

Assessment of the Chernobyl Radiological Consequences

Mikhail V. MALKO

*Institute of Physical and Chemical Radiation Problems of the Academy of Sciences of Belarus
Minsk, Sosny, 220109, Republic of Belarus; fax: + 375 (0172) 467317*

INTRODUCTION

The Chernobyl accident has been the worst accident in the history of peaceful use of nuclear energy. The nuclear explosion and the following 10 days graphite fire have not only completely destroyed the fourth unit's reactor of the Chernobyl NPP but, as well, resulted in the release of a large amount of radioactive species into the environment. This accident caused radioactive contamination in a lot of countries of the Northern hemisphere, even in countries many thousand kilometers away from Chernobyl. For example, the deposition of different radionuclides has been found even in Japan [1-3].

The Belorussian Republic was affected by the Chernobyl accident much more than any other country in the world [4]. Twenty three percent of its territory were contaminated by caesium-137 with 1 Ci/km² and higher. As a result of the accident at the Chernobyl NPP, large territories in the Russian Federation and in the Ukraine have been contaminated as well [5-7].

Experts of different countries and international organizations are unanimous in the opinion that the Chernobyl accident has caused enormous socio-economic consequences in Belarus, the Russian Federation, and the Ukraine [4, 7-9]. It is also recognized that residents of the affected areas of the former USSR have been subject to various psychological burdens soon after the Chernobyl accident [4, 7-11].

However, there exists a significant controversy among specialists about the medical consequences (other than psychic) of the Chernobyl accident. For example, according to the assessment of J. Gofman [12] this accident will result in additional 475,000 fatal solid cancers, 19,500 leukemia and additional 475,000 non-fatal solid cancers. The abovementioned data were evaluated by J. Gofman [12] for all countries of the Northern hemisphere affected by the Chernobyl accident. Significant medical consequences, especially additional thyroid cancers and leukemia, have been as well predicted by E. Ivanov [13].

The whole International Radiation Community, on the contrary, rejected the possibility of serious medical consequences other than psychic stresses and feeling of anxiety suffered by the residents of the affected areas [8-11, 14-16]. Such controversy is unbelievable in the light of the reliable data

established in the affected regions of the former USSR [4,7,17].

One of the reasons for such controversy has been explained by J. Gofman [18]. He managed to show that the abovementioned discrepancies in prognosis of medical consequences of the Chernobyl accident arose due to the incorrect risk coefficient of ionizing radiation employed by some specialists to forecast additional number of solid cancers and leukemia induced by Chernobyl radiation.

Another incorrectness that can seriously influence the forecasting of biomedical consequences of the Chernobyl accident is related to the collective dose estimation. It is well known, that assessments of authors [8, 12-16] have been made on the basis of data of nuclides release into the environment established soon after the accident [19, 20]. During the last years, however, more accurate data were established on the total discharge of radioactive species due to the Chernobyl accident, as well as more accurate data on deposition of different radionuclides in the affected areas of the former USSR [5-7].

The facts discussed above justify any independent analysis of possible medical consequences of the Chernobyl accident. This paper presents our attempt to assess the pure radiological consequences of the accident at the Chernobyl NPP.

The following limitations were taken into consideration in our assessment. First, we have restricted our analysis to stochastic effects of ionizing radiation only, such as solid cancers and leukemia. Second, we have also excluded from our analysis members of the personnel of the Chernobyl NPP and the cohort of liquidators. It means that our study was concentrated only on the population of areas affected by the Chernobyl accident. Third, our assessment was based on the use of simplified model of collective dose estimation very similar to the models used by authors [13-16,20]. The first step in collective dose assessment is the calculation of the exposition dose in air on the basis of experimental data on radionuclide deposition on the ground. The results of our assessment are given below.

METHOD OF THE COLLECTIVE DOSE ASSESSMENT

The collective irradiation dose within some time τ , H_{τ}^{coll} , can be estimated as:

$$H_{\tau}^{coll} = N \cdot \overline{H}_{\tau} \quad (1)$$

where,

N = number of irradiated people,
 \overline{H}_{τ} = mean individual effective equivalent dose accumulated within the time τ .

The value of \overline{H}_{τ} is estimated as a sum of external, $\overline{H}_{\tau, ext}$, and internal, $\overline{H}_{\tau, int}$, doses:

$$\overline{H}_{\tau} = \overline{H}_{\tau, ext} + \overline{H}_{\tau, int} \quad (2)$$

On the basis of data given in the Catalogue of doses [21] we have estimated that average contributions of external and internal irradiation to the equivalent doses delivered to inhabitants of the affected areas of Belarus in 1991-1992 were 60 and 40 percent respectively.

Assuming that the same contribution of external and internal radiation will be sustained at any time within a period of time τ we can write:

$$\overline{H}_{\tau} = \frac{\overline{H}_{\tau, ext}}{0.6}, \quad (3)$$

$$\overline{H}_{\tau} = \frac{\overline{H}_{\tau, int}}{0.4}. \quad (4)$$

Any of these expressions can be used for assessment of the collective equivalent dose delivered to the Belorussian population.

We shall base our investigation on the equation (3) because the procedure of assessment of $\overline{H}_{\tau, ext}$ is much easier than that of $\overline{H}_{\tau, int}$. The mean external equivalent dose, $\overline{H}_{\tau, ext}$, can be determined by means of the equation:

$$\overline{H}_{\tau, ext} = H_{\tau, ext}^* \cdot \overline{A}_s^0 ({}^{137}Cs) \quad (5)$$

where

$H_{\tau, ext}^*$ = mean external individual equivalent dose of inhabitants living in areas with initial contamination level by ${}^{137}Cs$ equal to 1 Ci/km²,
 $\overline{A}_s^0 ({}^{137}Cs)$ = average initial deposition level of ${}^{137}Cs$ determined for the total area of contaminated territories.

Thus, the value of $\overline{A}_s^0 ({}^{137}Cs)$ is given by:

$$\overline{A}_s^0 ({}^{137}Cs) = \frac{Q_0}{S} \quad (6)$$

where

Q_0 = total amount of ${}^{137}Cs$ deposited on all affected territories (source term)
 S = total area of contaminated territories

As can be seen from the equation given above the task of the collective equivalent dose assessment results in

values: $\overline{H}_{\tau, ext}^*$, Q_0 and S . The mean individual equivalent dose of external irradiation normalized to the initial level of ${}^{137}Cs$ contamination equal to 1 Ci/km², $\overline{H}_{\tau, ind}^*$, can be determined on the basis of measured or calculated exposition dose rates in contaminated areas. By means of exposition dose rates integration for the period of time τ one can then compute the exposition dose P_{τ} . This value can be transformed to the air-absorbed dose D_{τ} by:

$$D_{\tau} = C_1 \cdot P_{\tau} \quad (7)$$

where

C_1 = conversion factor equal to $0.873 \frac{rad}{rem}$ [22].

By means of another conversion factor C_2 which is determined in $\frac{rem}{rad}$ one can later estimate the required equivalent irradiation dose:

$$H_{\tau} = C_2 \cdot D_{\tau} \quad (8)$$

DOSE RATE AND DOSE IN AIR RECONSTRUCTION

There are only sparse measurement data on exposition dose rates in different areas of Belarus affected by the Chernobyl accident. Thus, one needs to assess these values by means of some computational methods and data on contamination of the soil.

The most simple model which can be used for computation of dose rates is based on the so-called model of infinite half-space source geometry at a reference height of 1 m. According to this model the exposition rate of external radiation at the time t is given by:

$$R_{\gamma}(t) = \sum_{i=1}^n K_{i,\gamma} \cdot \sigma_i^0 \cdot \exp\left(-\frac{0.693}{T_{1/2}^i} \cdot t\right) \cdot K_{iL}(t), \quad (9)$$

where

n = number of nuclides contributing to the total exposition dose rate,
 $K_{i,\gamma}$ = conversion factor of i th nuclide per unit deposition, (mR/hr)/(Ci/km²),
 σ_i^0 = initial surface contamination with i th nuclide normalized to initial surface contamination equal to 1 Ci/km² of ${}^{137}Cs$,
 $T_{1/2}^i$ = half-life of i th nuclide,
 $K_{iL}(t)$ = shielding factor of i th nuclide originated from its penetration into the soil (function of time).

Computation of $R(t)$ is usually carried out on the basis of the assumption, that all nuclides have the same shielding factor $K_{iL}(t)$. Then the equation (9)

can be written in the form:

$$R_{\gamma}(t) = K_L(t) \cdot \sum_{i=1}^n K_{i,\gamma} \cdot \sigma_i^0 \cdot \exp\left(-\frac{0.693}{T_{1/2}^i} \cdot t\right), \quad (10)$$

Integration of the equation (10) from $t=0$ up to $t=\tau$ gives the exposition dose of external radiation accumulated within the period of time τ :

$$P_{\tau} = \int_0^{\tau} K_L(t) \cdot \sum_{i=1}^n K_{i,\gamma} \cdot \sigma_i^0 \cdot \exp\left(-\frac{0.693}{T_{1/2}^i} \cdot t\right) dt. \quad (11)$$

Data on exposition dose rates and doses calculated on the basis of the equations (10) and (11) for different areas of Belarus are given in Fig. 1 and in Tables 1, 2 and 3. In computing these data experimental data on deposition of radionuclides as a result of the Chernobyl accident given in the book [5] were used (see Table 4). Table 5 consists of values of half-lives of gamma-emitting nuclides considered by

calculation of R_{γ} and P_{τ} . The shielding factor K_L was calculated for the exponential model as it was done by T. Imanaka, T. Seo and H. Koide [23]:

$$K_L = a_1 \cdot \exp(-l_1 \cdot t) + a_2 \cdot \exp(-l_2 \cdot t), \quad (12)$$

where

- a_1 and a_2 = fractions of fast and slow migration of radionuclides into the soil
- l_1 and l_2 = constants of vertical migrations into the soil

Values of these fractions and constants for different

periods of time after the Chernobyl accident are given in Table 6. They were determined from experimental data on vertical migration of radionuclides into the soil measured by specialists of Goshydromet of the former USSR [5]. They measured the vertical migration of radionuclides in the undisturbed soil for different kind of soils. We used data given in [5] for the sod-podsolic soil as more characteristic for contaminated territories of Belarus.

Figure 1 shows the change in exposition dose rates of external radiation in different areas of Belarus within the first weeks after the nuclear explosion at the Chernobyl NPP.

One can see that as a result of different composition of radionuclides deposited on the ground, roofs and walls of houses and other buildings the exposition dose rate in air in different contaminated areas of Belarus can differ by factor 3 even at the same ^{137}Cs contamination level.

The highest exposition dose rate had to be in the Northern sector of the so-called "nearest zone". This zone is a not very broad stripe that is extended in the Northern direction up to 100 kilometers from the Chernobyl NPP.

The lowest exposition dose rate had to be in the so-called "caesium spots", which are characterized by relative enrichment of radioactive deposition by caesium isotopes.

The difference in exposition dose rates diminished very quickly because of a radioactive decay of short-lived isotopes. At the end of the first month after the explosion at the Chernobyl NPP the exposition dose rates at different areas of Belarus were quite similar.

1. Sector "North" of the near zone;
2. Averaged composition of the total release;
3. Gomel oblast;
4. "Caesium" spots;
5. Mogilev oblast.

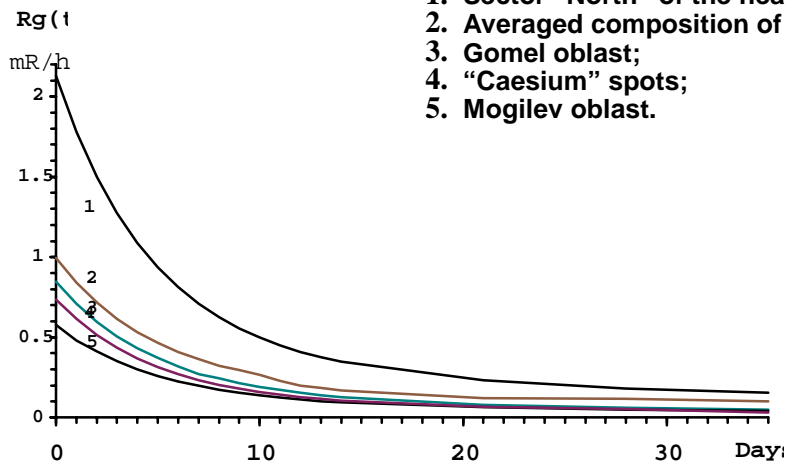


Fig. 1 Exposition dose rates in air at a height of 1 m during the first weeks after the Chernobyl accident in different areas of Belarus (normalized to the contamination level of caesium-137 equal to 1 Ci/km^2).

