METHODOLOGICAL APPROACHES TO THE RECONSTRUCTION OF RADIONUCLIDE INTAKE FOR RESIDENTS OF THE EAST URALS RADIOACTIVE TRACE AND KARACHAY TRACE

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ABSTRACT

Project 1.1 is charged to provide credible estimates of doses to the members of the Extended Techa River Cohort (ETRC), who were exposed to releases of wastes by the Mayak Production Association (MPA). For the average member most of the dose from environmental sources came from residence in villages along the River. However, there were other sources of environmental exposure. There was an explosion in 1957 in a waste tank at the MPA that released 2×10^6 Ci into the air and formed the East Urals Radioactive Trace (EURT). After the releases to the Techa River became known, discharges were diverted to Karachay Lake. In 1967 this lake partially dried out, and material was dispersed by resuspension; about 600 Ci were released. Another source of environmental exposure, which is not considered in this document, was the release of large amounts of noble gases and radioiodines from the stacks at the MPA.

About 4,000 members of the ETRC who were more heavily exposed due to residences on the river near the source of release were evacuated and moved to new villages that were subsequently in the path of the EURT and the Karachay Trace (KT). The object of this report is to develop a protocol for reconstruction of dose to persons who exposed to the EURT and the KT. In a previous report (Peremyslova et al. 2004), we detailed the kinds of data that are available for that purpose, how all such data available at the Urals Research Center for Radiation Medicine had been collected, and how data bases on environmental and human data were formed into databases or registers.

Two basic approaches have been considered for the reconstruction of doses, both of which employ unit dose factors; that is, dose per unit ground deposition (Gy per kBq m^{-2}). The first approach is based upon measurements of radionuclides in local foodstuffs. The second approach makes use of measurements related more directly to humans. Examples include measurement of ^{90}Sr in human bones, measurement of total-beta activity in excreta, and measurement of whole-body content of ^{90}Sr and/or ^{137}Cs. The first approach had been developed before by several investigators. This report provides the first description of attempts to use the human data directly. This is not an easy problem, particularly, for a measurement of ^{90}Sr in bone, and the inverse problem must be solved of deriving an intake function. Fortunately, we already had experience in solving such an inverse problem for the Techa River problem.

This report describes our experience in using both approaches in order to compare and contrast results. In general, direct use of human data provides better results, but not all villages had a sufficient number of persons with measurement. In general, the first approach results in overestimates of the dose by a factor of 3 to 4. Special attention in this report is given to the reconstruction of dose from ingestion of short-lived radionuclides for persons living on the EURT. For a first time the analysis of unique data is described on measurements of total-beta activity in feces obtained for residents of EURT settlements during the first period after the explosion. The data on excreta contamination obtained in 1958 and 1959 were used for validation of the intake of short-lived radionuclides. The estimates of daily intakes derived from measurements of bone samples and feces are in good agreement. It should be emphasized that good agreement among the results obtained with use of independent sets of data indicates the reliability of assumptions used for the reconstruction of the intake of short-lived radionuclides.

1. INTRODUCTION

It is known that significant population exposure in the Urals region occurred as a result of liquid and airborne releases of radioactive materials from the Mayak Production Association (MPA). The major sources of environmental radioactive contamination were the discharges of about 2.7×10^6 Ci of liquid wastes into the Techa River (1949–1956); an explosion in the radioactive waste-storage facility in 1957 (the so-called Kyshtym Accident) that formed the East Urals Radioactive Trace (EURT) due to dispersion of 2×10^6 Ci into the atmosphere; gaseous aerosol releases within the first decades of the facility's operation, and windblown of material (about 6000 Ci) from Lake Karachay in 1967 to which effluents had been discharged after the contamination of the Techa River became known.

In an effort to determine if a dose-rate-effectiveness-reduction factor might exist for persons exposed to high doses at low-to-moderate dose rates, a cohort of residents exposed due to radioactive releases into the Techa River (the Extended Techa River Cohort, ETRC) and a cohort of their offspring (the Techa River Offspring Cohort, TROC) were formed at the Urals Research Center for Radiation Medicine (URCRM). It is known that a few thousand members of the ETRC and TROC were relocated away from the upper Techa River or migrated from the Techa River settlements and into the future path of the EURT (Degteva et al. 1996). As a result, they were additionally exposed due to residence on the territories contaminated in 1957 and 1967. Fig. 1 shows a schematic map of soil contamination of the Urals territories by ^{90}Sr as measured in 1992–1997 by specialists from the government hydro-meteorological service (IDCRM 2000). This map demonstrates that residents of the northern part of the Chelyabinsk Oblast (including members of the ETRC and TROC) continue to be exposed to low-level chronic irradiation.

Our previous Milestone 10 report (Peremyslova et al. 2004) concerned a review of historical data on contamination of the EURT and Karachay Trace (KT) territories and a review of data sets and models available for the reconstruction of individual doses due to residence on the EURT and KT areas. It was shown that a considerable number of both environmental radionuclide examinations and measurements of ^{90}Sr in human-bone samples collected at autopsy were performed at the URCRM since 1958. It was suggested that the dose-reconstruction process for the EURT and KT areas can be based on extensive measurements of food-stuff contamination and exposure in humans for "referent" settlements that serve as sites of long-term monitoring. For other settlements deposition density-to-dose-conversion-factors for every year of exposure are to be derived. Individualized doses due to residence on the contaminated territories for the members of the ETRC and TROC can then be reconstructed by combining deposition density-to-dose-conversion-factors with individual-residence histories within the contaminated areas. Also, it was shown that long-lived ^{90}Sr can be assumed as a "referent" radionuclide for reconstruction of the intake of short-lived radionuclides, with due consideration of the radionuclide composition of fallout and environmental transfer coefficients.

In order to implement the recommended dose-reconstruction process it is necessary to create a Data Directory (DD) on ^{90}Sr-contamination density of Urals settlements. Various surveys and maps of the EURT and KT deposition densities were reviewed to create the DD

