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INHALATION OF RADIONUCLIDES DURING AGRICULTURAL WORK IN AREAS CONTAMINATED AS A RESULT OF THE CHERNOBYL REACTOR ACCIDENT

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Abstract—Radionuclide concentrations have been determined inside and outside the cabs of tractors operated on soils that are typical of the 30 km exclusion zone around the Chernobyl nuclear power plant. It was found that when the total plutonium deposit exceeded 3.7 kBq m^{-2} and the ^{137}Cs deposit exceeded 7.4 MBq m^{-2}, the levels of these radionuclides in the operator's cabin could exceed the maximum permissible air concentrations. However, due to the seasonal nature of work, the quantities of these radionuclides inhaled would not exceed the annual limit on intake. Dose to the lungs caused by the inhalation of hot particles has been addressed by either including or neglecting spatial dose distribution. The levels of risk of carcinogenic changes in cells of lung tissue calculated according to each of the two approaches have been shown to be of the same order of magnitude.

1. INTRODUCTION

As a result of the accident at the Chernobyl nuclear power plant, large agricultural areas were contaminated by radioactive materials. Some of the radioactivity released to the environment was in the form of fine fragments of reactor fuel, so-called hot particles. Once such particles have been deposited, they can become resuspended as a result of wind action or technogenic influences (i.e. mechanical actions), particularly during agricultural work. This has been confirmed by examining air filters attached to agricultural machinery operating in contaminated areas (Kashparov, unpublished data). Once the particles become resuspended, they can present an inhalation risk.

This paper examines two issues: firstly, it quantifies the levels of dust and associated hot-particles that are resuspended during agricultural work; secondly, it examines the lung dose to agricultural workers following the inhalation of these particles.

2. MEASUREMENT OF AIRBORNE CONCENTRATIONS

In 1988–1989, the concentrations of radioactive aerosols were measured in contaminated areas close to the 30 km exclusion zone, during agricultural activity. The experiments were conducted at several locations with different soil types (see Table 1), where a considerable amount of the contamination is due to the presence of hot particles. The experiments were performed under various conditions of wind speed (1–10 m s^{-1}), air temperature (13–25°C) and air humidity (40–80%), and represented a range of agricultural activities.

Aerosol mass concentrations were determined using aspirated air filters [flow rate 18 l min^{-1}, located either inside or outside the tractor cab (see Table 1)]. The air pump was powered by the 12 V tractor battery and the total air volume sampled depended on the aerosol concentration, varying between 3 and 20 m^3. The mass of material on the air filter was measured using an analytical balance. Gamma spectrometry of soil and dust samples was by means of a low background spectrometer (ADCAM-300) coupled with a high-purity germanium detector (GEM-30185).

Table 1 lists the airborne dust concentrations at the various experimental sites. A wide range of results is apparent. The largest fraction of atmospheric particles (77–99% by mass)

Table 1. Details of agricultural resuspension experiments

Experiment number	Date	Region	District	Village	Type of agricultural work	Tractor	Soil type	Soil humidity (%)	Atmospheric dust concentration ($mg\,m^{-3}$)	Location of air sampler (inside or outside tractor cabin)
1	4/88	Kiev	Chernobyl	Stakhalessie	Soil discing	T-150K	Sandy	3–5	9.4 ± 1.6	Inside
2	4/88	Kiev	Chernobyl	Stakhalessie	Soil harrowing	T-150K	Sandy	3–5	3.0 ± 0.4	Inside
3	4/88	Kiev	Chernobyl	Gubin	Potato planting	DT-75	Sandy	3–6	103 ± 8†	Outside
4	4/88	Kiev	Chernobyl	Gornostaipol	Potato planting	DT-75	Sandy	4–6	203 ± 17†	Outside
5	5/88	Gomel	Khoinitov	Mokish	Inter-row treatment	MTZ-82	Light loam	14	61 ± 7	Inside
6	8/88	Gomel	Bragin	Kovali	Soil ploughing	T-150G	Light loam	10	78 ± 10	Inside
7	8/88	Gomel	Bragin	Jaseni	Soil cultivation	T-150G*	Loam-sandy	8	6.3 ± 0.9	Inside
8	8/88	Gomel	Bragin	Jaseni	Soil cultivation	DT-75	Loam-sandy	12	67 ± 7	Inside
9	9/88	Gomel	Bragin	Chernev	Soil ploughing	K-701*	Loam-sandy	20	0.3 ± 0.03	Inside
10	9/88	Gomel	Bragin	Jaseni	Soil rolling	K-700A	Peaty	116	1.7 ± 0.2	Inside
11	9/88	Gomel	Bragin	Puchin	Soil cultivation	T-150K	Sandy	12	1.6 ± 0.8	Inside
12	6/89	Gomel	Khoinikov	Berestecko	Fertiliser application	MTZ-80	Sandy	—	170 ± 21†	Outside
									13 ± 3	Inside

