# Investigation of the Radiation Exposure of Inhabitants of Contaminated Areas in northern Ukraine

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## ABSTRACT

The external and internal radiation exposure of evacuees returning to contamination zone II in northern Ukraine was investigated using two approaches: radioecological modeling and direct measurement. Radioecological estimates turned out to be highly uncertain. Direct surveillance of a group of returned evacuees in the village Christinowka yielded additional radiation exposure of "normal" inhabitants due to $^{137}$Cs in 1998/99 of 1.0 $\cdot 1.3^{\pm 1}$ mSv/a. "Non-normal" behavior, i.e. frequent stays in forests and high mushroom consumption, caused a maximum of the additional radiation exposure of 20 mSv/a which could be avoided by a change of personal habits. The additional exposure of "normal" inhabitants appears not to be reducible under the actual social conditions.

## INTRODUCTION

Large areas of northern Ukraine have been contaminated with various radionuclides emitted during the Chernobyl accident in April 1986. As a consequence, massive evacuation of inhabitants took place. Evacuation measures were based on intervention levels considering the radionuclides $^{137}$Cs, $^{90}$Sr and $^{239}$Pu. A system of 4 contamination zones was established. The zones were distinguished according to their ground contamination levels of $^{137}$Cs: zone I (> 1480 kBq/m$^2$), zone II (555 kBq/m$^2$ - 1480 kBq/m$^2$), zone III (185 kBq/m$^2$ - 555 kBq/m$^2$) and zone IV (37 kBq/m$^2$ - 185 kBq/m$^2$) (1,2). The inhabitants of zones I and II were evacuated. Although it is still forbidden to return into these zones, some of the evacuees returned to their former homes in zone II for permanent residence. Most of them make their living from what they themselves plant, produce and collect on the contaminated ground.

Presently, of all the radionuclides of the Chernobyl-fallout, $^{137}$Cs causes the bulk of the radiation exposure of residents of zone II. $^{137}$Cs is decaying slowly enough to contribute to the radiation exposure for long times, and it has been transported far away from the emission source. Shorter-lived nuclides, as for instance $^{134}$Cs, today are nearly fully decayed. Other long-lived radionuclides like $^{90}$Sr and $^{239}$Pu were not transported far enough from the reactor to contribute significantly to the radiation exposure in zone II.

This work deals with the modeling and measurement of the actual radiation exposure due to $^{137}$Cs of people living presently in zone II. Determination of the expected radiation exposures in zone II are crucial for answering the question for resettlement of the evacuees. In a first step, we investigated deposition and downward migration in soil of $^{137}$Cs in different contaminated areas of Ukraine and transfer of $^{137}$Cs from the soil into the food chain under the actual conditions in contaminated villages of zone II in order to estimate the external and internal radiation exposure of the returned evacuees, respectively, on the basis of radioecological model calculations.

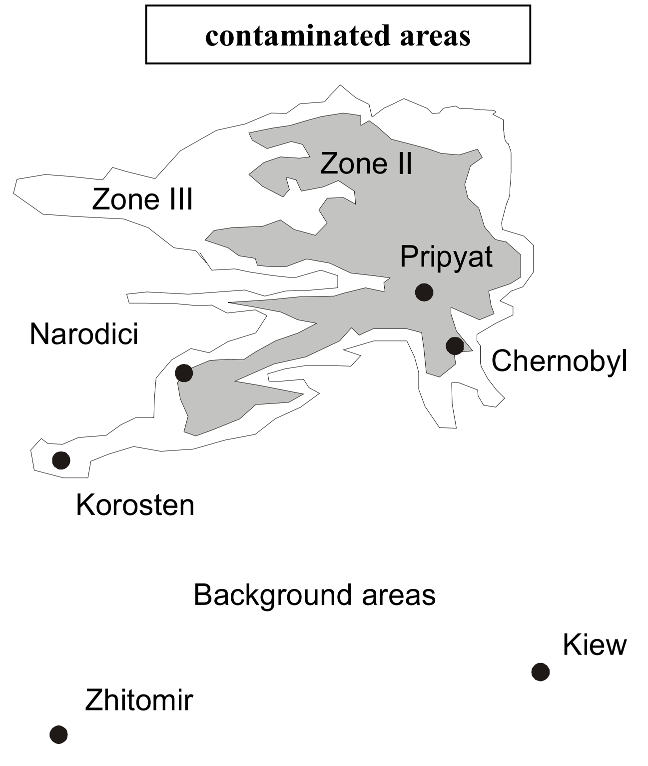
In a second step, a selected population of returned evacuees in zone II was surveyed for one year and their actual exposure due to $^{137}$Cs was determined. To this end, a small village named Christinowka was selected. This village is located near the town of Narodici in zone II. The population of Christinowka once consisted of about 100 families living in a purely agricultural environment. Three years after the accident all inhabitants were evacuated to a city near Zhitomir. During the last four years, more and more of them returned illegally. Up to now, about one third of the evacuees returned to their former homes. The social behavior and the live-style of the returned inhabitants is quite typical for rural villages in the area of Polissya in zone II.

