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Pathways, Levels and Trends of Population Exposure after the Chernobyl Accident

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Abstract. In this paper main regularities of the long-term exposure of the population of former USSR after the Chernobyl accident are described. Influence of some natural, human and social factors on the forming of external and internal dose in the rural and urban population was studied in the most contaminated regions of Belarus, Russia and Ukraine during 1986-1994. Radioecological processes of I, Cs and Sr nuclides migration in biosphere influencing the processes of population dose formation are considered. The model of their intake in human body was developed and validated by large-scaled measurements of the human body content. The model of external exposure of different population groups was developed and confirmed by the series of individual external dose measurements with thermoluminescent dosemeters. General dosimetric characteristics of the population exposure are given along with some samples of accumulated external and internal effective doses in inhabitants of contaminated areas in 1986-1995. Forecast of the external and internal population effective dose is given for the period of 70 years after the accident.

1. Introduction

After the Chernobyl accident the environment appeared contaminated with complex mixture of radionuclides - products of nuclear fission and neutron activation in the reactor Unit 4 - released in the atmosphere during 10 days, at least. The Chernobyl NPP is located close to common borders of Belarus, Russia and Ukraine, this being the reason why the population in all these republics of the former Soviet Union were affected by external and internal irradiation from many radionuclides with different radiological properties. Ratio of external and internal dose, of activities of different radionuclides incorporated in the human body, significantly depends on radionuclide composition of the cloud and fallout from it in each particular region, on meteorological conditions of fallout (mainly, amount of precipitations) and later on - from dominating soil type, agricultural practices and countermeasures applied.

This paper distinguishes between two groups of people that were exposed to significantly higher doses than the entire population of the former Soviet Union as a result of the Chernobyl accident:

- urgently evacuated population;
- population of contaminated area.

The urgently evacuated population consists of forty nine thousand inhabitants in the town of Pripyat, situated 3 km from the Chernobyl NPP, who were evacuated on 27 April

1986 owing to the danger of acute radiation injury, and fifty three thousand inhabitants in the 30-km zone around the Chernobyl NPP evacuated over a period of ten consecutive days. It is known that they were subject to external exposure and incorporation of radioactive substances during a period from 1-11 days. No cases of acute radiation sickness have been found in the population that were evacuated in 1986.

Population of the contaminated area. About 4 million people permanantly live and are subjected to external and internal irradiation in the area with Cs-137 surface activity over 0.04 MBq/m^2 (1 Ci/km^2) with the area over 131 thous. km^2. About 270 thousand of them remained in 1986 in the so called "controlled area" (CA) of 10.3 thousand km^2 with a surface activity of Cs-137 over 0.6 MBq/m^2 (15 Ci/km^2) and higher, including: in Russia - 112 thousand people in 2.4 thousand km^2 in the Bryansk region, in the Ukraine - 52 thousand people in 1.5 thousand km^2 in Kiev and Zhitomir regions, and in Belorussia - 109 thousand people in 6.4 thous. km^2 in the Gomel and Mogilev regions. The package of active countermeasures for radiation protection of the population has been constantly performed in the CA since 1986: delivery of non-contaminated meat and dairy products, decontamination of settlements, measures on decrease of radionuclide content in agricultural products, etc. The population of the CA villages with the greatest level of radioactive contamination was during the period from 1986-1992 gradually resettled to noncontaminated areas.

This paper presents a review of main regularities of exposure of two indicated population groups, both from external and internal (incorporated in the body) sources of radiation during the past ten years after the Chernobyl accident. We also consider prognose of population exposure for the future sixty years and altogether estimate the exposure for seventy years after the event, which is close to the average duration of human life.

2. Radionuclide composition of Chernobyl fallout

The analysis of regularities of population exposure in contaminated areas is naturally based on the data on radionuclide composition and levels of contamination. Radionuclide composition of the release of the Chernobyl accident products into the atmosphere varied considerably as far as the temperature and conditions were concerned [10]. During the same period, the change in weather conditions caused distinctions of radioactive fluxes in different directions, even in their initial nuclide composition [2, 11]. The basic cause of further separation of radioactive mixture in the cloud was the different deposition rate of aerosol particles of different dispersivity and density. The largest of them, mainly of fuel composition, fell out in the so called "near zone", i.e., at the distance of some tens of kilometers from the source. To some extent, the element composition of the radioactive depositions was influenced by deposition mechanism: wet deposition with precipitations or dry one under the action of gravitation, atmospheric mixing and diffusion.

