive decay is disregarded. If it is taken into account, $\sigma(t) = \sigma_0\cdot\exp(-\lambda_N t)$. λ_N is the effective half life of nuclide N including radioactive decay and terrestrial transport by e.g. solution etc. Both, the convective velocity and the diffusion coefficient can be determined from experimental nuclide profiles at a certain time. Typical values for D are in the range10^{-8} cm²/s and for u in the range 10^{-10} cm/s. Examples for depth distribution profiles for different times are shown in Fig. 1. It is important to note that the the temporal evolution of the surface activity concentration $A_s(z=0,t)$ follows a $t^{-0.5}$-dependence.

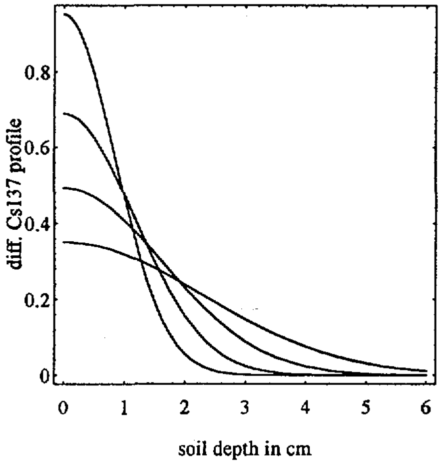

Fig. 1: *The convective diffusion model based on fits to experimental profiles allows the activity concentration profile for other times to be calculated: shown are curves for 2, 4, 6, and 8 years after deposit in Zapolye. Distributions spread out in time, and surface concentration decays with the inverse square root of time.*

2.2 TRANSFER MODULE

The purpose of this module is to describe depletion and enrichment during the resuspension process and to link the easily available soil-specific activity information with the specific activity of airborne dust. This is not a trivial question as radionuclides may have their own particle size distribution which can be different from the soil distribution; therefore, dispersion and fractionation may occur. The soil-air transfer function $T_{s\rightarrow a}$ relates the specific activities of air and soil via $A_a = T_{s\rightarrow a} A_s(z=0)$. It is expected to have a complex dependence on soil type and humidity, wind speed and mechanical activity. Indeed, this was observed as Figure 2 shows, but so far, we have no explanation for this behaviour: It may be due to the dispersion process or simply reflect the size and transport distance dependence of the specific activity since the median diameter changes from approx. 4 μm for low concentrations to about 50 μm for concentrations measured by means of the SSRT [2].

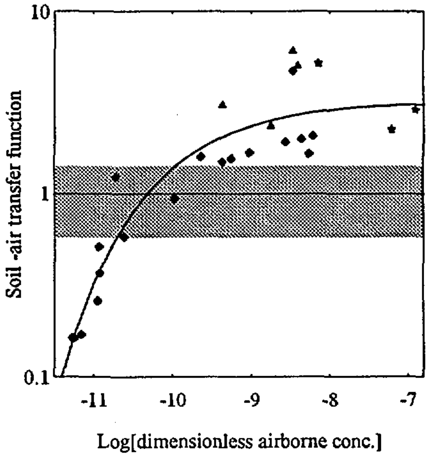

Figure 2: *Soil-air transfer function* $T_{s\rightarrow a}$ *as a function of the decadic logarithm of the dimensionless airborne Cs137 concentration (which is given by the ratio of airborne activity concentration in Bq/m³ to soil surface concentration also in Bq/m³). All data from natural and anthropogenic resuspension in Zapolye are included (diamonds). Anthropogenic experiments from Bragin are shown as triangles, and SSRT experiments from Bragin as stars. The shaded area is the typical experimental scatter of soil samples. It can be clearly seen that the transfer factor is positively correlated with airborne concentration, and becomes saturated for high concentrations at* $T_{s\rightarrow a} \approx 3.4$.

As of now, not enough data are available for a scientifically sound parameterization procedure. It is therefore suggested to assume neither depletion nor enrichment during the resuspension process, i.e. $T_{s\rightarrow a} = 1$. For conservative estimates, $T_{s\rightarrow a} = 3.4$ could be used for all nuclides.