The work presented here is part of a research project supported by the DFG (German Research Community) which is carried out in cooperation with the State Agroecological Academy of Ukraine. This project deals more generally with the fall-out of radionuclides nuclides from the reactor accident in the northern Ukraine and the pathway of radionuclides through the food-chain to man and the evaluation of the past, present and future radiation exposure (3-13).

## DEPOSITION DENSITIES OF THE FALLOUT NUCLIDES AND EXTERNAL RADIATION EXPOSURE

To allow for a general survey of the deposition densities of fall-out radionuclides from the Chernobyl accident, soil profiles were taken in three regions of northern Ukraine exhibiting differing degree of contamination in 1995 (Fig. 1). $^{137}$Cs and $^{134}$Cs was measured in all layers of each profile by $\gamma$-spectrometry. Additionally,

$^{90}$Sr concentrations were measured by liquid-scintillation β-spectrometry (7), and the concentrations of $^{129}$I were determined via radiochemical neutron activation analysis (RNAA) or accelerator mass spectrometry (AMS) (11). Fig. 2 gives some examples of the respective results and table 1 summarizes the ranges of the deposition densities determined. Detailed discussions of these data and their interpretation with respect to radionuclide migration in soils may be found elsewhere for $^{90}$Sr (6-8), $^{137}$Cs (3-5), and $^{129}$I (4,9-13).




sampling sites

| zone | area | village |
|---|---|---|
| back-ground | Zhitomir | Baraschewka<br>Oserjanka<br>Dawidowka<br>Lewkow |
| III | Korosten | Nemirowka<br>Woronewe<br>Kupetsch<br>Tschigiri |
| II | Narodici | Nosdristshe<br>Nowe Scharno<br>Christinowka |

$^{137}$Cs-deposition densities:
zone III: more than 185 kBq/m$^2$
zone II: more than 555 kBq/m$^2$

Figure 1. Map of sampling sites in northern Ukraine. For the extension of zone I, which is more or less equivalent with the 30 km zone around the Chernobyl nuclear power plant, see (1).

Table 1. Deposition densities in three areas of northern Ukraine measured so far in this project. Activities are normalized to April 26, 1986.

| zone | Cs-137 | | | Sr-90 (7) | | I-129 (11,12) | |
|---|---|---|---|---|---|---|---|
| | no. of profiles | official (2) [kBq/m$^2$] | measured [kBq/m$^2$] | no. of profiles | measured [kBq/m$^2$] | no. of profiles | measured [Bq/m$^2$] |
| II | 26 | 555 - 1480 | 740 - 4700 | - | - | 6 | 0.4 - 1.2 |
| III | 25 | 185 - 555 | 230 - 850 | 3 | 3.0 - 5.7 | 24 | 0.07 - 0.30 |
| background | 11 | ~ 0 | 0 - 3 | 2 | 1.7 | 12 | 0.02 - 0.10 |