Table 1. Free air gamma exposition doses at a height of 1 m accumulated in different contaminated areas of Belarus within the period from 26.04.1986 to 26.04.2056 (normalized to the level of ^{137}Cs contamination of $1 \text{ Ci}/\text{km}^2$, mR).

Year	Vetka rayon of Gomel oblast	Krasnopolje rayon of Mogilev oblast	“Caesium spot”	Sector “North” of the near zone	Average composition of the total release
1986	258.0	212.7	225.1	622.5	369.1
1987	414.0	358.8	366.7	815.1	517.6
1988	531.7	471.9	476.8	947.9	628.0
1989	623.4	561.4	564.2	1048.6	715.5
1990	698.0	635.0	636.2	1128.8	787.5
1991	760.8	697.2	697.4	1195.1	848.7
1992	815.2	751.4	750.8	1251.7	902.1
1993	863.2	799.3	798.2	1301.3	949.5
1994	906.5	842.6	841.1	1345.7	992.4
1995	946.2	882.2	880.5	1386.1	1031.8
1996	983.0	919.1	917.2	1423.4	1068.5
1997	1017.4	953.4	951.4	1458.1	1102.7
1998	1049.8	985.8	983.8	1490.2	1135.0
1999	1080.5	1016.6	1014.4	1521.5	1165.7
2000	1109.9	1046.0	1043.8	1551.1	1195.1
2001	1138.0	1074.0	1071.8	1579.2	1223.1
2002	1164.9	1101.0	1098.7	1606.3	1250.0
2003	1191.1	1127.3	1125.1	1632.4	1276.3
2004	1216.3	1152.4	1150.1	1657.4	1301.4
2005	1240.3	1176.4	1174.1	1681.3	1325.4
2006	1263.2	1199.3	1197.1	1704.2	1348.3
2016	1447.8	1383.9	1381.6	1888.8	1532.8
2026	1573.8	1509.9	1507.6	2014.7	1658.7
2036	1660.8	1596.9	1594.6	2101.8	1745.7
2046	1721.1	1657.2	1654.9	2162.1	1806.0
2056	1760.4	1696.6	1694.3	2201.4	1845.3

Table 2. Contribution of different radionuclides to the summary free air gamma exposition dose, accumulated within the period from 26.04.1986 to 31.08.1986 in contaminated areas of Belarus.

Radionuclide	D_i / D , %				
	Vetka rayon of Gomel oblast	Krasnopolje rayon of Mogilev oblast	“Caesium spot”	Sector “North” of the near zone	Average composition of the total release
^{239}Np	0	0	0	0.9	0.8
^{99}Mo	0	0	0	0.2	0.1
^{132}Te	25.3	21.6	26.9	22.1	19.5
^{131}I	12.6	10.7	10.5	6.6	7.3
^{140}Ba	9.1	7.6	6.5	11.3	16.6
^{141}Ce	0	0	0	0.8	0.5
^{103}Ru	10.0	11.1	11.6	10.2	5.2
^{95}Zr	0	0	1.4	27.8	25.0
$^{110\text{m}}\text{Ag}$	0	0	0	0	0
^{144}Ce	0	0	0	0.7	0.7
^{106}Ru	6.8	3.3	4.0	3.7	2.0
^{134}Cs	21.1	26.7	22.1	9.9	12.6
^{125}Sb	0	0	0	0	0
^{137}Cs	15.1	19.0	17.0	5.8	9.7

According to [7], there are places in the 30 kilometers zone with level of contamination by ^{137}Cs as high as many hundred Ci/km^2 . It means that soon after the explosion the exposition dose rate in air could reach in such places many hundred millirentgen per hour and therefore exceed many hundred thousand times the exposition dose rate in air before the Chernobyl accident.

According to our calculation nuclides with half-lives shorter than 1 year played an important role during the first months after the Chernobyl accident.

It can be seen from Table 3, where individual contributions to the total exposition dose of external radiation of different nuclides at different areas of Belarus are given.

Data presented in Table 2 show that short-lived

Table 3. Contribution of different radionuclides to the summary free air gamma exposition dose, accumulated within the period from 26.04.1986 to 31.04.2056 in contaminated areas of Belarus.

Radionuclide	D _i / D, %			
	Vetka rayon of Gomel oblast	Krasnopolje rayon of Mogilev oblast	“Caesium spot”	Sector “North” of the near zone
²³⁹ Np	0	0	0	0.2
⁹⁹ Mo	0	0	0	0
¹³² Te	2.7	1.9	2.5	5.1
¹³¹ I	1.3	0.9	1.0	1.5
¹⁴⁰ Ba	1.0	0.7	0.6	2.6
¹⁴¹ Ce	0	0	0	0.2
¹⁰³ Ru	1.2	1.1	1.2	2.6
⁹⁵ Zr	0	0	0.2	8.3
^{110m} Ag	0	0	0	0
¹⁴⁴ Ce	0	0	0	0.6
¹⁰⁶ Ru	3.0	1.2	1.6	3.4
¹³⁴ Cs	16.4	17.0	15.5	16.0
¹²⁵ Sb	0	0	0	0
¹³⁷ Cs	74.4	77.2	77.4	59.5

Table 4. Composition of nuclide deposition in the affected areas of Belarus (normalized to the activity of ¹³⁷-Cs) [5]

Radionuclide	D _i / D, %				
	Vetka rayon of Gomel oblast	Krasnopolje rayon of Mogilev oblast	“Caesium spot”	Sector “North” of the near zone	Average composition of the total release
²³⁹ Np				33.33	6.67
⁹⁹ Mo				3.33	3.33
¹³² Te	14.13	9.5	12.78	33.3	16.7
¹³¹ I	14.13	9.5	10.0	20.0	16.7
¹⁴⁰ Ba	1.086	0.714	0.67	3.67	3.33
¹⁴¹ Ce				3.67	3.67
¹⁰³ Ru	1.957	1.714	1.994	5.33	2.67
⁹⁵ Zr			0.056	3.33	3.33
^{110m} Ag					0.01
¹⁴⁴ Ce				2.00	2.33
¹⁰⁶ Ru	1.413	0.55	0.722	2.00	1.0
¹³⁴ Cs	0.545	0.545	0.5	0.67	0.5
¹²⁵ Sb					0.02
¹³⁷ Cs	1.00	1.00	1.00	1.00	1.0

nuclides determined more than 50 percent of the total exposition dose in air delivered within the first months after the accident.

In case of the Northern sector of the so-called “near zone” (Bragin district is settled in this zone) short-lived nuclides gave about 85 percent of the total exposition dose.

It is clear that one needs to consider the total spectrum of the deposited radionuclides in the assessment of the possibility of direct effects of radiation on inhabitants of 30 kilometers zone, that were evacuated within the first months after the Chernobyl accident.

The total contribution of short-lived nuclides to the exposition dose of external radiation which can be delivered within quite a long period is not very large. Such conclusion may be drawn on the basis of data

given in Table 3. In this table results of the exposition doses calculated for different areas of Belarus for the period of time from 26.04.1986 to 26.04.2056 (70 years period) are presented.

As can be seen from this table nuclides with half-life shorter than the half-life of isotope ¹³⁴Cs, give together only about 7% of the total exposition dose in air delivered during the 70 years after the Chernobyl accident.

It means that caesium isotopes determine practically the total exposition dose of external radiation delivered during a rather long period of time after the Chernobyl accident.

So, in the assessment of the total collective irradiation dose one does not have even to take into consideration nuclides other than caesium isotopes and concentrate the efforts on accuracy of

Table 5. Half lives and conversion factors of radionuclides deposited in the areas affected by the Chernobyl accident [5].

Nuclide	Half life, $T_{1/2}$, days	Conversion* factor, $K_{i,g}$
²³⁹ Np	2.35	2.9
⁹⁹ Mo	2.73	5.1
¹³² Te	3.27	45.9
¹³¹ I	8.04	7.3
¹⁴⁰ Ba	12.6	41.5
¹⁴¹ Ce	32.5	1.2
¹⁰³ Ru	39	8.9
⁹⁵ Zr	64	28.3
^{110m} Ag	250	50.3
¹⁴⁴ Ce	284	0.8
¹⁰⁶ Ru	368	3.8
¹³⁴ Cs	755.6	29.1
¹²⁵ Sb	985.5	7.9
¹³⁷ Cs	11023	10.7

* Note: Conversion factors are given in units $\frac{mR/H}{Ci/km^2}$

Table 6. Parameters of nuclide vertical migration in soil.

Period of time, years	a_1 —	l_1 year ⁻¹	a_2 —	l_2 year ⁻¹
$0 \leq t \leq 1$ year	0.61	1.25	0.39	- 0.4
$0.5 \leq t \leq 16.5$ years	0.4407	0.18	0.4068	$2.75 \cdot 10^{-3}$
$16.5 \leq t \leq 100$ years	0.5345	0.18	0.4934	$1.375 \cdot 10^{-2}$

computational models and accuracy of data on contamination levels of caesium isotopes.

Only in case of the Northern sector of the “near zone” the contribution of nuclides other than caesium isotopes to the total exposition dose in air delivered over the 70 after the Chernobyl accident has reached about 25%.

It is well known, that radioactive contamination of the soil in the major part of the affected territories of Belarus, the Russian Federation and the Ukraine is similar to contamination in “caesium spots”.

This fact simplifies the assessment of collective irradiation doses of the affected population in Belarus, Russia and the Ukraine because it allows to use some uniform data that transform data on the initial surface contamination of the soil to external exposition doses. According to the data given in Table 1, the total exposition dose of external radiation in air at a reference height of 1 m delivered over the 70 years after the Chernobyl accident in an area with ¹³⁷Cs isotope contamination equal to 1 Ci/km² is about 1,700 mR.

The contribution of the ¹³⁷Cs isotope to the total exposition dose is about 1,311 mR or 77.4 percent within the 70 years period.

SETTLEMENTS ENVIRONMENT

It is clear that the data established for the areas with undisturbed soil can not be used for assessment of the collective irradiation doses delivered by external radiation because only a small fraction of population affected by the Chernobyl accident has a regular access to such areas.

For example it was established by the Ukrainian specialists [7] that children at the age of 7 years and under living in contaminated areas spend only 13 percent of the day outside the houses and other buildings. This means automatically that such children forming the most sensitive subpopulation to irradiation spend 87 percent of day inside the buildings and at least 87 percent of their time in settlements.

Children and teenagers at the age of 7-18 years according to the Ukrainian National Report [7] (see Table 4.1.3 on pages 4.18) spend about 18 percent of their time outside the buildings and this means about 82 percent inside the buildings.

The largest fraction of time outside the buildings spend pensioners. It reaches 36 percent of the day.

These data show that the inhabitants of contaminated areas spend about 20 percent of their time outside the buildings and 80 percent of time inside the buildings.

DOSE RATES AND DOSES IN

Table 7. Mean exposition dose rates in different areas of Bryansk oblast in autumn 1990 at a height of 1 m ($\mu\text{R/h}$) [24].

Settlement	Mean level of contamination, Ci/km ²	Street	Bench	Yard	Bed	Garden	House
Fedorovka	2.2	19	18	19	20	21	14
Glinnoe	5.2	27	23	27	28	28	15
Klintsy	5.9	20	19	19	21	22	14
Veliki Topol	7.1	28	28	27	30	32	16
Lopatni	8.1	32	30	31	34	34	17
Unoshevo	10.8	35	39	39	45	48	17
Lesnovka	15.9	54	51	49	61	73	26
Novo-zybkov	18.5	53	52	49	58	62	19
Gordeevka	21.6	50	65	67	79	84	25
Zlynka	28.4	106	85	90	87	100	25
Vyshkov	29.6	82	85	89	100	109	47
Mirnyi	32.6	58	65	78	109	113	22
Staryi Vyshkov	33.9	145	132	108	112	143	32

Table 8. Mean exposition dose rates outside and inside the buildings in contaminated areas of Bryansk oblast in autumn 1990 at a height of 1 m ($\mu\text{R/h}$).

Settlement	Mean level of contamination, Ci/km ²	Outside the building	Inside the building
Fedorovka	2.2	19.4	14
Glinnoe	5.2	26.6	15
Klintsy	5.9	20.2	14
Veliki Topol	7.1	29	16
Lopatni	8.1	32.2	17
Unoshevo	10.8	41.2	17
Lesnovka	15.9	57.6	26
Novozybkov	18.5	54.8	19
Gordeevka	21.6	69	25
Zlynka	28.4	93.6	25
Vyshkov	29.6	93	47
Mirnyi	32.6	84.6	22
Staryi Vyshkov	33.9	128	32

These values show that at least 80 percent of time the inhabitants of contaminated areas spend in settlements or areas with disturbed soil.

Therefore, use of the data calculated for areas with undisturbed soil for the assessment of the collective dose will cause a significant overestimation of the collective doses.