In Table 1 we present the data on composition of radioactive fallouts in the whole spots separately for the near (up to 100 km) and the far zones in the form of the ratio of the surface activity σ_r of the r-th radionuclide on soil to the surface activity σ_{137} of the most radiologically significant nuclide of the Chernobyl accident, cesium-137 [2,11]. The list of radionuclides is separated into three groups: volatile (isotopes and compounds of I, Te, Cs. etc.) refactory nonvolatile (Zr, Ce, Pu, etc.), and intermediate ones as to this attribute (Ru, Ba, Sr). Regarding volatile radionuclides, considerable separation with respect to Cs-137 was not noted. Considerable difference of relative content of refractory radionuclides in the fallouts in the far zone as compared with the composition of the release engages our attention. It thereby, quantitatively characterizes the process of the radioactive cloud

Table 1.

General composition of radionuclide depositions in different regions of the European territory of the former Soviet Union [2, 10, 11] (σ_r/σ_{137} on April 26, 1986) *

Radionuclide	Entire release [10]	Near zone (< 100 km)	Far zone (> 100 km)	
			"Cesium spots" in Belorussia and Russia	South of Kiev region
^{131}I	20	15-30	10-14	(1.0)
^{132}Te	5	13-18	(13)	(1.0)
^{134}Cs	0.5	0.5	0.5	0.5
^{137}Cs	1.0	1.0	1.0	1.0
^{125}Sb	-	0.02-0.1	0.03-0.07	0.1
^{110m}Ag	-	0.005-0.01	0.005-0.014	(0.01)
^{103}Ru	2.0	3-12	1.7-2.0	2.7
^{106}Ru	0.4	1-5	0.5-1.4	1.0
^{140}Ba	2.0	3-20	0.7-1.1	(0.5)
^{89}Sr	1.0	1-12	0.2-0.3	0.3
^{90}Sr	0.10	0.1-1.5	0.01-0.03	0.03
^{91}Y	-	3-8	0.06	0.17
^{95}Zr	2.0	3-10	0.03-0.11	0.3
^{99}Mo	-	3-25	(0.11)	(0.5)
^{141}Ce	2.3	4-10	0.07-0.16	0.5
^{144}Ce	1.6	2-6	0.04-0.15	0.3
^{239}Np	20	7-140	(0.6)	(3)

* values in parentheses were estimated from indirect data.

depletion and of the fallout from the cloud as it moved off the release source, of less volatile particles predominantly of the fuel composition, including refractory products of fission and activation. This also relates within certain limits to barium and strontium isotopes.

The Central, Bryansk-Belorussian, and Kaluga-Tula-Orel spots are separated in the map of radioactive contamination of the European part of the former USSR [2]. The Central radioactive spot was formed around the Chernobyl NPP during about 10 days of the release with predominant direction of contamination to the west and north-west in the territory of Ukraine and Belorussia. The Bryansk-Belorussian spot centered at 200 km to the north-north-east from the Chernobyl NPP was formed on 28-30 April 1986 as a result of rainfalls at the interface of the Bryansk region of Russia and the Gomel and Mogilev regions of Belorussia. The surface activity of Cs-137 (σ_{137}) in the most contaminated soil sites here reaches 3-5 MBq/m^2. The Kaluga-Tula-Orel spot in Russia with its center at the distance of about 500 km to the north-east from the Chernobyl NPP is also "cesium" one and was formed because of rains on 28-30 April from the same radioactive cloud that the Bryansk-Belorussian spot was formed. Here the levels of depositions from the depleted cloud are lower, and σ_{137} does not reach 0.6 MBq/m^2 [2,11].

3. Pathways of population exposure

The relation between sources and types of radiation, ways of incorporation of radionuclides into body and the role of separate nuclides turned out to be considerably different for the categories of exposed persons indicated above. This difference is primarily determined by their staying in different zones of radioactive contamination and in different periods after the accident. This caused different isotopic composition of nuclides mixture and the spectral composition of their radiation, and different levels of irradiation.

Taking into account these considerations, in Table 2 we systematized basic exposure pathways of separate categories of people during early and long-term periods after the Chernobyl accident. The squares of the table present basic nuclides or groups of nuclides responsible for the given pathway. In the case of ingestion, only the radionuclides absorbed in the alimentary tract are shown.

The urgently evacuated population of the near zone of the accident were subjected to external gamma exposure from the cloud and to beta and gamma exposure from the radionuclides deposited on the surface during 1-11 days after the reactor explosion. When estimating the committed effective dose, we take into account the role of inhalation of radionuclides from the cloud and of resuspended ones. Food products were subjected to surface contamination. Intake of I, Cs, and Sr radionuclides with local milk could be decreased because population was notified about the accident and prohibited to consume contaminated products. According to the data of our measurements in 1986, the dose in thyroid of some children reached tens of Gray.

The population in contaminated areas has been subjected to exposure during many years. In connection with long-term accumulation of the dose, the contribution into it of the exposure from the radioactive cloud is insignificant in comparison with the external exposure from deposited radionuclides: according to available data of measurements, less than 10 % of the dose during the first year. The contribution of inhalation from the initial cloud and of resuspended radionuclides from wet deposition is also insignificant as compared with ingestion of I, Cs, and Sr isotopes. It is necessary to take into account external exposure of skin by high-energy beta radiation in the first months after the accident. Later on, as the radionuclides decay and deepen into soil, the role of this factor decreases.