Many soil profiles showed by far more $^{137}$Cs than covered by the official limits for the individual zones (table 1). The results obtained were used to model the expected external exposure of a person living on the contaminated territory. According to such model calculations, no significant additional exposure is expected in the background areas and in zone III. However, in zone II the modeled additional external exposure ranged from 2 mSv/a to 8 mSv/a strongly depending on both, the measured deposition densities and the living habits assumed. Comparison of direct measurements of γ-dose rates 1 m above ground and of the deposition densities yielded aggregated dose factors for the external exposure in 1995 between 1.2 mSv m$^2$ MBq$^{-1}$ a$^{-1}$ and 2.3 mSv m$^2$ MBq$^{-1}$ a$^{-1}$ in zone II with an average of 1.9 mSv m$^2$ MBq$^{-1}$ a$^{-1}$, which is in between the value of 1.7 mSv m$^2$ MBq$^{-1}$ a$^{-1}$ determined in 1992/93 by Hille (14) and the official value for 1991 of 3.51 mSv m$^2$ MBq$^{-1}$ a$^{-1}$ given by the Institue of Hydrometeorology of the former Soviet Union. From the migration into depth of $^{137}$Cs between 1986 and 1995, effective half-value times of the external exposure of 6.3 years were determined for undisturbed soils away from forests in zone III. In soils of zone II, effective half-value times ranged from 3.6 to 5.7 years.