2.3 RESUSPENSION/TRANSPORT/DEPOSITION MODULE

From the two preceding modules, specific activities of airborne dust can be obtained. If we now provide a scheme to calculate gravimetric airborne particle size distributions and concentrations as a function of source type and transport distance, the prognostic problem is essentially solved.

Wind is the only factor stirring up particles in natural resuspension. In contrast, anthropogenic resuspension is characterized by mechanical soil disturbance with the wind acting as vector only. Because of this different nature both processes are treated separately.

2.3.1 NATURAL RESUSPENSION

Depending on whether an actual or an average forecast is necessary, the input data required will be different. The two following subsections describe possible approaches.

2.3.1.1 Gravimetric area source strength

Natural resuspension and wind erosion are extremely complicated and not well understood processes, partly because measurements are extremely difficult [3]. Due to the lack of a general consensus concerning the numerical dependence of vertical flux density on wind speed, we (more or less arbitrarily) choose the relation of Gillette [4]

$j_\uparrow = \psi \cdot u_*^5$ where the empirical constant is $\psi = 3\cdot 10^{-6}\frac{kg\cdot s^4}{m^7}$ (2)

The power exponent is well in the range of values reported in the literature. According to Gillette, this relation approximately holds for many soils but the error margin may well be plus/minus two orders of magnitude.

As an applicability check, the above formula was applied to our measurements in Zapolye. Assuming resuspension - deposition equilibrium, for each particle size $j_\uparrow = v_\downarrow \cdot c$ (3)

Since the soil particle size distribution was found to be close to log-normal with a mass median aerodynamic diameter of $d_0 \approx 100\mu m$ and a geometric standard deviation $\sigma_g \approx 3.55$, the airborne equilibrium particle size distribution of the concentration c is proportional to

$$c \propto j_\uparrow / v_\downarrow \propto j_\uparrow / d_{ae}^2 \qquad (4)$$

It is therefore given by the -2nd moment of the soil particle size distribution (for details of the method see ECP1 Final Report). This is due to the fact that the deposition velocity is closely approximated by the sedimentation velocity which is $\propto d_{ae}^2$. According to the Hatch-Choate conversion formula [5], the median of the q-th moment of a log-normal distribution with median d_0 is given by

$$d_q = d_0 \cdot Exp\left[q \cdot \ln^2 \sigma_g\right] \qquad (5)$$

Then, with q = - 2, we obtain a median diameter of 4 µm and a $\sigma_g \approx 3.55$ for the airborne soil resuspension-deposition equilibrium size distribution from the above considerations. This is in remarkable agreement with the experimentally determined distribution of the natural resuspension event shown in Fig. 3.

Using the total airborne mass concentration of 57 µg/m³, we arrive at a measured resuspension flux density of $j_\uparrow = 3.7*10^{-7}$ kg/(m²s) which implies an ensemble average deposition velocity of 6.5 mm/s corresponding to a particle size of 14 µm which is reasonable for the distribution of Fig. 3. These values also compare favourably to the flux density of $9*10^{-8}$ kg/(m²s) suggested by Gillette's formula assuming Berlin wind statistics and $u_* = 0.1*u$. We therefore consider it a reasonable basis for assessing the resuspension flux density under natural conditions in the Chernobyl area.

Equation (2) should be applied for (nonequilibrium) area source scenarios in conjunction with the specific soil activity and the soil-air transfer function yielding the activity area source strength in Bq/(m²s). The resulting airborne activity concentrations can then be calculated from a suitable theory [6], not always easily, however.

2.3.1.2 Long-term resuspension behaviour

A more direct and frequently used approach to immediately estimate airborne activity concentrations is via the resuspension factor R. It is defined by the ratio of airborne contamination concentration c (in Bq/m^3) at a certain reference height (which is usually not well defined) and surface contamination density σ (in Bq/m^2) i.e.

$$R = \frac{c}{\sigma} \qquad (6)$$

From this definition it follows that it can be strictly applied under equilibrium conditions only since for instance contamination tranported by advection into an uncontaminated area where σ is zero would lead to an infinite resuspension factor, and we still have the problem with σ. On the other hand, under equilibrium conditions, the resuspension rate $\beta_\uparrow = j_\uparrow / \sigma$ is proportional to the resuspension factor i.e. $\beta_\uparrow^{eq} = R \cdot v_\downarrow$ (7)