Table 2

Main pathways and nuclides of population exposure after the Chernobyl accident

Category of Exposed Persons	Time after Accident, days	External Exposure		Internal Exposure	
		β	γ	Inhalation	Ingestion
Evacuated Population	1-11	^{106}Ru/Rh ^{144}Ce/Pr ^{132}Te/I	^{132}Te/I ^{131}I IRG*	^{131,133}I ^{132}Te/I TUE**	^{131}I ^{132}Te/I ^{134,137}Cs
Population of contaminated area	< 100	^{106}Ru/Rh ^{132}Te/I	^{132}Te/I ^{131}I ^{134,137}Cs	^{131}I TUE**	^{131}I ^{134,137}Cs ^{89}Sr
	> 100	-	^{134,137}Cs ^{106}Ru/Rh	TUE** ^{106}Ru/Rh ^{144}Ce/Pr	^{134,137}Cs ^{90}Sr/Y

* IRG denotes Inert Radioactive Gases (Kr, Xe).
** TUE denotes radionuclides of TransUranium Elements (Pu, Am, Cm).

The leading factor of internal exposure during the first month after the accident was incorporation of I-131, especially in children with milk. Later on, cesium radioisotopes (Cs-137 and Cs-134) play the leading role in internal exposure of population. Their intake into the body during the first months is determined by surface contamination of the environment, and later it strongly depends on the properties of local soil and the time after contamination.

4. Dosimetry of external exposure

The deterministic model of exposure of different age and social groups of the population has been developed on the basis of experimental investigations in 1986-1994 [5, 6,13]. These studies included hundreds of thousands of measurements of the exposure dose rate in different periods after the accident above the virgin soil, in typical plots of settlements, including residential, industrial, and social buildings; the results of the poll of about one thousand inhabitants of the Bryansk region of Russia [5] and of rural inhabitants of the Ukraine [13] about their mode of behavior during different seasons; the results of 450 analyses of Cs-137 and Cs-134 in profiles of virgin soil taken in 1986-1994 in Russia, Ukraine, Bavaria and Sweden, the results of over 5 thousand measurements of individual doses in inhabitants done with thermoluminescent method [5, 6, 13].

Dr. V. Golikov in Russia [5] and Dr. D. Novak in Ukraine exposed anthropomorphous phantoms of people of different age ranging from one year to adult, containing TL-detectors in many organs showing conditions of exposure to Cs-137 and Cs-134 radionuclides outdoors and indoors, to determine conversion factors from the exposure dose to organs and effective doses.

For reconstruction of the external dose in evacuated population, results of measurements of the exposure dose rate in the town of Pripyat and in many settlements of the 30-km zone, beginning from the 26 April 1986, data of the polling of about 35 thousand inhabitants on the mode of their behavior after the accident and before evacuation together with isotopic composition of environmental samples are used [12].

According to the deterministic model presented on Fig.1 the average annual effective dose E_k in the k-th group of a settlement inhabitants depends on ***dose rate in the air*** at the height of 1 m above an open plot of virgin soil in this settlement and its vicinity $\dot{D}(t)$; **location factor** LF_i equal to the ratio of dose rate at the i-th typical plot in the settlement to $\dot{D}(t)$; ***time factor*** TF_{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.

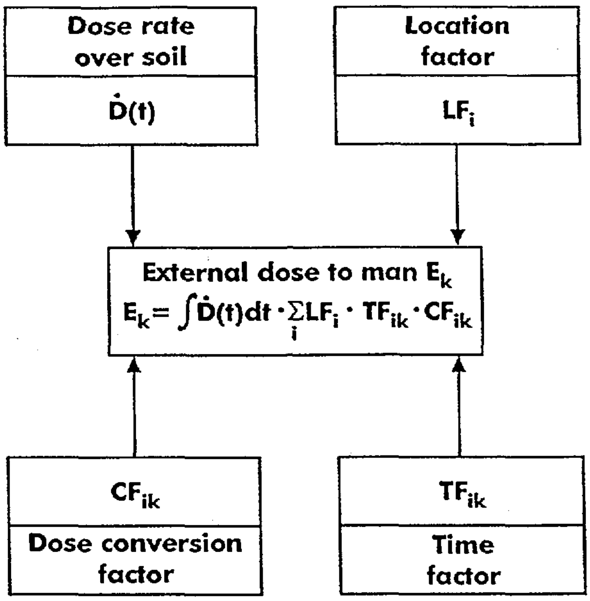

Fig.1. Model of external dose formation in k-th occupational group of population

In April-June 1986, short-lived radionuclides as Te/I-132, I-131, Ba/La-140 etc. made great contribution to the dose rate. This contribution was about 80-90% in May, 40-60% in June and in the whole year 1986. Since 1987, the dose rate was mainly determined by gamma radiation of Cs-134 and Cs-137. Isotopic composition of fallout and initial dynamics of the dose rate are well known [1, 2, 5] and were used in the model. Dose rate in the air $\dot{D}(t)$ is considered as sum of dose rate from short-lived and medium-lived radionuclides and from long-lived Cs radionuclides:

