SCIENTIFIC ARTICLES

Exposure of the population in the Russian Federation as a result of the Chernobyl accident

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The paper presents results of field studies over ten years of levels and features of external and internal exposure doses for the population of Bryansk, Tula and Orel regions of Russia affected by the radioactive contamination after the Chernobyl accident. Consideration is given to radioecological processes of migration of ^{131}I, ^{134}Cs, ^{137}Cs, ^{89}Sr and ^{90}Sr in the biosphere, their intake and changes in human body for the residents of the contaminated areas with different soil conditions and extent of radiation protection. A model has been developed to account for external exposure of the public to γ-radiation of radionuclides occurring in the environment. The model has been verified against mass-scale measurements of individual absorbed doses by the thermoluminescence method. The paper also dwells on the models for intake of iodine, cesium and strontium radionuclides in human body which have been verified against mass-scale measurements with " whole body counter" and ^{90}Sr in the section material. Examples are given showing exposure of residents of Russia in 1986-1994 and later. The collective dose from thyroid exposure to incorporated ^{131}I in Russia and expected cancer thyroid morbidity has been assessed.

Introduction

The main feature of the Chernobyl accident governing the complex character of radiation effects on man was the destruction of the reactor as a result of the explosion and its subsequent burning, which led not only to a release of inert radioactive gases and radioisotopes of volatile elements (iodine, cesium, tellurium and others) to the environment, but also to evaporation of nuclear fission products of lower volatility (barium, strontium and others) and dispersal of fuel particles. Another feature of the radioactive contamination as compared with the global atmospheric fall-out of nuclear fission products is a relatively fast deposition of long-lived radionuclides on the ground surface leading to long-term irradiation of man. The third peculiarity is a combined and strong influence on man irradiation of natural soil-climatic and anthropogenic factors, first of all, extensive measures on radiation protection of the population.

The Chernobyl NPP is located about 150 km from the west Bryansk region. It was this region which was most affected by the radioactive contamination after the accident, the levels being close to those in Ukraine and Belarus. On this area comprehensive dosimetric monitoring and radiation protection of the population is being implemented. The contamination was somewhat lower in the Tula, Kaluga and Orel regions. In Russia 13 other regions were significantly contaminated with ^{137}Cs. The total area with the ^{137}Cs contamination density of soil in 1993 above 1 Ci/km^2 was 57 thousand km^2 according to Roshydromet data.

The paper considers the influence of the main natural and social factors on formation of external and internal doses on the contaminated areas of Russia in three regions: the Bryansk, Tula and Orel which differ significantly by their soil conditions. The processes of iodine, cesium and strontium migration in the biosphere are considered and a model of their intake in the body is presented. A model of external exposure of the population to γ-radiation was developed and large-scale measurements of individual dose with thermoluminescent dosimetry were made. Gene-ral dosimetric characteristics are given along with samples of doses in inhabitants in the Bryansk, Tula and Orel regions in 1986-1994 and later on. The ^{131}I thyroid dose has been reconstructed and prediction of thyroid cancer incidence is made.

1. Radioactive contamination of the territory of Russia

The analysis of the influence of radiation factors on the population is based on the data on the contamination levels, isotopic composition and dynamics of the depositions. These data were collected from the first day of the accident by the services and institutions of Goshydromet of USSR and later Russia and were published in [1-3].

1.1. Geography of the radioactive contamination

On the map of the Chernobyl contamination of the European part of the former USSR one can distinguish three main radioactive “patches”: Central, Bryansk-Belarus and Kaluga-Tula-Orel.

<u>The Central “patch”</u> is on the territory of Ukraine and Belarus and its primary direction is west and north-west.

<u>The Bryansk-Belarus “patch”</u> with the centre at about 200 km north-north-east of the Chernobyl NPP was formed on 28-30 April 1986 during the passage of the radioactive cloud resulting in rainfall of different intensity at the borders of the Bryansk region of Russia and the Gomel and Mogilev regions of Belarus. The average surface ^{137}Cs contamination density in the most contaminated populated points of the Mogilev region was 3-5 MBq/m^2 (1 MBq/m^2 = 27 Ci/km^2) and 4 MBq/m^2 in the settlement of Zaborye of the Bryansk region in 1986. The dose rate on the open area immediately after the accident varied from 3 μGy/hour (1 μGy/hour = 115 μR/hour) to 300 μGy/hour, and from 0.04 to 4 μGy/hour. The Bryansk-Belarus patch is located in the remote contamination zone where the radionuclide composition is significantly different from the composition of the release and depositions in the nearest zone (see 1.2). On this patch soddy-podzolic soils of different size distribution prevail.

<u>The Kaluga-Tula-Orel “patch”</u> on the territory of Russia with the centre at about 500 km north-east of the Chernobyl NPP is also of “cesium” type and was formed on 29-30 April from the same radioactive cloud as the Bryansk-Belarus one. The ^{137}Cs contamination density here does not exceed 0.6 MBq/m^2. The dose rate in the first period after the accident in the open area varied from 3 to 30 μGy/hour and from 0.04 to 0.4 μGy/hour in 1994. In the contaminated areas of the Kaluga region the prevailing soils are soddy-podzol, sandy and sandy-loamy and in the Tula and Orel regions - chernozem.

Beyond the main “patches“ on the territory of Russia there are numerous areas contaminated with ^{137}Cs at density 0.04-0.2 MBq/m^2. These areas are east of the Chernobyl NPP on the territory of the Belgorod, Voronezh, Kursk, Lipetsk, Nyzhny Novgorod, Penza, Ryazan, Saratov, Tambov, Ulyanovsk regions and the Republic of Mordovia; north of the Chernobyl NPP - on the territories of the Leningrad and Smolensk regions.

1.2. Radionuclide composition of the depositions

The radionuclide composition of the atmospheric release after the Chernobyl accident was not only different from that in the nuclear reactor because of different volatility of the elements and their derivatives, but also varied significantly with time as the temperature and conditions of the release changed [4, 6]. Besides, in this period the meteorological conditions changed more than once and as a consequence the flows in different conditions changed by their nuclide composition. The primary cause of further separation of radionuclides was different deposition rate of aerosol particles of different size and density. The elemental composition of the radioactive depositions was also influenced by the deposition mechanism: wet deposition with precipitation or dry deposition under atmospheric mixing and diffusion.

Proper estimates of population doses of each contaminated area should be based on data about isotopic composition of the depositions in the given region. But when data on the composition of depositions in some area are not available specialists widely use generalised data about depositions on a larger area. Table 1 shows ratios of surface soil contamination density for some radionuclides to ^{137}Cs contamination density for the Bryansk, Kaluga and Tula regions [1-3]. All radionuclides are divided into 3 groups: *volatile* (isotopes and compounds of I, Te, Cs an so on), *refractory non-volatile* (Zr, Ce and others) and of *intermediate volatility* (Ru, Ba, Sr). This classification correlates well with the table of boiling temperatures of the corresponding elements and (or) their oxides [7].

As can be seen from Table 1 there is no significant separation with respect to ^{137}Cs in the group of volatile radionuclides. It is worth noting the significant difference in relative content of refractory radionuclides in the depositions of the far zone as compared with the release composition. This qualitatively characterises the depletion of the radioactive cloud and precipitation of low-volatility hot particles, primarily of the fuel origin (refractory fission products and activation products) as one moves away from the source. This also, to a certain extent, applies to the isotopes of barium and strontium.

Table 1

Generalized characteristics of radionuclide composition of the release and soil depositions north-east of the Chernobyl NPP

Ratios of activities of radionuclides to the activity of ^{137}Cs by 26 April 1986 are given in the table.

Group elements	Volatile			Intermediate				Refractory non-volatile		
Radionuclide	^{131}I	^{132}Te	^{134}Cs	^{103}Ru	^{106}Ru	^{140}Ba	^{90}Sr	^{95}Zr	^{141}Ce	^{144}Ce
$T_{1/2}$	8.0 day	3.3 day	2.1 year	39 day	386 day	12.7 day	28.5 year	64 day	33 day	284 day
Entire release [1, 6]	20	5	0.5	2.0	0.4	2.0	0.10	2.0	2.3	1.6
Cesium “ patches” in Belarus [1]	10	13	0.5	1.9	0.7	0.7	0.014	0.06	0.11	0.07
Bryansk region [1-3]	10	(17)	0.5	1.7	0.5	0.7	0.02	0.07	-	-
Tula region [1-3]	9	(17)	0.5	2.3	0.5	0.6	0.03	0.05	-	0.07
Kaluga region [1-3]	10	(17)	0.5	1.5	-	0.7	0.04	0.04	-	-

The nuclide composition in different parts of the Bryansk-Belarus “ patch” and Kaluga-Tula-Orel “ patch” is quite homogeneous. The ratio of ^{131}I contamination density to that of ^{137}Cs changes insignificantly, depositions of low-volatile radionuclides were scarce as compared with those of ^{137}Cs; the average ratio of ^{90}Sr to ^{137}Cs contamination density ranges from 0.01 to 0.06. The isotopic composition of the depositions in Russia presented in Table 1 agrees well with the data of work [8] with respect to γ-emitting radionuclides (except ^{132}Te).

As to the contamination with plutonium isotopes, the data are limited because of difficulty of measuring its activity. In the area of the Bryansk-Belarus " patch" the ^{239}Pu + ^{240}Pu contamination density of soil varies from 0.07 to 0.7 kBq/m^2 and from 0.07 to 0.3 kBq/m^2 in the Kaluga-Tula-Orel " patch" . There is no correlation between the density of contamination with ^{239}Pu + ^{249}Pu, ^{137}Cs and ^{90}Sr in the far zone.

2. Major radiation factors affecting the population

The population was exposed to external and internal irradiation from a mix of radionuclides since contamination of the area was contaminated. Table 2 summarises major radiation factors affecting the population of the " far zone" at different times after the Chernobyl accident, except the short term direct effects of the radioactive cloud. The table columns indicate the main radionuclides responsible for the action of a particular factor.

Table 2

Major radiation factors of the Chernobyl accident affecting the population

Time interval after the accident, days	External irradiation		Internal irradiation	
	β-radiation	γ-radiation	Inhalation intake	Food intake
less than 100	$^{106}Ru+^{106}Rh$, $^{132}Te+^{132}I$	$^{132}Te+^{132}I$, ^{131}I, ^{134}Cs, ^{137}Cs	^{131}I, RE *	^{131}I, ^{134}Cs, ^{137}Cs, ^{89}Sr
more than 100	-	^{134}Cs, ^{137}Cs, $^{106}Ru+^{106}Rh$	RE, $^{106}Ru+^{106}Rh$, $^{144}Ce+^{144}Pr$	^{134}Cs, ^{137}Cs, $^{90}Sr+^{90}Y$

* - refractory elements of nuclear fuel and fission fragments.

Because the accumulation of external absorbed dose takes a long time, the contribution to the dose from the radioactive cloud is rather small in comparison with the contribution of radionuclides deposited on the ground. By our estimation, this contribution is less than 10% of the external dose in 1986 and according to [12] from 1 to 3%. Also of little significance is the input from inhalation from the primary cloud and resuspended radionuclides during wet deposition as compared to intake of isotopes of I, Cs and Sr through the food chain. In the first months after the accident account should also be taken of the external exposure of skin with high-energy γ-radiation. Later on as radionuclides underwent decay and moved deeper down the soil profile, so, the role of this factor becomes smaller. It should be admitted that the contribution of the above radiation factors to doses in the early period is still to be determined more accurately.

Of the radiation factors of the Chernobyl accident the best understood are dose formation factors, namely: external γ-irradiation and internal irradiation with mobile radionuclides of iodine, cesium and strontium which get into the body with food (see highlighted columns in Table 2). In the first weeks and months a significant contribution to the external γ-irradiation was made by short-lived radionuclides of iodine, but as soon as from June 1986 the leading role became to be played by isotopes of ^{134}Cs and ^{137}Cs.

The main factor contributing to internal irradiation of the population in May 1988 was ^{131}I which enters the body primarily with local milk and green vegetables. The radioactive iodine accumulated in human thyroid and irradiated it selectively (see section 4). Since summer 1986 the main factors of internal irradiation becomes isotopes of cesium coming with milk and meat as well as natural products. The contribution of the isotopes of strontium (^{89}Sr, ^{90}Sr) to the internal dose of the population of Russia is only 1-5% and is generally of purely scientific interest. The internal dose from inhalation of hot particles and diffusion forms of the isotopes of plutonium (^{238}Pu, ^{239}Pu, ^{240}Pu) and ^{241}Am formed from ^{241}Pu with time is an order of magnitude lower.

The external dose from γ-irradiation of depositions and internal dose from β-, γ-irradiation of incorporated radionuclides of cesium is distributed in human body almost evenly. On the other hand, β-radiation of ^{89}Sr and $^{90}Sr+^{90}Y$ has a selective effect on the bony tissue and marrow, where as α-radiation of the isotopes of plutonium and ^{241}Am - on lungs, liver and bony tissue. A measure of radiation effect summing up the dose in different organs is an effective dose $\boldsymbol{E}$ [9]. Since in part of the population, particularly children, irradiation of thyroid with incorporated radioactive iodine in 1986 is much higher the dose in other organs, it is appropriate to distinguish a thyroid dose $\boldsymbol{D_{th}}$ as an important dosimetric characteristic along with the effective dose $\boldsymbol{E}$.

3. External exposure of the population to γ-irradiation

Estimation of the dose from γ-irradiation from radioactive depositions is based on results of the practice over 9 years of radiation monitoring of the population and environment which we have been conducting in the most contaminated areas of Russia (the Bryansk, Tula and Orel regions). The field studies were of two kinds:

1 - determination of qualitative characteristics of the radioactive contamination of the environment and characteristics of γ-radiation field;

2 - individual dosimetric monitoring of different categories of population by thermoluminescence dosimetry. In addition to determinations of current annual doses by both methods, a model was developed to assess external doses of population living on the contaminated territory permitting both retrospective and prognostic assessments of this value [10].