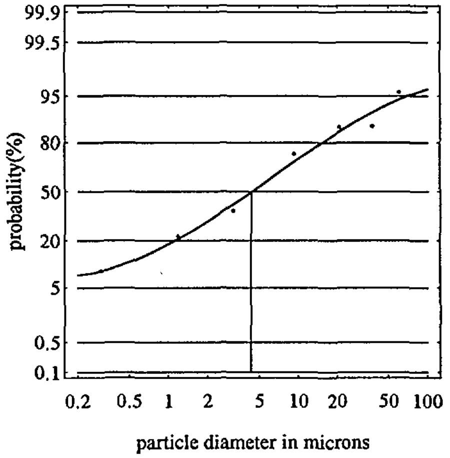

Fig. 3: *Typical airborne cumulative mass size distribution during natural resuspension. Mass median aerodynamic diameter was 4.3 µm, and geometric standard deviation was* $\sigma_g = 4.0$ *at a total mass concentration of 57 µg/m³.*

Because of its practical importance and well-established empirical data base, we consider the temporal behaviour of the resuspension factor. Resuspension data for a short time after Chernobyl are not abundant. In Hannover, about 15 days after primary deposition resuspension factors in the range $2{*}10^{-6}$ to $2{*}10^{-5}$ m^{-1} were found depending on wind speed [7]. These data are shown together with UAAS experimental data from Chernobyl [8] in Fig. 4. The curve is a regression to the Chernobyl data with a best fit representation to the time t in days

$$R(t) = 2.09 \cdot 10^{-4} m^{-1} \cdot \left(\frac{t}{d}\right)^{-1.67} \qquad (8)$$

The best fit exponent of - 1.67 is very reasonable considering the surface activity concentration decay proportional to $t^{0.5}$ which would have to be added to the exponent of -1.07 expected from theory (see Reeks et al. [9]).

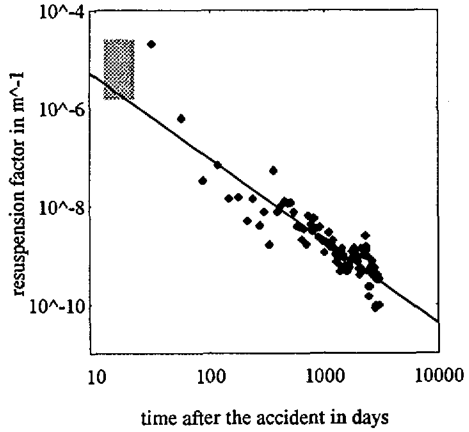

Fig. 4: *Experimental data of the resuspension factor measured in Chernobyl (corrected for radioactive decay of Cs-137). First data point is from June 1986. The straight line shows the fit to the data with a power exponent of -1.67. Short-time fluctuations caused mostly by wind speed and soil humidity fluctuations do not exceed ± half an order of magnitude. The rectangle in the upper left corner are data from Hannover 12 - 22 days after primary deposit.*

Adopting the above average equilibrium deposition velocity of 6.5 mm/s, we can integrate the equilibrium resuspension rate using equations (7) and (8) with respect to time, and obtain the integrated resuspended fraction (IRF) during the first 10 years (Fig. 5). It is important to realize that this IRF becomes effective only at a contamination edge since inside the contaminated zone there is a resuspension - deposition equilibrium. The consequences of this transport into the clean area is discussed in the next section.

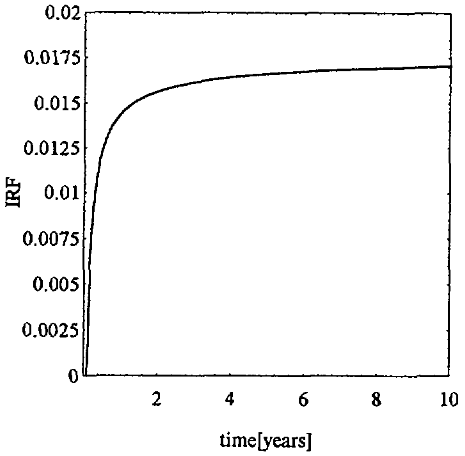

Fig. 5: *Integrated resuspended fraction (IRF) of Cs-137 calculated from equilibrium natural resuspension at Chernobyl as a function of time (years) starting one month after the accident.*

2.3.1.3 Assessment of contamination migration

Another important questions is how quickly de-contaminated zones become re-contaminated again under natural resuspension conditions without storm events. The situation is illustrated in Fig. 6.