In order to avoid this mistake one needs to correct the equations (10) and (11) by introducing an additional correcting factor K_S , which is determined as a ratio of the exposition dose rate in air measured in settlements to the exposition dose rate in air over the undisturbed soil measured at the same level of radioactive contamination.

The equations (10) and (11) can be then rewritten as follows:

$$R_{\gamma}^*(t) = K_S \cdot K_L(t) \sum_{i=1}^n K_{i,\gamma} \cdot \sigma_i^0 \cdot \exp\left(-\frac{0.693}{T_{1/2}^i} \cdot t\right),$$

$$P_{\tau}^* = K_S \cdot \int_0^{\tau} K_L(t) \cdot \sum_{i=1}^n K_{i,\gamma} \cdot \sigma_i^0 \cdot \exp\left(-\frac{0.693}{T_{1/2}^i} \cdot t\right) dt \quad (13)$$

(14)

where:

R_{γ}^* = exposition dose rate at a reference height of 1 m in the settlements environment.

P_{τ}^* = exposition dose of external radiation in air at a reference height of 1 m in the settlements environment delivered over a period of time τ

We describe here a very simple method that allows to consider the differences in external radiation in settlements and in areas with the undisturbed soil. It is based on experimental data on exposition dose rates measured by specialists of the scientific organization "Typhoon" of the Goshydromet of the former USSR

[24].

Specialists of this organization have carried out extensive measurements of dose rates in autumn 1990 in different contaminated settlements of the Bryansk oblast.

They performed measurements of exposition dose rates in the streets, yards, on benches, over beds of kitchen gardens, in gardens and inside the houses as well. Dose rates measured in the course of this investigation and averaged for each studied settlement are given in Table 7.

On the basis of data given in columns 3-7 of Table 7 we can estimate the mean arithmetic dose rates

outside the buildings, $R_{\gamma}(t)_{out}$, by:

$$R_{\gamma}(t)_{out} = \frac{R_{\gamma}(t)_{str.} + R_{\gamma}(t)_{bn.} + R_{\gamma}(t)_y + R_{\gamma}(t)_b + R_{\gamma}(t)_g}{5} \quad (15)$$

where:

$R_{\gamma}(t)_{str.}$ = exposition dose rates measured in the streets,

$R_{\gamma}(t)_{bn.}$ = exposition dose rates measured at benches,

$R_{\gamma}(t)_y$ = exposition dose rates measured in yards,

$R_{\gamma}(t)_b$ = exposition dose rates measured over beds of kitchen gardens,

$R_{\gamma}(t)_g$ = exposition dose rates measured in gardens.

Values of $R_{\gamma}(t)_{out}$ determined this way are presented in the third column of Table 8. Here are also given the values of exposition dose rates measured by [24] inside the houses for comparison (see the fourth column of Table 8).

Values of $R_{\gamma}(t)_{out}$ as a function of effective contamination levels, A_{eff} , are also shown in Fig. 2.

Here A_{eff} is estimated by:

$$A_{eff} = \frac{1}{K_{\gamma}(^{137}Cs)} \cdot \sum_{i=1}^n K_{i,\gamma} \cdot A_i^0 \cdot \exp\left(-\frac{0.693}{T_{1/2}^i} t\right), \quad (16)$$

where:

$K_{\gamma}(^{137}Cs)$ = conversion factor of ^{137}Cs per unit deposition, $(\mu R/h)/(Ci/km^2)$,

A_i^0 = initial surface contamination of the soil by i th nuclide.

Figure 2 shows the existence of a strong dependence of $R_{\gamma}(t)_{out}$ from the effective contamination

levels A_{eff} that can be described on the basis of the linear function:

$$R_{\gamma}(t)_{out} = A + B \cdot A_{eff}, \quad (17)$$

where A and B are some constants.

They have a very easy meaning. As can be seen from

(17), at $A_{eff} \rightarrow 0$ $R_{\gamma}(t)_{out} \rightarrow A$. It means that A is the exposition dose rate on territory not contaminated by the Chernobyl accident or the exposition dose rate of the background radiation. The constant B in the equation (17) is the exposition dose rate in autumn 1990 per unit of the effective contamination A_{eff} , $(\mu R/h)/(Ci/km^2)$.

On the basis of the standard LSM procedure we have established the following values of A and B : $A=8.555 \mu R/hr$, $B=2.381 (\mu R/h)/(Ci/km^2)$.

Substitution of quantities A and B into the equation (18) transforms it to:

$$R_{\gamma}(t)_{out} = 8.555 + 2.381 \cdot A_{eff}, \quad (18)$$

where $R_{\gamma}(t)_{out}$ is expressed in $\mu R/h$.

The solid line in Fig. 2 was drawn on the basis of the equation (18).

We have performed the same procedure with the data on measured exposition dose rates established by [24] inside the houses of settlements of the Bryansk oblast (see column 8 of Table 7 or column 4 of Table 8).

For the exposition dose rates inside the buildings

$R_{\gamma}(t)_{in}$, we have established the following formula:

$$R_{\gamma}(t)_{in} = 11.814 + 0.505 \cdot A_{eff} \quad (19)$$

The solid line in Fig. 3 was calculated by means of the equation (19). One needs to notice much larger scattering of measured data from the solid line in Fig. 3 in comparison to Fig. 2.

This phenomenon has an easy explanation. Conditions of irradiation outside the houses and other buildings in different settlements of the Bryansk oblast do not differ very much. On the contrary - conditions of irradiation inside the houses and other buildings can differ very significantly. It is known that in rural settlement houses and other buildings are mostly constructed of wood that has much lower attenuation capability than brick or concrete used as a construction materials in urban settlements. Therefore, the exposition dose rates inside the urban buildings are lesser than in rural settlements even if the exposition dose rates outside the buildings are the same. This is a reason of much larger scattering of experimental points from solid line in Fig. 3 than in Fig. 2.

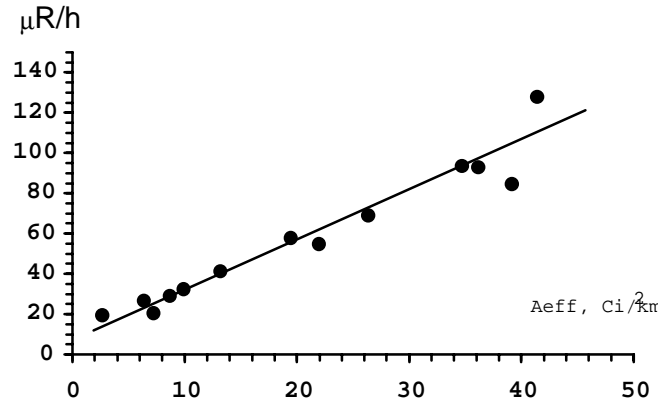


Fig. 2. Exposition gamma dose rates at a height of 1 m outside the buildings as a function of Aeff

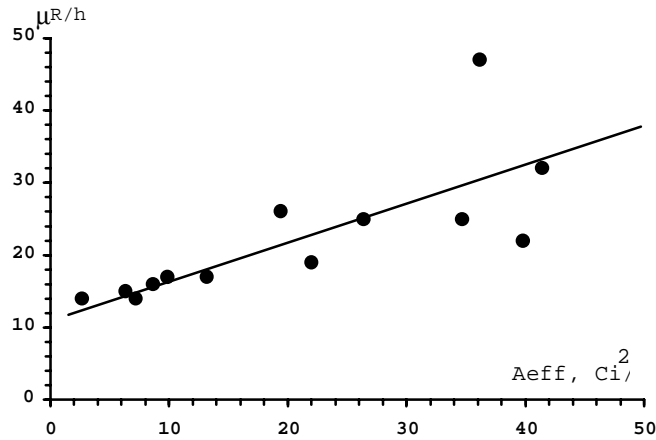


Fig. 3. Exposition gamma dose rates at a height of 1 m inside buildings as a function of Aeff

One needs to remember that the equations (18) and (19) can be used only for calculation of exposition dose rates outside and inside buildings in settlements environment in autumn 1990.

They can be transformed to such equations that will allow the assessment of the exposition dose rates at any arbitrary time t .

Let us rewrite the equation (16) in the following form:

$$A_{eff}(t) = \frac{A^0(^{137}Cs)}{K_{\gamma}(^{137}Cs)} \cdot F(t), \quad (20)$$

where:

$A^0(^{137}Cs)$ = initial surface contamination by the nuclide ^{137}Cs ,

$F(t)$ = some function of time.

This function is given by:

$$F(t) = \sum_{i=1}^n K_{i,\gamma} \cdot \sigma_i^0 \cdot \exp\left(-\frac{0.693}{T_{1/2}^i} \cdot t\right). \quad (21)$$

On the basis of the equation (20) one can estimate $F(t)$ as:

$$F(t) = \frac{K_{\gamma}(^{137}Cs)}{A^0(^{137}Cs)} \cdot A_{eff}(t). \quad (22)$$

Then the equation (13) can be rewritten as:

$$R_{\gamma}^*(t) = K_S \cdot K_L(t) \cdot \frac{K_{\gamma}(^{137}Cs)}{A^0(^{137}Cs)} \cdot A_{eff}(t). \quad (23)$$

The value of $R_{\gamma}^*(t)$ in 1990 $R_{\gamma}^*(90)$, can be calculated from the following formula:

$$R_{\gamma}^*(90) = K_S \cdot K_L(90) \cdot \frac{K_{\gamma}(^{137}Cs)}{A^0(^{137}Cs)} \cdot A_{eff}(90), \quad (24)$$

where:

$K_L(90)$ = numeric value of shielding factor originated from natural vertical migration of nuclides into the soil,

$A_{eff}(90)$ = effective contamination of the soil

in 1990.

On the other hand the equation (18) can be written as:

$$R_{\gamma}(90)_{out} = R_{\gamma bgr.} + R_{\gamma}(90)_{ch}, \quad (25)$$

where:

- $R_{\gamma}(90)_{out}$ = exposition dose rate outside the building in settlements environment in autumn 1990,
- $R_{\gamma bgr.}$ = exposition dose rate of background radiation; does not depend on time,
- $R_{\gamma}(90)_{ch}$ = contribution of Chernobyl nuclides to the exposition dose rate.

Comparison of the equations (18) and (25) gives:

$$R_{\gamma}(90)_{ch} = 2.381 \cdot A_{eff}(90) \quad (26)$$

Let us transform the last equation by dividing its left and right parts by $A^0(^{137}Cs)$:

$$\frac{R_{\gamma}(90)_{ch}}{A^0(^{137}Cs)} = 2.381 \frac{A_{eff}(90)}{A^0(^{137}Cs)}. \quad (27)$$

The left part of this the equation can be denoted as

$R_{\gamma}^*(90)_{ch}$. It is the exposition dose rate of external radiation normalized to the initial surface contamination by ^{137}Cs .

It is clear that:

$$R_{\gamma}^*(90)_{ch} = R_{\gamma}^*(90)_{ch}. \quad (28)$$

Combining the equations (24), (27) and (28) gives the following equation:

$$\begin{aligned} K_s \cdot K_L(90) \cdot \frac{K_{\gamma}(^{137}Cs)}{A^0(^{137}Cs)} \cdot A_{eff}(90) \\ = 2.381 \cdot \frac{A_{eff}(90)}{A^0(^{137}Cs)}. \end{aligned} \quad (29)$$

From here:

$$K_s \cdot K_L(90) \cdot K_{\gamma}(^{137}Cs) = 2.381. \quad (30)$$

The equation (30) can be rewritten as follows:

$$K_s = \frac{2.381}{K_L(90) \cdot K_{\gamma}(^{137}Cs)}. \quad (31)$$

Let us insert the correcting factor K_s determined by the equation (31) into the equation (23). After some changes this gives the following:

$$R_{\gamma}^*(t) = \frac{2.381}{K_L(90)} \cdot \frac{1}{A^0(^{137}Cs)} \cdot A_{eff}^*(t), \quad (32)$$

where $A_{eff}^*(t)$ is determined by:

$$A_{eff}^*(t) = K_L(t) \cdot A_{eff}(t). \quad (33)$$

Multiplication of the left and right parts of the equation (32) by $A^0(^{137}Cs)$ gives:

$$R(t)_{ch} = \frac{2.381}{K_L(90)} \cdot A_{eff}^*(t), \quad (34)$$

where:

- $R(t)_{ch}$ = exposition dose rate of external radiation at the time t at the initial surface contamination with ^{137}Cs originated from the Chernobyl accident equal to $A^0(^{137}Cs)$.

The numeric value of $K_L(90)$ can be estimated by means of the equation (12). It gives $K_L = 0.604$. Insertion of this value into the equation (34) transforms it into:

$$R(t)_{ch} = 3.944 \cdot A_{eff}^*(t), \quad (35)$$

where:

- 3.944 = exposition dose rate in air per unit of the effective contamination expressed in $(\mu R/h) / (Ci/km^2)$.

