MEASUREMENTS AFTER THE CHERNOBYL ACCIDENT IN RELATION TO THE EXPOSURE OF AN URBAN POPULATION

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Abstract

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After the Chernobyl accident *in-situ* gammaspectrometric measurements have been performed in Munich and in smaller towns in Southern Bavaria. At the measurement sites about two thirds of the total contamination was deposited by rain. For grassland, the attenuation of the radiation from ^{131}I, ^{103}Ru, ^{134}Cs, and ^{140}Ba due to the initial migration of the radionuclides in the ground and due to the surface roughness was found to be similar. However, large variations between the retention of the various elements on smooth surfaces have been observed. The absorbed dose-rate inside houses due to Chernobyl radionuclides was the range of one tenth to one hundredth of the absorbed dose-rate over open grassland, depending on the type of house and the location in the house, especially on the angle of view from the detector position to outside locations. The absorbed dose-rate in air due to caesium isotopes was measured over a period of 1 month to 8 years after the accident. To facilitate a use in models on radiation doses in urban environments, the time dependence of the results were approximated by analytical functions.

1. INTRODUCTION

The radiation exposure of the population after a contamination of an urban environment with caesium is dominated by the external irradiation (Amaral et al., 1991). Also for contamination of larger areas due to severe reactor accident the external radiation has been identified as the most important pathway for the exposure of the urban population (Kelly, 1987). This paper describes results on the behaviour of radionuclides which have been deposited after the reactor accident of Chernobyl in urban environments and on external exposures due to these radionuclides.

At the time t after a deposition of radionuclides, the **equivalent dose rate** $\dot{H}_{ni}(t)$ (ICRP 1991) in an organ n of a member of a population group i may be calculated by

$$\dot{H}_{ni}(t) = \sum_N A_N \cdot \dot{K}_{Nni} \cdot \exp(-\lambda_N \cdot t) \cdot r_N(t) \cdot \sum_j p_{ij}(t) \cdot f_{Nj}(t), \qquad (1)$$

where the summation index N indicates the N-th deposited radionuclide, λ_N the corresponding decay constant, and the summation index j indicates locations, where members of the population group i are assumed to have probabilities $p_{ij}(t)$ of stay. The other quantities in eq. (1) are discussed in the following paragraphs. Eq. (1) is applicable, if all relevant progenies in the detain chain of a deposited radionuclide can be assumed to be in radioactive equilibrium (Jacob et al., 1988). Otherwise, instead of the exponential factor in eq. (1) non-trivial time dependencies have to be taken into account (Jacob and Paretzke, 1988).

The **activity A_N of radionuclide N, deposited per unit area** on a reference site, may be determined with environmental samples or by *in situ* gamma-ray spectrometry.

Environmental sampling and measuring is laborious, especially when the activity per unit area on the reference site is inhomogeneous. The method is only recommended when an *in situ* gamma-ray spectrometry equipment is not available or when the knowledge about the activity distribution in the soil is considered to be too poor to derive reliable results from *in situ* gamma-ray spectrometry. *In situ* gamma-ray spectrometry is a powerful method to determine radionuclide activities per unit area (ICRU, 1994). In the first year after the deposition, the attenuation of the caesium radiation by the soil may be derived from the measured photon fluences in the 32 keV x-ray peak and in the 662 keV gamma-ray peak (Rybacek et al., 1992). Alternatively, information is derived from the ratio of the photon fluence in a peak to the fluence of scattered photons in a spectral window below the peak (Zombori et al., 1992; Hillmann and Jacob, 1994).

For members of a population group i standing on an open contaminated field, the factor $\dot{K}_{Nni}$ is defined as the **equivalent dose rate in an organ n per activity per unit area of a radionuclide N.** For adults $\dot{K}_{Nni}$ has been calculated by Eckerman and Ryman (1993) for plane sources on a smooth ground and for slab sources with a thickness of 1.5 cm and of 15 cm in a ground with a density of 1.6 g•cm^{-3}. Petoussi et al.(1991) calculated $\dot{K}_{Nni}$ for foetuses, babies, children and adults for plane source in the ground below a slab of soil with a mass per unit area of 0.5 g• cm^{-2}.