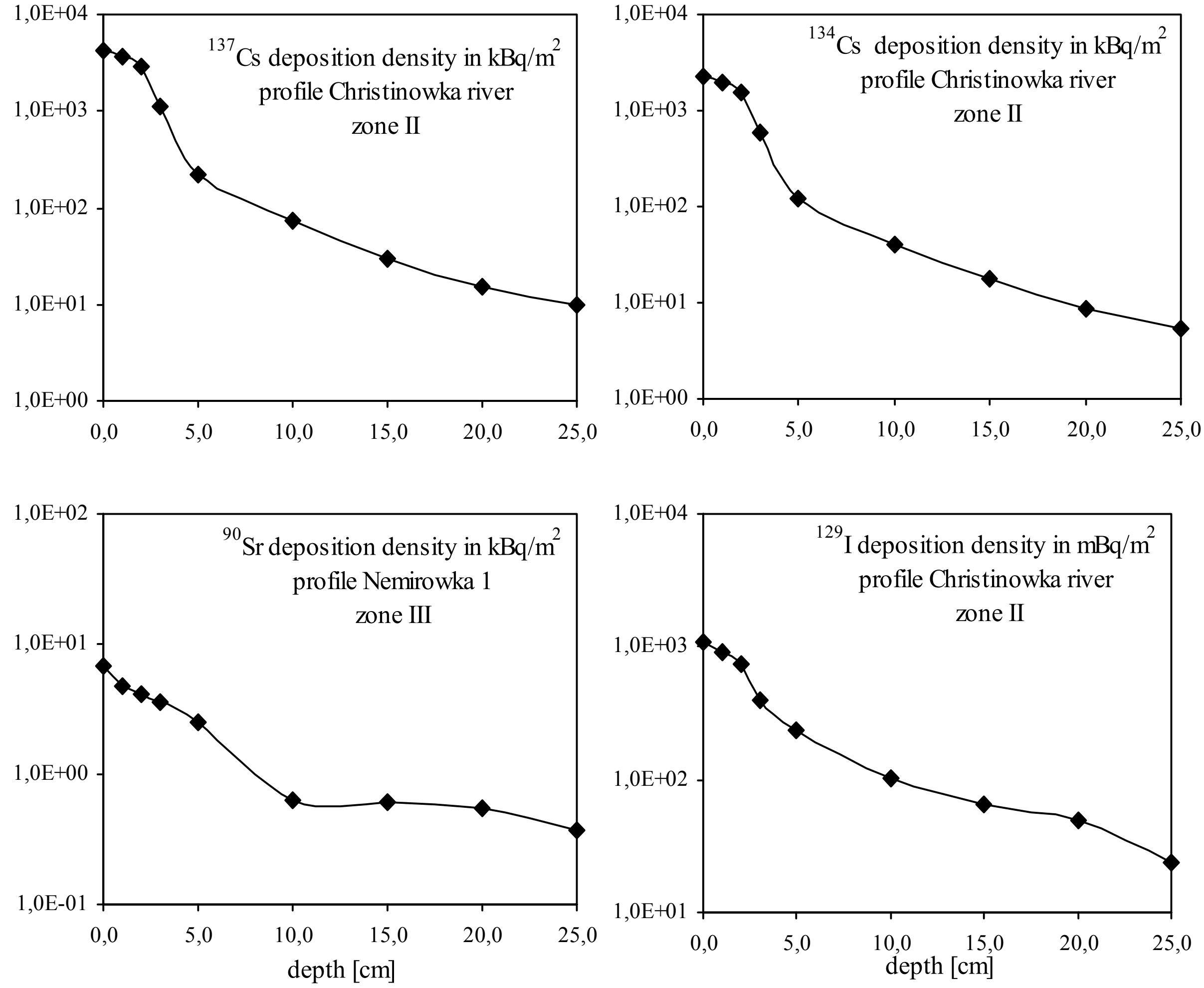



Figure 2. Depth profiles of deposition densities of $^{137}$Cs, $^{134}$Cs, $^{90}$Sr and $^{129}$I in soils from northern Ukraine. Activities are calculated for April 26, 1986.

A reliable modeling of the individual external exposure on the basis of deposition densities turned out to be impossible because of the high variation of the deposition densities. For example, one of the highest (4700 kBq/m$^2$) and the lowest deposition densities of $^{137}$Cs (740 kBq/m$^2$) were found in zone II within a few hundred meters distance. Further, there were much higher $^{137}$Cs deposition densities observed in forest soils than in soils from rural areas close to the villages. As a consequence the additional exposure was considered to be only assessable by direct dosimetry of individual persons living in zone II.

Such direct measurements of the external radiation exposure were performed for inhabitants of Christinowka. To this end, 14 persons were equipped with personal thermoluminescence (TL) dosemeters as they are used in Germany for the purpose of dosimetry of occupational exposure. The dosemeters were changed evrey three months. The additional external radiation exposure due to $^{137}$Cs was estimated by subtracting an average background dose rate of 2 µSv/d. The results for the annual additional external exposure are compared in table 2 with the data for the period of the first three months (July 15, 1998 – October 15, 1998). With two exceptions, the additional annual exposure is rather uniform with a mean value of 0.7 ± 0.2 mSv. The exceptions are two males (persons no. 17 and 18) with additional annual exposures of 1.2 mSv and 4.3 mSv, respectively. The reason for their higher exposure is that these persons spent unusually long times of their out-door life in the forests where generally much higher deposition densities are observed around Christinowka than in the non-woody areas.

As indicated by the results obtained during the first three months, the bulk of the external exposure occurs during late summer and early fall when harvesting and collection of berries and mushrooms increase the frequency of out-door activities.

Table 2. Additional external exposure due to $^{137}Cs$ of inhabitants of Christinowka (zone II) near Narodici, measured in 3-month intervals between July 1998 and July 1999 with TL dosemeters.

| person no. | annual 1998/99 [mSv/a] | July 15 - October 15, 1998 [mSv/3 months] | person no | annual 1998/99 [mSv/a] | July 15 - October 15, 1998 [mSv/3 months] |
|---|---|---|---|---|---|
| 1 | 0.6 | 0.2 | 12 | 0.6 | 0.4 |
| 2 | 0.7 | 0.4 | 13 | 0.4 | 0.3 |
| 6 | 0.8 | 0.5 | 14 | 0.6 | 0.4 |
| 7 | 0.8 | 0.5 | 15 | 0.7 | 0.3 |
| 9 | 0.8 | 0.5 | 16 | 0.5 | 0.4 |
| 10 | 1.1 | 0.7 | 17 | 1.2 | 0.6 |
| 11 | 0.4 | 0.3 | 18 | 4.3 | 1.4 |

## RADIONUCLIDES IN FOODSTUFF AND THE INTERNAL RADIATION EXPOSURE

To gather information about the internal exposure, samples of all relevant types of food were collected in zone II and analyzed for $^{137}Cs$. The daily intakes given in table 3 are based on our own detailed inquiry about nutritional habits and on published data (15). Drinking water from local wells turned out to be without relevance for the radiation exposure. Results of the $^{137}Cs$ activity concentrations and of the calculated resulting internal radiation exposure are also shown in table 3. Assuming equilibrium conditions, the expected internal exposure ranges from 0.45 mSv/a (without consumption of mushrooms) to 10.7 mSv/a (with consumption of mushrooms). From the other nutrients, milk and berries make up the bulk of the exposure, followed by potatoes and meat. Evidently, the exact amount of consumed mushrooms is crucial for a realistic calculation of the internal exposure. As data about consumption habits originating from simple inquiries may be particularly uncertain with respect minor components of the food-basket, estimates of the internal radiation exposure due to such minor components will be highly uncertain.