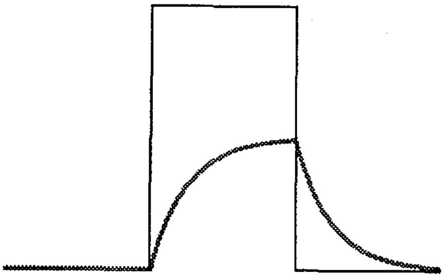

Fig. 6: *Diagram of a contamination strip. For explanations see text.*

Wind coming from the left enters a contaminated strip (thin line) and the air concentration (thick line) increases as a consequence of resuspension. Past the end of the contaminated zone, the concentration decreases again due to deposition, and at the same time soil contamination builds up at such a rate that the total amount of contamination is conserved. If the contaminated strip is very wide, resuspension-deposition equilibrium is established. The situation of a clean area embedded into a contaminated zone is the same, mirrored at the horizontal axis (i.e. upside down): past the clean zone edge, the air concentration decreases at the expense of the increasing surface contamination. Although rigorous treatment of the coupled soil-air transport equation (see e. g. [10]) is beyond the scope of this study, the order of magnitude can be easily assessed using a few simplifying assumptions [1]. The result of a simplified mathematical model is shown in Fig 7. It can be clearly seen that even in the close neighbourhood of the contaminated zone, the natural resuspension does not suffice to cause more than a relative contamination density of approx. 0.5. At a distance of 100 km, values of 0.1 can be reached after several years. It has to be emphasized that the above model exaggerates the actual contamination transport since constant wind speed and direction were assumed while in reality the wind changes; therefore, the resulting stochastic transport is considerably smaller than calculated above.

2.3.2 ANTHROPOGENIC RESUSPENSION

Probably the hardest experiments to explain quantitatively are the ones on anthropogenic resuspension. The reason is threefold: first of all, we have to sample close to the source. This means that we have an extremely non-homogeneous situation where size-dependent dilution and deposition of particles have to be taken into account simultaneously. Secondly, the particle size distribution changes extremely rapidly, and instrumental insufficiencies may distort the data. Finally, these data have to be evaluated using adequate three-dimensional size-dependent particle transport models in spite of the fact that physically correct models are virtually intractable mathematically. Nevertheless, a simple model for a line source derived on a semi-empirical basis works reasonably well, as demonstrated in the following. The 2D concentration distribution is assumed to be

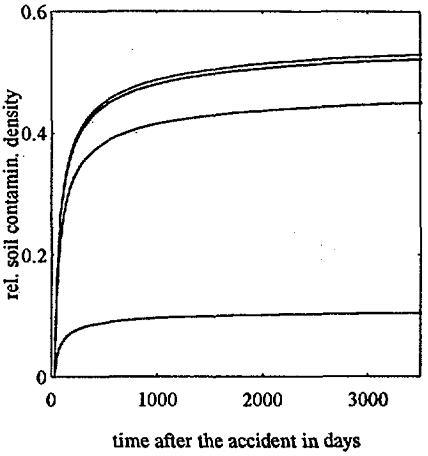

Fig. 7: *Temporal evolution of relative soil contamination density which is given by the ratio of actual contamination density* $\sigma(t)$ *to upstream contamination density* σ_{up} *of an infinitely wide zone. The curves refer to distances of 0.1, 1, 10, and 100 km downstream of the contamination edge. Calculation was started 30 days after the primary deposition event with actual values of the natural power-law Chernobyl resuspension factor.*

$$c(x,z,v_{sed})=\frac{Q_l(0)}{h_0 u+\left(\kappa u_*-v_{sed}\right)\cdot x}\cdot Exp\left(-\frac{z}{h_0+\left(\kappa u_*-v_{sed}\right)\cdot\frac{x}{u}}\right)\cdot\left[1+\left(\kappa u_*-v_{sed}\right)\cdot\frac{x}{h_0 u}\right]^{-\frac{v_{sed}}{\kappa u_*-v_{sed}}} \tag{9}$$

where x is the horizontal and z the vertical coordinate, u is the (constant) wind speed, u_* is the friction velocity, κ is von Karman's constant, $Q_l(0)$ is the line source strength, and h_0 is the mixing depth at the location of the anthropogenic disturbance. The concentration profile will also depend on the particle sedimentation velocity v_{sed}.