3.1. Radiation monitoring of the environmental media

Estimation of external dose

Construction of the model of external irradiation of the population consisted of the following stages:

analysis of dynamics of γ-radiation dose rate in the first months after the accident due to the decay of short-lived radionuclides;

studies of regularities in natural decline in dose rate from γ-radiation of long-lived radionuclides with allowance for their migration in soil;

adding the model with estimates of dose due to modifying anthropogenic factors: location (screening of γ-radiation field by buildings, impact of economic activities) and behaviour (living conditions and habits of different age, social and professional groups in rural and urban areas);

experimental determination of factors to convert measured quantities (exposure dose, absorbed dose to the skin) to effective dose in the body.

The radionuclide composition of depositions shown in Table 1 was typical of the entire region of Russia under study which is a far zone of the radioactive contamination. Another common feature of the contaminated areas was that the radioactive “ patches” were formed as a result of “ wet” depositions. To reconstruct the external absorbed dose of the population in the early period we calculated the expected dynamics of reduction in dose rate on the basis of the radionuclide composition of depositions (Table 1) and compared the calculation curve with the values measured in the first month after the accident in the Bryansk, Tula and Orel regions.

Figure 1 shows average results of the dose rate measurements in 20 populated points of the Bryansk region normalised to the dose rate 15 days after the accident and compared to the calculated curve. It can be seen that the composition of radionuclides in the deposition that we used agrees with dose rate measurements in the first period after the accident.

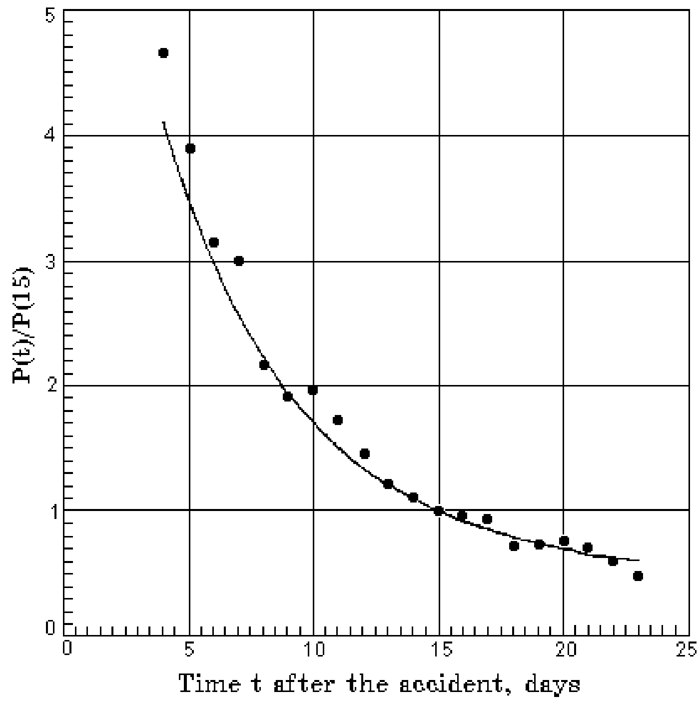

Fig. 1. Mean dose rate ***P(t)*** measured in 20 populated points of the Bryansk region (dots) as a function of time ***t*** after the accident. The dose rate is normalized to dose rate 15 days after the accident. Solid line - calculations based on radionuclide composition of depositions.

Figure 2 presents the contributions of γ-radiation of some radionuclides to the dose rate calculated in accordance with the radionuclide composition of the depositions during the first 4 months after the accident in the Bryansk region. It can be noticed that in the first days after the accident the primary contribution was made by ^{132}Te + ^{132}I and ^{131}I. For example, on 1 May 1986 it was about 70%. However, three months later the dose rate was fully dictated by ^{134}Cs and ^{137}Cs. By 1 January 1987 about 8% in dose rate was the input of ^{106}Ru and ^{103}Ru and the rest was due to γ-radiation of ^{134}Cs and ^{137}Cs.

In the long term as a primary quantitative characteristic of γ-radiation field from a mix of cesium radionuclides we take a dose rate at a height of 1 meter above a virgin land section normalised to surface activity of ^{137}Cs. Its value depends on two factors: physical decay of radionuclides and their distribution in the upper soil layer.

During 8 field study seasons more than 300 samples of virgin soil have been collected and analysed. In each measurement point surface activity of ^{137}Cs was determined as was distribution of activity along the soil profile and dose rate. The analysis of dose rate dynamics due to γ-radiation of ^{137}Cs and ^{134}Cs in the study area in 1986-1994 has shown that the dose rate decreased, on the average, by a factor of 5 and this was equally due to radioactive decay and movement of radionuclides down the soil profile. It should be pointed out that there was no much difference in the dose rate dynamics on soddy-podzolic soils of the Bryansk region and chernozems of the Tula and Orel regions.

As the starting data for creating a model of dose rate dynamics we took distributions of activity of cesium radionuclides in the upper soil layer obtained in the field studies of 1987-1994 in the Bryansk, Tula and Orel regions of Russia. These were added with results on ^{137}Cs distribution in the soils of the north-east area of the USA similar in their characteristics which were contaminated after the nuclear testing on the Nevada testing site [11]. The age of this contamination is 24 years which extends the observation period and permits more correct estimation of the dose.

Using the method of non-linear regression, we approximated the dependence of specific (per unit density of ^{137}Cs soil contamination) absorbed external dose rate on time which is dependent on only migration of cesium radionuclides, by the following relation:

$$\dot{d}(t) = \dot{d}_0 \cdot [0.42 \cdot e^{-\frac{0.693 \cdot t}{T}} + 0.26], \quad (1)$$

$r = 0.71$,

where $\dot{d}_0$ = 22.7 (μGy/year)/(kBq/m^2) is absorbed dose rate from a flat isotropic source of ^{137}Cs with the surface activity of 1 kBq/m^2 occurring on the air-soil interface;

T = 4.4 years;

r is correlation coefficient.

With allowance for radioactive decay and migration in the soil, the relation for the specific absorbed dose rate in the air at height of 1 m above the surface resulted from gamma-radiation of the Chernobyl mix of ^{134}Cs and ^{137}Cs with the activity ratio at the time of precipitation of 0.54 can be written as follows:

$$\dot{d}(t) = \dot{d}_0 \cdot e^{-0.023 \cdot t} \cdot [1 + 1.4 \cdot e^{-0.31 \cdot t}] \cdot [0.42 \cdot e^{-0.16 \cdot t} + 0.26], \ (\mu Gy / y) / (kBq / m^2) \quad (2)$$

Formula (2) allows the reconstruction of γ-radiation dose rate for cesium on a virgin land in the past, estimation of this value in the present and prediction for the future. In reconstructing the dose in 1986 account should be taken of the contribution of the short-lived radionuclides (see above).

Other factors affecting the external dose rate of the population are living conditions in the urban and rural areas. To quantify this factor we polled about 1000 urban and city dwellers in the Bryansk region and asked them about their habits in different seasons. At the same time dose rate was measured in different points within a populated area and in its vicinity. The results of the polls and measurements have been analysed and are presented in Table 3 as generalised factors of dose reduction R_k (for the k-th population category) with respect to its value on the open virgin land.

Separation in the factors of dose reduction with time after the accident associated with the existence in 1986 of additional irradiation sources (besides soil and covers on it): house roofs, walls, trees etc. The population groups differing by dose were adults working primarily outdoors (group 1) and indoors (group 2), herdsmen and children of different age. It can be seen from Table 3 that within one populated point the average external dose of the population belonging to different groups can differ by a factor of 1.5-2.5. The largest doses are received by adults working in the open air (herdsmen, field workers) and those living in wooden houses and the lowest - preschool children and adults working indoors and people living in brick houses.

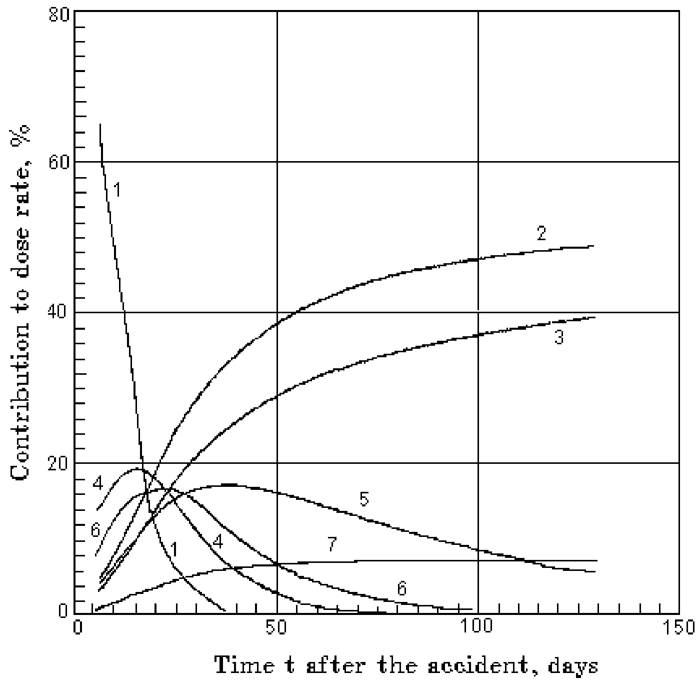

Fig. 2. Contribution of γ-radiation of different radionuclides (axis of ordinate) to dose rate as a function of time ***t*** after the accident.
1 - ^{132}Te+^{132}I; 2 - ^{134}Cs; 3 - ^{137}Cs; 4 - ^{131}I; 5 - ^{103}Ru; 6 - ^{140}Ba+^{140}La; 7 - others.

Table 3

Mean annual factors of reduction in absorbed dose of external exposure to γ-radiation in depositions R_k for rural and urban population

Population	Time after the accident, year	Population groups					
		Group 1	Group 2	Herdsmen	School children	Preschool children	Represen-tative group**
Rural	1 st	0.41/0.34*	0.32/0.24	0.56/0.50	0.39/0.31	0.32/0.25	0.38
	Subsequent	0.36/0.31	0.26/0.22	0.52/0.48	0.34/0.29	0.27/0.22	0.31
Urban	1 st	0.29/0.23	0.23/0.15	-	-	-	0.22
	Subsequent	0.25/0.20	0.20/0.13	-	-	-	0.20

* - the first number is wooden buildings; the second (after the slant) - brick buildings in villages and tenement houses in cities;
** - rural population: 50% - group 1 living in wooden houses; 20% - group 1 living in brick houses;
15% - group 2 living in wooden houses; 15% - group 2 living in brick houses.

At the next stage we experimentally determined the conversion factors from measured values (absorbed dose in the air or dose to the skin surface registered with individual dosimeters) to effective dose. In field experiments in the Bryansk region we used anthropomorphic heterogeneous phantoms of adults and children of 5 and 1 years old, on the surface and within which thermoluminescent detectors from lithium fluoride were placed. Based on the results of measurements, conversion factors from the absorbed dose in the air to the effective dose in persons of different age were determined.

The vertical profiles of ^{137}Cs activity on the experimental plots approximated by the exponential distribution had the relaxation length 0.6-2 cm. The experimental ratios of effective dose to the absorbed dose in the air and to the dose registered with an individual dosimeter, depending on the profile distribution of the source and phantom type ranged from 0.7 to 1.1 Sv/Gy and 0.9 to 1.2 Sv/Gy, respectively. The lower values are characteristic of the adult phantom and the higher - 1 year old baby.

Summing up the above results we estimate the effective dose from γ-irradiation of radioactive depositions for different population groups. The effective dose E can be conveniently divided into two components corresponding to the contributions of γ-radiation of short-lived radionuclides (E^K) and a mix of isotopes ^{137}Cs and ^{134}Cs (E^{Cs}). Considering this, the effective dose rate for representatives of the k-th population group due to γ-irradiation of these components can be written as

$$\dot{E}_k^K(t) = \sigma_{137}\cdot C^1\cdot R_k^1\cdot\sum_i\frac{\sigma_i}{\sigma_{137}}\cdot G_{0,i}\cdot e^{\lambda_i t},$$

μSv/year, (3)

$$\dot{E}_k^{Cs}(t) = \sigma_{137}\cdot C^{1,2}\cdot R_k^{1,2}\cdot S_C\cdot\dot{d}(t),$$

μSv/year, (4)

where superscript 1 corresponds to the first year after the accident;

superscript 2 corresponds to all subsequent years;

σ_{137} is the ^{137}Cs surface soil contamination density referred to the time of the accident in the vicinity of a populated point, kBq/m^2;

$C^{1,2}$ is a conversion factor from the absorbed dose in the air to the effective dose, Sv/Gy;

adults,	$\tilde{N}^1$ = 0.8;	$\tilde{N}^2$ = 0.7;
schoolchildren - 3-7 years old	$\tilde{N}^1$ = 1.0;	$\tilde{N}^2$ = 0.9;
children - 0-3 years old	$\tilde{N}^1$ = 1.1;	$\tilde{N}^2$ = 1.0;
children -		

$R_k^{1,2}$ is dose reduction factor (Table 3);

σ_i/σ_{137} is a ratio of densities of contamination with the i-th radionuclide and ^{137}Cs referred to the accident time;

$G_{0,i}$ is a conversion coefficient from surface density of soil contamination with the i-th radionuclide to absorbed dose rate for the initial depth of radionuclide occurrence (μGy/year)/(kBq/m^2) [10];

$\dot{d}(t)$ is calculated by formula (1);

S_c = 0.9 is a coefficient allowing for the screening effect of γ-radiation by the snow cover;

λ_i is the decay constant of the i-th radionuclide, 1/year.