Table 3. Concentrations of $^{137}Cs$ in relevant food items from zone II (summer 1998)

| food item | daily consumption [kg] | Cs-137 activity concentration [Bq/kg] | Cs-137 daily intake [Bq] | $H_{eff,50}$ according to (16) [mSv/a] |
|---|---|---|---|---|
| milk | 1.000 | 54 | 54. | 0.275 |
| potatoes | 0.500 | 9.1 | 4.5 | 0.023 |
| turnip | 0.050 | 3.8 | 0.2 | 0.001 |
| cabbage | 0.050 | 1.5 | 0.1 | 0.001 |
| garden fruits | 0.400 | 4.7 | 1.9 | 0.010 |
| meat | 0.200 | 20 | 4.0 | 0.020 |
| fish | 0.050 | 12 | 0.6 | 0.003 |
| eggs | 0.140 | 2.5 | 0.4 | 0.002 |
| berries | 0.011 | 2,600 | 28 | 0.143 |
| mushrooms | 0.010 | 200,000 | 2,000 | 10.22 |
| total without mushrooms | 2801 | - | 96 | 0.49 |
| total including mushrooms | 2.811 | - | 2096 | 10.71 |

Therefore, a further investigation was carried out including the direct measurement of $^{137}Cs$ body burden of inhabitants of zone II. For the inhabitants of Christinowka, we investigated their nutritional habits and the ranges of activity concentrations in their foodstuff in more detail. The daily intake of milk, mushrooms and berries of selected families was carefully recorded under supervision of two reliable inhabitants. Furthermore, additional large numbers of food samples were collected and their $^{137}Cs$ concentrations were measured. As mushrooms appeared to be responsible for more than 90% of the $^{137}Cs$ intake, we concentrated on measuring different mushroom species (table 4). Of the other nutrients, we here only give the results for milk and berries in table 4. The sample numbers of the different mushroom species reflect the collection and consumption habits.

The most frequently consumed mushroom species (boletus edulis) showed extreme variation variability of the $^{137}Cs$ activity concentrations. For the calculation of means we preferred logarithmic means and standard deviations in table 4 in spite of the fact that the distribution is not a log-normal one, but exhibits the influences of strong variability of ground contamination. But, the arithmetic means would give an even worse representation of the averages. The variations of $^{137}Cs$ activity concentrations observed in berries and milk are with factors of about ten much smaller than those of the mushrooms and the logarithmic means and standard deviations adequately describe their distributions.

The mean consumption of mushrooms turned out to be much less than expected from the inquiry before. An adult eats about 0.7 kg of dry mushrooms per year, resulting in an yearly intake of only ~ 125 kBq $^{137}Cs$. But in one case extreme case (person no. 18) consumption of up to 10 kg of dry mushrooms per year was found. A presentation of all the results obtained and detailed modeling of resulting internal exposure is in preparation (17).

Table 4. $^{137}Cs$ activity concentrations in mushrooms, berries and milk, collected respectively produced around the village of Christinowka (zone II) near Narodici in 1998 and 1999.

| food item | number of samples | range of activity concentrations [Bq/kg d.w.] | logarithmic mean and sample standard deviation [Bq/kg d.w.] |
|---|---|---|---|
| Boletus edulis | 50 | 8,000 - 1,400,000 | $170,000 \cdot 1.6^{\pm 1}$ |
| Can. cibarius | 5 | 115,000 - 433,000 | $314,000 \cdot 2.0^{\pm 1}$ |
| (Boletus) Lec. scabrum | 7 | 27,000 - 1,150,000 | $182,000 \cdot 2.0^{\pm 1}$ |
| (Boletus) Lec. aurantiacum | 5 | 16,000 - 12,8000 | $30,200 \cdot 1.3^{\pm 1}$ |
| L. volemus | 1 | 1,640,000 | |
| „Polskije griby“ | 1 | 4,090,000 | |
| (Boletus) Su. (lx.) luteus | 1 | 1,120,000 | |
| (Boletus) Xe. badius | 1 | 1,890,000 | |
| R. vesca | 1 | 5,120,000 | |
| berries | 30 | 500 - 5,000 | $1,500 \cdot 2.5^{\pm 1}$ |
| milk | 33 | 2.5 - 20* | $9.0 \cdot 1.6^{\pm 1}$ |

*activity concentration of milk in Bq/l.