The model validation strategy was as follows: Starting from the soil particle size distribution the airborne particle size distribution evolution with distance and height was calculated and compared with the vertical and horizontal flux densities such as a cloud would produce and the 'equivalent line source strength' for the activity determined in this way. As an example, the calculated vertical flux density vs transport distance is shown in Fig. 8 in comparison with experimental data. It has to be emphasized that the absolute height of the curve is not fitted but rather calculated from the model using the source strength (73 mBq/(ms)) obtained by the airborne concentration measured by the WRAC [11]. The complete discussion of the model and the experimental results is given in a separate publication [12].

As demonstrated, the transport/deposition model works reasonably well provided the source strength is given. While for agricultural activities the source strength was determined experimentally using the method described above, it would be interesting to generalize the method for other situations. Unfortunately, the understanding of the detailed physical mechanisms of traffic resuspension on unpaved roads is not good at present. As a consequence, empirical formulae were derived [13] which describe the emission strength q in grams per metre travelled as functions of the soil characteristics and the truck properties. If the number of wheels on the truck is w, its mass m in tons, its speed v in km/hr then

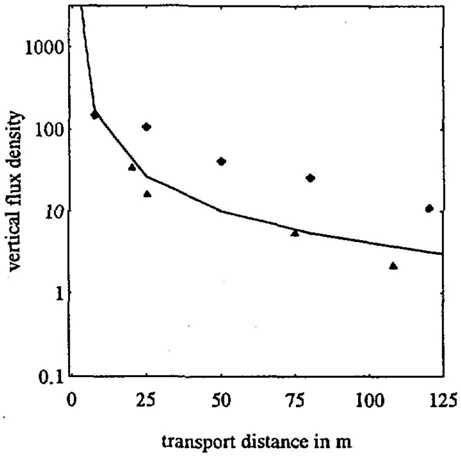

Fig. 8: *Vertical flux density in mBq/(m²s) as determined experimentally (diamonds: UIAR; triangles: UAAS) and theoretically from the above model (curve) with the same source strength as above. The data point closest to th source has no well-defined distance, but the others have. The experimental data of UIAR are probably too high since their comparison with the horizontal flux density would result in an extremely high deposition velocity representing particles of > 100 microns.*

$$q = 0.61 \cdot \left(\frac{s}{12}\right) \cdot \left(1 - \frac{p}{365}\right) \cdot \left(\frac{v}{48}\right) \cdot \left(\frac{m}{2.7}\right)^{0.7} \cdot \left(\frac{w}{4}\right)^{0.5} \tag{10}$$

The soil properties are taken into account by the silt content s (in %) of the road surface material, and the soil humidity influence parameterized by the number of days p with ≥ 0.254 mm of precipitation. It is claimed that the 95% confidence interval for the above equation is a factor of 1.46. The above equation applies for days with less than 0.254 mm of precipitation, and zero emission is assumed for rainy days. The point source strength Q_p in g/s of a moving truck is then proportional to the vehicle speed. Instead of the moving point source, a quasi-instantaneous line source described by the preceding formula can be assumed if the distance is large enough so that the truck travel time is much smaller than the plume travel time. We have only two experiments on resuspension with a truck on an unpaved road. They were performed in Zapolye, and yielded gravimetric mass concentrations (as determined by the WRAC) of 2-3 mg/m³ connected with cesium activities of 24-39 mBq/m³ which is the same order of magnitude as during agricultural activities, and in reasonable agreement with formula (10).