Then the total effective dose rate for the k-th population group is:

$$\dot{E}_k(t) = \dot{E}_k^K(t) + \dot{E}_k^{Cs}(t),$$ μSv/year, (5)

and the effective dose E_k for the k-th group for T years after the accident is

$$E_k(T) = \int_T \dot{E}_k(t)\cdot dt,$$ μSv. (6)

Table 4 shows the estimated effective doses for rural and urban population groups in the study area after the Chernobyl accident. The dose is due to γ-radiation of all deposited radionuclides and is normalised to the surface density of ^{137}Cs soil contamination referred to the accident time. At equal contamination levels villagers receive, on the average, a dose 1.7 times higher than city dwellers who spend more time indoors, in particular in brick and panel houses, and therefore, are better protected from external radiation. Notice how rapidly the dose accumulates: the average dose for the first year after the accident is 20% of the dose for 70 years and in 9 years after the accident already more than 50% of the expected dose is accumulated.

The authors of [12] reconstructed external dose for the population of the Bryansk region too. The deviation of their results from ours, on the average, does not exceed 15%, which suggests good agreement.

Table 4

Mean effective dose for rural and urban population normalized to surface contamination density of ^{137}Cs

Population group	E/σ_{137} , μSv/(kBq/m^2)			
	1 st year	1986-1994	1986-2056	1995-2056
Urban	8	21	40	19
Rural	13	34	64	30

3.2. Individual monitoring of external gamma-radiation dose

The method of dose estimation described in the previous section is based on information about characteristics of the radioactive contamination of the environment. More detailed dosimetric data and using social and demographic data have made it possible to estimate irradiation of separate population groups. The logic of the individual dosimetric monitoring method (IDM) when used for these purposes is the opposite and is based on conversion from the dose measured in separate people to characteristics of irradiation of a group of inhabitants of a populated point (PP) [13, 14].

Measurements of individual doses were made with thermoluninescent detectors from lithium fluoride. To read indications Harshow-2000D device was used. The detectors and instrumentation was certified in Centre of Standardisation and Metrology (St.-Petersburg). The lower detection limit was 80 μGy, the square mean error of dose measurements was above 100 μGy - about 10%, for lower doses it reaches 20%.

The measurements of individual doses were made selectively. A population sample (about 50 people in a PP) contained main social and professional groups. As a rule, inhabitants received dosimeters for 1 month. In calculation of effective dose for a month of detector exposure account was taken of conversion factor from dosimeter indications to effective dose, and for estimating annual effective dose seasonal variations in external irradiation were considered. Overall, about 100 populatied points were surveyed from 1987 to 1994 and more than 5 thousand values of individual dose were obtained.

The individual dosimetric monitoring of external irradiation of the population was conducted with a view to:

annul current monitoring of the population in areas with different contamination levels;

statistical analysis of measurements to estimate how dose is affected by such factors as type of populated point (city, settlement, village), house type (wooden or brick), profession, decontamination measures etc.;

verification of the model estimating external dose.

The total annual results of measurements were studied using the linear regression analysis method in which as an independent variable the surface ^{137}Cs soil contamination density was used. The free term of the regression equation corresponded to dose from the natural radiation background, and the coefficient of regression line slope - to specific effective external dose. Figure 3 illustrates this kind of analysis by data of IDM in 1991 [13, 14].

Figure 4 presents IDM results showing dynamics of average effective external dose for part of the population of the Bryansk region from 1987 to 1992. It also shows the dose reduction curve in the first 10 years after the accident derived with formulae (3) and (4). It can be seen that the estimated doses are in good agreement with IDM data.

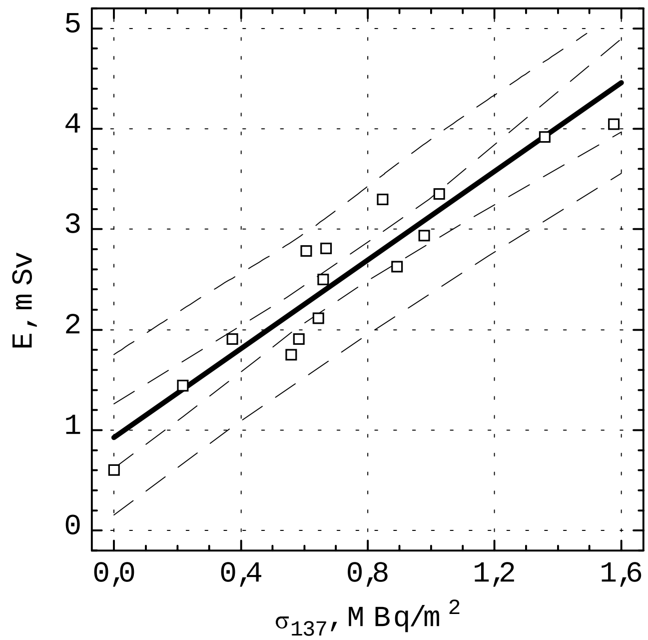

Fig. 3. Dependence of mean effective external dose ***E*** for the rural population of the Bryansk region in 1991 on surface contamination density σ_{137}.
Regression equation: $\boldsymbol{E = (0.8 \pm 0.2) + (2.2 \pm 0.2)\cdot\sigma_{137}}$, mSv.

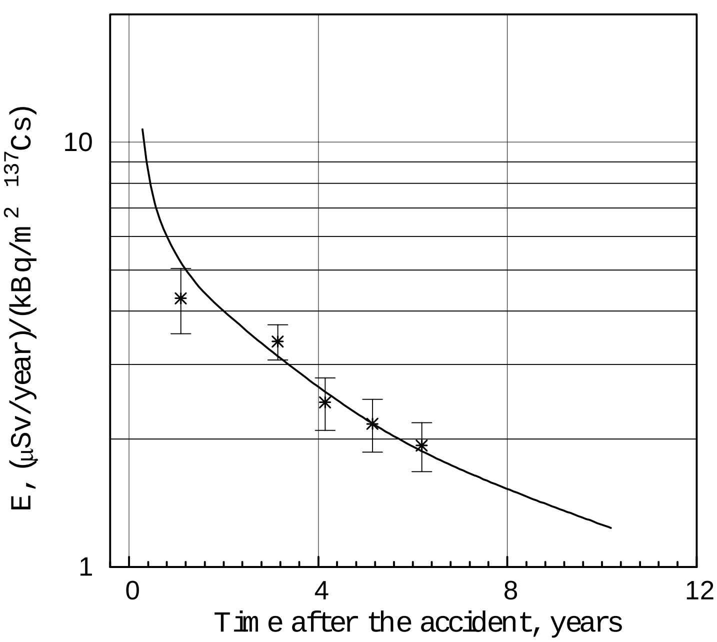

Fig. 4. Dynamics of the mean annual effective external dose for rural population of the Bryansk region normalized to surface contamination density σ_{137}.
Curve - model calculations; dots - results of individual dosimetric monitoring

External doses in towns and cities appear to be 1.4-1.7 times lower those in the villages at equal soil contamination with ^{137}Cs. The reduction of external doses of the population as a result of decontamination works in some populated points of the Bryansk region in the summer of 1989, according to IDM data is estimated at 1.2-1.5 times.

The influence of other anthropogenic factors on dose can be illustrated by summarised data of Table 5 based on the results of IDM of rural population in the Bryansk region in 1992. The effects of statistical significance were house type (wooden or brick) and working conditions (indoors or outdoors). The ratio in doses for the population groups differing by these attributes was 1.2 and 1.4 correspondingly.

For the population groups which were extreme in terms of exposure (machine operators and housewives) the ratio of average normalised doses is 1.9. The results of IDM agree with the range of dose reduction factors for different population groups (Table 3).

The intercomparisons of IDM results for the Bryansk region population conducted in 1991-1992 as part of collaboration with specialists of Sweden and Norway and a joint Russian-German programme in 1992 have shown good agreement (within a relative error ± 20%) [15, 16].

An important result of the above mentioned study was a good agreement in external doses estimated by two different methods. This fact and good correlation with data of foreign specialists lead us to assert that estimated external doses in the time after the accident are quite correct. Over this period more than 50% of the dose expected in 70 years life span have already been accumulated. With this in mind, we hope that the predictions of external doses in 70 years life time are also realistic.

Table 5

Mean external dose for different rural population groups of the Bryansk region in 1992 based on 1 month measurements of an individual dosimeter normalized to mean surface contamination density of ^{137}Cs in the vicinity of a populated point (excluding natural γ-emitters)

Classification criterion	Mean monthly dose, μSv/(MBq/m^2)
Gender:	
Females	140 ± 6
Males	165 ± 6
House:	
Brick	130 ± 7
Wooden	160 ± 5
Work:	
Outdoors	175 ± 9
Indoors	125 ± 7
Profession:	
Machine-operators	185 ± 13
Pensioners	183 ± 9
Odd-job men	165 ± 9
Cattle farmers	155 ± 15
Drivers	155 ± 16
Field workers	153 ± 30
Office workers	130 ± 7
School children	110 ± 10
Housewives	100 ± 10

4. Internal irradiation with ^{131}I

The dose of thyroid exposure to incorporated ^{131}I for the population of Russia was determined with measurements of the radionuclide in the organ, the calculation procedure taking into account features of formation of the radiation situation and protection measures. It was shown in section 1 that the "patches" of higher contamination on the areas of the Bryansk, Tula, Kaluga and Orel regions were primarily formed due to wet precipitation of radionuclides from the same radioactive cloud resulting from the reactor releases on 27 April 1986 [1, 3, 17]. This conclusion supported by the radionuclides ratios in the soil samples collected and measured in the last week of May 1986 [3] allows us to believe that there are common features in formation of doses from iodine radioisotopes in these areas [18].

4.1. Measurements of ^{131}I content in thyroid in the population of Russia

Among the population of the contaminated areas of Russia thyroid examinations were performed in May-June 1986 in the radiodiagnostic laboratories of central regional hospitals using the equipment designed for study of the thyroid function with ^{131}I and with a non-specific portable radiometers (FSR-68-01, DRG-03 and others) calibrated for this purpose. Altogether, in May-June 1986 (to 15 June) in the contaminated areas of Russia quality measurements of thyroid were made in 960 inhabitants of the Bryansk region, 677 in the Tula region and 1620 - in the Orel region. Besides, using FSR-68-01 about 13 thousand measurements of the same kind were conducted in the Bryansk region (dosimetric results for this category are not presented in this work as the data analysis has not been completed yet) and in the Kaluga region - about 30 thousand measurements [18, 19]. About 50-80% of these were measurements in children.

The highest levels of ^{131}I in thyroid of 200-300 kBq were reported on 16-17 May in the settlements of Barsuki and Nikolaevka of the Krasnogorsk district of the Bryansk region, where ^{137}Cs contamination of the soil was about 3 TBq/km^2 [2]. In other populated points of the monitored Bryansk region the content of ^{131}I in the thyroid was an order of magnitude lower. This is explained not only by lower levels of radioactive contamination but also by earlier implementation of protection measures.

4.2. Dosimetric model

To calculate absorbed thyroid dose in the population of the contaminated areas of Russia we used a model of ^{131}I intake by which the daily intake was constant for 15 days and then was reduced in line with the change in the radionuclide concentration in milk with the period of 5 days (Figure 5). The proposed model was based on the observed dynamics of ^{131}I concentration in milk in the contaminated areas of Russia. In the first days when the radionuclides concentration in milk was growing, the inhalation component and intake of leaf vegetables complemented the intake with milk. The model does not specify the role of separate pathways of radionuclides to the body, as with numerous uncertainties in the starting data (including those on the nature and time function of depositions, uneven character of pastures contamination etc.) excess details will bring in more errors than certainty. When having more information, the intake model parameters can be determined more accurately foe separate populated points and areas.

For calculation of thyroid absorbed dose $\boldsymbol{D_{th}}$ from results of ^{131}I activity using the above mentioned model we took dosimetric parameters of people of different age from ICRP publication 56 [20]. The thyroid doses estimated with this model are in good agreement with calculations of other authors [21].

The protective measures have changed the natural intake of radionuclides and reduced the doses received by the population. Special efforts were made to decide on the time and type of protective measurements in separate areas and points so that account could be taken of their influence on the absorbed dose. For example, in some areas of the Bryansk region 7-10 days after the accident local contaminated milk was banned for consumption and then iodine prophylaxis was conducted, which reduced the thyroid dose by 2-3 times as compared to the maximum possible. These facts are considered in the dose calculation scheme [18].

4.3. Dose estimation from measurements

Table 6 shows estimated average absorbed thyroid doses of some populated points in the Tula and Orel regions based on the measurements of ^{131}I in May-June 1986. In these regions the protection measures to reduce ^{131}I intake were conducted too late. This allows us to assume that ^{131}I got into the body without deterrent and the formed thyroid dose was maximum possible for the given contamination level.

In the Tula region the highest radioactive contamination of soil was found in Plavsk (σ_{137} = 0.47 TBq/km^2) and Plavsk district. The average absorbed thyroid doses in children up to three years old in the populated points of this district are 50-70 cGy. In the Orel region the exposure to radiation was the highest in some villages of the Bolkhov district where the average thyroid dose in preschool children was about 30 cGy.

In the Bryansk region from the first days of May workers of the sanitary and epidemiological service explained to the population the danger of consuming milk from private farms. In Novozybkov and settlements of the Novozybkov district supply of local milk to kindergartens and schools was stopped starting from 4 May and since 7 May milk from uncontaminated areas was supplied to shops. In the neighbouring contaminated districts similar measures were carried out somewhat later. Table 7 summarises estimated average absorbed thyroid dose in the Bryansk region for two cases: $\boldsymbol{D_1}$ - the calculations are similar to those in the Tula and Orel regions assuming no bans on ^{131}I intake with milk; $\boldsymbol{D_2}$ - account is taken of the average date when milk was stopped to be consumed in a particular populated point according to the polls. For cities and towns where milk was substituted by uncontaminated in a centralised manner $\boldsymbol{D_2}$ estimate was quite realistic. For villages in which inhabitants were consuming milk from private farms consumption of milk could be stopped only by informing people about the radiation threat and the dose depended on how they perceived this threat.