The total exposition dose rate outside the buildings expressed in $\mu R/h$ can be described by the following equation:

$$R(t)_{out} = 8.555 + 3.944 \cdot A_{eff}^*(t). \quad (36)$$

The same procedure allows to develop the equation for calculation exposition dose rates in air inside the buildings (expressed in $\mu R/h$):

$$R(t)_{ins} = 11.814 + 0.836 \cdot A_{eff}^*(t) \quad (37)$$

Here the numeric constant 11.814 in the part of the equation (37) determines the average exposition dose rate inside buildings, originated from the background radiation. The second member of the right part of this equation gives the contribution of the Chernobyl nuclides to the total exposition dose rate

inside buildings, $R(t)_{ch}$ (expressed in $\mu R/h$):

$$R(t)_{ch} = 0.836 \cdot A_{eff}^*(t). \quad (38)$$

There are some arguments allowing to state that the equations (35)-(38) can be used for the assessment of the collective doses not only in settlements of the Bryansk oblast but outside of this area. These arguments are discussed below.

Data on measurements of exposition dose rates in air outside and inside were measured by specialists of the "Typhoon" in settlements of the Bryansk oblast that borders the Gomel oblast. That allows the supposition that (35)-(38) are also valid for contaminated territories in the Gomel oblast.

One also needs to consider that the major part of the total deposition of radioactive species in the

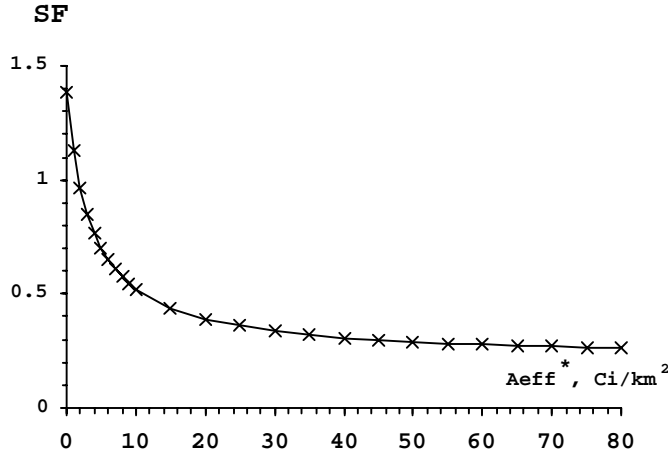


Fig. 4 Shielding factors as a function of contamination levels

former USSR lies in the Belarussian-Ukrainian Woodland with quite uniform geochemical characteristics. Moreover, urban and rural settlements in the affected areas of Belarus, Russia and the Ukraine are very similar as well as are the life-style and occupational activities of their inhabitants.

Our assumption on the similarity of irradiation of the Bryansk oblast inhabitants and inhabitants of other affected areas of the former USSR is also supported by the data on the natural radiation background in Belarus prior to the Chernobyl accident [25].

So according to the publication [25], the average exposure dose rate in air in 1981-1982 was 10.6 $\mu\text{R/h}$ in urban areas of Minsk, Borisov, Vitebsk, Soligorsk and 9 $\mu\text{R/h}$ in rural areas of Minsk rayon. These values very well agree with the dose rate of background radiation ($\sim 8.6 \mu\text{R/h}$) that we have estimated for the settlements environment in the Bryansk oblast.

An additional evidence of justified application of the equations (18), (19) and (35)-(38) for assessment of exposition dose rates and doses in the settlements environment outside of the Bryansk oblast gives also a very good agreement between the shielding factors of buildings SF, calculated on the basis of the equations (18), (19) or (36), (37) and estimated on the basis of experimental data.

The shielding factors of buildings are expressed as a ratio of the exposition dose rates inside and outside the buildings.

They can be calculated on the basis of the equations (18), (19) or (35)-(38).

Figure 4 shows the shielding factor estimated by the following equation:

$$SF = \frac{11.814 + 0.836 \cdot A_{eff}^*}{8.555 + 3.944 \cdot A_{eff}^*}. \quad (39)$$

As can be seen from Fig. 4 this factor decreases

with the increase of the A_{eff}^* . Its value changes from about 1.4 at $A_{eff}^* = 0$ (noncontaminated territory) to 0.4-0.3 in the interval of A_{eff}^* from 20 to 80 Ci/km^2 .

Table 9 demonstrates the data on the exposition dose rates in air outside of buildings that were calculated for different periods of time on the basis of the equation (35). Here are shown separately individual contributions of short-lived nuclides, isotopes of caesium as well as the total exposition dose rates. Data of Tables 1 and 3 have been also used by calculation of data given in Table 9.

On the basis of Table 9 we have calculated the air-absorbed doses inferred only by ^{137}Cs in settlements environment accumulated over different periods of time τ after the Chernobyl accident. Results of this calculation are presented in Table 10. There are also our estimates on the air-absorbed doses in areas of "caesium spots" with the undisturbed soil. They were calculated on the basis of data presented in Table 1 and 3 of our report.

We have also included in Table 10 the data estimated on the basis of data of Miller et al [27] and data used by J. Gofman [12] in his assessment of the Chernobyl consequences.

As it is known, J. Gofman [12] did not carry out a study for estimation of the air-absorbed doses inferred by the isotope ^{137}Cs . He had based his assessment on investigations conducted by H. Beck and G. de Planque [28] and recommendations of UNSCEAR [29].

Data in Table 10 shows that there is very good agreement between our values of air-absorbed doses estimated for areas with undisturbed soil and values of air-absorbed doses delivered in forest that we estimated on the basis of data [27]. Our doses calculated for areas with undisturbed soil as well very

good agree with data estimated on the basis of data used by J. Gofman [12]. On the other hand, our results for settlements environment fall into intervals formed by data of Miller et al [27] estimated for plowed lands with depth plowing of 15 and 30 cm respectively.

It is also necessary to notice that our air-absorbed doses estimated for settlements environment practically coincide with the arithmetic mean values calculated on the basis of data [27] estimated for different depth of plowing.

For example, air-absorbed doses that we have estimated by use of data of Miller et al [27] for the period of time $\tau=70$ years are 0.559 rad for the plowed land with depth plowing of 15 cm and 0.348 rad for depth plowing of 30 cm (see Table 10).

The arithmetic mean of these values is 0.453 rad. The last value is only about 7 percent higher than the value of air-absorbed dose that we have calculated for the settlements environment (0.425).

This agreement is surprising, especially, if one remembers that our estimations are based on experimental data of [24] established in areas of the Bryansk oblast affected by the Chernobyl accident and contaminated by ^{137}Cs to very high levels.

On the contrary, the data of K. Miller et al [27] have been established in course of experimental investigations of ^{137}Cs soil-penetration due to global fallout from atmospheric nuclear weapons tests. Moreover, these investigations have been carried out in the USA, which means in areas many thousand

kilometers away from the contaminated territories of the Bryansk oblast.

Taking into consideration all arguments given above one can conclude that our method of dose rates estimation and doses described in this part of our report gives quite correct data.

One can also agree with our statement that the assessment of the collective doses delivered to the population affected by the Chernobyl accident has to be based on results estimated for the settlements environment. The use of data established for undisturbed soil for this purpose will cause an overestimation of the collective dose at least by factor 3. Taking in account this conclusion we shall carry out our further calculation on the basis of data given in Table 9.

The value of the mean equivalent dose of external radiation normalized to the level of contamination by ^{137}Cs equal to 1 Ci/km² can be estimated by use of data from Table 9 on the basis of the equation:

$$H_{\tau \text{ ext}}^* = C_1 \cdot C_2 \cdot F_1 (F_2 + (1 - F_2) F_3) \cdot P_{\tau}, \quad (40)$$

where:

- C_1 = conversion factor from exposition dose to tissue-absorbed dose (rad/R),
- C_2 = conversion factor from tissue-absorbed dose to equivalent dose (rem/rad),
- F_1 = correction factor (considers different factor that can influence the exposition dose in air, for example snow cover, etc.),

Table 9. Exposition doses in air at a height of 1 m in “caesium spots”, accumulated during different periods of time after the Chernobyl accident (normalized to 1 Ci/km² of ^{137}Cs), in mR.

Periods of time, years	Short lived isotopes	^{134}Cs	^{137}Cs	All nuclides together
50	45.4	98.6	449	593
70	45.4	98.6	486.6	630.6
90	45.4	98.6	508.6	652.6

Table 10. Calculated doses of caesium-137 in air at a height of 1 m accumulated during different periods of time after deposition (given in rads) normalized to 1 Ci/km²

Place	Period of time, years				Source of information
	50	70	90	Infinite time	
Forest	1.195	1.365	1.495	—	Kevin M. Miller et al [27]
Undisturbed field	0.707	0.807	0.866	—	Kevin M. Miller et al [27]
Plowed land (to 15 cm depth)	0.481	0.559	0.625	—	Kevin M. Miller et al [27]
Plowed land (to 30 cm depth)	0.296	0.348	0.370	—	Kevin M. Miller et al [27]
Undisturbed field	1.058	1.145	1.193	—	M.Malko, this paper
Settlement, outside the buildings	0.392	0.425	0.444	—	M.Malko, this paper
Used for assessment of the Chernobyl consequences	1.15*	1.25**		1.44	J.Gofman [12]

Notice: * this value is evaluated by multiplication of the value 1.44 rad per km² by factor 0.80;
 ** this value is evaluated by multiplication of the value 1.15 rad per km² by factor 0.425/0.392.

- F_2 = occupancy factor (fraction of time spent outside the buildings, dimensionless),
 F_3 = shielding factor of buildings (dimensionless).
 P_τ = exposition dose in air (R).

By carrying out the calculations of $H_{\tau,ext}^*$ we used the following numeric values of these factors: $C_1=0.93$ rad/R; $C_2=0.72$ rem/rad; $F_1=1$; $F_2=0.2$ [20], $F_3=0.211$.

We estimated the value of factor F_3 by use of the equations (35) and (38). Therefore: F_3 is determined by the equation:

$$F_3 = \frac{0.836 \cdot A_{eff}^*}{3.944 \cdot A_{eff}^*} = \frac{0.836}{3.944} = 0,212 \quad (41)$$

As can be seen from the equation (41), the shielding factor of buildings F_3 does not depend on the effective contamination level A_{eff}^* . It means that F_3 is a uniform factor for all contaminated areas. The differences in shielding factors of buildings (39) and (41) arises from the fact, that the equation (39) determines the shielding effect of buildings from combined action of background radiation and Chernobyl nuclides. On the contrary, the equation (41) describes only the shielding effect against radiation caused by nuclides deposited on the ground as a result of the Chernobyl accident. As the task of our study is the assessment of the consequences of the Chernobyl accident we need to separate the influence of background radiation and radiation caused by the accident.

Insertion of the numeric values of the factors C_1 , C_2 , F_1 , F_2 and F_3 into the equation (40) results in the following formula:

$$\overline{H_{\tau,ext}^*} = 0.247 \cdot P_\tau. \quad (42)$$

The next step is estimation of the total mean equivalent dose $\overline{H_{\tau,ext}^*}$ normalized to the initial surface contamination by ^{137}Cs equal to 1 Ci/km^2 .

On analogy to the equation (3) one can write:

$$\overline{H_\tau^*} = \frac{\overline{H_{\tau,ext}^*}}{0.6}. \quad (43)$$

Combination of the two last equations gives:

$$\overline{H_\tau^*} = 0.412 \cdot P_\tau. \quad (44)$$

Application of the equation (44) to a 70 years period of time yields the following value of the normalized mean equivalent dose: $\overline{H_\tau^*} = 0.26 \text{ rem} / 1 \text{ Ci/km}^2$.

The last value was calculated by use of the value $P_\tau = 0.631 \cdot R$ given in Table 9.

SOURCE TERM

The total release of nuclides to the environment (source term) is an important parameter in any radiological accident because it determines the scale of this accident. Soon after the Chernobyl accident the Soviet specialists had suggested their data on the amounts of radionuclides that escaped from the destroyed Chernobyl reactor [19]. In this paper these data are presented in Table 11.

According to the estimations of the Soviet specialists about 100 MCi of different nuclides including 50 MCi of radioactive inert gases came into the environment over the 10 days after the first explosion at the reactor of the fourth unit of the Chernobyl NPP.

Later it was recognized that the data published in [19] were underestimated. For example, the UNSCEAR had shown in its report published in 1988 [20], that the total release of ^{137}Cs into the environment as a result of the Chernobyl accident had been in reality 2 times higher than claimed by the Soviet specialists.

According to the Ukrainian specialists [7] the total release of all radioactive isotopes during the accident at the Chernobyl NPP reached 10,813 PBq (about 296 MCi). This value is about factor 3 higher than the estimations of the specialists of the former USSR in 1986. The data of the Ukrainian specialists on the total release of nuclides from the Chernobyl reactor are presented in this paper in Table 12.