* Tractors equipped with filtered air supply.
† Trailer with people performing the agricultural work being towed by the tractor.

was in the sub-micrometre range, although this decreased with increasing soil humidity. Soil humidities are listed in Table 1 also and were calculated from the percentage of the mass of water in the soil sample to the mass of the dry soil. Experiment 10, which had a soil humidity of 116%, was carried out on a peaty soil which had a low mineral content and an especially high water content.

Provision of a filtered air supply into the tractor cabins reduced the airborne dust concentrations inside the cab by a large factor over the external dust concentration: 10–100 times (mean dust concentration inside the cabin with a filtered air supply, 3.3 mg m^{-3}; mean concentration outside cabin, 159 mg m^{-3}). Filtration of the incoming air supply reduced the airborne dust concentration by around an order of magnitude in relation to levels in normal tractor cabins (mean dust concentration inside cabin without filtered air supply, 29 mg m^{-3}).

It was found that airborne dust and radionuclide concentrations in ambient air varied by as much as a factor of two during a single day. It is possible that this variation was due to the drying of the upper layers of soil which increased the probability of resuspension.

The levels of ^{144}Ce and ^{137}Cs in soil and airborne dust are shown in Table 2, together with the plutonium in air concentrations estimated from the measured ^{144}Ce:Pu ratio in Chernobyl fallout. It is important to note the enhanced specific activities in air in comparison to soil. Soil fractions with particle sizes greater than 50 μm were divided into organic and inorganic components. The organic material showed an enhancement of activity per unit mass of 10–50 times that of the mineral component.

3. LUNG DOSE ASSESSMENT DUE TO DEPOSITION OF HOT PARTICLES

Two approaches to lung dose assessment were considered:

(a) The radioactivity associated with all hot particles deposited in the lungs was assumed to be evenly distributed throughout the lung volume. The lung dose was then calculated as the total energy imparted to lung tissue by ionizing radiation divided by the lung mass (ICRP 30, 1982).

(b) The total lung dose is the sum due to all the deposited hot particles. The dependence of dose with distance from a hot particle was calculated according to a semi-empirical formula for β-radiation (Ivanov, 1988; Bochkarev *et al.*, 1972) and according to the method of Osanov (1977) for α-radiation. The self-absorption of α-radiation by the particle was taken into account when the dose due to α-radiation was calculated.

If the first approach is used, then the risk of carcinogenic transformation of a lung cell is given by:

$$R = NR_x, \tag{1}$$

Table 2. Measurements of radioactivity in soil, dust (< 10 μm) and air during agricultural work in contaminated areas

Experiment number	Radionuclide activity in the samples: Soil (kBq kg^{-1}) ^{144}Ce	^{137}Cs	Atmospheric dust (kBq kg^{-1}) ^{144}Ce	^{137}Cs	Atmospheric dust (mBq m^{-3}) ^{144}Ce	^{137}Cs	Estimated total Pu	Dose equivalent (mSv)
1	0.6	0.2	10.7 ± 2.6	2.6 ± 0.5	96 ± 30	22 ± 4	0.4	0.19
2	0.6	0.2	—	< 5	—	—	—	—
3*	0.4	0.2	4.1 ± 0.7	2.0 ± 0.4	444 ± 111	215 ± 41	1.9	0.9
4*	0.7	0.4	1.4 ± 0.4	1.1 ± 0.2	278 ± 89	241 ± 44	1.1	0.6
5	1.1	1.5	7.8 ± 0.7	12.6 ± 1.1	481 ± 74	770 ± 110	1.9	1.1
6	0.3	1.9	2.7 ± 0.4	7.8 ± 0.7	220 ± 37	592 ± 75	0.7	0.5
7	1.5	7.4	11.8 ± 2.2	35.2 ± 0.9	74 ± 15	222 ± 41	0.3	0.2
8	2.2	7.4	6.7 ± 1.5	22.6 ± 1.5	407 ± 110	1443 ± 120	1.5	1.2
9	0.7	14.6	—	62.9 ± 11.1	—	19 ± 3	—	—
10	1.1	2.6	—	8.9 ± 3.0	—	15.4	—	—
11	1.9	5.6	7.4 ± 3.7	22.9 ± 2.2	13 ± 7	37 ± 4	0.04	0.04
12(a)*	0.6	0.7	1.1 ± 0.4	5.6 ± 1.8	185 ± 81	925 ± 296	1.3	0.65
(b)	—	—	—	6.3 ± 2.4	—	81 ± 37	—	—