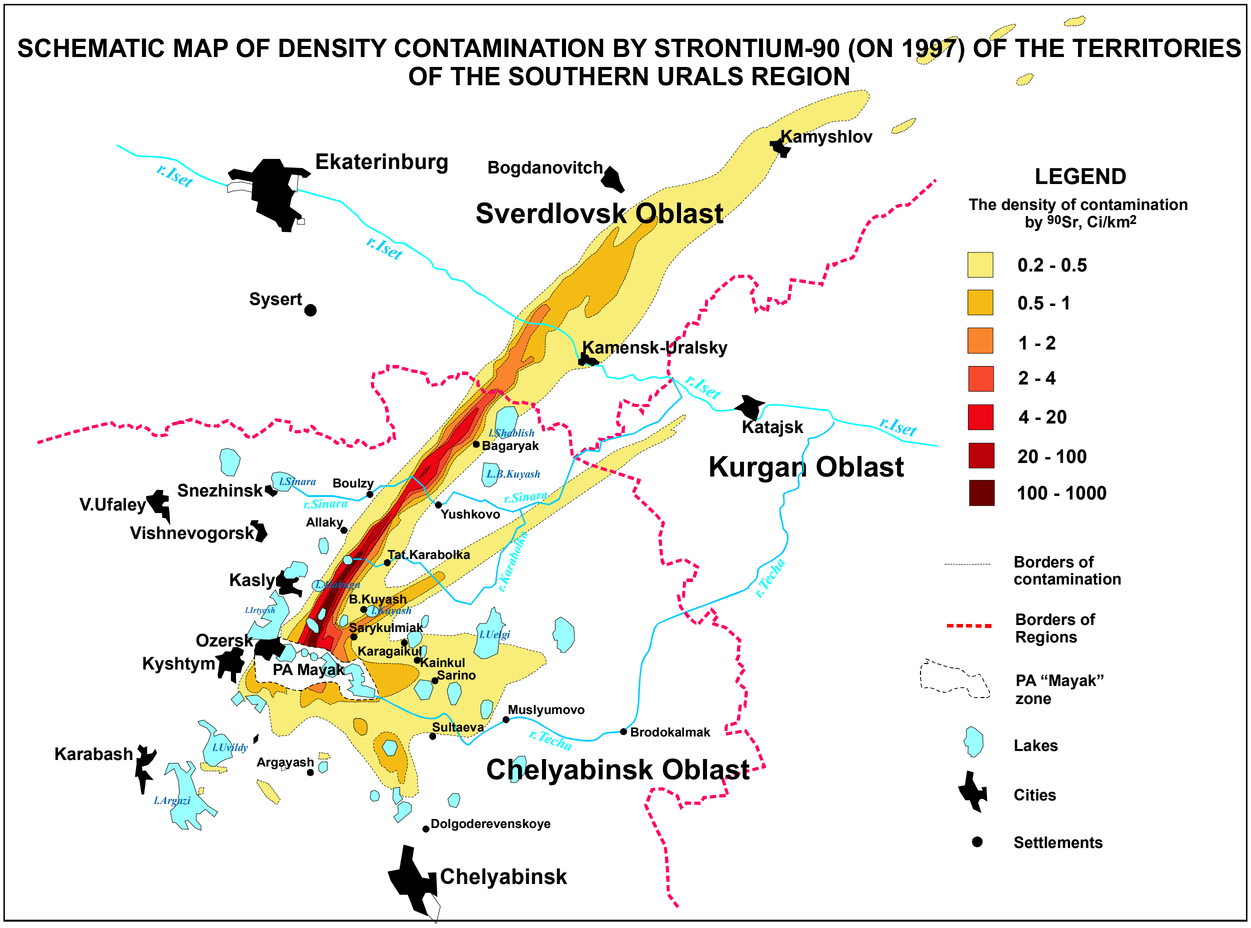

Fig. 1. Schematic map of contemporary (normalized to 1997) contamination of soils by ^{90}Sr of territories of the Urals region (according to IDCRM, 2000). Existing referent settlements on EURT and KT areas are illustrated (a description of these referent settlements is provided in Tables 1 and 2).

described briefly in (Peremyslova et al. 2004). Appendix 1 of the current report provides the data on contamination density extracted from this DD for 190 settlements covered by the EURT and KT (the tabulated range of densities is from 0.1 to 650 Ci km^{-2} of ^{90}Sr).

The characteristics of "referent" settlements for the EURT and KT are shown in Tables 1 and 2. As can be seen from Table 1, the residents of some EURT settlements were evacuated after the accident. The terms of evacuation depended on the level of contamination density. The residents of three villages with maximal level of ^{90}Sr contamination (400–650 Ci km^{-2}) were evacuated within 10 days. Later (within 250–670 days after the accident), all residents of the EURT area with contamination density higher than 2 Ci km^{-2} were removed. As for the KT (Table 2), the levels of contamination density in residence areas were relatively low, and there was no evacuation. As can be seen from Table 2, the KT is mainly superimposed on the areas already contaminated as a result of Kyshtym accident in 1957.

Table 1. Characterization of referent settlements for the EURT area.

Settlement	Distance from the source of contamination, km	^{90}Sr-contamination density in 1957[a], Ci km^{-2}	Period of residence after the accident, days
Berdyanish	12.5	650	10
Satlykovo	18	400	10
Galikaevo	23	400	10
R. Karabolka	35	65	250
Yugo Konevo	55	10.8	250
Allaky	28	0.9	Permanent
Tat. Karabolka	31	1.3	Permanent
Boulzy	40	0.8	Permanent
Yushkovo	45	0.7	Permanent
Bagaryak	65	2.0	Permanent

[a] Contamination density depends not only on the distance from the explosion site, but also on the position of the settlement relative to the axis of the EURT.

Table 2. Characterization of referent settlements for the KT area.

Settlement	Distance from the source of contamination, km	Contamination density for ^{90}Sr, Ci·km^{-2}, due to the KT, 1967	Contamination density for ^{137}Cs, Ci·km^{-2}, due to the KT, 1967	Contamination density for ^{90}Sr, Ci·km^{-2}, due to the EURT, 1957
Kainkul	35	0.9	2.6	0.5
Karagaikul	27	0.4	1.7	0.3
Sarino	35	0.5	1.4	0.5
Sultayevo	40	0.3	1.0	0
Sarykulmiak	18	1.5	4.4	0.5

Analysis of residence-history data for each member of the ETRC and the TROC was performed in order to identify persons who migrated to the EURT and KT areas. The results of this analysis are presented in Appendix 2. The territorial distribution of residence locations for members of the ETRC and TROC within the EURT areas with different levels of soil contamination is shown in Table 3. Only persons who lived in the EURT during the first three years after the accident (September 1957 through 1960) are considered. As can be seen, more than 4,000 of the ETRC members and about 1,300 TROC members were additionally exposed due to the Kyshtym accident. Maximal doses were received by 55 persons who were evacuated from the most contaminated territories of the EURT with ^{90}Sr-contamination density 2–650 Ci km^{-2}. For some of these persons doses due to residence on the EURT exceed doses obtained on the Techa River.

Table 3. The number of members of the ETRC and TROC who migrated to EURT settlements, located on territories with different ^{90}Sr-contamination density.

Range of ^{90}Sr-contamination density in 1957, Ci km^{-2}	Number of ETRC members	Number of TROC members
≥ 2[a]	44	11
1–2[b]	1,304	372
0.2–1[b]	1,187	363
≤0.2[b]	1,524	548
Total: 0.1–650 Ci km^{-2}	4,059	1,294

[a] Group of evacuated settlements;
[b] Groups of existing settlements.

In considering the additional exposure due to windblown material from Lake Karachay in 1967, it must be noted that the KT is superimposed on the areas of the EURT. Table 4 shows the EURT and KT settlements in which more than 100 members of the ETRC lived. As can be seen, the territory of almost all these settlements was contaminated both in 1957 and in 1967. The majority of these settlements were places of compact habitation of people evacuated from the Techa Riverside villages. For example, residents of Metlino had been evacuated to the ONIS settlement, residents of Kurmanovo – to New Kurmanovo, residents of Asanovo – to Bashakul, residents of M. Taskino – to B. Taskino etc. So, Table 4 shows that persons removed from the Techa River continue to be exposed to low-level chronic irradiation.

The main purpose of this report is to develop methodological approaches to the reconstruction of radionuclide intake for residents of the EURT and KT areas. These approaches are based on the following assumptions derived from our analysis of data available for dose reconstruction (Peremyslova et al. 2004):

Table 4. Settlements located on the EURT and KT areas where more than 100 members of the ETRC lived.