## MEASUREMENTS OF THE WHOLE-BODY ACTIVITY OF CAESIUM-137

In order to determine the actual internal exposure of the 18 inhabitants of Christinowka, four measurements each of their whole-body activities of $^{137}Cs$ were carried out between July 1998 and July 1999 in three months intervals. These measurements were carried out with the mobile whole-body counter of the Korosten hospital, beginning in July 1998 and ending with the fourth series of measurements in July 1999. The results are shown in Figs. 3a and b.

The whole-body activities range over nearly three orders of magnitude and even the activity concentrations cover slightly more than two orders of magnitude. The whole-body $^{137}Cs$ activities of children (nos. 3, 4, 5, and 8) show the smallest values, the measured data being close to the detection limit of the whole-body counter used. But, also the activity concentrations of the children are the lowest of all persons measured. The $^{137}Cs$ whole-body activities clearly reflect the individual consumption and living habits. On the one hand, the persons nos. 17 and 18 consume fare more mushrooms than the average, leading to whole-body activities up to 130 and 700 kBq and activity concentrations of more than 1000 Bq/kg and 10,000 Bq/kg, respectively. As mentioned above, these two men also spend much of their time in the surrounding forests giving rise to the highest external exposures. On the other hand, the persons nos. 9 and 10, a couple, are concerned about their radiation exposure and are eating no mushrooms at all, however, do not avoid berries. This behavior leads to whole-body activities of only 4.1 kBq and 7.3 kBq and activity concentrations of 65 Bq/kg and 104 Bq/kg, respectively.

The average whole-body activity is $(8.0 \cdot 2.1^{\pm 1})$ kBq for adults (except persons no. 17 and 18), equivalent to a mean activity concentration of $(102 \cdot 2.3^{\pm 1})$ Bq/kg body weight. The average whole-body $^{137}Cs$ activity in children of $(2.2 \cdot 1.2^{\pm 1})$ kBq and, less significant, the mean activity concentration of $(80 \cdot 1.3^{\pm 1})$ Bq/kg body weight are lower than the respective values for adults. With a conversion factor of 0.038 mSv/a per Bq for adults and 0.55 to 0.045 mSv/a per Bq for children of different ages [14] this leads to an additional internal exposure of $(0.4 \cdot 3.3^{\pm 1})$ mSv/a for adults and $(0.2 \cdot 1.3^{\pm 1})$ for children. For the extreme habits, the internal exposure is much higher going up to 17 mSv/a for person no. 18.

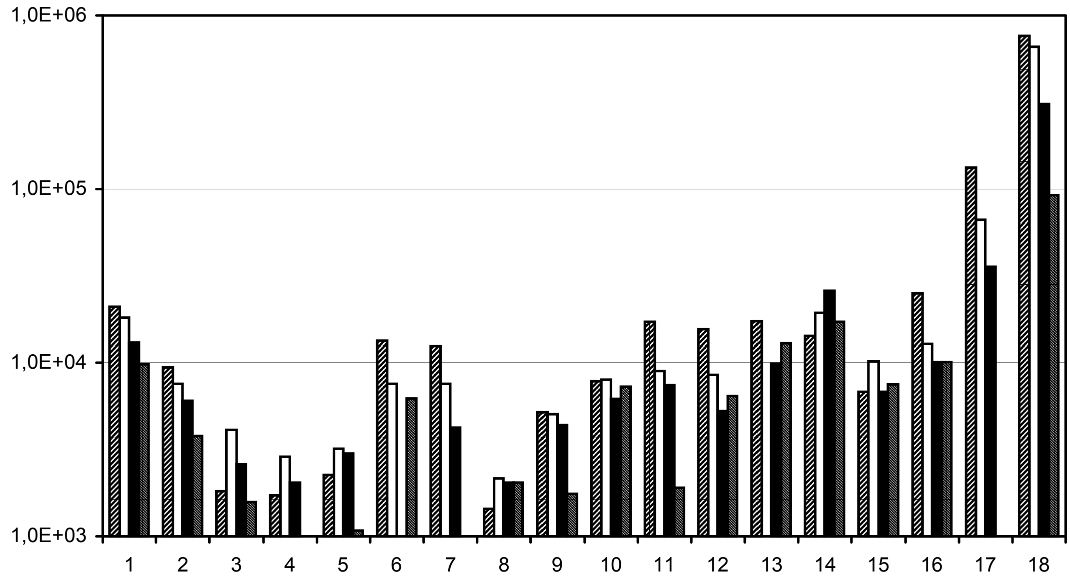



Figure 3a. Whole-body activity of $^{137}$Cs in Bq of 18 inhabitants of Christinowka measured in three-months intervals from July 15, 1998 to July 15, 1999.

