DISTRIBUTION OF EXTERNAL EXPOSURES IN THE RUSSIAN POPULATION AFTER THE CHERNOBYL ACCIDENT

M.I. BALONOV, V. YU. GOLIKOV, V.G. ERKIN, A.V. PONOMAREV
Institute of Radiation Hygiene,
St. Petersburg, Russian Federation

Abstract

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The data of the monitoring of external exposure in the population of the Chernobyl accident area in Russia during seven years are presented. The deterministic model has been developed for estimation of the average dose of external exposure for different groups of urban and rural populations. The model has been verified with the results of over 10 thousand measurements of individual doses in inhabitants by means of thermoluminescent dosimeters. The stochastic model is being developed by forming the dose of external exposure in the population of a contaminated area, which allows to predict the dose distribution in critical groups of a population for the purposes of radiation protection.

1. INTRODUCTION

In the history of radiation accidents, one can distinguish at least three kinds of radioactive contamination of settlements. Chronologically the first accident was realised from 1949 in the basin of the river Techa (Cheljabinsk region, Russia), into which the waste products of the nuclear enterprise “Mayak” were poured. Radionuclides were present in the water and in river silt, and in the soil of flood-lands. The river and its flood-lands in villages were a narrow local source of exposure of people living near the river or visiting it. In Goiânia in 1987, several buildings and parts of urban area near them were subjected to accidental local contamination by powder of $^{137}\text{Cs}$. Accordingly, the inhabitants of these buildings and visitors of the area were exposed. In the cases of wide-scale aerial contamination of areas due to nuclear explosions or serious accidents with the release of radionuclides' mixtures in the atmosphere (Kyshtym, 1957; Windscale, 1957; Chernobyl, 1986), settlements far from the source were contaminated, as a rule, homogeneously. The present paper is devoted to the description of regularities in forming the dose of external exposure in different categories of urban and rural population namely in the last situation, using the inhabitants of the Bryansk region of Russia as an example. It should be stressed that gamma radiation of radionuclides deposited on soil, artificial coverings, buildings and vegetation is the leading factor of exposure of the population after the Chernobyl accident.

2. MATERIALS AND METHODS

CHARACTERISTICS OF THE REGION AND OF THE FALLOUT

The south-west districts of the Bryansk region are located at a distance of about 200 km to the north-east of the Chernobyl nuclear power plant in the flat country. The dominating soil type is turf-podzol sandy and sandy loam, the annual quantity of precipitation is 500–700 mm. About half of the population of the area lives in villages in one- and two-storey brick or wooden houses and are involved mostly in agricultural activity. The second half of the population lives in small towns with the number of inhabitants from 10 to 70 thousand in multi-storey or separate houses and are employed mostly in industry.
The area of the Bryansk region was subjected to radioactive contamination as a result of rains from the radioactive cloud that passed over it on 28-29 April 1986. The isotopic composition of the fallout differs considerably from the initial composition of the release due to separation of refractory elements and decay of short-lived radionuclides. It is shown in Table I, according to the data of the Russian Hydrometeorological service [1]. The mapping of the area was performed with the $^{137}$Cs surface activity ($\sigma$) on soil. The average $\sigma$ in town Novozybkov is 0.7 MBq/m$^2$ for $^{137}$Cs, and in the villages of the region — from 0.02 to 4 MBq/m$^2$.

**TABLE I. RADIONUCLIDE COMPOSITION (REL. UN.) OF CHERNOBYL ACCIDENT RELEASE AND OF DEPOSIT ON RUSSIAN TERRITORY (TO 26.04.86)**

<table>
<thead>
<tr>
<th>Group of elements</th>
<th>Volatile</th>
<th>Intermediate</th>
<th>Refractory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclide</td>
<td>$^{131}$I</td>
<td>$^{132}$Te</td>
<td>$^{134}$Cs</td>
</tr>
<tr>
<td>$T_1/2$</td>
<td>8.04 d</td>
<td>3.28 d</td>
<td>2.06 y</td>
</tr>
<tr>
<td>Entire Release</td>
<td>20</td>
<td>5</td>
<td>0.5</td>
</tr>
<tr>
<td>Bryansk and Tula Regions</td>
<td>11</td>
<td>(13)</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**METHODS OF MONITORING OF EXTERNAL EXPOSURE**

During seven seasons of field investigations in the contaminated areas of Russia, over 1000 samples of virgin soil were taken and analysed. In each point, the surface activity of $^{137}$Cs, depth distribution of activity in soil, and the dose rate in the air were determined. No considerable difference in the dynamics of the dose rate was found over turf-podzol soils of the Bryansk region and chernozems of the Tula and Orel regions.

Additional factors considerably influencing the dose of external gamma radiation are conditions of living and activity of a population in urban and rural environments. For the quantitative estimation of this factor, about 1000 urban and rural inhabitants of the Bryansk region were polled about their behaviour during different seasons. Simultaneously with the poll, the dose rate in typical points in the settlement and its surroundings was measured.