CAESIUM DEPOSITION IN BELARUS, RUSSIA AND THE UKRAINE.

Over the years that passed since the Chernobyl accident extensive measurements of contamination levels by ^{137}Cs have been undertaken in Belarus, Russia and the Ukraine. Results of these measurements allowed to establish the mean contamination levels by ^{137}Cs in many thousand settlements in these countries.

The total area of contaminated territories with initial levels of contamination by ^{137}Cs that change from some minimal value $A_{s,min}^0$ to some maximal value $A_{s,max}^0$ has also been determined.

As a rule 6 different intervals for characterizing of areas of contamination were established:

- 0.27-0.54 Ci/km² (10-20 kBq/m²);
- 0.54-1.0 Ci/km² (20-37 kBq/m²);
- 1-5 Ci/km² (37-185 kBq/m²);
- 5-15 Ci/km² (185-555 kBq/m²);
- 15-40 Ci/km² (555-1480 kBq/m²);
- and higher than 40 Ci/km² (> 1480 kBq/m²).

Table 11. Radionuclide composition of discharge from damaged unit of Chernobyl nuclear power plant* [19]

Nuclide***	Activity of discharge, MCi		Fraction of activity discharge from reactor on 6 May 1986, %
	25.04.86	06.05.86**	
¹³³ Xe	5	45	Possibly up to 100
^{85m} Kr	0.15	—	- “ -
⁸⁵ Kr	—	0.5	- “ -
¹³¹ I	4.5	7.3	20
¹³² Te	4	1.3	15
¹³⁴ Cs	0.15	0.5	10
¹³⁷ Cs	0.3	1	13
⁹⁹ Mo	0.45	3	2.3
⁹⁵ Zr	0.45	3.8	3.2
¹⁰³ Ru	0.6	3.2	2.9
¹⁰⁶ Ru	0.2	1.6	2.9
¹⁴⁰ Ba	0.5	4.3	5.6
¹⁴¹ Ce	0.4	2.8	2.3
¹⁴⁴ Ce	0.45	2.4	2.8
⁸⁹ Sr	0.25	2.2	4.0
⁹⁰ Sr	0.015	0.22	4.0
²³⁹ Np	2.7	1.2	3.2
²³⁸ Pu	0.1•10 ⁻³	0.8•10 ⁻³	3%
²³⁹ Pu	0.1•10 ⁻³	0.7•10 ⁻³	- “ -
²⁴⁰ Pu	0.2•10 ⁻³	1•10 ⁻³	- “ -
²⁴¹ Pu	0.02	0.14	- “ -
²⁴² Pu	0.3•10 ⁻⁶	2•10 ⁻⁶	- “ -
²⁴² Cm	3•10 ⁻³	2.1•10 ⁻²	- “ -

*) Error of estimate ± 50%

**) Total discharge up to 6 May 1986

***) The data presented relate to the activity of the main radionuclides measured on radiometric analyses

Table 12. Radionuclide composition in the active core before the accident and in the total discharge recalculated on 26.04.1986 [7].

Inventory of the active core before the accident (26.04.1986)			Total discharge recalculated on (26.04.1986)	
Nuclide	Half life	Activity (PBq)	Released fraction of inventory, %	Activity (PBq)
¹³³ Xe	5.3 d	6 500	100	6500
¹³¹ I	8.0 d	2 300	50-60	-1760
¹³⁴ Cs	2.0 a	180	20-40	-54
¹³⁷ Cs	30.0 a	280	20-40	-85
¹³² Te	78.0 h	2 700	25-60	-1150
⁸⁹ Sr	52.0 d	2 300	4-6	-115
⁹⁰ Sr	28.0 a	200	4-6	-10
¹⁴⁰ Ba	12.8 d	4 800	4-6	-240
⁹⁵ Zr	1.4 h	5 600	3.5	196
⁹⁹ Mo	67.0 h	4 800	> 3.5	> 168
¹⁰³ Ru	39.6 d	4 800	> 3.5	> 168
¹⁰⁶ Ru	1.0 a	2 100	> 3.5	> 73
¹⁴¹ Ce	33.0 d	5 600	3.5	196
¹⁴⁴ Ce	285.0 d	3 300	3.5	-116
²³⁹ Np	2.4 d	27 000	3.5	-95
²³⁸ Pu	86.0 a	1	3.5	0.035
²³⁹ Pu	24 400.0 a	0.85	3.5	0.03
²⁴⁰ Pu	6 580.0 a	1.2	3.5	0.042
²⁴¹ Pu	13.2 a	170	3.5	-6
²⁴² Cm	163.0 d	26	3.5	-0.9
Total		73559.05		-10933.007

Notice: The discharge activity recalculated on 6 May 1986 is about 2000 PBq

The data on the total area of contaminated territories of Belarus, Russia and the Ukraine characterized by these intervals of contamination levels by ^{137}Cs are presented in Tables 13-16.

The data given there allow to estimate the minimal amounts of ^{137}Cs deposited in Belarus, Russia and the Ukraine by means of the following equation:

$$Q_{\text{min}}^i = A_{s,\text{min}}^{0,i} \cdot S_i, \quad (45)$$

where:

Q_{min}^i = the minimal amounts of ^{137}Cs deposited on the area with the initial contamination by ^{137}Cs equal to $A_{s,\text{min}}^{0,i}$ (Ci);

S_i = the area of territories contaminated by ^{137}Cs at the level $A_{s,\text{min}}^{0,i}$ (km^2).

The results of our calculation on the basis of the equation (45) are given in Table 17. In case of Belarus this method gives $Q_{\text{min}}^i = 260,000$ Ci.

Division of this minimal deposition value of ^{137}Cs , Q_{min}^i by the total area of Belarus (207.6 thousand

square kilometers) gives the following minimal average contamination of the total territory of Belarus by ^{137}Cs :

$$A_{s,\text{min}} \approx 1.25 \text{ Ci} / \text{km}^2 \text{ or } 46.3 \text{ kBq} / \text{m}^2.$$

It is interesting to notice that the UNSCEAR performed its assessment of the collective irradiation doses originated from the Chernobyl accident by the average contamination of Belarus equal to 39 kBq/m^2 [20]. This value is about 20 percent lower than the value 46.3 kBq/m^2 which was calculated on the basis of the equation (45).

It is clear that the real average contamination of Belarus by ^{137}Cs has to be higher than 1.25 Ci/km^2 .

We have developed a simple method for estimation of more correct data on the total contamination of Belarus by ^{137}Cs .

The corrected amount of the deposited ^{137}Cs , Q_{tot} , as a result of the Chernobyl accident can be calculated by the following equation:

$$Q_0 = \sum_{i=1}^N \overline{A_{s,i}^0} \cdot \Delta S_i \quad (46)$$

Table 13. Contaminated areas in Belarus with the level of caesium-137 equal to 1 Ci/km^2 or higher (square kilometers) [31].

Oblast	Level of contamination, Ci/km^2			
	1-5	5-15	15-40	> 40
Brest	3800	470		
Vitebsk	35			
Gomel	16870	6740	2760	1625
Grodno	1690	12		
Minsk	2030	48		
Mogilev	5490	2900	1450	525
Total	29915	10170	4210	2150

Table 14. Contaminated areas in the Russian Federation with the level of caesium-137 equal to 1 Ci/km^2 or higher (square kilometers) [31].

Oblast	Level of contamination, Ci/km^2			
	1-5	5-15	15-40	> 40
Belgorod	1620			
Bryansk	6750	2628	2130	310
Voronezh	1320			
Kaluga	3500	1419		
Kursk	1220			
Lipetsk	1690			
Leningrad	850			
Nizhni Novgorod	15			
Orel	8840	132		
Penza	4130			
Ryazan	5210			
Saratov	150			
Smolensk	100			
Tambov	510			
Tula	10320	1271		
Uljanovsk	1060			
Total	48915	5450	2130	310

where:

N = number of all contaminated settlements;
 $\overline{A_{s,i}^0}$ = the average level of initial surface contamination by ^{137}Cs in i th settlement, (Ci/km^2);
 ΔS_i = area of the territory that belonged to i th settlement (km^2).

The equation (46) can be simplified in order to make the estimation of the value Q easier.

It is known that there is no significant difference in the population density in the affected regions of Belarus. The same conclusion can be made in relation to Russia as the Ukraine. It is also known that the majority of settlements in the affected regions have quite similar number of inhabitants.

Considering the abovementioned facts we can estimate the value of ΔS_i by:

$$\Delta S_i \approx \frac{S}{N}, \quad (47)$$

where:

S = the total area of all contaminated territories.

Combination of the equations (46) and (47) gives:

$$Q_0 \approx S \cdot \sum_{i=1}^N \frac{\overline{A_{s,i}^0}}{N} = S \cdot \overline{A_S^0}, \quad (48)$$

where:

$\overline{A_S^0}$ = contamination level by ^{137}Cs averaged over the total contaminated area (Ci/km^2).

As can be seen from the equation (48) the value of

$\overline{A_S^0}$ is determined by the equation:

$$\overline{A_S^0} = \sum_{i=1}^N \frac{\overline{A_{s,i}^0}}{N}. \quad (49)$$

The last equation was used for the calculation of the averaged levels for areas with the level of contamination $\overline{A_S^0} \geq 1 \text{ Ci}/\text{km}^2$. Results of the calculation performed on the basis of the experimental

data on $\overline{A_{s,i}^0}$ presented in the publication [32] are given in Table 18. There are also the averaged levels of contamination by ^{137}Cs at levels of contamination $\overline{A_S^0} \leq 1 \text{ Ci}/\text{km}^2$. In this case the following equation was used:

Table 15. Contaminated areas in the Ukraine with the level of caesium-137 contamination equal to 1 Ci/km^2 (square kilometers) [31].

Oblast	Level of contamination, Ci/km^2			
	1-5	5-15	15-40	> 40
Vinnitsy	1944	38		
Volyn	582			
Dnepropetrovsk	38			
Donetsk	410			
Zhitomir	9192	1780	336	154
Ivano-Frankovsk	606			
Kiev	7695	957	546	417
Kirovograd	219			
Nikolaev	24			
Odessa	27			
Rovno	9332	181		
Sumy	491			
Ternopol	357			
Cherkasy	3233	72		
Chernigov	2221	135		
Chernovtsy	500	14		
Kharkov	31.4	16		
Chmelnytsk	319			
Total	37205	3177	882	571

Table 16. Caesium-137 contaminated areas in Belarus, the Russian federation and the Ukraine with level 10-37 kBq/m^2 [6].

Countries	Area (in 1000 km^2) contaminated above specified levels	
	10-20	20-37
Belarus	60	30
Russia	300	100
Ukraine	150	65

Table 17. Minimal deposition of caesium-137 on territories of Belarus, the Russia Federation and the Ukraine

Range of contamination, Ci/km ²	Q, Ci		
	Belarus	Russia	Ukraine
0.27-0.54 (10-20 kBq/m ²)	16200	81000	40500
0.54-1 (20-37 kBq/m ²)	16200	54000	35100
1-5	29915	48915	37205
5-15	50850	27250	15885
15-40	63150	31950	13230
> 40	86000	12400	22840
Total deposition	262315	255515	164760
Rounded total deposition, Ci	260000	255000	165000

Table 18. Calculated average contamination levels in different affected areas of Belarus.

Range of contamination levels, Ci/km ²	Average contamination level, Ci/km ²
0.27-0.54 (10-20 kBq/m ²)	0.405
0.54-1.0 (20-37 kBq/m ²)	0.77
1-5	2.98
5-15	8.58
15-40	24.30
> 40	52.7

Table 19. Total deposition of caesium-137 on territories of Belarus, the Russian Federation and the Ukraine.

Range of contamination levels, Ci/km ²	Q, Ci		
	Belarus	Russia	Ukraine
0.27-0.54 (10-20 kBq/m ²)	24300	121622	60810
0.54-1 (20-37 kBq/m ²)	23100	77027	50066
1-5	89147	145767	110871
5-15	87259	46761	27259
15-40	102305	51759	21433
> 40	113305	16337	30092
Total deposition, Ci	439414	459273	300531
Rounded total deposition, Ci	440000	460000	300000

$$\overline{A_s^0} = \frac{A_{s,\min}^0 + A_{s,\max}^0}{2} \quad (50)$$

By use of the data given in Tables 13-16 and 18 data on the initial contamination of the affected areas in Belarus, Russia and the Ukraine were calculated. Table 19 shows the results of this calculation. The data given in Tables 17 and 19 show that the described method of calculation has given increased amounts of deposited ¹³⁷Cs in Belarus, Russia and the Ukraine by factor 1.7 (Belarus) -1.8 (Russia, Ukraine) estimations made on the basis of the equation (45).