The factor $r_N(t)$ is defined by the **ratio of equivalent dose rate per activity per unit area at the reference site and $\dot{K}_{Nni}$.** In the current approach open areas of grassland have been chosen as reference sites, and the equivalent dose rate factors $\dot{K}_{Nni}$ for plane sources in the ground below a slab of 0.5 g•cm^{-2} are used. For caesium, measurement results on the time dependence of $r_N(t)$ have been presented and analytically approximated in Jacob et al. (1994). Results for iodine, ruthenium, caesium and barium will be presented below. **Location factors $f_{Nj}(t)$** are defined by the equivalent dose rate due to the radionuclide N at a location of type j relative to the reference site. This paper will mainly deal with measurement results for $r_N(t)$ and for outdoor and indoor location factors.

2. ABSORBED DOSE RATES IN AIR OVER OPEN GRASSLANDS

After the reactor accident of Chernobyl measurements were performed at several open areas of grassland in Bavaria, where more than 85 % (at one site (Giglberg) 77 ± 9%) of the activity was deposited with rain. The attenuation of the absorbed dose rate in air was determined by the following method: First, at each site 6 soil samples have been taken, each consisting of 5 soil cylinders, 15-20 cm deep and with a ground surface of 18 cm^2. The 5 cylinders have been taken from the edges and the center of a 10m×10m square. The ^{134}Cs activity per unit area was then obtained by gamma-spectrometric measurements of the soil samples. A_N was derived from this value by assuming relative activity depositions as measured in Neuherberg (Hötzl et al., 1987), taking into account that some weeks after the deposition the ^{140}La activity is by 15 % higher than the ^{140}Ba activity (Jacob and Paretzke, 1988). Second, *in situ* gamma-ray spectrometry was used to measure the unscattered photon fluence with energies of 365 keV for ^{131}I, of 497 keV for ^{103}Ru, of 796 keV for ^{134}Cs and of 1596 keV for ^{140}La. Using the assumption, that the radionuclide activity distribution has an exponential shape, which has been shown to be a good approximation for the first few years after a deposition (Jacob et al., 1994), the absorbed dose rates in air were calculated from the two sets of measurements. From the results in Table I two conclusions may be drawn:

i) The attenuation of the radiation from the different radionuclides is very similar. Therefore, for the first half year after the deposition $r_N(t)$ may be approximated by the same function for all relevant radionuclides.

ii) The values in Table I are close to unity, i.e. the observed attenuation of the radiation by surface roughness and by migration into the soil is the same attenuation as for plane sources in the ground below a slab of 0.5 g•cm^{-2}. It may be concluded that the energy and angular characteristics for these radiation fields are similar, and that the measured attenuation of the absorbed dose rate in air may be directly used for the function $r_N(t)$.

TABLE I. ABSORBED DOSE RATE IN AIR AT OPEN GRASSLANDS IN SOUTHERN BAVARIA IN THE YEAR 1986 RELATIVE TO PLANE SOURCES AT A DEPTH OF 0.5 G•CM^{-2}, AS DERIVED FROM MEASUREMENTS OF SOIL SAMPLES AND *IN SITU* GAMMA-RAY SPECTROMETRY. THE CALCULATED UNCERTAINTY OF THE GIVEN VALUES CORRESPONDS TO A STANDARD DEVIATION LESS THAN 15%, FOR VALUES IN PARENTHESES LESS THAN 20%.

Measurement Site	Date	Relative absorbed dose rate in air I-131	Ru-103	Cs-134	La-140
Neuherberg B	04 June	0.96	0.87	0.96	0.81
Neuhaus	04 June	1.08	1.02	1.02	0.81
Neuherberg C	09 June	0.99	0.87	0.96	0.81
Aurach	10 June	1.23	1.07	1.03	0.90
Giglberg	10 June	(1.19)	0.99	1.07	1.08
Neuherberg B	03 July	—	0.95	1.00	—
Neuherberg C	03 July	—	0.87	0.93	—
Grafing	04 July	—	0.74	0.85	0.70
Neuhaus	17 July	—	1.17	1.15	—
Aurach	17 July	—	1.01	0.97	—
Neuherberg B	08 Sep	—	0.81	0.91	—
Grafing	23 Sep	—	0.63	0.75	—
Neuhaus	30 Sep	—	1.13	1.04	—
Aurach	30 Sep	—	0.90	0.90	—
Bad Reichenhall	09 Oct	—	0.92	0.93	—
Neuherberg A	15 Oct	—	0.98	1.07	—