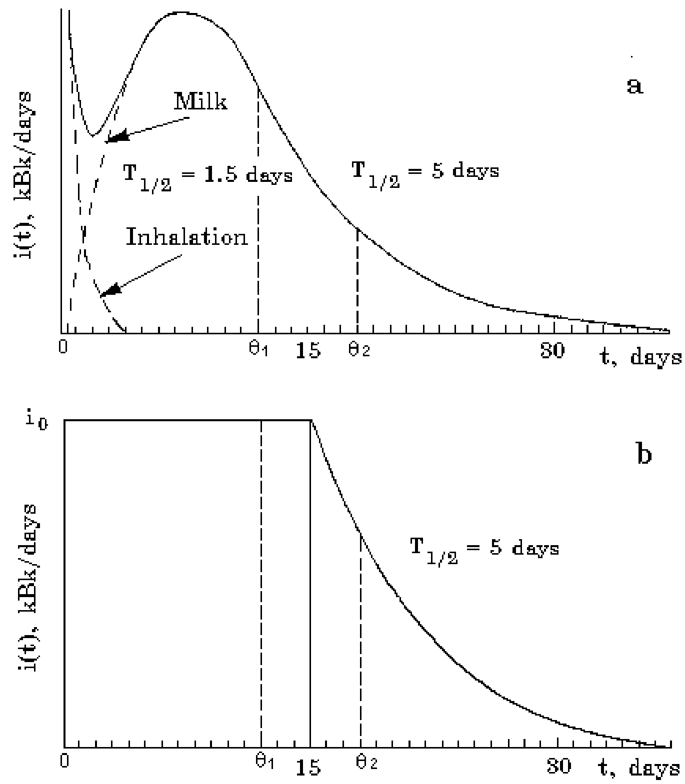

Fig. 5. Diagram (a) and model (b) of ^{131}I intake ***i(t)*** for the population of the contaminated areas of Russia.

Table 6

Mean absorbed thyroid dose from incorporated ^{131}I for the population of some populated points in the Tula and Orel regions of Russia (cGy)

Populated point	σ_{137} in 1986, TBq/km^2	Age as of 1 May 1986, years					
		less than 1	1 - 2	3 - 6	7 - 11	12 – 17	More than 18
Tula region							
Plavsk	0.47	65 ± 13 (36)*	35 ± 17 (11)	35 ± 14 (20)	7.8 ± 1.1 (22)	3.8 ± 2.3 (4)	4.8 ± 0.5 (77)
Shchekino	0.05	-	-	6.0 ± 0.8 (2)	4.2 ± 0.8 (12)	6.1 ± 2.1 (2)	1.9 ± 0.2 (17)
Arsen'evo	0.15	-	-	-	2.8 ± 0.5 (9)	-	1.8 ± 0.8 (10)
Krekshino	0.11	-	18 ± 8 (8)	8.3 ± 1.1 (8)	-	-	3.6 ± 0.9 (13)
Lipovo	0.30	21 ± 4 (5)	43 ± 7 (5)	11 ± 3 (4)	26 ± 17 (7)	-	5.8 ± 1.2 (12)
Oktyabr-skoe	0.15	33 ± 17 (2)	13 ± 4 (12)	7 ± 3 (2)	5.4 ± 1.6 (8)	-	2.4 ± 0.4 (18)
Strelet-skoe	0.10	-	-	7.2 ± 0.9 (9)	5.4 ± 1.1 (6)	-	2.2 ± 0.2 (13)
Orel region							
Orel	0.05	14.5 ± 3 (10	8.5 ± 1 (81)	7.0 ± 0.3 (943)	5.0 ± 0.5 (61)	3.7 ± 0.3 (29)	1.4 ± 0.3 (267)
Bolkhov	0.18	-	-	14 ± 2	-	-	4 ± 1 (12)

Dmitrovsk	0.10	-	-	(60) 10 ± 1 (74)	7 ± 3 (6)	-	2.3 ± 0.6 (14)

* - in the brackets is the number of surveyed persons.

Table 7

Mean absorbed thyroid doses for inhabitants of some populated points of the Bryansk region, cGy

Populated point	σ_{137}, TBq/km^2	θ, day	Age as of 1 May 1986, years					
			< 1	1 - 2	3 - 6	7 - 11	12 - 17	> 18
Novozybkov	0.7	10	17±6(1) 64±29(2) (3)(3)	13±2 39±9 (5)	12±2 33±8 (23)	6.8±0.7 15±2 (24)	8.6±3.8 20±9 (5)	1.8±0.2 3.9±0.4 (57)
Zlynka	1.1	10	- - -	7.1±2.8 20±8 (3)	8.0±3.4 21±7 (6)	5.7±1.1 15±3.5 (7)	- - -	1.4±0.3 3.3±0.6 (27)
Mirny	1.3	15	- - -	45±21 85±37 (5)	33.5±7 67±1 (17)	12±2 19±4 (16)	14±4 22±7 (9)	5.8±1.1 8.9±1.7 (52)
Krasnaya Gora	0.25	15	110±36 127±43 (8)	93±30 136±36 (11)	40±11 52±13 (23)	12±3 16±4 (17)	3.8±1.2 4.6±1.1 (6)	6.3±2.1 8.3±2.4 (32)
Zabor'ye	4.4	14	- - -	52±14 99±34 (7)	65±22 130±64 (3)	51±17 74±24 (2)	- - -	14±5 26±10 (11)
Nikolaevka	3.3	13	180±68 250±93 (5)	180±24 230±31 (17)	100±16 130±20 (31)	66±18 91±29 (22)	100±78 155±120 (2)	61±20 82±31 (5)
Selets	0.6	17	- - -	- - -	15±8 26±17 (4)	11±2 16±3 (6)	9.2±6.5 11±8 (2)	5.3±1.1 7.5±1.9 (12)
Barsuki	2.7	13	180±50 250±60 (5)	140±25 210±50 (17)	100±20 120±20 (21)	62±12 75±15 (27)	150±40 210±50 (4)	25±7 30±8 (11)
Uvel'e	1.8	13	100±0 390±0 (2)	78±26 260±92 (8)	32±8 94±23 (10)	- - -	3.1±1.3 8.0±3.3 (2)	2.3±0.6 5.4±1.4 (17)
Vereshchaki	0.7	10	- - -	17±9 28±15 (2)	12±2 19±3 (16)	20±6 29±8 (7)	- - -	4.2±0.7 6.2±1.0 (14)
St. Vyshkov	1.4	8	- - -	- - -	11±3 18±5 (7)	9.3±3.0 15±5 (4)	2.8±0 4.3±0 (1)	3.1±1.2 4.5±1.7 (6)
Svyatsk	1.6	10	- - -	- - -	15±2 24±3 (9)	8.1±1.8 13±2.9 (4)	- - -	3.9±1.5 5.7±2.2 (3)

(1) - individual doses are estimated on the assumption that there were restrictions on limits to ^{131}I intake;
(2) - individual doses are estimated on the assumption of imposing restrictions on ^{131}I intake started, on the average, θ days (3d column) after the radioactive contamination of the area;
(3) - in the brackets is the number of surveyed persons.

The difference between the numbers in the first and second rows (to which are attached footnotes 1 and 2) in each city of Table 7 may seem counterintuitive and needs further explanation. All the dose estimates are " anchored" at a dose measured late in May or June. If there were no restrictions on I_{131} intake, these measured doses included doses from iodine recently consumed in milk and vegetables, and projection backward to the time of the accident assumed that such consumption was the same at the crucial period at the end of April and beginning of May. If, on the other hand, there were restrictions, the measured doses did <u>not</u> include iodine recently consumed from milk, and projection back to the time of the accident assumes that milk consumption was <u>greater</u> before the restrictions were set in place. Thus, although the restrictions clearly reduced the dose to the population, the dose calculated from the later measurement is greater than if the restrictions had not been present. It is interesting that the difference is also an indication of the reduction that would have occurred if the restricted measures had been in force from the start of the accident.

The largest absorbed thyroid doses were received by inhabitants of the Krasnogorsk district of the Bryansk region where the educational compaign was started only on 10 May. There are two contamination " patches" in this area: near villages Nikolaevka (σ_{137} = 3 TBq/km^2) and Zabor'ye (σ_{137} = 4 TBq/km^2).

The average absorbed thyroid doses in children up to three years old in the villages lying in those " patches" are 250-270 cGy and in adults - 30-90 cGy.

Average absorbed thyroid doses for each populated point were estimated for six age intervals: less than 1 year old, 1-2, 3-6, 7-11 and 12-17 and adults. Within the age group the dose frequency distribution has as asymmetric shape close to lognormal. The maximum value of an individual absorbed dose is seldom higher the average than by a factor of 3 to 5. Examples of the distribution of individual thyroid doses in inhabitants of different age in some populated points of the contaminated areas are given in Figure 6 and 7.

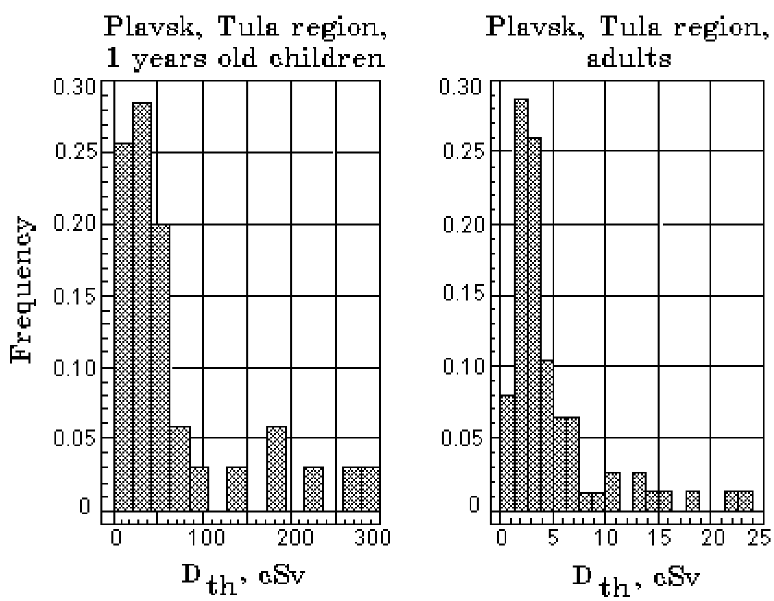

Fig. 6. Frequency distribution of individual thyroid doses for inhabitants of different age groups in the populated points of the Tula region of Russia.

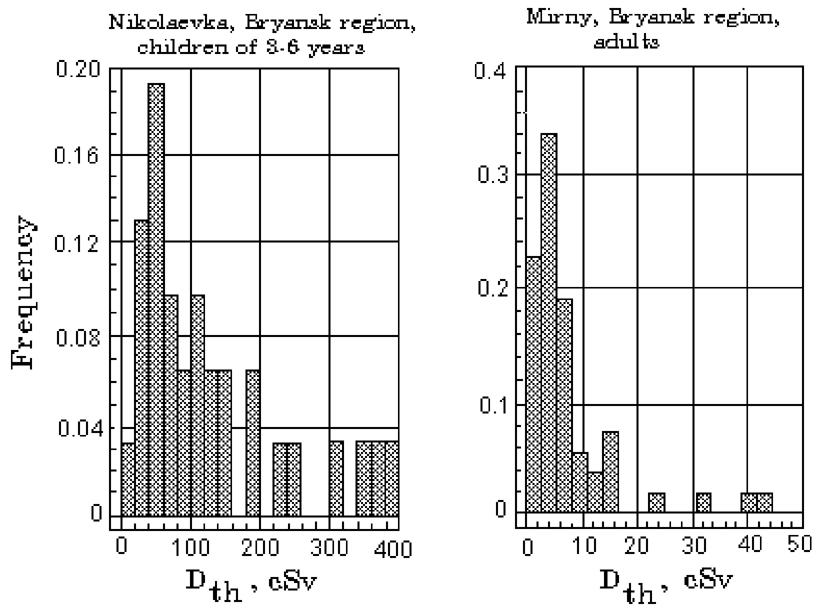

Fig. 7. Frequency distribution of individual thyroid doses for inhabitants of different age groups in the populated points of the Bryansk region of Russia.

When analysing age relations of absorbed thyroid doses it was noticed that they differed for the urban and rural population. Table 8 shows the results of this analysis.

The ratios of absorbed thyroid doses presented in Table 8 are associated not only with age differences in iodine metabolism but also with social factor and different diet of rural and urban populations: a rural population consumes a lot of milk and uses less artificial baby products as compared to the city dwellers. As a result, at equal contamination of soil with ^{131}I the average absorbed thyroid dose of village residents was 1.5-2.5 times higher than that of city residents. The age dose ratios of Table 8 were used to estimate average absorbed dose in those age groups in which ^{131}I activity in the thyroid was not measured.

Table 8

Ratio of mean absorbed thyroid dose in children and adolescents to mean dose in adults

Type Of populated point	Age as of 1 May 1986, years					
	> 1	1 - 2	3 - 6	7 - 11	12 – 17	> 18
City	13 ± 3	9 ± 4	6 ± 2	2.5 ± 0.8	1.5 ± 1.0	1
Settlement	5 ± 3	5 ± 2	3 ± 1	2.2 ± 1.0	3 ± 2	1

4.4. Method of reconstruction of average thyroid dose in inhabitants of a populated point

Since in May-June 1986 in many villages in contaminated territories no measurements were made of ^{131}I in thyroid, it became necessary to reconstruct absorbed dose from indirect data. This was done in two phases: first, average doses in a populated point were determined and then individual doses were estimated [18, 22].