One needs to notice that the amount of ¹³⁷Cs deposited in the Ukraine which is shown in Table 19 does not include big amounts of this isotope in the 30 kilometer zone. According to the Ukrainian National Report [7] there is about 470 thousand Ci of ¹³⁷Cs in temporary storages of radioactive materials, in the soil, in hydrosystems, etc.

By taking into account this value and the data on the deposition of ¹³⁷Cs in Belarus, Russia and the Ukraine

given in Table 19 as well as the data on the deposition of this isotope outside of the former USSR (1.2 MCi [20]) one can assess the approximate amounts of ¹³⁷Cs that was discharged from the destroyed Chernobyl reactor. It reaches 2.87 MCi. Summing up this number with the amounts of ¹³⁷Cs deposited in the Baltic States and Countries of the CIS other than Russia, Belarus and the Ukraine one can assess the total discharge of ¹³⁷Cs to the environment as a result of the Chernobyl accident equal to about 3 MCi of the core inventory of this nuclide before the accident. The last figure coincides with upper limit of the estimations given in publication [7].

COLLECTIVE DOSE ASSESSMENT

As it was shown earlier, the collective irradiation dose can be calculated by means of the equation (1). It is possible to use for this purpose the equation:

$$H_{\tau}^{\text{coll}} = N \cdot H_{\tau}^* \cdot \overline{A_s^0} \quad (51)$$

Insertion of the value A_S given by (6) into the equation (51) gives the following:

$$H_{\tau}^{\text{coll}} = N \cdot \overline{H_{\tau}^*} \cdot \frac{Q^0}{S} \quad (52)$$

The total number of the inhabitants of the affected areas N can be estimated by the following:

$$N = \overline{\rho} \cdot S, \quad (53)$$

where:

$\overline{\rho}$ = the average population density in contaminated areas (man/km²).

The combination of equations (52) and (53) gives:

$$H_{\tau}^{\text{coll}} = \overline{\rho} \cdot H_{\tau}^* \cdot Q^0 \quad (54)$$

Results of the collective equivalent doses calculation that can be delivered to affected population of Belarus, Russia and the Ukraine within the period of 70 years after the Chernobyl accident are obtained on the basis of the equation (54) and are given in Table 20. This table also contains data on the total deposition of the isotope ¹³⁷Cs in Belarus, Russia and the Ukraine, the total areas of contaminated territories of these states as well as the data on the mean contamination levels, mean population density and mean dose delivered over 70 years on a territory with the contamination level by ¹³⁷Cs equal to 1 Ci/km².

The data on population density presented in Table 20 were calculated for 1986 on the basis of data of the statistical handbook of the USSR [33]. Analysis of data given in Table 20 shows that the highest equivalent irradiation dose has to be delivered to the Ukrainian population. It can be estimated as $6.6 \cdot 10^4$ man·Sv over 70 years. The collective equivalent irradiation doses of inhabitants of the affected areas of Belarus and Russia according to our estimation are $5.5 \cdot 10^4$ and $4.4 \cdot 10^4$ man·Sv respectively. At the same time the highest mean individual equivalent dose can be delivered to inhabitants of the contaminated territories of Belarus. It is practically 3 times higher than the respective values estimated for

Russia and the Ukraine.

ASSESSMENT OF COLLECTIVE THYROID DOSES

The assessment of collective thyroid doses delivered to the population of Belarus, Russia and the Ukraine can be performed on the basis of the data established in the course of extensive studies by V. Stepanenko, A. Tsyb, Yu. Gavrilin et al. [34].

By use of the experimental data on [31] accumulation in thyroid measured within the first days after the nuclear explosion at the Chernobyl accident these Russian specialists estimated the collective thyroid dose of 3,674,000 residents of contaminated territories of 7 oblasts of Russia (Bryansk, Tula, Kaluga, Orel, Riasan, Kursk, Leningrad) as 234,000 person·Gy. [34]. This value can be used for the estimation of the factor q_{th} that determines the collective thyroid dose commitment per unit deposition of ¹³¹I.

In order to fulfill this task one needs to determine the total deposition of ¹³¹I in “7 oblasts” of the Russian Federation. It can be done by means of the equation:

$$Q_7^0(^{131}I) = \psi \cdot Q_7^0, \quad (55)$$

where:

$Q_7^0(^{131}I)$ = total deposition of ¹³¹I in 7 oblasts of Russia,

Q_7^0 = total deposition of ¹³⁷Cs in 7 oblasts of Russia,

ψ = correlation factor averaged over the total area of contaminated territories of “7 oblasts” expressed as a ratio of surface contamination level by ¹³¹I to surface contamination by ¹³⁷Cs

Experimental values of the factor ψ at 23.05.1986 measured in different settlements of Belarus and Russia [35] are given in Table 21 of this report.

Table 22 shows the values of the factor ψ recalculated to 26.04.1986. On the basis of these values we have estimated the mean values of factor ψ

Table 20. Collective equivalent irradiation doses of populations of Belarus, the Russian Federation and the Ukraine.

Parameter	Belarus	Russia	Ukraine
Total deposition of caesium-137, Ci	440000	460000	300000
Total area of contaminated territories with level of caesium-137 ≥ 0.27 Ci/km ² (10 KBq/m ²), in km ²	136445	348915	256835
Mean contamination level, Ci/ km ²	3.225	1.318	1.168
Mean dose equivalent commitment during 70 years after the accident (normalized to 1 Ci/ km ²), rem	0.26	0.26	0.26
Mean population density, person/km ²	48.2	36.6	84.5
Total number of people living in contaminated areas	6576649	12770289	21702558
Collective dose, manrem	5514520	4376123	6590633
Collective dose in man Sv, rounded	$5.5 \cdot 10^4$	$4.4 \cdot 10^4$	$6.6 \cdot 10^4$
Mean individual dose, rem	0.84	0.26	0.30

Table 21. Ratios of nuclide activities to Cs-137 activity in soil of different contaminated areas of Belarus and the Russian Federation by 23.05.1986 [35].

Settlement	¹³¹ I	¹⁰³ Ru	¹³⁴ Cs	⁹⁵ Zr + ⁹⁵ Nb	¹⁴⁰ La + ¹⁴⁰ Ba	⁹⁰ Sr
Belarus						
Gomel	3.48	1.74	0.42	4.54	1.97	0.17
Mozyr	1.16	1.0	0.39	1.06	1.06	0.13
Pinsk	5.68	1.98	0.58	2.28	1.0	—
Zhitkovichi	1.78	3.89	0.53	2.22	1.67	—
Khoyniki	1.62	3.49	0.56	11.2	4.6	0.07
Jurovichi	1.47	2.50	0.43	6.47	2.21	0.06
Russia, Bryansk oblast						
Barsuki	0.64	0.86	0.54	0.13	0.30	0.11
Makarichi	0.74	0.93	0.4	0.08	0.39	—
Novozybkov	0.88	0.85	0.46	0.07	0.38	—
Nikolaevka	0.82	0.83	0.55	0.09	0.36	0.008
Berezovka	2.05	1.58	0.55	0.14	0.34	0.008
Svjatsk	1.17	1.11	0.56	0.13	0.31	0.03
Bartolomeevka	0.68	1.0	0.63	0.14	0.06	0.04
Russia, Kaluga oblast						
Zhisdra	0.91	1.0	0.52	0.03	0.25	—
Mileevo	0.95	0.85	0.53	0.1	0.37	—
Kolodjassy	0.95	1.01	0.56	0.07	0.31	—
Russia, Tula oblast						
Belev	1.03	1.34	0.54	0.06	0.23	—
Plavsk	0.55	0.69	0.53	0.06	0.45	—
Dubovka	0.63	1.02	0.54	0.14	0.14	—
Uzlovaja	1.26	2.55	0.45	0.05	0.26	—

Table 22. Calculated values of I-131/Cs-137 activity ratio in contaminated areas of Belarus and the Russian Federation by 26.04.1986.

Settlement	I-131 Cs-137 (23.05.86)	I-131 Cs-137 (26.04.86)
Belarus		
Gomel	3.48	38.9
Mozyr	1.16	12.96
Pinsk	5.68	63.45
Zhitkovichi	1.78	19.9
Khoyniki	1.62	18.1
Jurovichi	1.47	16.4
Russia, Bryansk oblast		
Barsuki	0.64	7.15
Makarichi	0.74	8.27
Novozybkov	0.88	9.83
Nikolaevka	0.82	9.16
Berezovka	2.05	22.9
Svjatsk	1.17	13.1
Bartolomeevka	0.68	7.60
Russia, Kaluga oblast		
Zhisdra	0.91	10.2
Mileevo	0.95	10.6
Kolodjassy	0.95	10.6
Russia, Tula oblast		
Belev	1.03	11.7
Plavsk	0.55	6.14
Dubovka	0.63	7.04
Uzlovaja	1.26	14.1

for Russia and Belarus as 10 and 20 respectively.

By use of factor $\psi=10$ and the data given in Tables 14 and 18 we have calculated the total deposition of

¹³¹I in “7 oblasts” of Russia as 2.24 MCi. By estimation of this value we did not take into consideration the contaminated territories in “7

Table 23. Collective thyroid dose of the affected populations in Belarus, the Russian Federation and the Ukraine.

Parameter	Belarus	Russia	Ukraine
Total deposition, Ci	8800000	4600000	6000000
Total area of contaminated territories, km ²	136445	456805	256835
Mean population density, person/km ²	48.2	36.6	84.5
Collective thyroid dose equivalent commitment per unit release, man.Sv/Bq	3.90·10 ⁻¹²	2.95·10 ⁻¹²	6.80·10 ⁻¹²
Thyroid collective dose, man.Sv	12.7·10 ⁵	5.0·10 ⁵	15.0·10 ⁵
Collective effective dose equivalent resulted from thyroid irradiation, man.Sv	6.35·10 ⁴	2.5·10 ⁴	7.5·10 ⁴
Mean individual dose of thyroid irradiation, rem	19.3	3.0	6.9

Table 24. Contributions of different nuclides to collective effective equivalent doses of irradiation during the period of 70 years after the Chernobyl accident.

Nuclide	Belarus	Russia	Ukraine
Short lived isotopes other than ¹³¹ I, man.Sv	0.4·10 ⁴	0.38·10 ⁴	0.48·10 ⁴
¹³⁴ Cs, man.Sv	0.86·10 ⁴	0.68·10 ⁴	1.03·10 ⁴
¹³⁷ Cs, man.Sv	4.24·10 ⁴	3.34·10 ⁴	5.09·10 ⁴
¹³¹ I, man.Sv	6.35·10 ⁴	2.5·10 ⁴	7.5·10 ⁴
Total collective effective equivalent dose, man.Sv	11.85·10 ⁴	6.9·10 ⁴	14.1·10 ⁴

*) Notice: these values were estimated by multiplication of collective thyroid doses by organ weighting factor 0.05 [36].

Table 25. Collective effective dose equivalent commitments per unit release of caesium and iodine nuclides.

Country, organization	Period of time, years	¹³⁴ Cs	¹³⁷ Cs	¹³¹ I
		man.Sv		
Belarus	50	1.06·10 ⁻¹²	2.42·10 ⁻¹²	1.95·10 ⁻¹³
	70	1.06·10 ⁻¹²	2.61·10 ⁻¹²	1.95·10 ⁻¹³
Russia	50	8.04·10 ⁻¹³	1.82·10 ⁻¹²	1.47·10 ⁻¹³
	70	8.04·10 ⁻¹³	1.96·10 ⁻¹²	1.47·10 ⁻¹³
Ukraine	50	1.86·10 ⁻¹²	4.23·10 ⁻¹²	3.38·10 ⁻¹³
	70	1.86·10 ⁻¹²	4.59·10 ⁻¹²	3.38·10 ⁻¹³
UNSCEAR, 1988	50	3·10 ⁻¹²	6·10 ⁻¹²	1·10 ⁻¹³

oblasts” of Russia with the contamination levels by ¹³⁷Cs less than 1 Ci/km².

Division of the collective thyroid dose established by V. Stepanenko, A. Tsyb, Yu. Gavrilin et al [34] for the residents of “7 oblasts” by the assessed deposition of ¹³¹I one can obtain the value of q_{th} factor equal to 2.82·10⁻¹²·Gy/Bq or approximately 2.82·10⁻¹²·Sv/Bq.

In order to emphasize the fact that the numerical values of q_{th} given above have been estimated on the basis of the data established by [34] for residents of “7 oblasts” we shall describe it as q_{th,7}.