In experiments performed in natural conditions of the Bryansk region, anthropomorphic heterogeneous phantoms of an adult and of children between 5 and 1 years of age, were used. LiF thermoluminescent detectors were placed inside and on the surfaces of the phantoms. With the results of measurements, conversion factors were calculated from the absorbed dose in the air to the effective dose to men of different ages.

Measurements of individual doses were performed with LiF thermoluminescent detectors. The Harshaw-2000D device was used to read the results. The lower limit of detection was 80 mkGy, the mean-root-square error of the dose measurement over 100 mkGy was about 10%, for lesser dose values it was up to 20%. Measurements of individual doses were done within a representative method. The population sample (about 50 inhabitants in the settlement) contained basic social and professional groups of inhabitants. Dosimeters were given to the population, as a rule, for one month. Conversion factors from the dosimeter readings to the effective dose were used to calculate the monthly effective dose; season variations of the external exposure were taken into account for the estimation of the annual effective dose. In all, about 100 settlements were investigated in the period from 1987 to 1993, about 10 thousand of values of individual doses were obtained.
3. RESULTS AND DISCUSSION

The deterministic model of exposure of different age and social groups of a population has been developed on the basis of literature data [2] and original experimental investigations in 1986-1993 [3, 4]. The average annual effective dose $E_k$ in the $k$-th group of a settlement of inhabitants in the first approximation includes a dose rate in the air at the height of 1 m above an open plot of virgin soil $d(t)$; location factor $LF_i$ equal to the ratio of the dose rate at the $i$-th typical plot in the settlement to $d(t)$; behaviour factor $BF_{ik}$ equal to the part of time spent during a year at the $i$-th plot; conversion factor $CF_{ik}$ from the absorbed dose rate in the air to the effective dose [3]:

$$E_k = \int_0^{365} d(t)dt \cdot \sum_i LF_i \cdot BF_{ik} \mu Sv$$  \hspace{1cm} (1)

From April-June 1986, short-lived radionuclides made a great contribution to the dose rate. This contribution was about 80% in May, 40% in June, and about 40% in the whole year 1986. Beginning from July 1986, in Russia, the dose rate was practically completely determined by the gamma radiation of $^{134}$Cs and $^{137}$Cs. Isotopic composition of fallout and initial dynamics of the dose rate are well known [1, 3] and were used in the model. In subsequent years parameters $d(t)$ and $d(t)/\sigma$ and location factors $LF_i$ were determined with the help of multiple measurements. To estimate behaviour factors $BF_{ik}$, results of the population poll were used. The set of model (1) parameters is presented in [3]. The ratio of the effective dose to the dose in the air and on the body surface was determined from a series of experiments with the exposure of tissue equivalent phantoms. Appropriate conversion factors $CF_{ik}$ were calculated for different age groups and typical locations. They are within the range 0.7-0.8 Sv·Gy$^{-1}$ for adults, 0.85-0.95 Sv·Gy$^{-1}$ for children of five years, and about 1 Sv·Gy$^{-1}$ for children of one year.

About 10 thousand measurements of individual doses in inhabitants of the Bryansk region within the thermoluminescent technique in 1986-1992 [7] allowed to verify generalised dose reduction factors $RF_k = \sum_i LF_i \cdot BF_{ik}$ in different groups, see Table II. The results of TL-measurements showed a linear statistical connection of the dose with soil contamination $\sigma$, see Fig.1.

**TABLE II. REDUCTION FACTORS RF$_k$ FOR RURAL AND URBAN POPULATION**

<table>
<thead>
<tr>
<th>Population</th>
<th>outdoor</th>
<th>indoor</th>
<th>school-children</th>
<th>representative group</th>
</tr>
</thead>
<tbody>
<tr>
<td>rural</td>
<td>0.36/0.31**</td>
<td>0.26/0.22</td>
<td>0.34/0.29</td>
<td>0.31</td>
</tr>
<tr>
<td>urban</td>
<td>0.25/0.20</td>
<td>0.20/0.13</td>
<td>---</td>
<td>0.20</td>
</tr>
</tbody>
</table>

* Wooden house  
** Brick house

After the decay of short-lived radionuclides and an initial intensive migration of $^{134,137}$Cs in the environment of settlements further dynamics of the dose rate are determined mainly by penetration of caesium radionuclides in the soil. An investigation of about 1000 soil samples during seven years was the basis for the model elaborated for convective-diffusive...
transfer and obtainment of two-exponential expressions for the average dose rate of $^{134,137}$Cs gamma radiation in the open area [3]:

$$\bar{d}(t) = \bar{d}_0 \sum_{i=1}^{2} a_i \cdot \exp(-1n2 \cdot t / T_i),$$

where

$$\bar{d}_0 = 0.10 \text{ (μGr/day)/(kBq/m}^2\text{)};$$

$$a_1 = 0.86; a_2 = 0.14; T_1 = 1.8 \text{ years}; T_2 = 15 \text{ years}$$

Taking into account the modifying factors described above allows to estimate the effective dose in inhabitants during each year after the accident and to forecast it for the future the curve in Fig. 2. Generalised data of individual TL-dosimetry of Bryansk region inhabitants plotted in Fig. 2 as points are verification of the model. These points indicate average annual doses in rural population standardised to the s and obtained as a regression coefficient for dependence analogous to Fig.1 [4]. Good agreement of the results of calculated and instrumental dosimetry gives confidence in validity of the dose estimation during the time period elapsed after the accident, and its prognosis for 70 years.