The method of linear regression was used to analyse the relation of average absorbed thyroid dose in 3-6 year old children based on thyroid measurements in May-June 1986 and various characteristics of contamination: ^{137}Cs contamination density, dose rate in air on 10-12 May 1986, average ^{131}I concentration in milk on 5-12 May 1986, radiocesium content in the body for adults of the same populated point in August-September 1986. For consistency we used the values of maximum possible doses $\boldsymbol{D}_{\infty}$ which were received or could have been received by the population without protection measures.

As was mentioned above, the radionuclide composition and meteorological conditions (rain) during the precipitation in the Bryansk and Tula regions were practically the same. This became the basis for the regression analysis of a combined data set for the two regions. It can be seen from Table 9 that the relation between the characteristics in all the cases was statistically significant with a rather high correlation coefficient - from 0.89 to 0.95.

By way of illustration, Figure 8 shows results of the regression analysis of the relation between absorbed thyroid dose for children of 3-6 years old averaged over a populated point and soil surface contamination density σ_{137}. The relation is reliably linear. According to the data of [21] in the south of Belarus this relationship is non-linear: the dose is relatively higher in the areas of low contamination density σ_{137}, compared to areas of higher σ_{137}. This difference is most probably due to different particle size distribution and chemical form of radionuclides deposited in the "nearest" zone, in the south of the Gomel region and in the "far" zone - on the territory of Russia as well as due to different meteorological conditions of radionuclides deposition ("wet" or "dry"). This issue, however, calls for further investigation. (*These problems are discussed in the paper by V.F.Stepanenko et al in the present issue of the Bulletin*).

The obtained regularities together with age ratios of absorbed thyroid doses in cities and villages (Table 8) were used for estimation of average absorbed thyroid doses for population of different age in the populated points in which no radiometry of thyroid was conducted in May-June 1986.

Table 9

Parameters used for reconstruction of mean absorbed thyroid dose in children of 3-6 years

Parameter	Number of populated points	Correlation coefficient
Mean contamination density of ^{137}Cs in the vicinity of a PP	22	0.95
Dose rate 10-12 May 1986 in PP	25	0.92
Mean milk contamination 5-15 May 1986	11	0.86
Mean cesium activity incorporated in the body for adults, August-September 1986	17	0.90

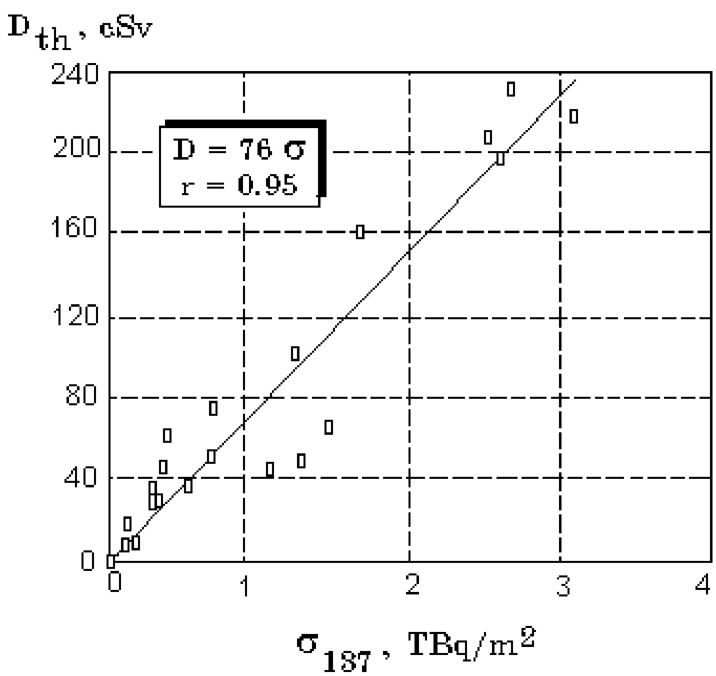

Fig. 8. Relationship between the mean thyroid dose in children of 3-6 years and the surface contamination density of ^{137}Cs in the vicinity of the populated point.

The regression equations estimate the maximum thyroid doses D_∞ given no protection measures. For each populated point we analysed a series of protection measures implemented there. The ultimate dose was estimated by comparing values derived by different regression equations, with consideration of reliability of initial parameters and introduction of correction for the performed protection measures. Preference was given to absorbed thyroid doses derived based on the amount of incorporated ^{134}Cs + ^{137}Cs in the body and ^{131}I concentration in milk. We believe that the errors for the average absorbed thyroid dose estimated in this way is not worse than 50%. It should be noted that the empirical relations of average absorbed thyroid dose and ^{137}Cs soil contamination level and dose rate in the air applies only to the territories with the radionuclide composition and meteorological conditions of depositions characteristic of the above territories of Russia.

The individual absorbed thyroid doses were reconstructed on the basis of data of individual polling of the population about consumption of milk in May 1986 or using correlation of absorbed thyroid dose with individual content of radiocesium in the body measured in August 1986. This was the method to do retrospective estimation of individual absorbed thyroid dose for about 60 thousand inhabitants on the monitored territory of the Bryansk region and 2300 children in the most contaminated populated points of the Tula region. For this purpose in January-March 1987 in the Bryansk and Tula regions inhabitants were polled using a special questionnaire about behaviour and diet in the post accident period. The poll was accompanied by measurements of content of radioisotopes of cesium in the body. The estimated doses for children and pregnant women and the filled out questionnaires were distributed in 1987 to the All-Union registry and local health care institutions.

4.5. Collective thyroid dose for the population of Russia and prediction of additional thyroid cancer incidence

The collective thyroid dose for the population of the selected regions with incorporated ^{131}I was calculated by summing collective dose in each populated point. The latter was calculated was a sum of products of average absorbed dose for the population by three age groups at the time of the accident: children younger than 7 years old, 7-17, 18 and older. The average dose is estimated for 47 populated points from the results of ^{131}I thyroid radiometry for the inhabitants and for the rest - by the reconstruction method. For most populated points with a low contamination the initial data were soil surface ^{137}Cs contamination density [2].

The results of estimation of collective absorbed thyroid dose are presented in Table 10. The highest collective doses for thyroid in Russia were received by the population of the Bryansk and Tula regions - about 60 thousand man·Gy. These values are 10-20% higher those published earlier [13] as new data became available from Roshydromet about ^{137}Cs contamination of the soil [2].

Table 10

Collective thyroid dose for the inhabitants of the most contaminated regions of Russia from incorporated ^{131}I due to the Chernobyl accident and prediction of additional thyroid cancer incidence

Area	Population, million	Collective absorbed thyroid dose, 10^3 person·Gy	Projected additional thyroid cancer incidence	
			Number of cases	Percentage of spontaneous level, %
Bryansk region	1.5	60	175	5 – 10
Bryansk region (monitored areas)	0.11	22	67	20 – 40
Tula region	1.9	60	175	5 – 10
Orel region	0.9	15	44	2 – 5
Kaluga region	1.0	10	30	2 – 5
All above areas	5.3	145	424	3 – 6

Much lower collective doses were received by the population of the Orel (15 thousand man·Gy) and Kaluga (10 thousand man·Gy) regions. As the value of the collective dose is equally dependent on average absorbed dose and the number of population in a populated point, it appears that the greatest contribution to the collective dose in the region is made by the territories with low contamination level, but higher population density. For example, the collective doses in the Bryansk and Tula regions prove to be equal, though the soil contamination levels in the Tula region are much less than those in the Bryansk region. At the same time, in the Bryansk region the exposure of 7.5% of the population of most contaminated " monitored" territory contributes about 40% to the collective dose of the whole region.

Table 10 also presents results of prediction of possible additional thyroid cancer incidence in the contaminated areas made by the method described in [18, 23]. Up to 10% of thyroid cancer incidence can be fatal. Comparison of the prediction with the pre-accidental thyroid cancer incidence in the central regions of Russia about 20 cases a year per 1 million people of all ages shows that on the territory of the Bryansk and Tula regions a considerable increase in thyroid cancer incidence should be expected.

The age dependence of the collective dose is such that half of it was formed in children and adolescents up to 18 years of age comprising about 25% of the population. It is this group of the population that is at increased risk of developing radiogenic thyroid cancers. It should be noted that the spontaneous incidence of thyroid cancer in children is about an order of magnitude lower than in the population in general. Therefore, the radioiodine induced incidence in children and adolescents can be several times the spontaneous level. Unfortunately, this prediction appears to be true. By May 1995 in the Bryansk region 48 cases of thyroid cancer were detected in children and adolescents and the first cases of thyroid cancer in children in the Kaluga region have been reported [19].

5. Internal exposure to radionuclides of cesium and strontium

The dose of internal irradiation of the whole body with radionuclides of cesium and strontium for the people living on the contaminated areas has been evaluated in two ways: by calculation of radionuclide intake in the body based on data on radionuclides content in foodstuffs and based on measurements of radionuclides content in the body. Altogether, the study involved about 300 thousand measurements with whole body counter and about 100 measurements of ^{90}Sr and Pu in autopsy samples.

5.1. Dynamics of cesium and strontium content in foodstuffs

Agricultural production was not stopped on the territory of Russia contaminated after the Chernobyl accident. That is why a lot of attention has been paid to determination and long-term prediction of characteristics of cesium and strontium transfer from contaminated soils to agricultural products, meat and later on to man. These characteristics are influenced by many factors: time passed after the contamination occurred, physico-chemical properties of deposited radioactive particles, agrochemical properties of soils, species features of plants and animals and other things.

The main parameter used in the paper describing radionuclide migration in the ecosystem is the transfer factor $\boldsymbol{F_t}$ (m^2/kg) which is a ratio of specific activity of a radionuclide in a air-dry sample of vegetation or natural foodstuffs to its surface contamination density σ.

In the early phase after the accident in May 1986 it was established in field studies that the maximum concentration of ^{134}Cs, ^{137}Cs and ^{90}Sr, ^{89}Sr in milk was achieved not later than 2 weeks after the contamination. The maximum values of soil-milk $\boldsymbol{F_t}$ were 0.04 m^2/kg for cesium radioisotopes and 0.006 m^2/kg for strontium. Later on, the values of $\boldsymbol{F_t}$ were decreasing with periods of 17 and 14 days, respectively, which is primarily the rate of natural decontamination of meadow grasses after surface contamination.

Starting from autumn 1986 when soil-root migration of radionuclides in the ecosystem started to prevail, major emphasis was placed on analysis of features and dynamics of radioactive contamination of critical links of the food chain responsible for formation of internal dose.

The " soil-plant" system is the most changeable part of the food chain, governing prolonged intake of Cs and Sr by the body with plant and animal products, since the transfer factors are strongly dependent on soil properties. Parameters of cesium and strontium transfer in the following parts of the food chain change insignificantly. For example, the average ratio of specific activity of ^{137}Cs in pasture grass, milk and meat is 1:0.004:0.16. The average ratio of specific activity of ^{90}Sr in dry grass and milk is 1:0.009.

As the major part of ^{137}Cs and ^{90}Sr on the contaminated territories of Russia is taken in with meat and milk products, estimation and prediction of internal doses of the population can be reduced to prediction of radionuclides content in natural grasses.

The types of soils predominant in different regions of Russia differ significantly: chernozems and grey forest soils in the Tula and Orel regions, soddy-podzolic soils in the Bryansk and Kaluga regions. Depending on soil type, the average value of the soil-grass transfer factor for cesium changes almost by three orders of magnitude. The soil-natural grass transfer factor of ^{90}Sr changes somewhat less than $\boldsymbol{F_t}$ for ^{137}Cs, namely 60 times.

A quantitative relation has been established between $\boldsymbol{F_t}$ of ^{137}Cs and ^{90}Sr and agrochemical soil properties: for ^{137}Cs this is content in soil of potassium, phosphorous and organic matter etc., and for ^{90}Sr - concentration of exchangeable bases etc. The corresponding regression equations can be used for prediction of contamination of foodstuffs and hence internal dose [24, 25].

In addition to soil properties the concentration of cesium radionuclides in agricultural produce is strongly influenced by their natural fixation in soil structures with time after the contamination. Tables 11, 12 and Figures 9 and 10 illustrate the dynamics of ^{137}Cs transfer factor from soil to natural grass and milk from the cattle grazing natural pastures. The specific activity of ^{137}Cs in grass, milk and meat of the cattle decreased by 1-2 orders of magnitude from 1987 to 1991-92. In a similar way ^{137}Cs content in agricultural crops grown on the arable lands: cereals, potatoes etc. (Figure 11). The period $\boldsymbol{T}$ of ^{137}Cs reduction in all these products in districts with different soil types changed in the range 7-25 months (on the average 14 months). Along with the annual decrease, radionuclides concentration in milk and meat varies considerably within a year from season to season depending on diet - it increases in the pasture period and decreases in the in-house period (Figure 12). In 1991-94 the process of natural decontamination of agricultural produce tended to slow down and this was first of all observed in the chernozem zone (Tables 11, 12).