$$\dot{D}(t)=\dot{D}_{sm}(t)+\dot{D}_{Cs}(t),\ \mu Gy \cdot h^{-1} \quad (1)$$

$$\dot{D}_{sm}(t)=\sigma_{137}\cdot\sum_r \sigma_r / \sigma_{137}\cdot d_r\cdot \exp(-ln2\cdot t/T_r) \ , \quad (2)$$

Where: σ_{137}, kBq · m^{-2}, - average surface activity of Cs-137 on soil in the locality on a day of the accident, 26.04.86;

σ_r, kBq · m^{-2}, - the same quantity for radionuclide r with decay half-period T_r;

d_r, (pGy· m^2)/(Bq· h) - dose rate coefficient equal to initial dose rate in air 1 m above ground created with the plane thin source of 1 kBq·m^{-2} of radionuclide r in soil for dry or wet fallout, respectively.

After decay of short-lived radionuclides and initial intensive migration of Cs-134, Cs-137 in the environment of settlements further dynamics of the dose rate is determined mainly by decay and penetration of cesium radionuclides in soil. Investigation of about 450 soil samples during eight years was the basis for obtaining by P.Jacob and V.Golikov of two-exponential expression for the average dose rate of Cs-134, Cs-137 gamma radiation in the open area at a distance of more than 100 km from Chernobyl NPP:

$$\dot{D}_{cs}(t)=\sigma_{137}(\, d_{137} \cdot \exp(-\ln 2\; t/30)+ 0.54\cdot d_{134} \cdot \exp(-\ln 2\cdot t/2.1))\cdot AT(t),\ \mu Gy\cdot h^{-1} \quad (3)$$

$$AT(t) = 0.57 \cdot \exp(-\ln 2\cdot t/1.5) + 0.57 \cdot \exp(-ln2 \cdot t/50),\ rel.\ un. \quad (4)$$

where: 0.54, rel..un., - average ratio of Cs-134 to Cs-137 activities in Chernobyl fallout;

30 and 2.1, years, - half-periods of Cs-137 and Cs-134 decay, respectively;

AT(t), rel.un., - attenuation function for dose rate in air due to migration of Cs radionuclides in soil. Second term of AT(t) is obtained with the help of data from [15];

d_{134} and d_{137} are taken as for a plane thin source at the soil depth of 0.5 g. cm^{-2}.

Table 3

Reconstruction and prognosis of the average effective dose of external exposure of an adult population in the areas contaminated after the Chernobyl accident.

Country, reference	Population group	E/σ_{137}, μSv per kBq · m^{-2}				
		1 year	1986-1990	1991-1995	1996-2056	1986-2056
Ukraine [13]	Rural	16	33	-	(32)**	(74)**
Russia [5,6]	Rural	13	28	8	28	64
	Urban	8	17	6	17	40

σ_{137} is given for 1986
** Preliminary estimates

As follows from the described model further decrease of dose rate in open air due to continued deepening and decay of Cs-137 is expected with a half-period of about 19 years or 3 to 5 per cent in a year. In Table 3 the generalised estimations are presented both in the external exposure dose accumulated during past 10 years and expected in the future. The average dose for adult inhabitants of rural (villages, settlements) and urban (towns with the population between 10 and 100 thousands persons) localities with socio-professional composition of population and structure of housing resources typical for temporary latitudes of the European part of former USSR in 80-th and 90-th is given . The dose is standardised to average soil surface contamination with Cs-137 in the locality and its vicinity in 1986. For more specific groups of inhabitants, the average dose calculated by means of Table 3 should be multiplied by factor of 0.6 to 1.7. Ratio of the dose in inhabitants of rural and urban localities with equal level of contamination is about 1.5. From the Table 3 one can conclude that the inhabitants of the contaminated zone have obtained during 10 years about 60% of the external dose and about 40% will be received in future.

To validate the model used for dose calculations Fig. 2 presents the time dependence of annual effective dose of external exposure of rural inhabitants of the Bryansk region of Russia estimated according the model described above and from large-scaled individual dose measurements with thermoluminescent dosemeters [6]. Agreement between calculated curve and measurements data corraborates correctness of accumulated and forcasted dose estimates.