Settlement	^{90}Sr-contamination due to the EURT, Ci/km^2	^{90}Sr-contamination due to the KT, Ci/km^2	Number of ETRC members	Number of TROC members
ONIS	1.5	1.2	1276	363
N. Kurmanovo	0.1	0.1-0.3	784	303
Chishma	0.2	0.1-0.3	289	111
B. Taskino	0.3	0.6	218	91
Ozersk	0.35	0.15	151	25
Sarino	0.5	0.5	142	48
Kamensk-Uralsky	0.6	0	127	11
Bashakul	0.4	0.38	123	48

- ^{90}Sr is considered as a referent radionuclide for soil contamination and intake reconstruction;
- All Urals settlements located on the territories of the EURT and/or KT with ^{90}Sr-contamination density higher 0.1 Ci km^{-2} (Appendix 1) are considered;
- Evacuated and non-evacuated EURT settlements are considered separately due to different exposure conditions (short-term intake versus chronic intake); this difference requires different methodological approaches for intake reconstruction;
- Radionuclide composition of the release of 1957 (which formed the EURT) is assumed in this report as given by Mayak specialists in 1985 (Ternovsky et al. 1985): ^{144}Ce+^{144}Pr – 66%, ^{95}Zr+^{95}Nb – 24.9%, ^{90}Sr+^{90}Y – 5.4%, ^{106}Ru+^{106}Rh – 3.7%, ^{137}Cs+^{137m}Ba – 0.036%;
- Data on radionuclide composition of the release of 1967 is not used in this report, because intake reconstruction for the KT is based on direct measurements of radionuclides in food-products and soil (available at the URCRM since 1967);
- For referent settlements the measurements of radionuclides in food-stuffs and humans are used to reconstruct the intake functions in these settlements and then to derive deposition density-to-intake-conversion-factors; and
- These conversion-factors are used to reconstruct the intake functions in other settlements located on the EURT and KT areas.

Individualized doses due to residence of members of the ETRC and TROC on the contaminated territories will be reconstructed by combining settlement-specific intake functions with individual-residence histories within the contaminated areas. On the basis of the results of the current report an algorithm for the calculation of individual internal doses due to residence within the EURT and KT areas will be developed. This algorithm will be incorporated into the new version of the dose-reconstruction system and will also provide dosimetric support for the epidemiological studies of the Techa River cohorts (ETRC and TROC) as well as for the cohort of EURT residents.

2. RECONSTRUCTION OF ^{90}Sr INTAKE FOR NON-EVACUATED RESIDENTS OF THE EURT

There are two basic approaches that could be applied to the assessment of the dietary radionuclide intake for a population living in areas contaminated by radioactive fallout:

1. Intake is derived from measurements of local foodstuff contamination and/or modelling of food chains; or
2. Intake is derived from measurements of the concentration of radionuclides in human body, tissues and excreta with the use of biokinetic models describing behavior of radionuclides in the human body. Thus, an inverse problem is to be solved compared to the first approach.

Usually, these approaches are used together with one of them prevailing. The latter approach is favorable because it is strongly based on data on radionuclide-body burden, which serves as a basis in dose assessment. However, data on measured radionuclide-body burden are usually restricted (they have gaps); therefore, these approaches are used in different combinations in dose assessment. For residents of non-evacuated settlements located on EURT territories, data on ^{90}Sr measurements in local foodstuffs and in bone-tissue samples are available in the URCRM database ENVIRONMENT. A detailed description of these data is provided in Peremyslova et al. (2004). In addition to this information, there are data on measured total-beta activity in foodstuffs available for the first period after the accident (1958–1960) contained in URCRM reports and archival documents.

There is a significant number of *post mortem* measurements of ^{90}Sr in bone tissues of residents and measurements of the radionuclide in local foodstuffs performed in different settlements of Chelyabinsk Oblast (Peremyslova et al. 2004). As a result, these settlements can be grouped for intake-reconstruction purposes depending on the completeness of available data and their characteristics.

In this report, the reconstruction of ^{90}Sr intake includes the following steps:

1. Reconstruction of ^{90}Sr intake on the basis of measurements of the radionuclide in local foodstuffs and bone samples;
2. Comparison of the estimates of ^{90}Sr intake obtained by use of different methods; and
3. Analysis of different possible dynamics of radionuclide intake and assessment of deposition density-to-intake-conversion-factors.

2.1. RECONSTRUCTION OF ^{90}Sr INTAKE ON THE BASIS OF LOCAL FOODSTUFF-CONTAMINATION DATA

2.1.1. Dietary composition

Assessment of dietary composition is the basis for evaluation of a radionuclide’s intake with foodstuffs. For EURT residents, evaluation of dietary intake during the first period after the accident is based on the results of studying dietary composition characteristic for residents of the EURT territories, including studies conducted in 1958–1959 in the three referent settlements of Allaky, Boulzy and Yushkovo (Skryabin et al. 1962).

For later periods after the accident, data on dietary composition for rural adult residents were obtained from the Statistical Department of Chelyabinsk Oblast. The weights of products, which were part of the same group (milk products, bread products, etc.), were normalized for the weight of the main product in a group (milk, bread, etc.) in the following way: The total weight of daily consumed cereals, macaroni, noodles, flour etc. was multiplied by 1.5; the weight of milk products (kefir, curdled milk, cheese etc.) was multiplied by “calcium coefficients” representing a ratio of Ca concentration in milk product to that of in milk. The values of “calcium coefficients” used in calculations are 1.0 for kefir and other sour-milk products, 1.25

for curdled milk and 6.7 for cheese (Budaguyan 1961). Data on daily dietary composition used in the calculations of dietary intake of radionuclides are complied in Table 5. During the first period after the accident data obtained in 1958–1959 were used in calculations, while for later periods, data averaged over the entire period were applied.

2.1.2. Evaluation of ^{90}Sr intake for the period 1957–1960 on the basis of total-beta-activity measurements of food products

The first period after the accident is the most significant for dose assessment, because maximal intake occurred during this time. The more important foodstuffs in terms of intake of radionuclides are milk and bread. During the first period after the accident (1957–1960) only total-beta-activity measurements of bread and milk were performed, because radiochemical methods for foodstuff monitoring had not yet been developed. The results of total-beta-activity measurements in food samples represented the sum of activities of natural radionuclides (^{40}K), activity of ^{90}Sr/^{90}Y and of non-^{90}Sr radionuclides. Therefore, it is important to evaluate the contribution of ^{90}Sr to measured total-beta activity. It is also important for the evaluation of dietary intake of short-lived radionuclides, which had a significant contribution in fallout (Table 6).

Bread

Usually, the intake of radionuclides with bread occurs during the subsequent year following the harvesting period; thus, grain collected in 1957 is used for making flour and baking bread during 1958 and so on. Therefore, the intake with bread in a current year reflects the contamination of grain in the previous year. It is assumed that bread made of grain collected in September of a particular year is consumed from November 1 of the particular year to November 1 of the subsequent year. This is important for interpretation of data on total-beta activity measurements. Such measurements were performed in different villages located on the EURT territories during the period from April 20, 1958, to October 1959. Homemade bread was baked

Table 5. Consumptions of the basic foodstuff by adult rural residents, g day^{-1}, for different years after the accident.

Dietary component	Calendar year				Average
	1958–59	1972	1982	1994	1958–1994
Milk and milk products[a]	500	610	600	764	620
Bread and bread products[b]	640	615	600	550	600
Meat and meat products	120	145	160	141	140
Potatoes	330	190	220	367	276
Vegetables	145	190	200	133	167

[a] Calculated per milk consumption;

[b] Calculated per bread consumption.

Table 6. Radionuclide composition of radioactive fallout; these values are used for the reconstruction of intake with foodstuffs.