Multiplication of q_{th,7} by the thyroid weighting factor 0.05 [36] converts it to the collective effective dose equivalent commitment per unit release of ¹³¹I equal to 1.41·10⁻¹³ man.Sv/Bq. The last value only insignificantly differs from the collective effective dose equivalent commitment per unit release of ¹³¹I estimated in 1988 by UNSCEAR in its assessment of the Chernobyl accident consequences. This surprising agreement is a very important evidence of sound scientific backgrounds of the methods used by

UNSCEAR [20] and by V. Stepanenko, A. Tsyb, Yu. Gavrilin et al in estimation of collective thyroid doses resulted from the Chernobyl accident. It also states that the numeric value of q_{th,7} = 2.82·10⁻¹² man.Sv/Bq can be used as the reference value of this factor. It is necessary to notice that the factor q_{th,7} is a function of population density. Therefore, one needs to correct the numeric value of q_{th,7} in case of population density ρ that differs from the average population density in “7 oblasts” of the Russian Federation. It can be made by means of the following equation:

$$q_{th} = q_{th,7} \cdot \frac{\rho}{\rho_7}, \quad (56)$$

where:

q_{th} = the collective thyroid dose commitment per unit of ¹³¹I deposition (man.Sv/Bq) by arbitrary population density,

q_{th,7} = the collective thyroid dose commitment per unit of ¹³¹I deposition (man.Sv/Bq) established on the basis of “7 oblasts” data,

- ρ = population density in contaminated area (persons per km²),
 ρ_7 = population density in contaminated areas of "7 oblasts" of the Russian Federation.

Table 23 presents the data on the collective thyroid doses estimated for population of Belarus, Russia and the Ukraine by means of factor q_{th} calculated on the basis of the equation (56).

These data can be possibly considered as upper limits of collective thyroid doses delivered to the populations of Belarus, Russia and Ukraine.

The total amounts of ¹³¹I deposited in these countries were calculated by means of the data on ¹³⁷Cs deposition presented in Table 19 as well as the following numeric values of factor ψ : 10 for Russia and 20 for Belarus and the Ukraine.

As can be concluded from the above-discussed facts, the correctness of the collective thyroid dose estimations is fully determined by the correctness of ¹³¹I depositions. This means that each improvement in the estimation of the total amounts of ¹³¹I deposited in areas affected by the Chernobyl accident will improve estimation of the collective thyroid doses.

The results of our estimations given in Table 23 show that the highest collective thyroid dose was delivered to the Ukrainian population and the lowest to the population of Russia. On the contrary, as can be seen from Table 23, the highest mean individual thyroid dose was estimated for the residents of the contaminated territories of Belarus. It is higher by factor 6.4 than the mean individual thyroid dose in Russia and by factor 2.8 than the mean individual thyroid dose in the Ukraine.

Table 23 as well contains the data on the collective effective dose equivalents resulted from irradiation of people by ¹³¹I in Belarus, Russia and the Ukraine. Table 24 shows the individual contributions of different isotopes to the total collective effective equivalent doses calculated on the basis of data given in the tables 20 and 23. The collective effective dose equivalent commitments per unit release of caesium and iodine nuclides are shown in Table 25.

LIFETIME MORTALITY RISK FROM SOLID CANCERS AND LEUKEMIA

The latest estimations of the risk coefficient of radiation induced solid cancers and leukemia are shown in the Table 26. In our prognosis of delayed radiological effects we have used the data of the UNSCEAR 94 [37] that are 2-fold less than the data estimated in 1994 by J. Gofman [38].

We preferred the UNSCEAR 1994 risk coefficient of radiation-induced solid cancers due to the following reason. It is well known that the risk coefficient of solid cancers induced by radiation is proportional to the frequency of spontaneous cancers which is a function of the life expectancy. J. Gofman

[38] had obtained his value on the basis of the Vital Tables of the USA population. However, the life expectancy of the American population is 10-15 years higher than the life expectancy in Belarus, Russia and the Ukraine [33, 39].

So, even in case the UNSCEAR will in future increase its estimations of the risk coefficient of radiation-induced solid cancers one needs to remember that estimations of the UNSCEAR are based on the data established for the atomic bomb survivors that have been living in a country with a very high life expectancy in comparison to the life expectancy of the people in Belarus, Russia and the Ukraine. One also needs to remember that in contrast to the USA, Japan and other developed countries characterized by a permanent increase of life expectancy, Belarus, Russia and the Ukraine have a permanent decrease of life expectancy.

PROGNOSIS OF STOCHASTIC EFFECTS

The estimations of the possible stochastic effects in the effected areas of Belarus, Russia and the Ukraine are given in Table 27. The data on morbidity and mortality from radiation-induced thyroid cancers were calculated by use of the data on the collective thyroid doses presented in Table 23 and the risk coefficients $160 \cdot 10^{-4} \text{Sv}^{-1}$ and $16 \cdot 10^{-4} \text{Sv}^{-1}$, respectively. The latter coefficients were estimated by the following method. According to the data given in the Table B-17 of ICRP Publication 60 [36] (see p.132 of Publication 60) the risk coefficient of fatal thyroid cancer for low dose, low dose rate and Low LET radiation (DDREF is equal 2) is $8 \cdot 10^{-4} \text{Sv}^{-1}$. For the case of an acute or quasi-acute irradiation (Chernobyl case) one needs to use as a risk coefficient of fatal thyroid cancer a value 2 fold higher or $16 \cdot 10^{-4} \text{Sv}^{-1}$ (DDREF=1). From here one can receive the lifetime morbidity risk coefficient $160 \cdot 10^{-4} \text{Sv}^{-1}$ as used for calculation of data shown in Table 27.

The data on mortality from solid cancers other than thyroid cancer were used on the basis of the risk coefficient from solid cancers estimated in 1994 by the UNSCEAR and "corrected" for fatal thyroid cancers. The "correction" was in reality a subtraction of the value $16 \cdot 10^{-4} \text{Sv}^{-1}$ from the value $1,090 \cdot 10^{-4} \text{Sv}^{-1}$ estimated by the UNSCEAR. One can receive on this simplified way the value $1,074 \cdot 10^{-4} \text{Sv}^{-1}$ as a risk coefficient for fatal solid cancers other than thyroid cancers. Such "corrected" risk coefficient was used in assessment of fatal cancers in Belarus, Russia and the Ukraine resulted from the Chernobyl accident.

By the calculation of leukaemia mortality we used the value $110 \cdot 10^{-4} \text{Sv}^{-1}$ determined by the UNSCEAR in 1994 [37].

According to our estimations the Chernobyl accident will cause about 20,000 additional thyroid cancers among children and adults of the affected areas of Belarus. About 10 per cent of this number can be fatal (2,000 fatal thyroid cancers). We have estimated the number of radiation-induced thyroid cancers in Russia as 8,000 (800 fatal thyroid cancers). For the Ukraine we predicted 24,000 additional thyroid cancers (2,400 fatal thyroid cancers). Considering our method of collective thyroid doses assessment one can believe that these data on the number of additional thyroid cancers are upper limits of possible thyroid cancers.

As can be seen from this Table, the numbers of additional fatal thyroid cancers in each state is similar to the numbers of additional leukaemia and about 10 times less than the numbers of additional fatal solid cancers other than thyroid cancer.

We have assessed the total number of radiation-induced fatal cancers and leukaemia in

Belarus, Russia and the Ukraine, as a result of the Chernobyl accident as about 44,000 with 16,030 cases in Belarus, 8,960 in Russia and 19,050 in the Ukraine.

As it was said above we have carried out our assessment only for populations living in the contaminated areas of these countries. We have estimated the total deposition of ¹³⁷Cs in these areas as 1.2 MCi (total deposition of ¹³⁴Cs about 0.6 MCi). The same amount of ¹³⁷Cs deposited in the countries outside the former USSR. If we assume that the number of radiation-induced cancers and leukaemia outside the former USSR caused by the Chernobyl accident will be the same as the total number of solid cancers and leukaemia in Belarus, Russia and the Ukraine because of similar deposition of ¹³⁷Cs, we will also obtain about 44,000 additional cancers and leukaemia for the countries outside the former USSR and about 90,000 fatal cancers for all the countries of the world including the former USSR. This assumption means that the Chernobyl accident will

Table 26. Lifetime solid cancers and leukemia mortality risk following acute whole body exposure to 1 Sv.

Projection method	Lifetime risk, %	Data source
Solid cancers		
Constant relative risk	10.9	[37]
Decline to risk for age at exposure 50 years	9.2	[37]
Decline to zero risk at age 90 years	7.5	[37]
Constant relative risk (UNSCEAR 1988)	9.7	[20]
Whole body Cancer Dose (J. Gofman - 1981)	37.31	[12]
Whole body Cancer Dose (J. Gofman - 1990)	26.64*	[18]
	25.56**	[18]
Whole Body Cancer Dose (J. Gofman - 1994)	23.37*	[38]
	22.35**	[38]
Leukemia		
Linear-quadratic dose response model	1.1	[37]
Constant relative risk (UNSCEAR 1988)	1.0	[20]

Notice: *) values determined by using T65DR dosimetric data of the RERF
 **) values determined by using DS86 dosimetric data of the RERF

Table 27. Forecast of stochastic effects in Belarus, the Russian Federation, and the Ukraine as a result of the Chernobyl accident (DDREF = 1).

Effect	Belarus	Russia	Ukraine
Thyroid cancer (morbidity)	20300	8000	24000
Thyroid cancer (mortality)	2030	800	2400
Leukemia (mortality)	1300	760	1550
Solid cancers other than thyroid cancer (mortality)	12700	7400	15100
All cancers and leukemia (mortality)	16030	8960	19050

Table 28. Forecast of stochastic effects in Belarus, the Russian Federation, and the Ukraine as a result of the Chernobyl accident (DDREF = 2).

Effect	Belarus	Russia	Ukraine
Thyroid cancer (morbidity)	10150	4000	12000
Thyroid cancer (mortality)	1010	400	1200
Leukemia (mortality)	650	380	775
Solid cancers other than thyroid cancer (mortality)	6350	3700	7550
All cancers and leukemia (mortality)	8010	4480	9525

cause in the affected countries the number of fatal cancers and leukaemia which is similar to the death numbers resulted from atomic bombardment of Hiroshima or Nagasaki.

One may also assume that the total number of potential victims in case of such accident in a country with very high life expectancy and high population density, for example in Japan, will be much higher as in the case of the Chernobyl accident.

The data discussed above have been estimated by use of the factor $DDREF=1$, which is recommended by the ICRP for the case of acute irradiation by high doses and dose rates [36]. For chronic irradiation of the population by low doses the ICRP recommends the value of the reduction factor $DDREFF$ equal to 2.

In the light of new data [37, 40, 41] it seems that even in cases of low doses and dose rates this factor is very close to 1 for solid cancers. But for leukaemia the $DDREF$ factor is about 2.5 or even higher [37, 41]. For comparison only we have also carried out the estimations of additional stochastic effects assuming that $DDREF=2$. The results of such estimation are presented in Table 28.

We understand that the results of our assessment have rather qualitative than quantitative character because of many limitations in our study. For example we did not consider the possible interaction of radiation and chemical contamination in the affected areas of Belarus, Russia, and the Ukraine. This can be a reason for the very significant difference in predicted and manifested stochastic effects among the people affected by the Chernobyl accident. However, at present, there is no such quantitative information that could be used in assessment of radiological consequences of this accident in the areas having a very strong chemical contamination. Because of a lack of necessary information we also did not consider deterministic effects that could be even more important as radiological consequences in comparison with stochastic effects as well as genetic effects and effects of a very strong increase in the incidence of general somatic diseases in the affected areas established by Belorussian, Russian and the Ukrainian specialists soon after the accident. At the same time we believe that our data are quite accurate for solving of some problems that arose due to the Chernobyl accident. It is well known, that the reliable data on the increase of the morbidity on thyroid cancer among children of the affected areas of Belarus were established already at the end of the 80's [42,43]. Now, practically all specialists in the field of radiation biology and medicine recognise that this increase is the result of the Chernobyl accident [44]. However, at the end of 80's no such increase in the morbidity on thyroid cancer was established in Russia or in the Ukraine. This fact was considered by specialists of many countries as an evidence of incorrectly assessed

data.

The difference in the change of the morbidity on thyroid cancer can be explained very easy on the basis of the data shown in Table 23. As it was said earlier, the highest mean individual thyroid doses were delivered by the Chernobyl accident to the residents of the affected areas of Belarus and the lowest to the Russian population. It is known that the latent periods of stochastic effects induced by the radiation depend from the irradiation doses. The lower the irradiation dose is, the longer is the latent period. This is an explanation why marked increase in the thyroid cancer incidence was registered first in Belarus and then in the Ukraine and later in Russia.

Our data can also answer the question why there are no reliable data on additional leukaemia among the residents of the affected areas of Belarus, Russia and the Ukraine up to present time [45-47]. This contrasts the data established among the Hiroshima and Nagasaki inhabitants that survived the atomic bombardment. Additional cases of leukaemia among them were registered firstly, and only then the radiation-induced solid cancer.

We suggest the following explanation for these differences in the manifestation of stochastic effects among the irradiated populations of Belarus, Russia, the Ukraine and the residents of Hiroshima and Nagasaki.