Table 11

^{137}Cs transfer factors, 10^{-3} m^2/kg, from soil to natural grass

Year	Bryansk region		Tula region	
	Range	Mean	Range	Mean
1986	10.0 – 840	188	–	–
1987	6.2 – 492	126	0.11 – 16.0	2.21
1988	1.2 – 404	41	0.07 – 1.10	0.47
1989	0.3 – 138	22	0.08 – 1.05	0.43
1990	0.2 – 27	6.1	0.03 – 0.75	0.22
1991	0.1 – 15	2.9	0.01 – 0.25	0.10
1992	1.1 – 8	3.5	0.005 – 0.47	0.11
1993	0.1 – 16	2.1	0.03 – 0.47	0.26
1994	0.4 – 6	2.5	0.05 – 0.55	0.19

Table 12

^{137}Cs transfer factors, 10^{-3} m^2/kg, from soil to milk from cows grazing natural pastures

Year	Bryansk region		Tula region	
	Range	Mean	Range	Mean
1986	1.8 – 58	10.1	–	–
1987	0.6 – 45	5.2	0.033 – 0.271	0.127
1988	0.2 – 13.2	2.3	0.037 – 0.217	0.104
1989	0.2 – 10.7	1.5	0.002 – 0.190	0.074
1990	0.1 – 6.7	1.0	0.001 – 0.120	0.027
1991	0.05 – 2.1	0.6	0.001 – 0.011	0.004
1992	0.06 – 1.3	0.3	0.002 – 0.014	0.006
1993	0.01 – 0.6	0.13	0.002 – 0.041	0.016
1994	0.01 – 0.4	0.1	0.003 – 0.050	0.020

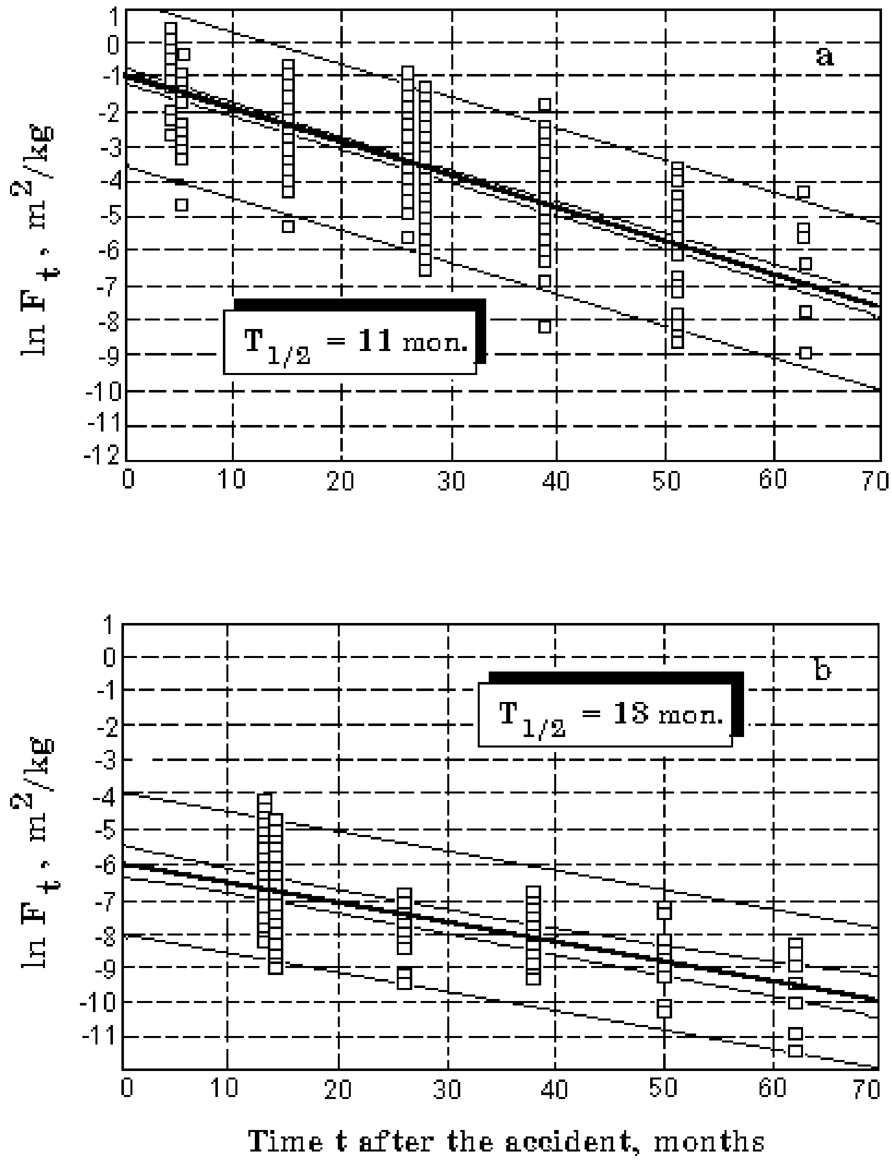

Fig. 9. Dependence of the transfer factor F_t of ^{137}Cs from soil to natural grass on time t passed after the Chernobyl accident. a - the Bryansk region; b - the Tula region. Each dot on the plot represents a mixed sample from one pasture. The box contains an effective half-reduction period F_t in months.

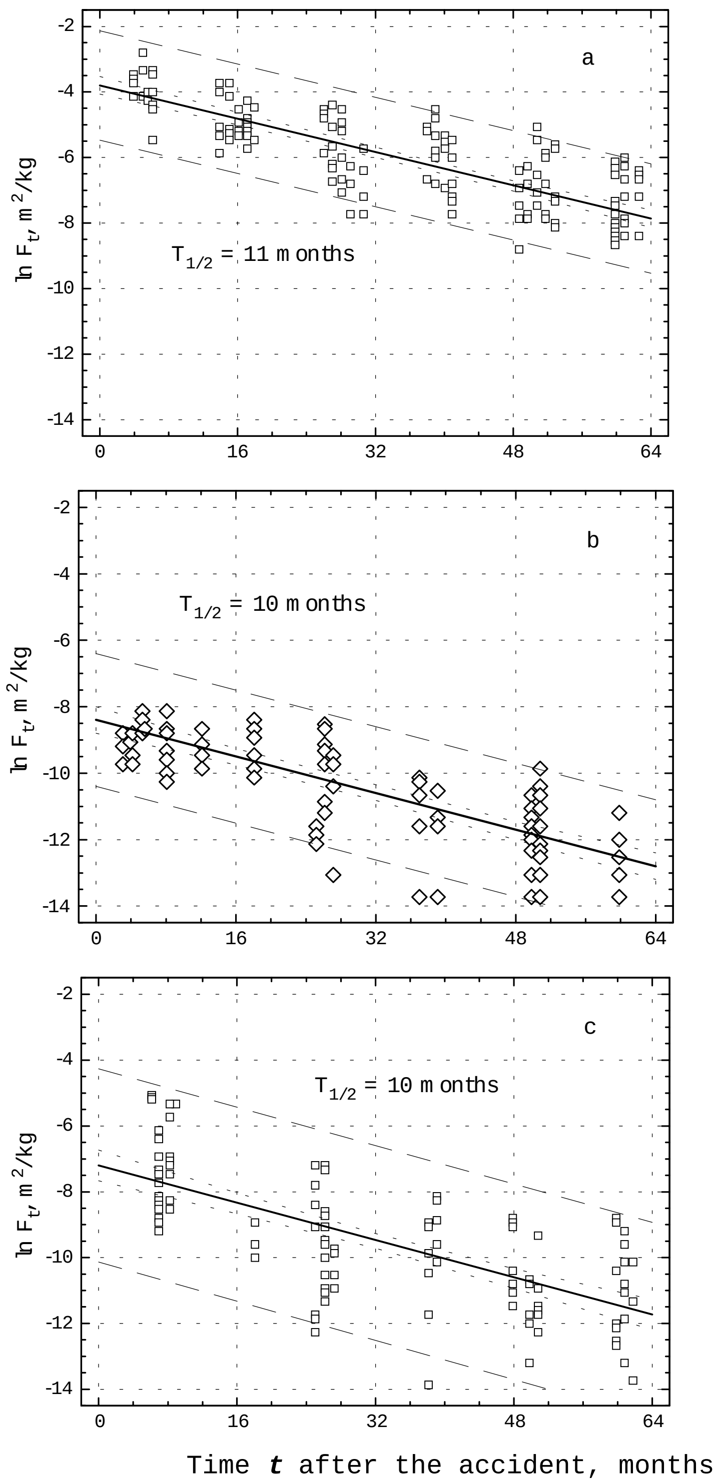

Fig. 10. Dependence of the transfer factor F_t of ^{137}Cs from soil to milk during the grazing period on time ***t*** passed after the Chernobyl accident.
a - the Bryansk region (soddy-podzolic soils); b - the Tula region; c - the Orel region. Each dot on the plot represents a mean over 4-30 samples for one milk producing farm.

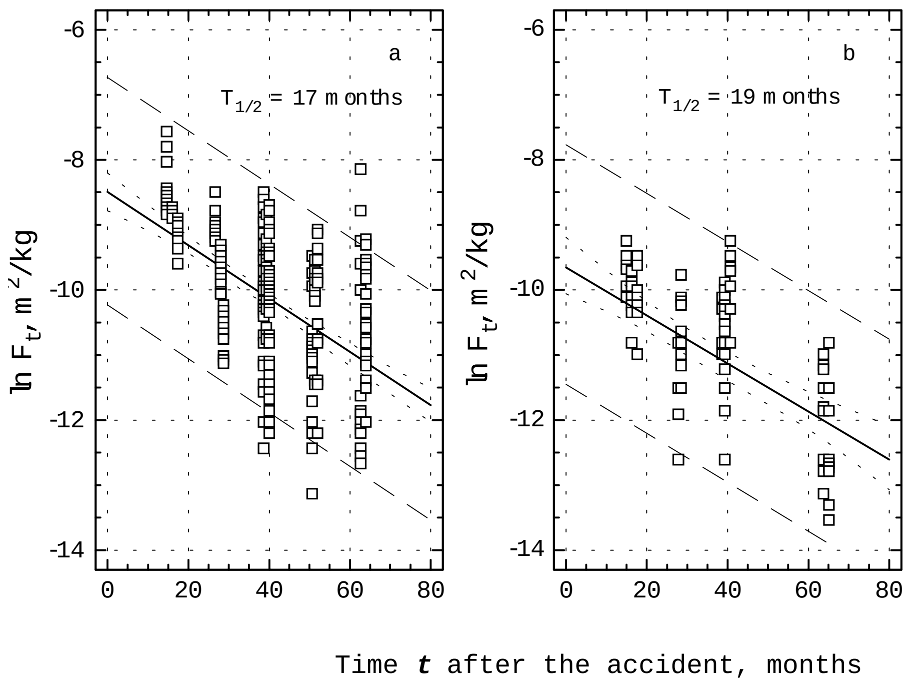

Fig. 11. Dependence of the transfer factor F_t of ^{137}Cs from soil to potatoes on time *t* passed after the Chernobyl accident in the Bryansk (a) and Tula (b) regions. Each dot on the plot is a mean for a farm.

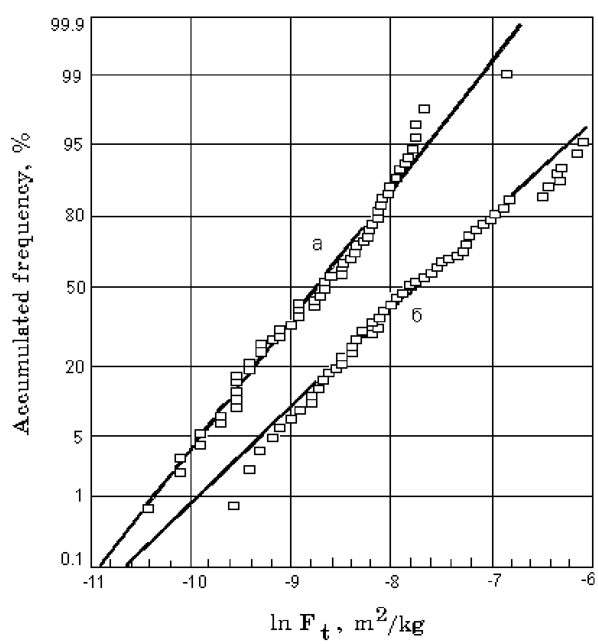

Fig. 12. Frequency distribution of samples of milk produced in 1992 in collective farms of the Bryansk region in house (a) and pasture (b) periods with respect to the ^{137}Cs transfer factor - F_t.

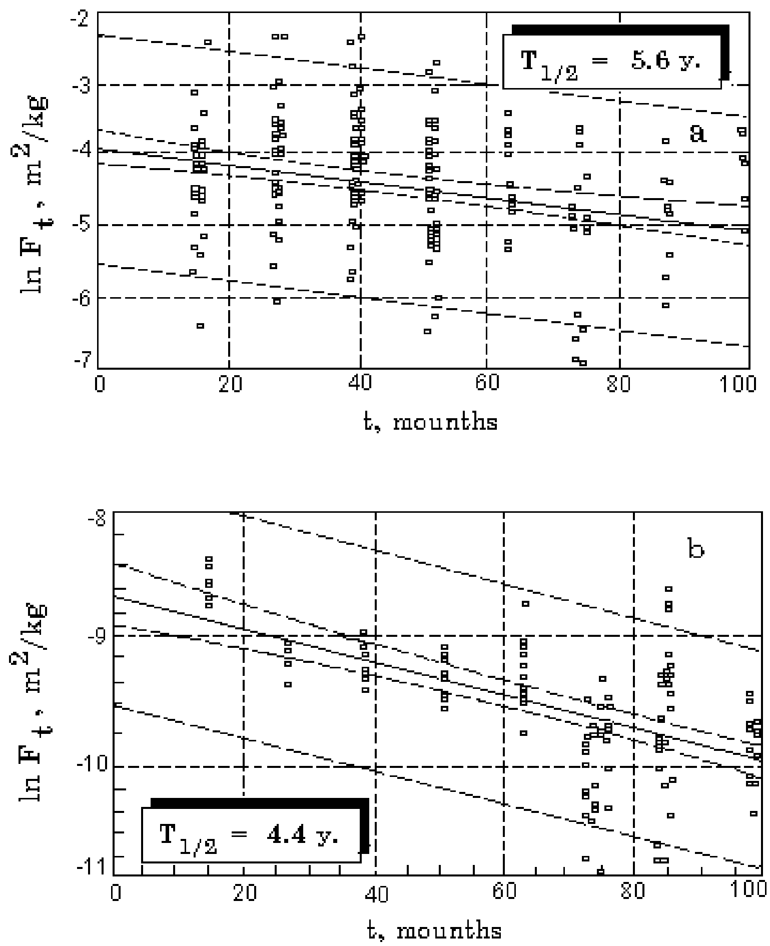

Fig. 13. Dynamics of the ^{90}Sr transfer factor $\boldsymbol{F_t}$ from soil to natural grass of the Bryansk region (a) and milk produced in collective farms of the Tula region (b). Each dot on the plot represents a mixed sample from one pasture (farm).