Radionuclide	Contribution to the total activity, %	Ratio to that of ^{90}Sr+^{90}Y
^{90}Sr+^{90}Y	5.4	1.0
^{95}Zr+^{95}Nb	24.9	4.6
^{106}Ru+^{106}Rh	3.7	0.69
^{144}Ce+^{144}Pr	66	12.2
^{137}Cs+^{137m}Ba	0.036	0.007

from grain grown by collective farms; therefore, beta activity of homemade bread in different settlements could be the same, if they used grain supplied by the same collective farm.

The contribution of ^{90}Sr to the total-beta activity measured in bread samples differed depending on the pathway of grain (and, therefore, bread) contamination. The characteristics of the first period of contamination are considered in detail:

1. *October 1957–November 1958: consumption of bread from the harvest of 1957.*

Contamination of bread was due to surface contamination of grain stored in open buildings or in fields. Therefore, the radionuclide composition of grain contamination corresponded to the radionuclide composition of fallout (Table 6) with consideration of radioactive decay of the individual radionuclides. It is assumed that the mix of radionuclides in bread is the same as that in grain, because it can be assumed that there is no preferential loss of one radionuclide versus another due to grinding, etc.

2. *November 1958–November 1959: consumption of bread of the harvest of 1958.*

Two sources of grain contamination were taken into account: (1) surface contamination by dust, including secondary (mostly wind) migration from surrounding territories and (2) contamination of grain as a result of radionuclide migration from soils to wheat through roots.

3. *November 1959–November 1960: consumption of bread of the harvest of 1959.*

As in the above case, two sources of grain contamination were taken into account: surface contamination and the migration of radionuclides from soils to wheat.

<u>Secondary surface contamination.</u> Experiments conducted in 1960 on experimental sites located on EURT territories showed that half of the radioactive contamination of grain was-derived from secondary surface contamination with dust (Fedorov et al. 1964). Nevertheless, it should be noted that half of the surface activity residing on the outer shell of a seed is lost due to the process of grinding. Also, the transfer of radionuclides through the outer shell into the seed is negligibly small for all radionuclides considered, except for ^{137}Cs (Annenkov et al. 1973).

Therefore, it can be concluded that 25% of the total-bread contamination is characterized by radionuclide composition due to secondary surface contamination (radionuclide composition of fallout with account for radioactive decay) and the residual 75% of the contamination is due to migration of radionuclides from soil to grain through roots.

Radionuclide composition due to migration of radionuclides from soil to grain is estimated by taking into account the radionuclide composition of soil and differences in radionuclide-specific migration from soil to grain. Estimates of radionuclide-specific transfer factors from soil to grain are taken from the paper of Müller et al. (1999). This paper contains data for soils and environmental conditions characteristic for Central Europe; these data are used because such data are lacking for the Urals region.

Table 7 shows a compilation of available data on measured total-beta activity of bread performed in different EURT settlements in 1958–1959 and radionuclide composition calculated on the basis of the assumptions mentioned above.

October 1957–November 1958: consumption of bread of the harvest of 1957. As can be seen from Table 7, measurements of the total-beta activity in bread for the period of surface contamination were performed only in two settlements (Boulzy and Kleopino), which were supplied from the same collective farm. Because of the short period of time between deposition and measurement, these values cannot be used as a year-averaged estimate of the radionuclide-specific intake with bread. The total-beta activity and radionuclide composition of bread for the entire period (October 1957–November 1958) was thus derived using radionuclide-specific radioactive decay rates and this single measurement of the total-beta activity of bread and its radionuclide composition in April–May, 1958.

November 1958–November 1959: consumption of bread of the harvest of 1958. More measurements of the total-beta activity in bread were performed in several villages in 1958–1959. Geometric means of the village-specific contamination of bread are shown in Table 7. Some comments on Table 7 are necessary.

It should be noted that Chuprovo Village was located on territories with high ^{90}Sr-contamination density (about 6–8 Ci km^{-2}) west from Bagaryak Village and was evacuated in 1959 (700 days after the explosion). Nevertheless, Chuprovo was supplied by grain from the Bagaryak collective farm, and, therefore, these measurements reflect levels of the contamination of bread made from grain from the Bagaryak collective farm. Pyankovo Village was supplied by grain from the Boulzy collective farm. Values for Pyankovo and Boulzy were further averaged for estimation of reference values of the radionuclide-specific activity in bread for corresponding periods of consumption of bread. In the URCRM archive there are journals containing data on measured beta activity in bread in Bagaryak and Tat.-Karabolka in 1959, but the date of sampling/measurements was not indicated. Therefore, it is not possible to distinguish between the 1958 and 1959 harvesting periods. Nevertheless, these measurements indicate the contamination of bread, which was consumed in 1959, and, thus, can be used to derive the average value of contamination in bread consumed from November 1958 to November 1959.

Table 7. Measurements of total-beta activity in bread in EURT settlements and evaluation of radionuclide-specific activity based on estimates of soil-deposition density and soil-to-grain transfer factors.

Settlement	Date of sampling	Year of harvesting	Total-beta activity excluding ^{40}K, Bq kg^{-1} (geometric mean)	Specific activity in bread[a], Bq kg^{-1}				
				^{90}Sr	^{144}Ce	^{95}Zr	^{106}Ru	^{137}Cs
Boulzy-Kleopino	April 20–May 20, 1958	1957	1128	59.8	446.5	29.3	28.2	0.4
Chuprovo	December 1958	1958	149	57.2	15.8	0.12	1.5	0.06
Pyankova	December 1958	1958	121	46.5	12.8	0.10	1.2	0.05
Yushkovo	April 1959	1958	36.4	14.3	3.5	0.01	0.3	0.02
Yushkovo	April 1959	1958	73.3[b]	28.8	7.1	0.02	0.7	0.03
Yushkovo	October 1959	1959	33.3[b]	13.7	2.7	0.002	0.2	0.02
Allaky	April 1959	1958	58.1[b]	22.8	5.7	0.02	0.5	0.03
Allaky	October 1959	1959	32.9[b]	13.5	2.7	0.002	0.2	0.02
Bagaryak	October 1959	1959	24.1[b]	9.9	1.9	0.001	0.2	0.01
Bagaryak	1959 (month not available)	1958–1959	94.4	37.2	9.0	0.02	0.9	0.04
Tat.-Karabolka	1959 (month not available)	1958–1959	38.4	15.1	3.7	0.01	0.4	0.02

[a] Radionuclide composition is estimated for the case of surface contamination (due to radionuclide decay) for the first period and for the case of both surface (as a result of wind migration, etc.) and ground contamination (due to radionuclide transfer from soil to roots). Radionuclide transfer from soil is based on data for Central Europe (Müller et al. 1999).

[b] Average value estimated on the basis of measurements of bread sampled from 18–20 families.

Table 8 summarizes the estimates of ^{90}Sr concentration in bread samples and evaluated ^{90}Sr intake with bread during the first period of contamination (1957–1960).

Milk and meat

The contribution of non-^{90}Sr radionuclides (^{144}Ce, ^{95}Zr, ^{95}Nb, ^{106}Ru, ^{137}Cs) into total-beta activity of milk could not be significant due to the low transfer of these radionuclides through biological barriers or to the small contribution of ^{137}Cs to total activity. For the first investigations performed on the EURT territories it was assumed that ^{90}Sr activity in milk constituted about 40% of the total-beta activity (without natural ^{40}K) in 1958 and about 45% in 1959 (Dubrovina 1961; Lyarsky 1962; Skryabin et al. 1985); thus, ^{90}Sr+^{90}Y contribution to total-beta activity of milk (without natural ^{40}K) constituted 80 and 90%, respectively. If data on ^{144}Ce

Table 8. Estimates of ^{90}Sr intake with bread for the period 1957–1960 on the basis of total-beta-activity data (per unit ^{90}Sr-contamination density).