3. EFFECTIVE ACTIVITY PER UNIT AREA FOR PAVED SURFACES

Time series of *in situ* gamma-ray spectrometry measurements were performed at five sites in Southern Bavaria, which were covered by asphalt or pavements. The source at these sites was limited by houses or other structures. The measured unscattered photon fluences rates in air were multiplied by corresponding geometry factors (Jacob et al., 1990) to obtain an assessment for fluence rates over infinite places with the same covering and the same contamination. To approximate the effect of surface roughness and migration of the radionuclides in slits of the pavement, the geometry of a plane source covered by a slab with a mass per unit area of 0.16 g cm^{-2} was assumed. Under this assumption effective activities $\overline{A}_N$ per unit area were derived. By division with the activity A_N deposited on a close lawn an estimation for the retention of the radionuclides on the surfaces is obtained, which is called here relative effective activity per unit area. This quantity has been analytically approximated in the form

$$\overline{A}_N / A_N = a_1 \cdot \exp(-\ln 2 \cdot t / T_1) + a_2 \cdot \exp(-\ln 2 \cdot t / T_2) \qquad (2)$$

Results are given in Fig. 1 and in Table II.

TABLE II. PARAMETERS OF ANALYTICAL APPROXIMATIONS FOR RELATIVE EFFECTIVE ^{137}CS ACTIVITIES PER UNIT AREA.

Site		a_1	T_1(years)	a_2	T_2(years)
Coubertinplatz	A	0.22±0.02	0.31±0.05	0.15±0.02	2.3±0.3
Suma-Parkplatz	B	0.38±0.02	0.40±0.04	0.06±0.02	4.4±4.0
Färbergraben	C	0.21±0.01	0.16±0.02	0.13±0.01	2.1±0.2
Bad-Reichenhall	D	0.28±0.08	0.77±0.46	0.11±0.09	9.3±x*
Kreittmayrstraße	E	0.41±0.03	0.39±0.05	0.16±0.01	4.5±0.6

* $x > T_2$

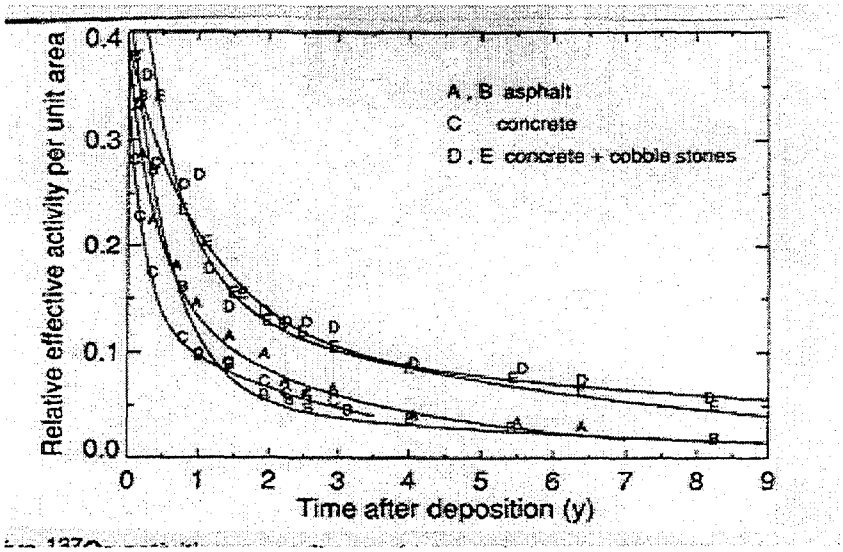

FIG. 1. Effective ^{137}Cs activities per unit area (see text) divided by the activity deposited per unit area by a wet deposition on a close lawn.

4. INDOOR LOCATION FACTORS

In situ gamma-ray spectrometry was performed at various indoor locations in three one-family houses and one multi-storey building. The results were normalised to the unscattered photon fluences over close areas of open grasslands. Results in Table III show how the attenuation of the unscattered radiation depends on the photon energy. In the attic of the one-family house Munich H, the 365 keV radiation is reduced by more than a factor of 3 stronger than the 1596 keV radiation. This is a combined effect of the better shielding for low energy radiation (Meckbach et al., 1988) and of the relatively low retention of iodine and also of ruthenium of roofs (Roed, 1987). In the administration building the 662 keV radiation was attenuated by a factor of four more than in the one-family houses. This difference is relatively small, because the detector was placed in the administration building not too far from large windows that reach from the ceiling to the floor.