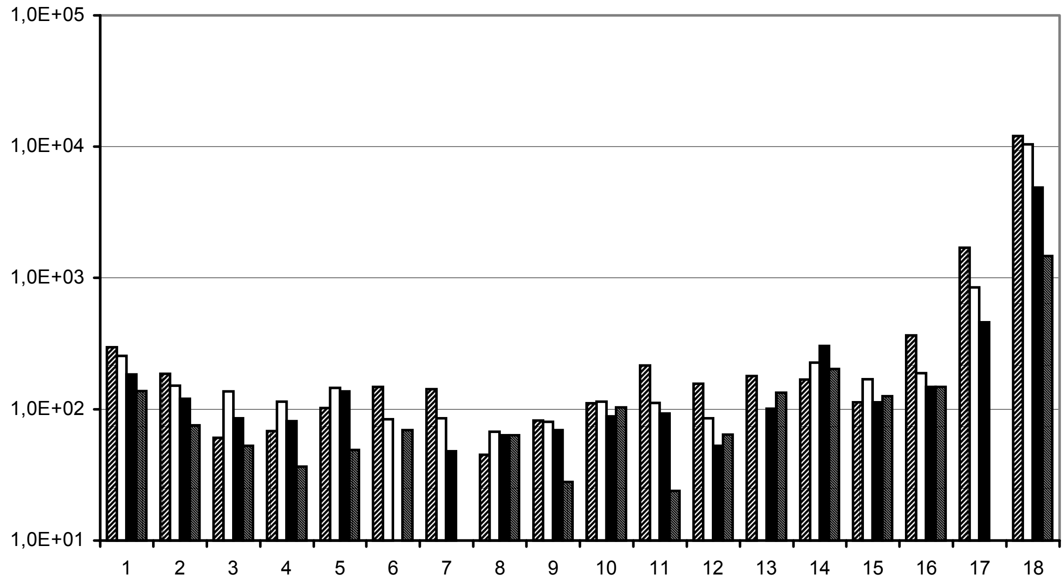



Figure 3b. $^{137}$Cs activity concentration in Bq/kg for 18 inhabitants of Christinowka

## TOTAL RADIATION EXPOSURE DUE TO CAESIUM-137

In order to discuss the total additional exposure due to $^{137}$Cs of the Ukrainian citizens living in the area of Christinowka, we summarize their exposure in table 5. Even in the small population surveyed, extreme habits can be recognized distinguished in table 5 as "concerned" and "extreme" inhabitants. The "extreme" inhabitants, persons nos. 17 and 18, two good friends, generally are not behaving normally compared to the other inhabitants. They consume much more mushrooms than the average population, spend more time in the forests and also their social behavior and general life-style is significantly different from average. Therefore we excluded them from our calculations of average exposures of the "normal" population and included them in what we call the "total" population in table 5.

For the "normal" inhabitants of Christinowka, the average total additional exposure due to $^{137}$Cs was ($1.0 \cdot 1.3^{\pm1}$) mSv/a in 1998/99. It was due to average external and internal exposures of ($0.7 \cdot 1.3^{\pm1}$) mSv/a and ($0.3 \cdot 1.9^{\pm1}$) mSv/a, respectively. Males among the inhabitants, such as persons nos. 10, 17, and 18, receive a slightly higher internal exposure of 0.3 mSv/a due to higher food consumption compared to females, for example no. 9 with 0.2 mSv/a. For "normal" inhabitants mushrooms make up about one third of the internal exposure, more than a factor of three lower than the estimates based on consumption habits of table 3. For both, "normal" and “concerned” inhabitants the external exposure dominates and the differences in their internal exposures are not significant. A reduction of the internal exposure of “normal” inhabitants would only be possible by renunciation of berries and by external supply of milk and meat. Both measures appear unlikely under present living conditions in zone II.