Period	Sampling sites (number of measurements)	Geometric mean of ^{90}Sr concentration in bread		Geometric mean of ^{90}Sr intake with bread	
		Bq kg^{-1}	nCi kg^{-1}	Bq d^{-1}	nCi d^{-1}
September 29, 1957, to November 1, 1958	Boulzy and Kleopino (7): (Boulzy collective farm)	59.8	1.6	38.3	1.0
November 1, 1958, to November 1, 1959	Chuprovo (17), Pyankova (56), Yushkovo (92), Allaky (18-20) Bagaryak (64), Tat.-Karabolka (30)	32.2	0.87	20.6	0.56
November 1, 1959, to November 1, 1960	Allaky (18-20) Bagaryak (18-20), Yushkovo (18-20)	9.9	0.27	6.3	0.17

transfer into milk and the radionuclide composition of fallout (Table 6) are considered, the estimated contribution of ^{144}Ce could not be more than 10% of the total-beta activity of milk (without natural ^{40}K). Therefore, in 1957–1958 the highest possible contribution of ^{90}Sr would constitute 45%.

At the end of the 1990s, parallel determinations of total-beta activity and of ^{90}Sr-specific activity in 52 milk samples (obtained in 1960) were found in archival documents and included in the database. Comparison of results based on the two methods shows that ^{90}Sr accounted for 20% of the total-beta activity (without natural ^{40}K). This value (20%) contradicts the early values used for estimation of ^{90}Sr intake (Lyarsky 1962; Skryabin et al. 1985) and calculated values. The reasons for such a low contribution of ^{90}Sr have not been discussed in available literature. However, this value (20%) was accepted in estimates of ^{90}Sr dietary intake for residents of the EURT settlements (Peremyslova et al. 2001).

With consideration of available data on transfer of short-lived radionuclides into milk, the following ^{90}Sr contributions to total-beta activity of milk (without natural ^{40}K) are assumed for evaluation of ^{90}Sr intake with milk: 40% in 1957–1958 and 45% in 1959–1960.

The results of measurements of the total-beta activity of milk obtained by URCRM scientists in several EURT settlements in 1958–1960 are compiled in Table 9.

Estimates of dietary intake of ^{90}Sr have not accounted for the intake of ^{90}Sr with milk from October 1957 to April 1958, because the intake of milk during this period was not significant (during a period when cows were often pregnant and/or living inside barns) and the main contribution to radionuclide intake was from consumption of bread baked from contaminated grain.

Table 9. Results of measurements of total-beta activity in milk (^{40}K is not subtracted) performed in 1958–1960 in different EURT settlements.

Settlement	Month of sampling	Number of samples	Average ± standard deviation, Bq L^{-1}	Geometric mean, Bq L^{-1}
Bagaryak	July 1958	98	162±10	131
	Dec 1958	64	192±22	142
	Dec 1959	9	99±15	89
	Aug 1960	19	67±4	65
Boulzy	Oct - Dec 1958	20	74±12	63
	May-Oct 1959	10	63±7	60
Tat.-Karabolka	June1958	3	104±10	87
	March 1959	181	134±17	100
	May 1960	4	89±11	84
Yushkovo	June1958	37	82±7	60
	Oct 1958	50	64±3	75
	June 1959	43	91±6	84
	April 1959	22	86±6	82
	May 1960	3	71±3	72
Allaky	June 1959	57	64±7	49
Scherbakovo	Aug 1959	8	68±6	66

It has been shown that ^{90}Sr transfer into *meat* is nearly the same as for milk (Peremyslova et al. 2004). The intake of ^{90}Sr with meat was accounted for in the following way: the mass of daily consumed meat (120 g according to data outlined in Table 5) was added to the mass of daily consumed milk and ^{90}Sr activity in the "combined" product was taken to be the same as in milk.

Vegetables

Reliable measurements of the total-beta activity in vegetables for the period of 1957–1960 are not available. Therefore, contamination of vegetables was estimated on the basis of transfer coefficients through food chains. It was assumed that the transfer coefficient for ^{90}Sr "soils→vegetables" (cabbage, carrots, potatoes) corresponds to that for potatoes. The value of this transfer coefficient normalized per unit ^{90}Sr-contamination density was obtained for the first period after the accident and constituted 180 pCi kg^{-1} per unit ^{90}Sr-contamination density (Ci km^{-2}) (Dibobes 1971). Estimates of ^{90}Sr intake with vegetables account for the total daily consumption of vegetables, i.e., potatoes and other vegetables (Table 5).

Estimates of the total daily ^{90}Sr intake normalized per unit ^{90}Sr-contamination density obtained on the basis of data for the non-evacuated referent settlements in the period from 1957 through 1960 are presented in Table 10.

Table 10. Estimated daily ^{90}Sr intake normalized per 1 Ci km^{-2} of ^{90}Sr-contamination density for adult residents of the non-evacuated EURT settlements (density-to-intake-conversion-factors).

Calendar year	Average daily intake, Bq day^{-1}	Average daily intake, pCi day^{-1}
1957	9.5	260
1958	43	1150
1959	31	830
1960	13	350

2.1.3. Reconstruction of ^{90}Sr intake for the period after 1960 on the basis of radiochemical measurements

Reconstruction of ^{90}Sr intake for the period after 1960 is based on the results of radiochemical measurements of foodstuff and human-body contamination performed on samples from the EURT referent settlements (Table 11). As can be seen from Table 11, detailed investigations of the soil-contamination densities within residence areas and settlement areas used for agricultural needs have been conducted in these settlements in 1996–1997. It was demonstrated that contamination of areas of a specific settlement was very heterogeneous, which should be taken into consideration in the reconstruction of radionuclide intake. So, for correct estimation of ^{90}Sr-dietary intake, probability distributions of radionuclide concentration in different dietary components should be analyzed. It must be noted that, as a result of substitution of contaminated grain by non-contaminated imported products, which commenced in 1960, contaminated milk has been the main contributor to ^{90}Sr intake since 1960. Therefore, it was assumed that the distribution of ^{90}Sr in local diet was determined by that in milk.

Table 11. Characteristics of radiochemical measurements of soil and the numbers of foodstuffs and human-bone measurements performed in EURT referent settlements after 1960.

Settlement	^{90}Sr-contamination density in 1996–1997,[a] Ci km^{-2}		Number of ^{90}Sr measurements in milk	^{90}Sr measurements in other foodstuffs [b]	Number of ^{90}Sr measurements in human bones
	Kitchen gardens	Agricultural areas			
Allaky	0.6±0.7	0.4±0.3	185	+	3
Tat. Karabolka	0.6±0.4	0.1-0.7	483	+	10
Boulzy	0.8±0.9	0.2±0.1	172	+	18
Yushkovo	-	0.5±0.1	108	+	12
Bagaryak	2.1±2.4	0.2-3.0	412	+	65

[a] Additional contamination in 1967: Allaky - 0.3 Ci km^{-2}; Tat.-Karabolka and Boulzy - 0.25 Ci km^{-2}.

[b] Bread and grain products; meat products; potatoes; vegetables.