TABLE III. UNSCATTERED PHOTON FLUENCES AT VARIOUS INDOOR LOCATIONS RELATIVE TO UNSCATTERED PHOTON FLUENCES OVER AN OPEN AREA OF GRASSLAND. UNCERTAINTIES OF THE GIVEN VALUE (EXPRESSED IN TERMS OF ONE STANDARD DEVIATION) ARE NOT GREATER THAN 15%, FOR THE VALUES IN PARENTHESES LESS THAN 20%.

house type /site / date of measurement	radionuclide / photon energy	location		
one-family house		ground fl.	first floor	attic
Munich H	^{131}I / 365 keV	(0.050)	—	0.11
30 May 1986	^{103}Ru / 497 keV	(0.053)	(0.034)	0.13
	^{137}Cs / 662 keV	0.068	0.057	0.23
	^{134}Cs / 796 keV	0.066	0.052	0.22
	^{140}La /1596 keV	—	—	0.33
administration build.		first floor	second fl.	fourth floor
Neuherberg 11 June 1986	^{137}Cs / 662 keV	0.015	0.015	(0.014)
one-family house		ground fl.	ground fl.	first floor
Munich J	^{137}Cs / 662 keV	0.060	0.051	0.044
23 June 1986				
one-family house		ground fl.	first floor	attic
Grafing	^{103}Ru / 497 keV	0.048	0.034	0.032
4 July 1986	^{137}Cs / 662 keV	0.057	0.046	0.066
	^{134}Cs / 796 keV	0.062	0.044	0.067

Extensive Monte-Carlo calculations have been performed to simulate the photon transport in urban environmental (Meckbach et al., 1988). Among the studied locations there were some, which were comparable to those, for which the gamma-ray spectra were measured. The calculated build-up factors and the location measured unscattered photon fluences were used to assess location factors. The results in Table IV confirm Monte Carlo calculations for wet depositions (Meckbach and Jacob, 1988).

TABLE IV. LOCATION FACTORS FOR VARIOUS INDOOR LOCATIONS. THE RESULTS WERE OBTAINED FROM *IN SITU* GAMMA-RAY SPECTROMETRY AND CALCULATED BUILD-UP FACTORS.

house type /site / radionuclide / date of measurement photon energy	location		
one-family house	ground fl.	first floor	attic
Munich H	^{131}I / 365 keV (0.08)	—	0.11
30 May 1986	^{103}Ru / 497 keV (0.08)	(0.06)	0.18
	^{137}Cs / 662 keV 0.11	0.10	0.32
	^{134}Cs / 796 keV 0.11	0.10	0.31
	^{140}La /1596 keV —	—	0.45
administration build.	first floor	second fl.	fourth floor
Neuherberg	^{137}Cs / 662 keV 0.02	0.02	(0.02)
11 June 1986			
one-family house	ground fl.	ground fl.	first floor
Munich J	^{137}Cs / 662 keV 0.09	0.08	0.07
23 June 1986			
one-family house	ground fl.	first floor	attic
Grafing	^{103}Ru / 497 keV 0.06	0.06	0.03
4 July 1986	^{137}Cs / 662 keV 0.08	0.08	0.08
	^{134}Cs / 796 keV 0.06	0.08	0.08

5. CONCLUSIONS

Equation (1) may be considered as the basic equation for assessments of external exposures of population groups. For a wet deposition of iodine, ruthenium, caesium and barium radioisotopes of grassland, the geometry of a plane source below a soil slab of 0.5 g • cm^{-2} was shown to describe well the radiation field in air. Therefore, if corresponding equivalent-dose rate factors (Petoussi et al., 1991) are used, a value of 1.0 for $r_N(t)$ is appropriate for the first months after a wet deposition.

Caesium was found to be removed effectively from surfaces covered by asphalt and paving in urban environments. Only about 2-3 % of the initial deposit is retained after some years on asphalt surfaces, the removal of this fixed component occurs with a half-life of a few years. For pavements the corresponding values are a retention of about 5 % and a half-life of several years. Measurements of indoor location factors confirmed previous Monte Carlo calculations.

A dominant part of the uncertainty of external exposures will generally be due to an appropriate description of the locations, where people stay, and of the time they stay at the various locations. These conditions will depend considerably on the country and the environment, where a larger contamination may occur, and have to be studied for each situation separately (e.g. Golikov et al., 1993; Erkin and Lebedev, 1993; Likhtariov et al., 1994).

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