* Outside tractor cab.

where R is the total risk for the lungs (relative units); N is the total number of cells in the lungs; R_x is the probability of carcinogenic transformation in a cell due to the dose D_x.

The probability is determined from the dose/effect dependence $R=f(D)$. Should the second approach be used, then an estimate of the concentration of hot particles in the lungs is required. This estimate is derived by using a chamber model of the respiratory tract and by assuming that the distribution of hot particles is uniform. If these criteria are satisfied, then the hot particle concentration in lung tissue is of the order of 0.1 per cm^3, i.e. the distance between hot particles may be several centimetres. The relationship between dose and the distance from the centre of a hot particle, for a number of hot particle radii, is shown in Fig. 1. Here we have assumed that the material absorbing the radiation is soft biological tissue (density of 1 $g\,cm^{-3}$). It is apparent in Fig. 1 that the dose at 1 cm is negligible so it can be assumed that the spheres of influence of individual hot particles do not overlap and consequently that the dose to any element of lung tissue is due to a single hot particle.

The risk due to a single hot particle may be estimated by using the following procedure.

(a) The dose D_i is determined at a distance x_i from the centre of a hot particle.

(b) The risk R_i for a cell that has received the dose D_i is determined by the dose/effect curve $R=f(D)$.

(c) The risk for a total of N_i cells at a distance x_i, R_T, is then given by:

$$R_T = R_i N_i. \tag{2}$$

(d) The total risk for the organ is calculated by means of numerical integration of x_i, i.e. by summing over spherical layers of lung tissue of volume $4\pi x_i^2 dx_i$.