Our studies have also a revealed statistically significant reduction in $\boldsymbol{F_t}$ from soil to vegetation and milk for ^{90}Sr during the first 8 years after the accident with the period of half-reduction of 4-6 years. The observed feature is illustrated in Figure 13.

5.2. Model of food intake and dose assessment

Based on our data on specific activity of cesium and strontium in foodstuffs in 1987 normalised to their surface contamination density (analogous to transfer factor $\boldsymbol{F_t}$) we estimated their average content in components of the diet of rural adult population of the Russian Federation equal to daily intake of ^{137}Cs, ^{134}Cs and ^{90}Sr - Table 13. Such calculations were made on an annual basis. It should be noted that the year-averaged intake $\boldsymbol{i_r}$ can be 1.5-2 times lower that given in Table 13 for the pasture period because of seasonal variations in radionuclides concentration in milk (see Figure 12). We did not take this fact into account because we assume that dose estimates are conservative.

On the basis of polling results, our own results and data of Table 13 enable us to estimate total (surface + root) annual intake of cesium and strontium with food by adult rural inhabitants with a usual diet during the j-th year after the Chernobyl accident y_j. The value y_j is normalised to unit surface contamination density of ^{134}Cs, ^{137}Cs or ^{89}Sr, ^{90}Sr ascribed to 1 May 1986:

$$y_1 = y_s + y_{r,1};$$

$$y_j = \begin{cases} y_{r,1} \cdot e^{-\frac{0.693\cdot(j-1)}{T_3}}, j = 2,\ldots,6; \\ y_{r,6} \cdot e^{-\frac{0.693\cdot(j-6)}{T_4}}, j > 6, \end{cases} \quad (7)$$

where y_s, m^2/year is the radionuclide intake by the surface pathway during the first year after the accident;

$y_{r,j}$, m^2/year is the radionuclide intake by the soil-root pathway during the j-th year after the accident;

T_3, years is the effective period of half-cleaning of the diet from 1987 to 1991 after the accident;

T_4, years is the same in the subsequent years.

The parameters of formula (7) for the soils prevailing in the Bryansk and Tula regions are presented in Table 14. The numerical value of y_s have been derived by calculations from the data on dynamics of radionuclides concentration in milk in the first period after the accident. The value $y_{r,1}$ for cesium radionuclides has been determined from data of Table 13 by extrapolation from the summer of 1987 to the summer 1986 with allowance for exponential decay in time. As soddy-podzolic sandy and chernozem soils are almost extreme cases in terms of clay content and other components essencially influencing cesium and strontium migration, it can be assumed that most values of $y_{r,1}$ for other soil types change within the ranges indicated in Table 14. Considering that ^{89}Sr has a small (53.6 days) half-life we assumed its intake with foodstuffs in both regions in the first year after the accident to be equal to y_s and later on - zero. We then use an assumption (conservative from the standpoint of further estimation of internal absorbed doses) that starting from 1993 (j > 6) reduction in ^{137}Cs and ^{90}Sr concentration in the diet will proceed slower - with the period T_4 = 10 years. A period of the biosphere cleaning of this magnitude was observed in 70-80 after the global fall-out of nuclear testing products [26, 27].

Table 13

Daily mean intake of ^{137}Cs and ^{90}Sr in 1987 in the grazing period with local foods by adults among the rural population of the regions with prevailing soddy-podzolic sandy (I) or chernozem (II) soils

Soil type	Food	F_t, 10^{-3} m^2/kg		Consumption, kg/day	K, relative units	Normalized to daily intake i_r, 10^{-3} m^2/day	
		^{137}Cs	^{90}Sr			^{137}Cs	^{90}Sr
I	Milk	5	0.16	0.7	1.0	3.5	0.11
	Pork	5	–	0.16	1.0	0.8	–
	Grain	0.18	1.6	0.4	0.2	0.02	0.14
	Potatoes	0.16	0.14	0.3	0.8	0.04	0.03
	Total					4.36	0.28
II	Milk	0.07	0.07	0.7	1.0	0.05	0.05
	Pork	0.07	–	0.16	1.0	0.01	–
	Grain	0.02	0.13	0.4	0.2	0.002	0.01
	Potatoes	0.03	0.05	0.3	0.5	0.007	0.01
	Total					0.07	0.07

* - culinary decrease coefficient.

The comparison of $y_{r,1}$ and y_s in Table 14 suggests that during the first year after the accident radionuclides of cesium and strontium were taken in by the inhabitants of the Tula chernozem zone primarily in May-June 1986 due to surface contamination of vegetation and later on the intake was insignificant. Additional intake of radionuclides with milk in 1986-87 was associated with feeding the cattle during the in-house period with the fodder prepared in the summer of 1986. This process is not considered in the model. On the contrary, on the soddy-podzolic soils of the Bryansk region the root pathway predominated during the entire 1st year except May-June when the role of surface contamination was prevailing.

Table 14

Numerical values of parameters of formula (7) for adults

Soil type	y_s, m²/year			$y_{r,1}$, m²/year		T_3, years			T_4, years		
	^{137}Cs, ^{134}Cs	^{90}Sr	^{89}Sr	^{137}Cs, ^{134}Cs	^{90}Sr	^{137}Cs	^{134}Cs	^{90}Sr	^{137}Cs	^{134}Cs	^{90}Sr
I*	1.2	0.22	0.17	3	0.1	1.2	0.8	5	10	1.7	10
II	1.2	0.22	0.17	0.05	0.03	1.2	0.8	5	10	1.7	10

* - soil type are the same as in Table 13.

The estimated average standardised rate of intake of cesium and strontium radionuclides with food for rural population of Russia living on the soddy-podzolic and chernozem soils which was not covered by monitoring allows us to reconstruct and predict internal doses for inhabitants of different age for 70 years lifetime. Such a calculation has been made with the use of age dosimetric models proposed in ICRP Publication 56 [20]. The consumption of milk by children and adolescents up to 12 years was estimated to be 1.5 times lower that of adults and the rest products - 2 times lower [25]. This assumption has been supported with the data of our polls of inhabitants in the contaminated Bryansk region and literature data.

When estimating internal dose the depositions were considered to include ^{134}Cs in the ratio $\sigma_{134}/\sigma_{137}$ = 0.54 and ^{89}Sr in the ratio σ_{89}/σ_{90} = 10 at the time of the accident. The dose for a certain time interval from j_1 to j_2 years after the accident is considered to be a dose expected to be received by 70 years old age resulted from intake of radionuclide over the indicated time interval (j_1, j_2). The formula for calculating effective dose normalised to surface contamination is as follows

$$E(j_1, j_2) = \sum_{j=j_1}^{j_2} y(j, A_0 + j) \cdot dk(A_0 + j), \quad (8)$$

where A_0 is age at the time of the accident, years;

j is number of the year since the accident;

$y(j, A_0+j)$ is average annual rate of radionuclide intake in the body normalised to surface contamination density at the age (A_0+j), m²/year;

dk, nSv/Bq is effective dose expected to be received by 70 years from intake of 1 Bq radionuclide at the age A_0+j [20].

The results of calculations for adults are presented in a generalised form in Table 15 and for the earlier age in work [25]. The age of an adult for receiving a conservative dose estimate is taken to be 18 years and the exposure time length after the accident is 52 years. As is seen from Table 15, internal dose from cesium radionuclides for the inhabitants with the usual diet is primarily determined by their intake in the first 6 years after the accident. The dose is also considerably influenced by the type of soil predominant in the region: long exposure levels are about 6 times lower on the chernozem soils than on soddy -podzolic soils.

Considering the actual isotopic composition of depositions on the territory of Russia, namely the average ratio σ_{90}/σ_{137} of 2-6%, the contribution of strontium radionuclides to internal effective dose for 70 years lifetime for the population group critical with respect to this factor - children born in 1986 - can make in the areas with the usual diet 2-3% on the soddy-podzolic soils and from 3 to 10-15% on chernozem soils.

To evaluate the role of inhalation of cesium radionuclides their concentration in the air was measured during the agricultural works in 1987-1988 in crop growing and peat production which were accompanied by considerable dust formation. The annual inhalation intake estimated based on these measurements does not exceed 5% of the food intake of ^{134}Cs, ^{137}Cs in the body in the Bryansk region.

Table 15

Estimated mean effective internal dose from cesium and strontium for adult rural population of Russia in different periods after the Chernobyl accident normalized to σ_{137} in 1986 (nSv·m^2/Bq)

Soil type	Time after the Chernobyl accident				
	2 months	1 year	8 years	1995-2056	70 years
I*	40	90	168	16	184
II	27	28	30	1	31

* - soil type are the same as in Table 13.

5.3. Radionuclide content in the body

To verify whether the modelling estimation of doses was correct we compared actual measured levels of cesium radionuclides in inhabitants of contaminated areas of Russia and calculated values derived with formula (7). The estimated level (curves marked by “ b“ in Figure 14) is based on the function of cesium intake in the body of adults and the function of long retention in it. As the samples consist of approximately equal number of males and females, it is assumed that 90% of incorporated cesium radionuclides is removed from the body with the period of 90 days [28]. It was taken into account that in the west areas of the Bryansk region as opposed to the Tula region consumption of milk even beyond the monitored zone since 1986 decreased by a factor of 2 for subjunctive reasons as compared with the pre-accidental time [29]. Seasonal variations in milk (Figure 12) and meat contamination were not considered, as they are smoothed by long retention in the body.

The initial fast rise in the calculation curves indicates the intake of cesium radionuclides due to surface contamination of vegetation. This process is independent of soil properties and therefore the difference in the standardised ^{137}Cs levels in the population of the two regions is not significant. Later on, since autumn 1986 the difference in the sorption properties of soddy-podzolic and chernozem soils comes into play, which leads to different levels in the body and the internal dose more than an order of magnitude higher.

Figure 14 also shows measured ^{137}Cs in the body for adults of the Bryansk and Tula regions in the areas with the usual diet in 1986-1992. The measurements were made with portable one-channel scintillation spectrometers (Robotron-20046) using the technique [30]. The point on the Figure 14 (the curves marked “ a“) are an average value for a populated point normalised by σ_{137} with the sample volume of 50 to 150 people. The reduction in cesium content in the body occurs in the Bryansk and Tula regions with the period of 15 and 13 months, respectively. In the Bryansk region where the root transfer of radionuclides to vegetation is rather high, the period of reduction of ^{137}Cs and ^{134}Cs in the body coincides with the period of reduction in concentration in milk. In the Tula chernozem zone where soil-grass transfer of cesium is low, the activity of ^{137}Cs and ^{137}Cs in the body accumulated in May-June 1986 decreases faster than in the Bryansk region, but much slower than the biological period for an adult equal to 90 days. This can be explained by the feeding of the cattle in the in-house period of 1986-1987 with contaminated hay stocked in the summer of 1986.

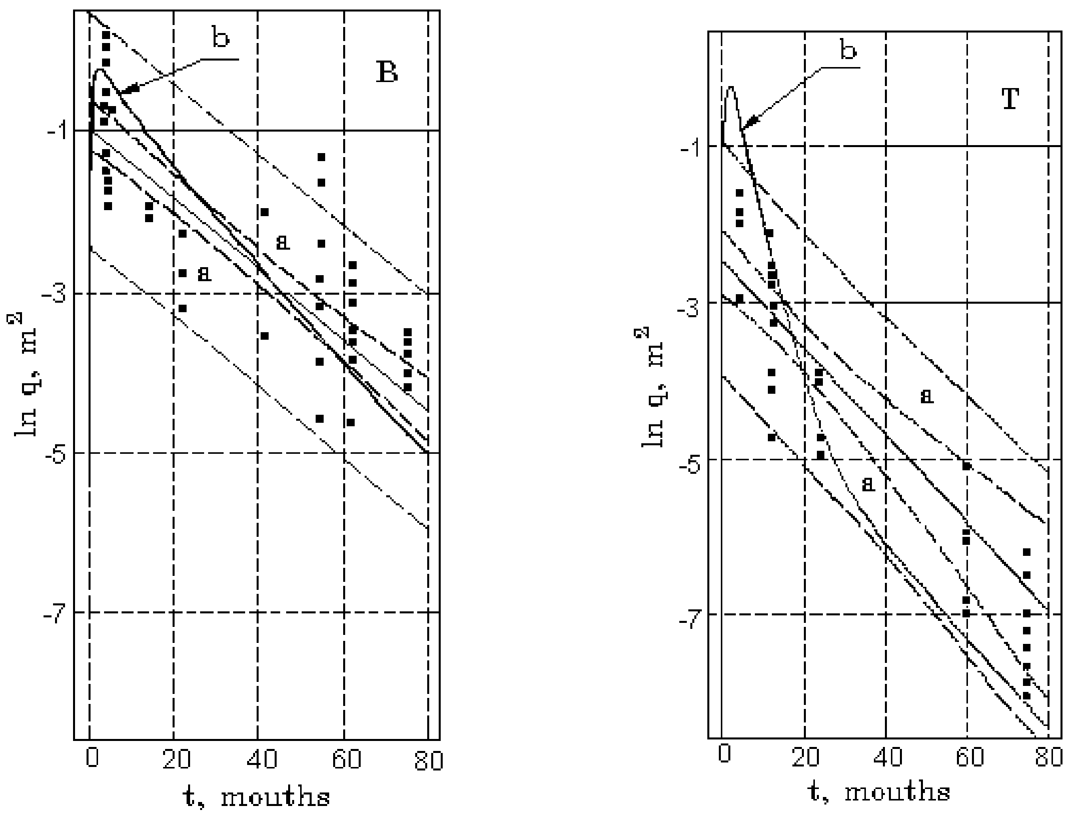

Fig. 14. Mean ^{137}Cs content ***q*** (m^2) normalized to ^{137}Cs surface deposition density in the body for adults of the Bryansk (B) and Tula (T) regions with normal diet. Each dot on the plot represent measurements with a whole body counter in one populated point; curves (a) are regression lines; (b) - calculated from intake function.