The survivors of the atomic bombardment of these Japanese cities received practically the same doses on bone marrow (the whole body dose) and on thyroid. The more earlier manifestation of leukaemia than thyroid cancers by inhabitants of Hiroshima and Nagasaki indicates that the latent period of leukaemia is shorter than the latent period of thyroid cancers when doses on bone marrow and thyroid are equal. Another situation arises in the case when thyroid doses are much higher than doses on bone marrow. Such situation has place by the people affected by the Chernobyl accident. Tables 20 and 23 demonstrate clearly that thyroid doses among the affected populations of Belarus, Russia and the Ukraine are practically one order in magnitude higher than doses on the whole body. This is according to our point view the reason of earlier manifestation of solid cancer (thyroid cancer) than leukaemia in Belarus, Russia and the Ukraine.

SUMMARY

An assessment of radiological consequences (stochastic effects) caused by the Chernobyl accident in Belarus, Russia and the Ukraine on the basis of experimental data on ^{131}I and ^{137}Cs in these countries has been carried out.

Results of this assessment show that the Chernobyl accident can be considered a real disaster. It can cause about 44,000 additional fatal cancers and leukaemia

among the affected populations of Belarus, Russia and the Ukraine.

On the basis of the data established in the course of this study explanations of some contradictions in manifestation of stochastic effects as a result of the Chernobyl accident have been suggested.

Acknowledgement

Fruitful discussion of this work with T. Imanaka and H. Koide as well as financial support from the Toyota Foundation are gratefully acknowledged.

REFERENCES

1. T. Imanaka, H. Koide. Radiocesium Concentration in Milk after the Chernobyl Accident in Japan. *J. Radioanal. Nucl. Chem. Letters*, v. 145, N 2, p. 151-157, 1990.
2. Takeo Hasizume. Fallout in Kyushu from the Accident of Chernobyl Nuclear Plant (Part I). *Rep. Fac. Sci., Kagoshima Univ. (Math. Phys. & Chem.)*, N20, p.63-69, 1987.
3. Takeo Hasizume. Fallout in Kyushu from the Accident of Chernobyl Nuclear Plant (Part II). *Rep. Fac. Sci., Kagoshima Univ. (Math. Phys. & Chem.)*, N 22, p. 135-139, 1989.
4. The Chernobyl Catastrophe Consequences in the Republic Belarus. National Report. Ministry for Emergencies and Population Protection from the Chernobyl NPP Catastrophe Consequences, Republic of Belarus. Academy of Sciences of Republic of Belarus. Edited by E.F. Konoplya and I.V. Ralevich. Minsk, 1996.
5. Chernobyl: Radioactive Contamination of Natural Environments. Edited by Y.A. Izrael. Leningrad. Hydrometeoizdat. 1990 (in Russian).
6. Atlas on Caesium Contamination of Europe after the Chernobyl Nuclear Plant Accident. Final Report of the Joint Study Project N 6 of the International Scientific Collaboration on the Consequences of the Chernobyl Accident (1991-95) carried out by European Commission, Belarus, the Russian Federation, the Ukraine. EUR 16542 EN, Brussels, Luxembourg, 1996.
7. Ten Years after the Accident at the Chernobyl NPP. National Report of the Ukraine. 1996. MinChernobyl, Kiev, 1996.
8. The International Chernobyl Project: Technical Report. Assessment of Radiological Consequences and Evaluation of Protective Measures. Report by an International Advisory Committee. IAEA, Vienna, October 1991.
9. Chernobyl. Ten Years on Radiological and Health Impact. NEA Committee on Radiation Protection and Public Health, November 1995. OECD. Paris 1995.
10. League of Red Cross and Red Crescent Societies: Report on Assessment Mission to the Areas Affected by the Chernobyl Disaster, USSR, 1990.
11. W. Burkart, N.E. Compton. Assessing Chernobyl's Radiological Consequences. *Nuclear Europe World-Scan*. N 3-4, p. 27-30, 1991.
12. John W. Gofman. Assessing Chernobyl's Cancer Consequences: Application of Four "Laws" of Radiation Carcinogenesis. Report presented at the 192nd National Chemical Society. Symposium on Low-Level Radiation. Division of Chemical Health and Safety. September 9, 1986. Anaheim, California, USA. (See chapter 36 in the book of John W. Gofman. *Radiation-Induced Cancer from Low-Dose Exposure: An Independent Analysis*. 1990: First Edition. Committee for Nuclear Responsibility. San Francisco, California 94101. Edited by Egan O'Connor).
13. E.P. Ivanov. "Prognosis of Forecasted Excess Leukaemia and Thyroid Cancer in Belarus as Consequence of the Chernobyl accident". *Atoms in Japan*. V.37, N4, 1993, p.24.
14. M. Goldman. Chernobyl: A Radiobiological Perspective. *Science*, vol. 238, October 1987, p.622-623.
15. L.R. Anspaugh, R.J. Catlin, M. Goldman. The Global Impact of the Chernobyl Reactor Accident. *Science*, vol. 242, December 1988, p. 1513-1519.
16. L.A. Ilyin, M.I. Balonov, L.A. Buldakov et al. "Radiocontamination Patterns and Possible Health Consequences of the Accident at the Chernobyl Nuclear Power Station". *J.Radiol. Prot.* 1990, v. 10, N1, pp.3-29.
17. I.M. Drobyshevskaja, N. A. Krysenko, A.E. Okeanov, V.A. Stezko. Health State of the Belarussian Population after the Chernobyl Disaster. *Zdravookhranenie*, N5, 1996, p. 3-7. (in Russian).
18. J.Gofman. "Low - Dose Exposure: an Independent Analysis". Committee for Nuclear Responsibility. Inc. San Francisco, California, USA, 1990.
19. A.A. Abagian, V.G. Asmolov, A.K. Guskova et.al. Information about the Accident at the Chernobyl NPP and Its Consequences prepared for the IAEA. *Atomnaja Energia*, vol. 61, N5, November 1986, p. 301-320 (in Russian).
20. UNSCEAR. Sources, Effects and Risks of Ionizing Radiation, UN, New York, 1988.
21. Catalogue of Irradiation Doses of Inhabitants of Settlements of the Republic of Belarus. Ministry of Health Care of the Republic of Belarus. Minsk, 1992 (in Russian).
22. V.F.Kozlov. Handbook on Radiation Safety. The fourth edition. Moscow. Energoatomizdat, 1991 (in Russian).
23. T. Imanaka, T. Seo, H. Koide. Radioactivity in the Highly Contaminated Area Near the Chernobyl Site. *J. Radioanal.Nucl.Chem.Letters*,vol.154,N2,p.111-9, 1991.
24. M.Y. Orlov, A.N. Silantjev, V.P. Snykov. Contamination with Radionuclides and Dose Rate on the Territory of Russia and Belarus after the Accident at the Chernobyl NPP. *Atomnaja Energia*, vol. 73, N3, September 1993, p. 234-238 (in Russian).
25. V.I. Ternov, A.G. Kondratjev. Gamma-Background Radiation of the Belorussian SSR in 1991-1982. *Zdravookhranenie Belarusi*. N6, June 1991, p. 61-63 (in Russian).
26. Retrospective Dosimetry and Dose Reconstruction. Final Report of the Experimental Collaboration Project N 10 of the International Scientific Collaboration on the Consequences of the Chernobyl Accident (1991-95) carried out by European Commission, Belarus, the Russian Federation, the Ukraine. EUR 16540 EN, Brussels, Luxembourg, 1996.
27. Kevin M. Miller, John L. Kuiper, Irene K. Helfer. ¹³⁷Cs Fallout Depth Distribution in Forest Versus Field Sites: Implications for External Gamma Dose Rates. *J. Environ. Radioactivity*, vol. 12, p. 23-47, 1990.
28. H.L. Beck, G. De Planque. The Radiation Field in Air Due to Distributed Gamma-Ray Sources in the Ground. U.S. Atomic Energy Commission Report HASL-195. New York, 1968.
29. UNSCEAR. Sources and Effects of Ionizing Radiation, UN, New York, 1977.
30. D.L. Preston, D.A. Pierce. The Effect of Changes in Dosimetry on Cancer Mortality Risk Estimates in the Atomic Bomb Survivors. *RERF TR 9-87*, 1987.
31. Y. Pokumeika. Radiological Situation on the

- Territory of the European Part of the CIS and Baltic States in January 1993. *Zvezda* (official newspaper of the Supreme Soviet and the Government of the Republic of Belarus), February 1993 (in Belorussian).
32. Data on Radioactive Contamination of Settlements of The Belorussian SSR with Caesium-137 and Strontium-90 (Juni 1989). Goshydromet of the USSR. Minsk, Polymya Publishing House, 1989 (in Russian).
 33. Population of the USSR 1987. Statistical handbook. Moscow. Finansy i statistika, 1988 (in Russian).
 34. V.F. Stepanenko, A.F. Tsyb, Yu.I. Gavrilin et al. Thyroid Dose Irradiation in Population of Russia as a Result of Chernobyl Accident (Retrospective Analysis). *Radiation and Risk. Bulletin of the All-Russia Medical and Dosimetric State Registry. Issue 7*, Moscow-Obninsk, 1995 (in Russian).
 35. M.Y. Orlov, V.P. Snykov, Y.A. Khvalensky, V.P. Teslenko. Radioactive Contamination of the Territory of Belarus and Russia after the Accident at the Chernobyl NPP. *Atmonaja Energia*, vol. 72, N4, April 1992, p. 371-376 (in Russian).
 36. 1990 Recommendations of the International Commission on Radiological Protection. ICRP Publication 60. Pergamon Press. Oxford, 1991.
 37. Kiyohiko Mabuchi, D.A. Pierce, D.L. Preston, Y. Shimizu, M. Vaeth. Cancer Risk Among Atomic Bomb Survivors. *Proceedings of the 1996 International Congress of Radiation Protection (IPRA 9)*. April 14-19, 1996, Vienna, Austria, p. 1-171 — 1-177.
 38. J. Gofman. *Chernobyl Accident: Radiation Consequences for This and Future Generations*. First Edition. Committee for Nuclear Responsibility, Inc. San Francisco, California, USA. Edited by Egan O'Connor. CNR Books and Vysheishaya Shkola Publishing House. Minsk, 1994 (in Russian).
 39. *Environmental and Health Atlas of Russia*. PAIMS Publishing House, Moscow, 1995. Edited by Murray Feshbach.
 40. B.G. Bennet. Assessment by UNSCEAR of Radiation Sources and Effects. *Proceedings of the 1996 International Congress of Radiation Protection (IPRA 9)*. April 14-19, 1996, Vienna, Austria, p. 1-37 — 1-46.
 41. D Beninson. Risk of Radiation at Low Doses. *Proceedings of the 1996 International Congress of Radiation Protection (IPRA 9)*. April 14-19, 1996, Vienna, Austria, p. 1-19 — 1-23..
 42. V.S. Kazakov, E.P. Demidchick, L.N. Astakhova. Thyroid Cancer After Chernobyl. *Nature*, vol. 359, 3 September, 1992, p. 21.
 43. E. Lengfelder, E. Demidchick, Yu. Demidchick et al. 10 Years After the Chernobyl Disaster. *Münchener Medizinische Wochenschrift*. Ig. 138, N15, 1996, p. 259-264 (in German).
 44. Health Consequences of the Chernobyl Accident. Results of the IPHECA Pilot Projects and Related National Programmes. Scientific Report of the International Programme on the Health Effects of the Chernobyl Accident. WHO. Geneva 1995.
 45. Epidemiological Investigations Including Dose Assessment. Final Report of the Experimental collaboration Project N 7 of the International Scientific Collaboration on the Consequences of the Chernobyl Accident (1991-95) carried out by European Commission, Belarus, Russian Federation, the Ukraine. EUR 16537 EN, Brussels, Luxemburg, 1996.
 46. E.P. Ivanov, G.V. Tolochko, L.P. Shuvaeva, R.F. Jaroshevich, V.E. Ivanov, V.S. Lazarev. Children Haemoblastoses of the Republic Belarus after the Chernobyl Accident. In: *State of Haematoimmunne System among Children of Belarus after the Disaster at the Chernobyl NPP*. Scientific and Practical Materials of 1986-1996. Edited by the Research Institute of Radiation Medicine of the Ministry of Health Care of Belarus and Endoecological Centre. Minsk, 1996, p. 46-54 (in Russian).
 47. D.M. Parkin, D. Clayton, R.J. Black, E. Komarova. Childhood Leukemia in Europe Following the Chernobyl Accident: Monitoring Incidence Trends Using Population-Based Cancer Registry Information. *Proceedings of the International Conference. One Decade After Chernobyl. Summing up the Consequences of the Accident*. Paper N CN-63/409. Vienna, Austria, 8-12 April 1996.