According to the data by I. A. Likhtarev and V. K. Chumak [12], the reconstructed average effective dose from external gamma exposure in inhabitants of Pripyat town evacuated on 27 April 1986 was 12 mSv, and in inhabitants of the villages of the 30-km zone evacuated before 4 May - 18 mSv. In some Ukrainian villages of the 30-km zone, the average dose during this period reached 110-130 mSv and individual ones - up to 383 mSv.

After evacuation of inhabitants of the 30-km zone, villages located in the Bryansk-Belorussian spot became the most contaminated with radionuclides inhabited areas. The average effective dose accumulated in inhabitants of the contaminated area during past ten years was from 1.3 mSv for $\sigma 137$ = 0.04 MBq/m2 (1 Ci/km2) to 150 mSv for $\sigma 137$ = 4 MBq/m2 (v. Zaborje, Bryansk region). The dose in separate groups of population, varies by 0.6-1.7 times, and in individuals - up to the factor of three to both sides.

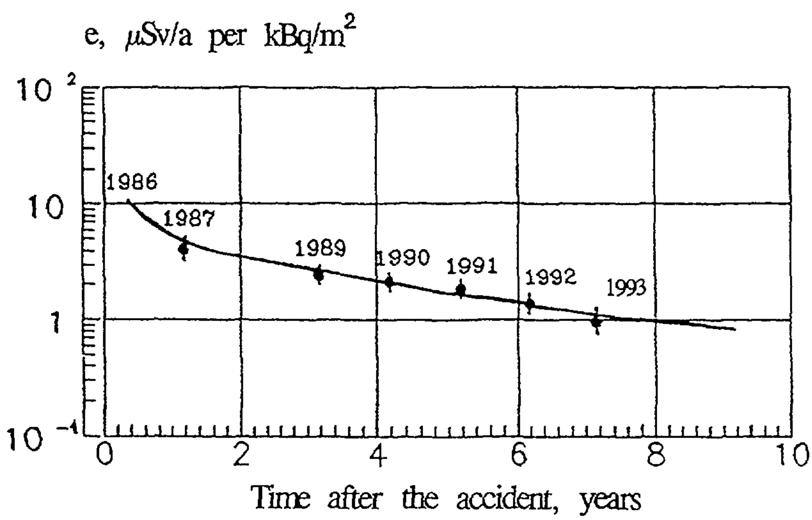

Fig. 2. Time dependence of annual effective dose of external gamma radiation in rural population of Bryansk region [5,6].

5. Dosimetry of internal exposure

The structure of the simple model of internal exposure of a man located in area contaminated with radionuclides is presented on Fig. 3. Main pathways of radionuclide intake in a body of a man of *k-th* age and gender group are considered: inhalation with average inhalation rate IR_k ($m^3.c^{-1}$) of the air with the time-dependent concentration of *r*-th radionuclide AC_r ($Bq.m^{-3}$) and ingestion of the set of *f*-th food products including drinking water with consumption rate CR_{fk} ($kg.day^{-1}$) with time dependent specific activity SA_{fr} ($Bq .kg^{-1}$). Data on radionuclide content in the air, drinking water, agricultural and natural food products are obtained during current radiation monitoring and radioecological studies. Rate of air inhalation by persons of different age and gender for different activities is well known from physiological studies. The consumption rate of different food products varies significantly both from age and sex and of local traditions of agricultural production, collection of natural food, dietary habits. For internal dose estimation after the Chernobyl accident these data were obtained by population polls [9,19] and from analysis of statistical data. Dose conversion factors are usually taken from ICRP-56 [16].