Fig. 2 shows statistical distributions of ^{90}Sr specific activity of milk in Bagaryak settlement in different calendar years. Statistical data on measurements of ^{90}Sr specific activity in milk in referent settlements are compiled in Table A3.1. Analysis shows that experimental data follow log-normal distributions rather than normal. Therefore, geometric means of ^{90}Sr concentrations in milk and in other products are used to evaluate the total dietary intake.

The results of radiochemical measurements of ^{90}Sr in different food products are presented in Appendix 3 (Tables A3.1–A3.4). These data have been used for the reconstruction of ^{90}Sr intake in the referent settlements. If data for a particular calendar year were not available for a given referent settlement, a linear interpolation was used between years when such measurements had been performed. Table 12 shows estimates of dietary ^{90}Sr intake in referent settlements normalized per unit density of ^{90}Sr contamination.

In addition to separate product sampling, in 1961–1964 the sampling of actual rations was performed in several EURT settlements. Sampling was performed using the "double ration method", i.e., a duplicate of the entire daily ration was taken with subsequent measurements of ^{90}Sr activity. Table 13 shows the results of measured daily intake of ^{90}Sr by adult residents of the settlements sampled compared with estimated ^{90}Sr intakes based on measurements of local foodstuffs and daily composition of local diet (Table 5).

It is seen from Table 13 that the daily intake of ^{90}Sr estimated on the basis of local food-product measurements is higher than that based on direct measurements of actual rations. This difference can be explained by the presence of imported non-contaminated products in actual rations of the residents of the EURT settlements.

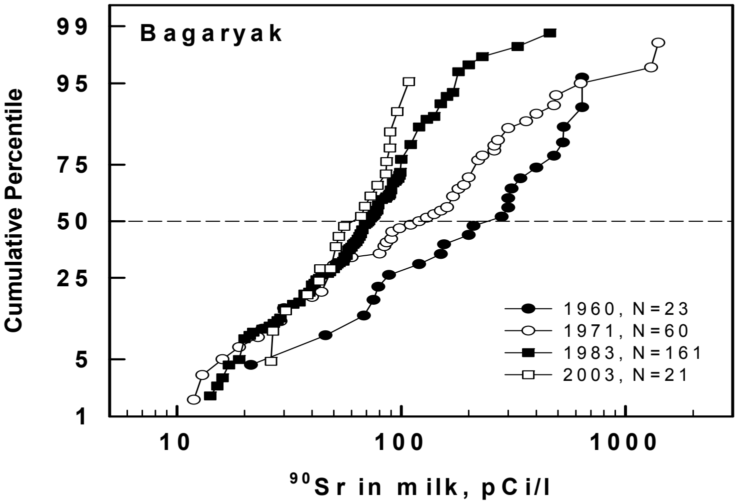

Fig. 2. Statistical distribution of ^{90}Sr concentration in milk samples analyzed at different times after the explosion in the settlement of Bagaryak.

Table 12. Estimated daily ^{90}Sr intake normalized per unit density of ^{90}Sr contamination (1 Ci km^{-2}) for adult residents of non-evacuated EURT settlements.

Calendar year	Average daily intake, Bq day^{-1}	Average daily intake, pCi day^{-1}	Calendar year	Average daily intake, Bq day^{-1}	Average daily intake, pCi day^{-1}
1961	12	330	1983	1.7	46
1962	10	270	1984	1.5	41
1963	9.0	240	1985	1.6	44
1964	8.5	230	1986	1.5	41
1965	7.6	210	1987	1.5	40
1966	7.1	190	1988	1.3	36
1967	6.3	170	1989	1.3	35
1968	5.7	150	1990	1.3	34
1969	5.0	140	1991	1.2	32
1970	4.4	120	1992	1.2	32
1971	3.7	100	1993	1.2	31
1972	3.6	96	1994	1.1	30
1973	3.5	93	1995	1.0	28
1974	3.2	87	1996	1.0	27
1975	3.0	81	1997	1.0	27
1976	2.7	73	1998	1.2	31
1977	2.6	70	1999	1.2	31
1978	2.4	66	2000	1.2	33
1979	2.4	65	2001	1.3	34
1980	2.3	61	2002	1.3	34
1981	2.2	60	2003	1.0	27
1982	2.1	57			

Table 13. Measured daily ^{90}Sr intake by adult residents of the EURT settlements compared with estimates obtained on the basis of measurements of local foodstuffs.

Settlement	Year of investigations	Measured ^{90}Sr intake with actual rations,[a] pCi/day		Estimated ^{90}Sr intake, pCi d^{-1}	Number of samples
		x_g	σ_g		
Allaky	1961	114	1.8	287	15
Bagaryak	1961	116	1.7	530	8
Boulzy	1964	155	2.3	210	89

[a] Geometric means and geometric standard deviations are given as appropriate statistical characteristics, because the distribution of ^{90}Sr in rations follows the log-normal distribution.

Fig. 3 demonstrates empirical distributions of ^{90}Sr concentrations in daily adult rations of residents of Boulzy settlement obtained on the basis of measurements of 89 samples performed in 1964. It is shown in Fig. 3 that the empirical distribution tends to be log-normal. This confirms that the geometric mean is an appropriate statistical characteristic for the derivation of deposition density-to-intake-conversion-factors.

2.2 RECONSTRUCTION OF ^{90}Sr INTAKE ON THE BASIS OF RADIONUCLIDE MEASUREMENTS IN BONES

Estimation of ^{90}Sr-intake for residents of the EURT settlements on the basis of measurements of radionuclide concentration in bones is a complicated task. Such measurements were performed in different calendar years after the accident, and samples were collected from donors of different ages in settlements located in areas with different densities of contamination. Another problem in the evaluation of such disparate data is the evaluation and subtraction of global ^{90}Sr, for which levels significantly changed during the 1960s. Therefore, the combination of data on measured ^{90}Sr concentration in bones and assumptions on the dynamics of radionuclide intake must be used.

Sampling was performed during postmortem examinations that took place mainly in departments of forensic medicine. The study encompassed a different number of settlements in different regions, and covered different time periods. The donors were born between the years 1865 and 1984; their age ranged from newborns to 99-years old; and the period of observation embraced 1951 through 1989. Database MAN allowed selection of information for donors included in the Roster of the exposed population (residents of the Techa River and/or EURT

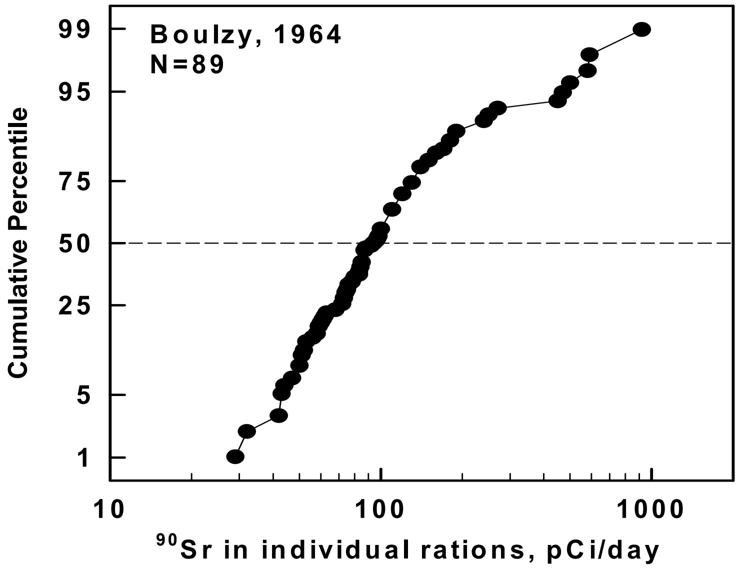

Fig. 3. Statistical distribution of ^{90}Sr concentrations in rations analyzed in 1964 for adult residents of Boulzy.

areas with contamination density higher 1 Ci km^{-2}). For these donors, detailed information on individual-residence history was extracted. For settlements located on territories of lower contamination, the Autopsy Registry contains information on the last location (village) of residence.