The good agreement in field measurements and calculation curves shows the accuracy of the dose estimates. This agreement, however, is noticed only for those areas where the radiation situation in 1986-1987 did not require large-scale protective measures and in particular, regular supply of uncontaminated products instead of the local ones. These measures have been implemented since the summer of 1986 in the populated points of the monitored territory of the Bryansk region where the ^{137}Cs surface contamination density does not exceed 15 Ci/km^2 (0.6 MBq/m^2).

It is only natural that such a change in the diet leads to a significant reduction in cesium intake in the body. These changes are strongly dependent on local features of supply and diet and therefore it is difficult to model and predict the actual cesium content in the body [29]. For correct estimation of internal dose on the monitored areas we used results of more than 200 thousand direct measurements of ^{137}Cs and ^{134}Cs in the body performed in 1986-92. Table 16 shows average results of annual checks of internal irradiation for inhabitants of some populated points on the monitored areas of the Bryansk region obtained with whole body counter.

The protective actions taken in 1986-1987 resulted in a rapid reduction, as a rule by 2-7 times, in radionuclides content in the body which in inhabitants of the monitored areas appears to be 5-10 times lower the possible level (in absence of protective measures). Later on the reduction slows down and in 1988-92 proceeds with the characteristic period of 2 years. In 1993-1994 the average ^{137}Cs content in the body for adults on the monitored areas raged from 0.1 to 1 μCi (4-40 kBq), which corresponds to the annual internal dose of 0.1-1 mSv.

The content of ^{137}Cs in children as a rule 1.5-2 times lower, and in pre-school children 2-5 times lower than in adults of the same populated point. The annual internal dose in children is normally somewhat lower than in adults.

The content of ^{90}Sr in bone tissue and plutonium isotopes (^{238}Pu, ^{239}Pu, ^{240}Pu) in lungs, lung lymph nodes, liver and bone tissues in inhabitants on the monitored territory of the Bryansk region started to be measured since 1990 in autopsy samples. The results confirm that the estimates of dose from ^{90}Sr presented in section 4.2 are conservative and the contribution of α- radiation of transuranic elements to dose is insignificant.

Table 16

Mean ^{137}Cs + ^{134}Cs content (μCi) in the body for adults of some populated points in west districts of the Bryansk region in different time periods after the Chernobyl accident

Populated point	Time after the Chernobyl accident								
	08. - 09.	12.	summer – autumn						
	1986	1986	1987	1988	1989	1990	1991	1992	1993
Novozybkov district									
Novozybkov	1.5	1.0	0.7	0.4	0.4	0.2	0.09	0.11	0.15
Kr. Kamen’	9	5.3	2.2	1.1	0.4	0.5	0.3	-	-
Svyatsk	4.7	4.0	1.3	0.6	0.5	0.3	0.2	0.16	0.14
Klintsy district									
Klintsy	-	-	0.8	0.5	0.2	0.2	0.1	-	-
Ushcherp’e	5.0	-	5.8	1.8	1.6	0.6	0.5	0.3	0.3
Unecha	10	-	8.7	3.1	2.0	1.5	1.3	1.3	1.0
Krasnaya Gora district									

Krasnaya Gora	2.3	1.0	0.7	0.3	0.3	0.1	30.14	0.12	-
Zabor'e	8.5	4.2	2.5	1.2	0.7	0.7	0.6	0.6	0.4
Bukovets	14	-	1.8	0.6	0.4	0.3	-	-	-

6. Total effective dose

The radiation dose received by the inhabitants of a contaminated area is made up of internal and external doses. In the majority of 10 thousand populated points of Russia surveyed by specialists of Roshydromet in 1986-1993 neither measurements of individual absorbed dose of external γ-radiation nor measurements of radionuclide content in the body were conducted on a regular basis, primarily due to the limited resources. The number of populated points in which such measurements were performed regularly were not more than 300 in the Bryansk region and 100 in the Tula, Kaluga and Orel regions together, i.e. about 4% of the total number. But it is in these most contaminated populated points of Russia that protective measures were implemented which radically reduces the dose as compared with calculation models described in this paper. Results of annual measurements by IDM and WBM techniques allow a rather correct estimation of dose in inhabitants of the most contaminated areas of Russia. By way of illustration Table 17 shows some estimated population doses in the Bryansk and Tula regions. The dose for 1986-1994 was calculated primarily with IDM and WBM data and for 1995-2056 - by models described in this paper in the conservative assumption that since 1995 supplies of uncontaminated produce to the population of the Bryansk region was stopped and they started consuming only locally produced foodstuffs.

The analysis of Table 17 shows that the effective dose function of ^{137}Cs soil surface contamination density is not single-valued. The relation, close to linear, exists between σ_{137} and external dose from depositions. On the contrary, the internal dose is strongly dependent on environmental and social factors. The influence of soil properties can be clearly seen from comparison of internal dose from exposure to cesium radionuclides for the population of the Bryansk region where soddy-podzolic soils are prevailing and in the Tula region with chernozem lands. However, even within the Bryansk region the ratio of internal and external doses changes appreciably. Where as in Novozybkov, Zabor'e and Svyatsk as in most points on the monitored territory the internal dose in 1986-1992 was 15-25% of effective dose, in Ushcherp'e and Unecha of the Klintsy district - 50 and 70%, respectively. The increased transfer of radionuclides to cows and with milk to man on these areas is associated with the use of flooded meadows in the plains of the rivers Iput and Unecha for grazing cattle and hay making. Besides, both villages were referred to the monitored areas only in 1987 and the cattle in private farms was not killed. It should be noted that the inhabitants have already received more than 50% of their lifetime external dose. The future anticipated internal dose depends on countermeasures and can be reduced by 5-10 times in the Bryansk region as compared with that given in Table 17, provided the population continues to be supplied uncontaminated products.

Table 17

Mean doses for population of different age living in some populated points of the Bryansk and Tula regions

σ - surface contamination density;
$\boldsymbol{D_{th}}$ - absorbed thyroid dose;
γ - effective dose of external exposure to γ-radiation of depositions for adults;
Cs (Sr) - effective internal dose from incorporated ^{134}Cs, ^{137}Cs (^{89}Sr, ^{90}Sr) for adults;

Σ - total effective internal and external dose for the whole body.

Populated point *	σ, MBq/m^2		D_{th}, Gy, for age groups:			Effective radiation dose for 1986-1994, mSv				Effective radiation dose for 1995-2056, mSv		
	^{137}Cs	^{90}Sr	<7 year	7-17 year	>17 year	γ	Cs	Sr	Σ	γ	Cs+Sr	Σ
Novozybkov	0.7	0.02	0.4	0.15	0.04	14	5	0.02	19	13	8	21
Zabor'e	4.3	0.04	1.2	0.7	0.3	98	19	0.03	117	130	60	190
Svyatsk	1.6	0.02	0.3	0.2	0.06	51	11	0.02	62	48	23	71
Ushcherp'e	0.7	-	0.6	0.4	0.15	24	22	0.06	46	21	10	31
Unecha	0.5	-	0.5	0.3	0.1	18	38	0.10	56	16	8	24
Plavsk	0.5	0.01	0.4	0.07	0.05	10	1.5	0.02	12	8.9	0.3	9
Rakhmanovo	0.4	-	0.4	0.3	0.1	12	2.0	0.03	14	10.4	0.6	11
Kamynino	0.3	-	0.4	0.3	0.1	9	1.8	0.03	11	7.9	0.5	8

* - The first 5 populated points (above the line) are in the Bryansk region with prevailing soddy-podzolic soils; the rest (below the line) are in the Tula region with prevailing chernozems.

For most contaminated populated points the main way of reconstruction and prediction of population dose is using the available models of external irradiation (section 3) and internal irradiation (section 5.2). After the Chernobyl accident the main parameters for calculations are surface contamination density of ^{137}Cs and type or agrochemical characterisation of arable lands (meadows and plowing lands). The radionuclides transfer factors from soil to agricultural produce have been derived for the main soil types characteristic of the central European part of Russia.

To assess the relative contributions of external and internal irradiation to total effective dose under different conditions one should compare data of Tables 4 and 15. Our data suggest that the dynamics of external irradiation is independent of soil type. It can be seen that in absence of protective measures the contribution of internal irradiation to the total dose in the first year is higher for the both types of soils. Even in the first year the dose is influenced by the higher transfer factor of cesium to plants on poor soils. Later on, the internal dose prevails only on soddy-podzolic soils, while on chernozem ^{137}Cs is strongly fixed and insignificantly migrates along the food chain to man.

Discussion of results

This work dealing with the action of main radiation factors of the Chernobyl accident presents new information on different aspects of the problem. The scientific principles lying behind these studies can be found in [5]. Let us note just two environmental factors which influence significantly the applied aspects of dosimetry.

The fast exponential reduction (with period of 1 year) in soil-plant transfer of cesium and its consequences are observed in different natural and agricultural objects, different trophic levels of terrestrial ecosystem up to human body, in different soil-geochemical zones hundreds of kilometres apart, which shows the fundamental character of this factor. The obtained results and the model for cesium intake with food in human body (section 5.2) improves the understanding of the process presented in the UNSCEAR Report [26] and by a series of authors [27]. According to the former concepts, the contribution of fresh depositions of ^{137}Cs in the dietary intake is significant for two years, and later on the nuclide transfer to foods goes on at a slower rate, decreasing with the period of 2.4 to 35 years, the average being 10 years. By our data it seems reasonable to single out the effect of surface vegetation contamination with radionuclides which can be noticed within a season and the root transfer of cesium from soil to plants during at least 5-6 years can be characterised with a decreasing exponent of 1-1.5 years period. Afterwards, the process of natural decontamination of the biosphere slows down. It may be assumed that the mentioned process of 1-1.5 years was not identified with certainty in the time of mass-scale study of the consequences of global fall out of nuclear testing products, as after 1963 the fallout rate was also decreasing with the period of about 1 year. Such a coincidence disguised the process on the land and the one-time contamination after the Chernobyl accident has revealed this process.

Another important inference of this work: the strong dependence of transfer factor $\boldsymbol{F_t}$ of cesium on soil properties was known earlier [26, 27]. In this respect the authors credit for establishing quantitative relationship $\boldsymbol{F_t}$ with the soil type and a number of agrochemical characteristics. The results of multi-factor regression analysis indicate a strong relation between cesium $\boldsymbol{F_t}$ from soil to natural grass and the totality of soil characteristics: content of mobile form of cesium in soil, potassium concentration, concentration of organic matter etc. [24, 25]. The quantitative dependence on soil types of $\boldsymbol{F_t}$ and radionuclide content in foodstuffs and in the body is of also primary importance for radiation protection of the population from internal irradiation. It is used in the recent dosimetric methodology and dose calculation in the population of Russia [31].

Analysing the developed model of radionuclides intake in the human body it should be admitted that the most variable and least understood part of it is the early stage of internal irradiation due to the surface vegetation contamination. This process is strongly dependent on a number of natural factors: type of depositions, physical and chemical form of radionuclides, state of vegetation cover etc. Therefore in dose reconstruction for the first months after deposition it is desirable to take onto account actual data on early contamination of plants and foods in each of the considered areas. Long-term processes of formation of internal and external irradiation are much less studied.

It should be noted that the main components of dose in the population living on the contaminated areas continues to monotonously decrease. For example, the external dose in 1991 in comparison with the first year after the accident has decreased by a factor of 5-10, the internal dose - by a factor of 10-100 and the total dose - by a factor of 10-20. Further the reduction in dose slowed down and was 10-20% a year from 1991 to 1994. In the recent years a considerable contribution to internal dose is made by cesium intake with natural foods: mushrooms, forest berries, lake fish.

The paper clearly shows a strong influence of radioecological features of the area on internal dose of the population and committed effective dose. It is obvious that one cannot correctly evaluate the dose from surface contamination density of ^{137}Cs and ^{90}Sr without consideration of these features. Otherwise, the error may be as big as one order of magnitude.

Conclusion

This paper, in a generalised form and using specific examples, shows main natural and social regularities in formation of internal and external dose in the population in the areas affected by the Chernobyl accident. These regularities are widely applied to reconstruct dose over the passed period, estimate the current exposure level and predict the future one. A milticomponent model was built for estimating external doses for population groups from γ-irradiation of depositions support with regular measurements of individual dose with thermoluminescence method.

The methodology of estimation of absorbed thyroid dose from incorporated ^{131}I for persons of different age is based on results of thyroid radiometry in May-June 1986 and on a statistical correlation between absorbed dose and factors of the radiation situation. The model estimating internal dose from cesium and strontium intake accounts for dependence of soil-produce transfer factors on soil type and time since the radioactive contamination. The model has been verified against numerous measurements of radionuclides content in human body. For the Bryansk region in which protective measures are actively applied the internal dose is estimated from measurements of whole body counter.

The stated regularities with allowance for radioecological features enable estimating dose in an arbitrary time interval after the Chernobyl accident in any populated point of Russia with a known contamination density of ^{137}Cs. Using detailed information of Roshydromet one can also estimate collective dose in the population of Russia due to the Chernobyl accident.

In conclusion we outline the main directions in practical application of the results of this work:

a) a regular comparison of actual mean doses of inhabitants with the existing normative documents and regulations of laws of Russian Federation on population protection;

b) prediction of health effects of the Chernobyl accident and justification of kinds and volume of medical help to the population of separate areas;

c) justification of protective measures adequate to the current and projected radiation situation and population doses;

d) improvement and verification of radioecological and dosimetric models.

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