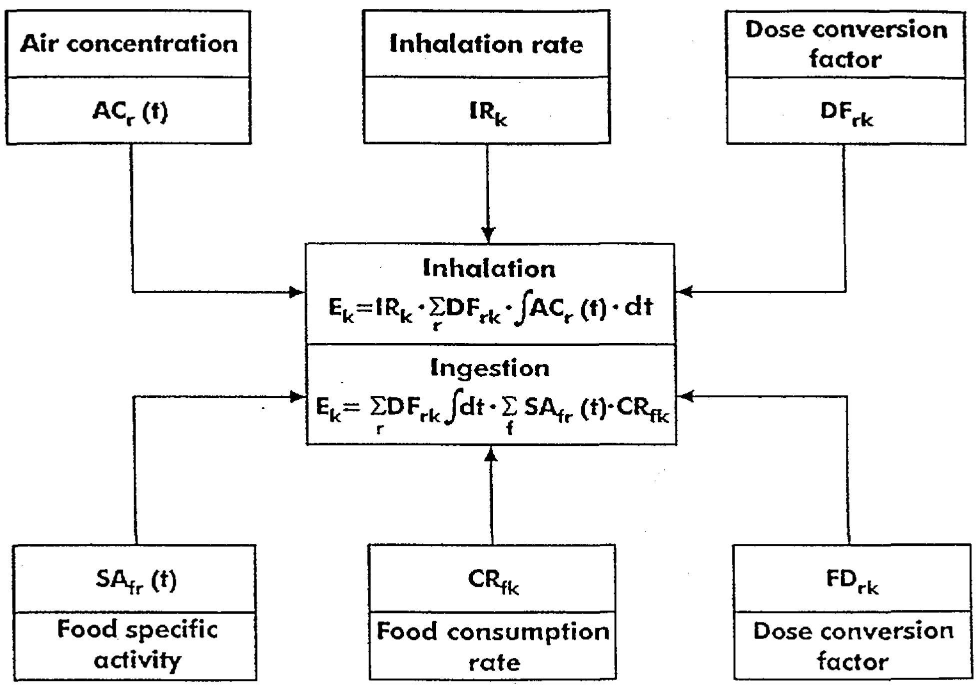

Fig.3. Model of internal dose formation in *k*-th age and gender group of population
r - radionuclide index;
f - food product index

Not many reliable experimental data on radionuclide content in air and food products were collected during the most important early period of the Chernobyl accident. This is why for the purposes of internal dose estimation about 350 thousand measurements of I-131 in thyroid gland were done in inhabitants of the three republics, 1 million measurements of Cs-

134,137 content in the body, hundreds of analyses for Sr-90 and tens of analyses for Pu isotopes in autopsy samples of tissues were performed. The results of these measurements are the basis for reconstruction of internal exposure dose in different groups of population of the contaminated area. Both these reconstructions and prognose require taking into account the time dependence of intake in the body.

5.1. Dose of radioiodine radiation in thyroid

As the function of intake of radioiodine in inhabitants of contaminated areas the two-exponential function was used, describing dynamics of iodine-131 content in milk [9], or the sum of this function with the function of inhalatory intake during the first days, or the similar simplified function that represents homogeneous intake during 10-15 days, and consequent decrease of intake with the period of 5 days [8] typical for natural decontamination of milk from I-131. The difference in results of the dose reconstruction by means of different intake models does not exceed 30 %.

By means of the dosimetric models described briefly above and in detail in [8, 9,20], the individual doses from I-131 content in thyroid were calculated. In each settlement the average dose value was usually estimated for six age intervals: under one year, 1-2, 3-6, 7-11, 12-17 years, and adults. In an age group, the frequency distribution in the dose usually has an asymmetric form close to lognormal one. The maximal value of the individual dose sometimes exceeds mean arithmetic value for the settlement by 3-5 times. Figure 4 shows an example of age dependence of average doses in thyroid of the inhabitants in Kiev [21]

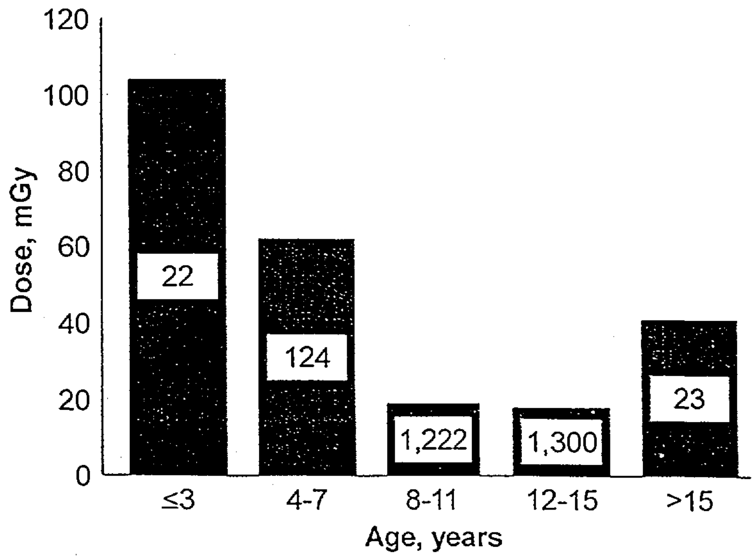

Fig. 4. Age dependence of the average thyroid dose in Kiev residents after the Chernobyl accident [21]

The relation of the average dose in thyroid determined with the measurements of the thyroid in May-June 1986 with different parameters of radioactive contamination of the environment in Russia (surface activity of Cs-137 on soil σ_{137}, dose rate in air on 10-12 May 1986, average concentration of I-131 in milk on 5-12 May 1986, the content of radiocesium in the body of adult inhabitants in the same village in August-September 1986) was analyzed within the technique of linear regression. The correlation coefficients of the parameters in all cases were highly significant:within the limits from 0.86 to 0.95 [8]. According to the data by V.T.Khrush and Yu.A.Gavrilin, this relation is nonlinear in the Southern Belorussia: the dose is relatively higher in the area of lower radioactive contamination [19].