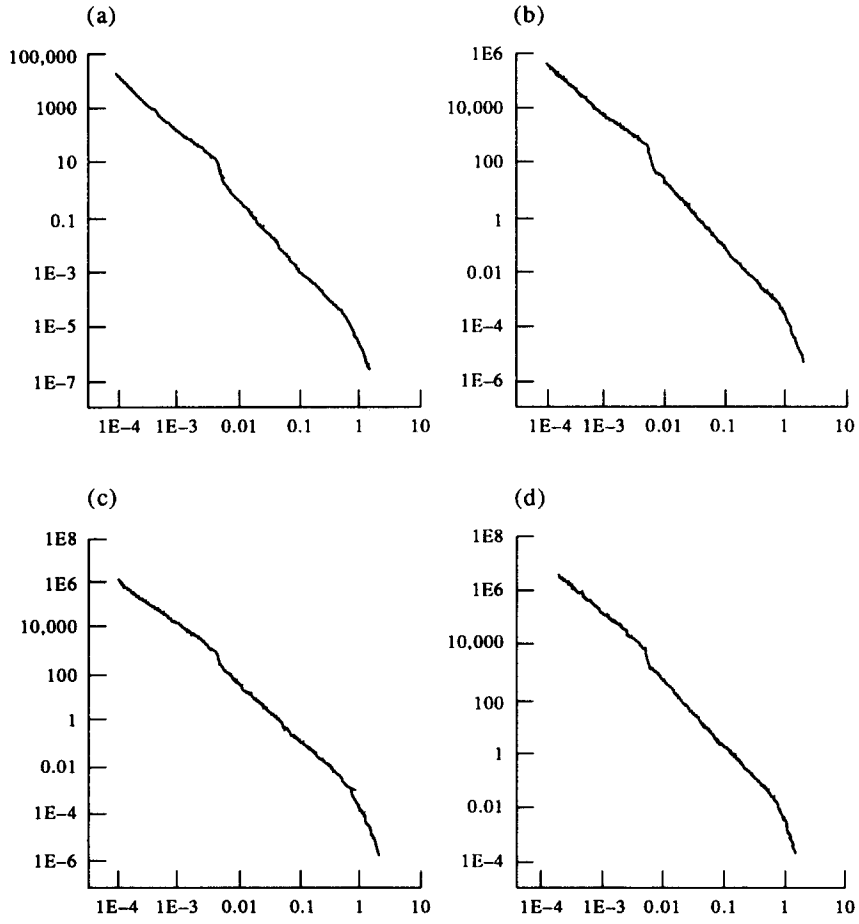

Fig. 1. The dependence of the total absorbed dose of α- and β-radiation (rad) on distance (cm) from the centre of a hot particle for particles of radii: (a) 0.1 μm; (b) 0.3 μm; (c) 0.5 μm; (d) 1.0 μm. Start of exposure—1 May 1986; time of exposure—one year.

(e) The total risk due to all deposited hot particles is expressed as the product of the number of hot particles and the risk value associated with one particle.

The risk values of carcinogenic transformations due to one hot particle using the two approaches outlined above are presented in the form of ratios in Table 3 for two radii, and for six exposure periods. R_{point} is the risk of carcinogenic transformations for a hot particle considered as a point source of radiation and R_{distr} is the risk considering the particle as a distributed source of radiation. It is evident in Table 3 that the risk calculated for the case of uniform activity distribution is two to three times higher than that calculated for point sources, in the short term. This is in agreement with experimental findings (Moscalev, 1982; ICRP 30, 1982).

4. ASSESSMENT OF LUNG DOSE DUE TO THE INHALATION OF RADIOACTIVE MATERIALS

The results in Table 3 show that the risks of the onset of carcinogenesis of the lung due to the inhalation of radioactive material is dependent on the distribution of deposited material within the lung. A uniform distribution of hot particles within the lung carries the highest risk of carcinogenesis. Therefore, in the short term, this has been assumed in assessing the risk to agricultural workers exposed to an aerosol containing finely dispersed hot particles.

The concentration and activity of resuspended material is given in Tables 1 and 2. These data were obtained during a variety of weather conditions. In order to calculate the lung dose to a typical agricultural tractor driver, we have used the data in Tables 1 and 2 and assumed a typical exposure period at these levels for 3–4 months per year with a 10 h working day. We have calculated the dose to the worker assuming exposure to these conditions for a single year after the accident (1988). The inhaled particles were assumed to have an AMAD of 1 μm and appropriate clearance parameters for particles of this size, from the lung, were used. Accounting for dose from 28 radionuclides present in hot particles from Chernobyl, the total dose to a worker during agricultural work within the 30 km exclusion zone is of the order of 1 mSv (see Table 2). The dose was calculated by estimating the ^{144}Ce activity of the inhaled particles and then inferring the activity of the other radionuclides based on the composition of the reactor fuel, allowing for decay. The 28 radionuclides used to calculate the dose to the lung were: ^{90}Yr, ^{90}Sr, ^{95}Zr, ^{95}Nb, ^{103}Ru, ^{106}Ru, ^{106}Rh, ^{125}Sb, ^{134}Cs, ^{137}Cs, ^{141}Ce, ^{144}Ce, ^{144}Pr, ^{154}Eu, ^{155}Eu, ^{235}U, ^{236}U, ^{238}U, ^{237}Np, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{241}Am, ^{243}Am, ^{242}Cm and ^{244}Cm.

5. CONCLUSIONS

The levels of dust and radionuclide concentrations have been measured in and around tractor cabins during various agricultural operations on a range of soil types. If the levels of deposition exceed 3.7 kBq m^{-2} for Pu and 7.4 MBq m^{-2} for ^{137}Cs, the airborne concentrations of these radionuclides may exceed their maximum permissible levels in the tractor cabins (M. Energoatomizdat, 1988). However, the average soil moisture content throughout the year would be higher than those during the experiments, and this would limit the

Table 3. Ratio between risks calculated for two particle radii

Time of exposure	R_{point}/R_{distr} for particles of different radii	
	Particle radius = 0.1 μm	Particle radius = 0.5 μm
1 hour	0.3	0.3
1 day	0.3	0.5
10 days	0.3	0.8
100 days	0.4	0.5
1 year	0.5	0.5
10 years	1.4	1.6

Exposure started on 1/1/87.

resuspension of contaminated soil. In addition, agricultural operations will be confined to certain seasons. Therefore, outside the 30 km exclusion zone the intake of radionuclides through the respiratory tract for agricultural drivers will usually be lower than the annual limit on intake.

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