^{90}Sr concentration in bone samples was determined by radiometric methods in 1957–1960; subsequently, radiochemical methods were used (Methodological Guidelines 1960). ^{90}Sr concentration was estimated as pCi ^{90}Sr per gram Ca in bone. Ca content in bone ash was assumed to constitute 36% (ICRP 1995). Most samples were of rib bones, because this type of bone tissue was considered to be representative for estimation of ^{90}Sr concentration in the skeleton. However, if a person was a donor of several bone samples (for example, femur, vertebrae, rib, temporal samples) average ^{90}Sr concentration in the skeleton was estimated by taking into account the weight contribution of each measured bone to total skeletal mass as given in (ICRP 1995).

2.2.1. Description of the database on ^{90}Sr measurements in human bone

As a result of monitoring of human exposure in the Urals Region, unique data on postmortem ^{90}Sr measurements in bones were compiled at the URCRM. On the basis of these data, a computer registry of autopsy measurements was established in 1995–2002. The registry includes three sets of information: information on donors (individual-identification code, sex, age, etc.); information on bone samples (name, wet weight, ash weight, ^{90}Sr concentration, etc.); and data on sources of archival information. The registry contains data on 11,200 samples from 6,000 residents of the Urals territories with different characteristics of contamination: global fallout (located far from Mayak), EURT and KT (Tolstykh et al. 2005).

Sampling was performed during postmortem examinations that took place mainly in departments of forensic medicine. The study encompassed a different number of settlements in different regions, and covered different time periods. The donors were born between the years 1865 and 1984; their age ranged from newborns to 99-years old; and the period of observation embraced 1951 through 1989. Database MAN allowed selection of information for donors included in the Roster of the exposed population (residents of the Techa River and/or EURT areas with contamination density higher 1 Ci km^{-2}). For these donors, detailed information on individual-residence history was extracted. For settlements located on territories of lower contamination, the Autopsy Registry contains information on the last location (village) of residence.

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2.2.2. Analysis of data on ^{90}Sr in bones for residents of areas with different contamination density

Characteristics of the groups of donors who lived on territories with different initial densities of ^{90}Sr-soil contamination are presented in Table 14.

As shown in Table 14, two groups of donors lived on EURT territories with two differing levels of ^{90}Sr-soil contamination density: >0.6 Ci km^{-2} (Group #1) and 0.2–0.6 Ci km^{-2} (Group #2). An additional two groups of donors lived in settlements beyond the borders of the EURT; these two groups are named "control-north" and "control-south." The division of the two control groups is determined by the location of the Mayak PA. According to our preliminary data, ^{90}Sr content in environmental and human-tissue samples in the northern part of Chelyabinsk Oblast and in adjacent territories of Sverdlovsk Oblast (where the density of ^{90}Sr-soil contamination in the 1990s was less than 0.1 Ci km^{-2}) exceeded average values characteristic for the Russian Federation. In the southern and west-southern part of Chelyabinsk Oblast, where the impact of Mayak PA was minimal, the levels of ^{90}Sr accumulation in bone were close to that from global levels.

Bone sampling was intermittent: Most samples were collected before 1975. Samples for the period from 1975 to 1982 are sparse. Bone sampling in the "control-south" group was performed only in 1973–1975 and in 1983–1986; therefore, the dynamics of ^{90}Sr content in the skeleton cannot be studied in this group.

Because each group of donors is represented by persons of different years of birth, only adult donors at the time of the accident were included in the analysis (donors of 1939 year of birth and older). This allowed exclusion of the effect of age on ^{90}Sr retention in bone. Because the distribution of ^{90}Sr in bones in population groups is described by a lognormal distribution (Schubert and Brodsky 1967), the geometric mean of ^{90}Sr concentration in the skeleton was calculated for each time point. Fig. 4 shows the dynamics of ^{90}Sr concentration in the skeleton

Table 14. Characteristics of groups of donors who lived on territories of different initial (in 1957) ^{90}Sr-contamination density.

Group	Settlement-specific ^{90}Sr-contamination density, Ci km^{-2}	Number of donors	Number of settlements	Period of sampling, year
1	>0.6	181	19	1957–1975; 1988
2	0.2–0.6	762	59	1960–1975; 1984–1988
3	<0.1 "control north"	1481	93	1961–1974; 1983–1985
4	<0.1 "control south"	369	45	1973–1975; 1984–1986

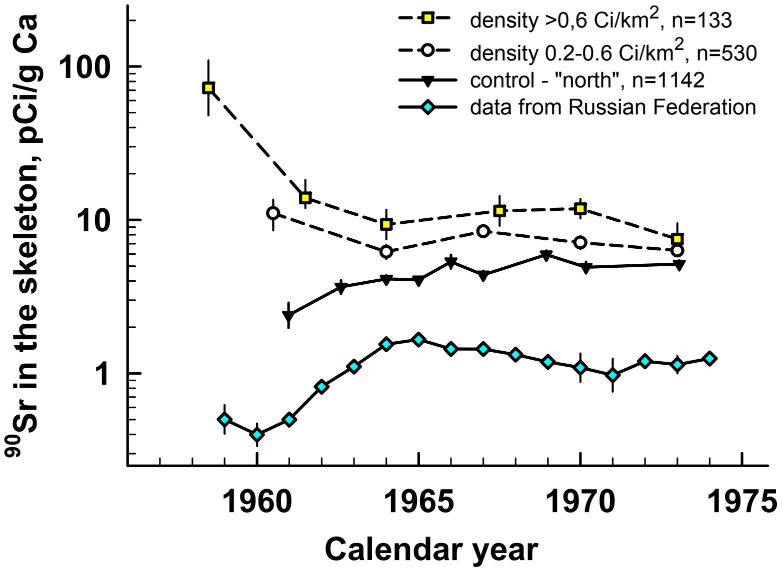

Fig. 4. The dynamics of ^{90}Sr concentration in the skeleton for donors who lived on territories with different ^{90}Sr-contamination density and average data for the Russian Federation (Tolstykh et al. 2005) on ^{90}Sr concentration in the skeleton due to global fallout. Geometric means and standard errors are indicated.

for donors who lived on territories with different levels of ^{90}Sr-contamination density. For comparison, average levels of ^{90}Sr concentration in bone are presented for residents of the Russian Federation (Tolstykh et al. 2005).

A statistically significant difference in ^{90}Sr concentration in the skeleton is observed among all groups of Urals residents in 1958–1970. These three groups are also significantly different from average data for the population of the Russian Federation. In 1973–1974, i.e., 17 years after the accident, statistically significant differences are observed only between the “most contaminated group” (settlement-specific ^{90}Sr-contamination density >0.6 Ci km^{-2}) and “control-north” group.

In donors of “control-south” group the average level of ^{90}Sr concentration in bone was about 2 pCi (g Ca)$^{-1}$ in 1973–1975. This value is slightly higher than average data for Russia [1.0–1.4 pCi (g Ca)$^{-1}$], but significantly lower than the corresponding value for “control-north” group [5.2 pCi (g Ca)$^{-1}$].