Actual average levels of exposure in adult inhabitants of Pripyat town, of the most contaminated districts of the Kiev and Zhitomir regions of Ukraine, and of the Gomel and Mogilev regions of Belorussia, are estimated about 0.4 Gy, and in the Bryansk region of Russia - 0.1-0.2 Gy. Accordingly, average doses in children of preschool age (1-6 years) are by 3-10 times higher and reach 3-5 Gy in separate settlements of these districts. Individual doses in children of Russia reached 8-10 Gy, and in Ukraine and Belorussia - 30 and even 50 Gy [8,9,21].

5.2. The dose from cesium, strontium and transuranium radionuclides

The process of dose formation from internal exposure to population due to intake of long-lived Cs-137, Cs-134, and Sr-90 through food chains can be separated into the stages of the surface contamination of vegetation in spring and summer 1986 and of the system (root) transfer of them from soil to plants since summer and autumn 1986. The parameters of deposition and migration at the first stage strongly depend on the distance from the source of release, the state of vegetation and weather conditions, and on the second stage - on agrochemical properties of soil and on agricultural practice. During a long period of time, the main amount of radiocesium (60-90 %) was incorporated in the body of local inhabitants with dairy and meat products.

Beginning from the autumn 1986, the "soil - plant" system is the most variable link of the food chain, which determines protracted incorporation of Cs and Sr radionuclides to the body of man with vegetable and animal products. The types of dominating soils in different regions of radioactive contamination differ considerably: black earths and grey forest soils in the Tula and Orel regions of Russia, turf-podzol soils in Belorussia and the Bryansk region, peat soils in the west of Ukraine and Belorussia. Depending on the type of soil, the average value of the cesium transfer factor to grass varies almost by three orders of magnitude. The transfer factor for Sr-90 from soil to natural grasses varies within narrower limits, namely up to 60 times [7, 17].

Besides soil properties, the process of natural fixation of cesium radionuclides in soil structures with time after the radioactive contamination of the area considerably influences their content in agricultural production. Fig. 5 illustrates the dynamics of the aggregated transfer factor for Cs-137 from soil to milk of cows pastured in semi-natural pastures. The specific activity of Cs-137 in grass, milk and meat of cattle decreased since 1987 to 1991-92 by 1-2 orders of magnitude. Similar decrease is observed in the content of Cs-137 in agricultural production from ploughed soils: cereals, potatoes, etc. The period of decrease of Cs-137 content in all these products in districts with turf-podzol and black soil varied within 0.6-2 years, and, was on the average, 1.2 years. In some districts of Rovno region in Western Ukraine where peat soil dominates transfer factors soil-vegetation-milk are significantly higher and their decrease is lower than in other areas. Along with annual decrease, the content of radionuclides in milk and meat varies considerably during a year in seasons depending on the ration of the cattle: it is increased during the pasture period and decreases when feeding cattle by fodder root-crops and mixed fodder during the stalled period . Since 1991-92, there is the tendency to slowing down of the process of natural decontamination of agricultural products, in the first place, in the black earth zone. On the contrary, cesium radionuclide content in many species of natural food products collected from the forest (mushrooms, berries) did not reveal significant decrease since 1986 extra to radioactive decay - see Fig. 5.

In the most contaminated areas of the former USSR, the measures of radiation protection of population were widely performed beginning from May 1986, including prohibition for consumption of local food products, in the first place, of dairy, meat and natural ones, and supply of noncontaminated food products. These actions considerably decreased intake of radionuclides in the body. The degree of decrease of intake in different settlements widely varies and is characterized by the factors from 1.5 to 15 [18]. Therefore, in the most contaminated area, the best method for assessment of the current dose in inhabitants is measurement of Cs-137 and Cs-134 content in the body, and calculation of actual dose during the investigated period, taking into account seasonal variations.

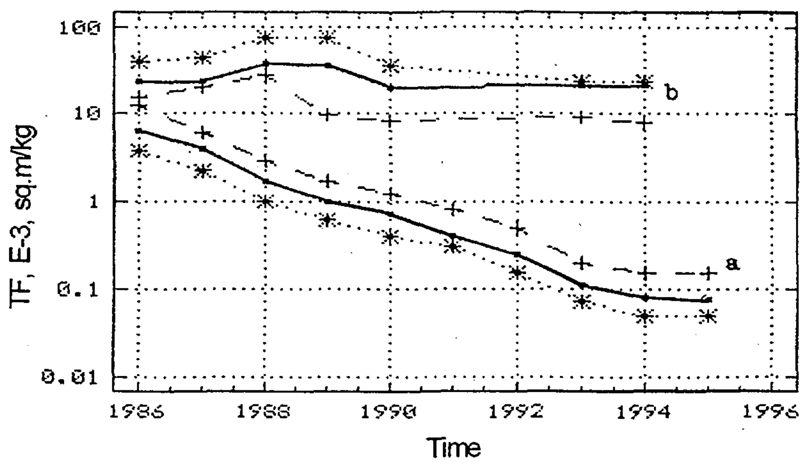

Fig. 5. Cs-137 transfer factor from soil to milk (a) and mushrooms (boletus luteus, b) in Bryansk region as a function of time after the Chernobyl accident [V. Shutov and G. Bruk, in press]