**FIG. 1. Dependence of average annual effective dose of external gamma radiation $E$ in Bryansk localities on the density of $^{137}$Cs surface activity on soil $\sigma$.**
Actually, during the eight years after the accident, the average dose of external gamma radiation in inhabitants of different villages of the investigated region was from 1 to 100 mSv, and in the critical groups (foresters, herdsmen) — up to 150-200 mSv. The average dose in inhabitants of the town of Novozybkov is about 13 mSv. According to the dynamic model, during eight years the population has received 60-65% of the life time dose of external gamma radiation.

Stochastic model. Actually, all natural and social processes of forming the dose of external gamma radiation in inhabitants of the contaminated area have a probabilistic character, and parameters describing them have considerable uncertainty. Finally, the probabilistic character of the processes of forming the dose causes uncertainty of the basic dosimetric value, the effective dose of external gamma radiation in persons living in a specific settlement and entering a specific social group. The characteristics of this uncertainty in the form of the frequency distribution of the annual individual dose measured with TLD in inhabitants of the town of Novozybkov and a number of villages, and its parameters normalised to the surface activity $\sigma$ are presented in Figs. 3 and 4. Both distributions have a lognormal form with the following parameters: the mean geometric in town in 1991 $1.0 \text{ mSv-m}^{-2}-\text{MBq}^{-1}$, and the standard deviation $0.4 \text{ mSv-m}^{-2}-\text{MBq}^{-1}$; in villages in 1989 $3.8$ and $1.8 \text{ mSv-m}^{-2}-\text{MBq}^{-1}$, respectively. The contribution of the inaccuracy of the TLD-method to the uncertainty of the dose should be taken into account. The average normalised dose in the inhabitants of the town in 1991 is by 3.8 times lower than the dose in rural machine-operators in 1989. The coefficient 1.7 of this relation is attributed to the decay of $^{134}\text{Cs}$ and $^{137}\text{Cs}$ nuclides and their deepening into soil during two years, and the coefficient 2.2 — to the difference in urban and rural conditions and in the way of life of the considered social groups. To model adequately the probabilistic process of forming the dose, it is necessary to take into account the stochastic nature and quantitative uncertainty of each parameter of the formula (1). Such stochastic model is being developed presently by the authors together with P. Jacob (GSF, Munich). As an example, Fig. 5 presents experimental data for one of the links of the model — the frequency distribution of location factors in town. As it is seen from Fig. 5, the values of the location factors are distributed close to the lognormal law with the variance
factor within the limits from 0.5 to 1.0, which can considerably influence the distribution of
the dose in inhabitants of the town. Similar information has been collected for all basic links
of the model. In the completed form, the stochastic model will allow not only to estimate and
predict the average dose in different groups of urban and rural inhabitants, but the frequency
distribution of the individual dose. Such probabilistic characteristics are important for
radiation protection of population, in particular, for the choice of critical groups of population
and standardisation of their exposure with respect to possible deterministic effects.

FIG. 3. Distribution of standardised external dose in Novozybkov adult inhabitants in 1991 according
TLD-measurements.

4. CONCLUSIONS

The regularities and levels of external exposure in inhabitants of the Chernobyl
accident in Russia has been studied experimentally. The deterministic model for estimation,
reconstruction and prediction of the effective dose in different groups of urban and rural
population has been developed. The model has been verified by means of about 10 thousand
individual measurements of the dose with the TLD–method. The average dose during eight
FIG. 4. Distribution of standardised external dose in rural tractor-drivers in 1989 according TLD-measurements.

FIG. 5. Distribution of Location Factors (rel. units) in typical urban areas of the town Novozybkov.
1 – undisturbed area, 2 – asphalt, 3 – wooden house [5], 4 – multi-storey house [3]

years in inhabitants of separate villages reaches 110 mSv, and in critical groups (foresters, herdsmen) — 150-200 mSv. During this period the population has received 60-65% of the life-time dose of external gamma radiation. On the basis of results of wide-scale measurements of the radiation situation and poll of inhabitants on the mode of their behaviour, a stochastic model of forming the dose of external exposure in different groups of population of the contaminated area is being developed. The model will allow to predict dose distribution in critical groups of population and ground adequate measures of radiation protection.

REFERENCES