Table 5. External and internal exposure for different groups of the population in mSv/a

| type of exposure | group of the population | | | | | |
|---|---|---|---|---|---|---|
| | “concerned” | | “normal” | “total” | “extreme” | |
| | no. 9 | no. 10 | nos. 1 to 16 | nos. 1 to 18 | no. 17 | no. 18 |
| external | 0.8 | 1.1 | $0.7 \cdot 1.3^{\pm 1}$ | $0.8 \cdot 1.7^{\pm 1}$ | 2.7 | 4.3 |
| internal | 0.2 | 0.3 | $0.3 \cdot 1.9^{\pm 1}$ | $0.4 \cdot 3.4^{\pm 1}$ | 10 | 17.3 |
| due to mushrooms | - | - | 0.1 | 0.2 | 9.7 | 17.0 |
| due to other food | 0.2 | 0.3 | 0.2 | 0.2 | 0.3 | 0.3 |
| total | 1.0 | 1.4 | $1.0 \cdot 1.3^{\pm 1}$ | $1.3 \cdot 2.4^{\pm 1}$ | 13 | 21.6 |

If the persons with extreme consumption habits are taken into consideration, the average total additional exposure due to $^{137}$Cs of the “total” population is only slightly raised to 1.3 mSv/a. But, given the relatively small number of persons surveyed in our investigation, we cannot make any estimate how frequent and relevant “extreme” behavior is in zone II. The actual total additional exposure due to $^{137}$Cs of persons nos. 17 and 18 of 13 mSv and ~ 22 mSv surely is not acceptable for members of the public. In zone II, “extreme” social and nutritional behavior defines a group at risk. Since improvements can only be obtained by changes of life-style, the inferred risk can only be lowered by better information and education and by improvements of the social situation but not via radiation protection measures.

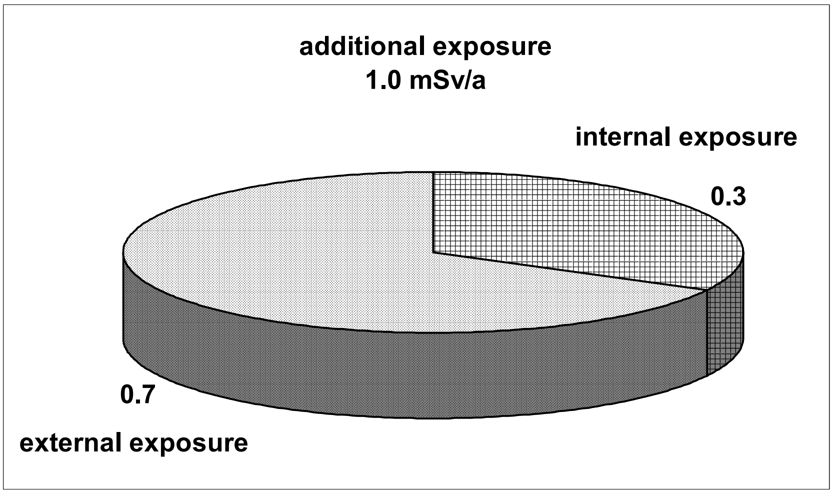



Figure 4. Additional internal and external exposure in mSv/a due to $^{137}$Cs of inhabitants of Christinowka (Zone II) without persons with extreme consumption habits (No. 17 and 18), measured by whole-body counting and TL dosemeters between July 15, 1998 and July 15, 1999.

The additional exposure due to $^{137}$Cs of $(1.0 \cdot 1.3^{\pm 1})$ mSv/a for the “normal” population in 1998/99 (Fig. 4) caused by the Chernobyl accident surely is within the variation range of the natural radiation exposure in Europe. In Christinowka, the external exposure is dominating. Its absolute magnitude demonstrates that aggregated dose factors based on the deposition densities strongly overestimate the external exposure. The same is true for the radioecological estimates of the internal exposure. The results obtained for the inhabitants of Christinowka demonstrate that the internal exposure can be kept at reasonable levels if recommendations to avoid mushrooms and berries from forest are accepted by the inhabitants. Then, the additional internal exposure can be reduced to less than 0.2 mSv/a.

## ACKNOWLEDGEMENTS

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