The maximal content of Cs-134,-137 in the body of inhabitants of the Chernobyl accident zone was reached in the first months after the accident. In summer 1986 the average content of the sum of these nuclides in the body of adult inhabitants of some villages in Belorussia and Russia reached 0.4-0.6 MBq, and individual one - up to 4 MBq. In the Novozybkov town of the Bryansk region with population of 46 thousands, the average Cs-134,-137 content in the body in summer 1986 was about 0.06 MBq. Further on, in the settlements, where "radiation-free" food products were supplied, the content of radiocesium decreased at first with the period less than one year, then with a period of 1-1.5 years. This process considerably slowed down in 3-4 years. In the villages, where consumption of local food products continued, the "fast" part of the process was absent, and slowing down of the decrease took place also in 3-5 years.

Table 4 shows in the generalized form the assessments of the average effective dose of internal exposure in adult rural inhabitants of Russia and Ukraine during different periods after the Chernobyl accident. The assessments are based on the above described radioecological data and dosimetric model for conditions without consequent active countermeasures, as applied to the areas with dominating peaty, turf-podzol sandy and black earth soils. According to our data, the dynamics of external exposure practically does not depend on soil type. It is seen with the comparison in Tables 3 and 4 that in the absence of protective measures the contribution of internal exposure to the total dose during the first year is greater than from the external one, for all these soil types. Already during the first year, the higher cesium transfer factor to vegetation in poor soils tells on the value of the dose. Further on, the dose of internal exposure prevails only on peaty and turf-podzol soil, and in black earth cesium-137 is strongly fixed, and weakly migrates to man through food chain. Actual doses in population of the area, where active countermeasures of protection from internal exposure (replacement of local food products, agricultural countermeasures) are considerably lower than those calculated according to Table 4.

Table 4

Reconstruction and prognosis of the average effective dose of external exposure of an adult rural population in the areas contaminated after the Chernobyl accident.

Country, reference	Soil type	E/σ^*_{137}, μSv per kBq · m-2				
		1 year	1986-1990	1991-1995	1996-2056	1986-2056
Ukraine [23]	Peaty	20-150	90-570	-	-	-
Russia [7]	Turf-podzol	90	150	20	14	184
	Black	28	29	1	1	31

* Prognosis does not take into account the future consumption of natural food products

** σ_{137} is given for 1986

Prognose of population internal exposure in particular area as well as current exposure depends strongly from the agricultural soil type, level of its contamination and from dietary habits of people. In the areas where black and turf-podzol clay soils dominate contribution of internal exposure in the total dose is insignificant since 1987 and in the future. But in the areas with sandy and especially peat soils this contribution remains significant for a long time and needs special attention.

The decrease of internal dose with time is expected different for population groups consuming agricultural food only which contains low Cs-137 activity and for people also consuming local natural food, especially forest mushrooms with high concentration of this nuclide. Typical ratio of Cs-137 concentration in forest mushrooms and cow milk obtained in 1990-th in the same area contaminated due to Chernobyl accident mainly varies in the range of 10 to 100. Future decrease of Cs-137 content in agricultural food products is expected with the effective half-period of about 10 years, according to previous observations [20] but in particular areas with peat soils - with half-period up to 20 years. The intake of Cs radionuclides with natural food did not change significantly during the last 10 years, except for radioactive decay. This means, relative contribution of natural food in internal dose increases with time. For mushroom-eaters in the contaminated areas it already contributes from 20 to 80% of the annual internal dose. According to modern models of radionuclide migration in forest, content of Cs-137 in "forest gifts" is not expected to decrease significantly faster than with half-period of about 30 years.

Thus, we expect for decrease of internal dose in persons not consuming natural food with half-period of about 10 years in most regions and up to 20 years in some regions with peaty soils. For people intensively consuming forest food, especially mushrooms with the rate of about 10 kilogramme per year and more, we can expect higher level of internal exposure decreasing with the half-period up to 30 years. Prediction of internal exposure dose for inhabitants of intermediate zone not consuming forest products is quantitatively presented in Table 4. For soil types indicated in this table consumption of natural products may increase future internal dose by a factor of 2 to 4.

In our methods of prognose we also take into account ingestion of Sr-90 and inhalation of transuranium isotopes with soil particles. Due to low content of Sr-90 in the Chernobyl release and fallout outside the 30-km zone its contribution in the internal effective dose does not exceed 5 - 10%, according to intake calculation and direct measurements of Sr-90 in human bones (autopsy samples). Similar contribution from the inhalation of Pu-238, -239, -240 and Am-241 originated from Pu-241 will not exceed 1% even for outdoor workers.

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