2.4 COMPREHENSIVE MODELLING AND EXAMPLE SCENARIOS

By comprehensive modelling we can understand the application of the whole chain of parameterized formulas discussed above. In this way, example calculations for radiologically important situations and prognoses are easily possible, and the results obtained in our field experiments can be generalized and become applicable to other locations and contamination patterns. A major problem is that published data on resuspension vary vastly [14]. Therefore, faced with the task of comprehensive modelling, a choice between the different publications had to be made based on an estimate of the reliability of the data. Without doubt, the choices are not entirely free from some arbitrariness and personal convictions but we hope to have made clear the rationale for the choices we have made in the previous sections.

2.4.1 NATURAL RESUSPENSION

The annual average value for the natural resuspension gravimetric flux density for a certain wind speed distribution is important as it allows the relevance of the omnipresent atmospheric circulation on the nuclide transport to be assessed. Using the soil - air transfer function, the annual average activity resuspension rate can be estimated, and compared with the values obtained by our spot measurements. Using the wind speed distribution of Berlin (which should be quite similar to the situation near Chernobyl), and Gillette's resuspension flux formula, we find an annual average flux density value of $4.1*10^{-8}$ kg/(m^2s) if we assume the friction velocity as 10% of the wind speed. If we further assume a specific activity of 10 Bq/g and an activity surface contamination density of 10^5 Bq/m^2, we obtain an average resuspension rate of $4.1*10^{-9}$ 1/s. This value is certainly plausible and compatible with our experimental results. An alternative, more classical approach would be via the resuspension factor formula (8) taking into account the square root decay of surface activity concentration due to migration. The advantage of this approach is that it actually describes average behaviour at certain locations for certain soils. Independently of the actual procedure, one has to conclude that natural resuspension long after an accident occurs at rather low speed, and therefore does not pose an immediate threat.

Of course, this is by far not a worst case scenario which might look as follows: Resuspension by wind shear is a highly nonlinear event which means that considerable fractions of the annual resuspension yield are produced within short time periods by gusts, dust devils and dust storms [15]. Gillette and Dobrowolski [16] measured deposition flux densities of 290 - 490 g/(m^2 yr), and similar values ranging between 20 - 500 g/(m^2 yr) are reported for Karakalpakia [17]. Wind erosion rates around Lake Aral averaged 2 - 3 mm per year over the last 30 years [18] which is equivalent to 3200 - 4800 g/(m^2 yr). *It is absolutely clear that such high erosion rates immediately after a primary deposition could effectively resuspend the whole contamination, which would be still at the very top of the soil at that time.* Even for a less dramatic scenario with a surface contamination density of 10^5 Bq/m^2 and a contamination depth of 5 mm, a soil surface-specific activity of $1.25*10^4$ bq/kg as in Zapolye, for semi-arid and windy conditions one would have contamination rates of 3600 - 6100 Bq/(m^2 yr) under the above assumptions.

2.4.2 ANTHROPOGENIC RESUSPENSION

The anthropogenic measurements were used to derive line source strengths. The conclusion we can draw is that anthropogenic resuspension is negligible compared to natural resuspension as far as transport is concerned. However, from the occupational point of view it is far more important than natural resuspension for risk groups like tractor drivers.

A sporadic but potentially very important means of contamination relocation are forest fires which have not been discussed here. The reason is that atmospheric transport calculations of buoyant plumes are very complicated. Forest fires can mobilize about 4% of the total inventory per event as compared to about 1.7 % for natural resuspension immediately at the border between a contaminated and a clean zone.

3 CONCLUSIONS

The prognostic model introduced above is based on physical principles, structurally complete and consists firstly of a source characterization module which describes the temporal evolution of the activity concentration of various sources. Secondly, the transfer module describes potential enrichment/depletion processes occurring during the resuspension process itself facilitating prognosis of activity data. Finally, the resuspension / transport / deposition module then describes source strengths, airborne transport (including change in concentration and particle size distribution) and deposition on a mass basis which links our radio-ecological approach with data on wind erosion. The model was validated by field experiments. Combining these modules, average and worst case assessments of activity can be made for any time after the accident. However, the uncertainty range for an actual forecast is rather large as for any meteorology-related event: It is estimated to ± one to two orders of magnitude while for monthly averages the uncertainty is probably only ± half an order of magnitude. This is (at least partly) due to the fact that not enough data were available for all dependencies on soil type, soil humidity, source type etc to allow reliable parameterization. Therefore, future research is necessary if more detailed prognostic power is desired.

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