The time dependencies shown in Fig. 4 allow analysis of the influence of three peaks of ^{90}Sr intake (1957-EURT formation; 1963–1964-peak of global fallout; and 1967-Karachay Trace formation) on ^{90}Sr concentration in bone for different groups of residents. As shown in Fig. 4, global fallout mainly influenced the concentration of ^{90}Sr in bone of individuals from the “control-north” group, for whom the ^{90}Sr concentration increased by a factor of three in the period from 1960 to 1965. The accident of 1957 dominated in the other Urals groups (contamination density by ^{90}Sr 0.2–0.6 and >0.6 Ci km^{-2}). In these groups a decrease in ^{90}Sr concentration in bone was observed in 1958–1965. Additional contamination of the territories adjacent to the Mayak PA in 1967, which superimposed on the already existing contamination of the EURT, did not result in a significant increase in ^{90}Sr concentration in bone (it is seen from Fig. 4 that a peak in ^{90}Sr concentration in 1967–1968 was not observed), but reduced the rate of ^{90}Sr elimination from bone. As a result, the concentration of ^{90}Sr in bone decreased only slightly after 1965. The concentration in "control-north" group compared to levels due to global fallout observed in the Russian Federation group were twice higher in 1964–1965 and three times higher in 1967–1968.

After 1975, bone sampling was performed in 1983–1988. The maximal ^{90}Sr concentration in bone [6 pCi (g Ca)$^{-1}$] was observed in residents of the more contaminated territories (>0.6 Ci km^{-2}). The concentrations of ^{90}Sr in bone in the other groups were as follows: northern groups ("control-north" and group 0.2–0.6 Ci km^{-2}) – 3.1–3.7 pCi (g Ca)$^{-1}$; "control-south" – 2.6 pCi (g Ca)$^{-1}$ (differences between these groups are significant). The average value of ^{90}Sr concentration in bone for residents of the Russian Federation at this time was 1.85 pCi (g Ca)$^{-1}$ (Prokofiev et al. 1987), which is not significantly different from the values for the "control-south" group. These results are in a good agreement with data published for the City of Snezhinsk located in the northern part of Chelyabinsk Oblast (^{90}Sr-contamination density <0.1 Ci km^{-2}). In 1983–1984, the average ^{90}Sr in rib of adult residents of Snezhinsk (1939 year of birth and older, n = 94) was 3.1 pCi (g Ca)$^{-1}$ (Gavrilovsky et al. 2004).

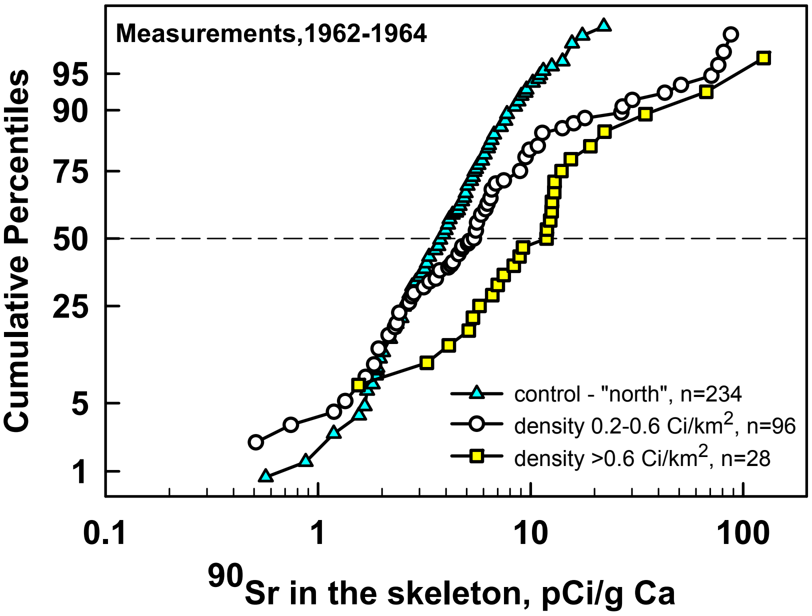

Fig. 5. The distributions of ^{90}Sr concentration in bone measured in 1962–1964 in different groups of donors.

Statistical distributions of ^{90}Sr concentration in bones of adult residents of different territories allow estimation of ^{90}Sr-bone variability within groups. Fig. 5 shows the distributions of ^{90}Sr concentration in bone measured in 1962–1964.

It is seen from Fig. 5 that the distributions for different groups are superimposed in the low-activity range. This activity level corresponds to global (average values for Russia) levels of ^{90}Sr concentration in the skeleton and, possibly, reflects those people who did not use local (contaminated) foodstuffs in their diet. However, median values of ^{90}Sr concentration in the skeleton differ significantly and are related to the contamination density of ^{90}Sr. Geometric standard deviations (σ_g) are close for territories with ^{90}Sr-contamination density >0.6 Ci/km^2 and 0.2–0.6 Ci km^{-2} ($\sigma_g = 3.7$ and 3.5, respectively); for "control-north" group (contamination density <0.1 Ci/km^2) the dispersion in values was significantly lower ($\sigma_g = 2.1$).

Data presented in Fig. 4 allow the assessment of the normalized value of ^{90}Sr concentration in the skeleton per unit initial soil-contamination density. The most interesting data represent measurements obtained before 1960, because they were obtained during the period of maximal ^{90}Sr ingestion and before additional contamination as a result of global fallout and windblown of activity from Karachay Lake in 1967. According to our data the average (geometric) ^{90}Sr concentration in bone in 1958–1960 per unit ^{90}Sr-contamination density (1 Ci km^{-2}) was 44 pCi (g Ca)$^{-1}$, which is characterized by high variability, $\sigma_g = 4.0$.

The following factors can influence the variability of normalized ^{90}Sr concentration in bone: (1) uncertainty in the estimate of ^{90}Sr-contamination density; (2) variability in ^{90}Sr migration through food chains; (3) rejection of contaminated local foodstuff and replacement by uncontaminated ones; and (4) natural migration of the population from the more contaminated territories. All these factors were characteristic for the Urals Region. Fig. 6 shows average concentrations of ^{90}Sr in the skeleton in adult residents of several settlements located on territories with different densities of ^{90}Sr contamination.

As shown in Fig. 6, there is no apparent dependence of ^{90}Sr concentration in bone with ^{90}Sr-contamination density. This can also be illustrated in the example of settlements located on territories with similar ^{90}Sr-contamination densities (Fig. 7). As seen in Fig. 7, the concentration of ^{90}Sr in bones of residents of Kasly and Ozersk, located on territories with similar initial^{90}Sr-contamination density (0.2–0.3 Ci km^{-2}), is significantly different. This fact can be explained by preferential use of imported foodstuffs by residents of the "closed" industrial town of Ozersk (where the workers from the Mayak PA lived) and use of foodstuffs from local farms by the residents of Kasly. In spite of the fact that the EURT did not cover the territory of Kasly, local cattle were grazed on highly contaminated pastures located near the town.

These results indicate the necessity of a very careful analysis of all available data used for the estimation of radionuclide accumulation in man and for the assessment of dose from internal exposure. Calculations based on settlement-specific ^{90}Sr-contamination density have high uncertainty and can result in unreliable estimates of dose. Therefore, priority should be given to a direct approach based on the use of available measurements. Data contained in the Autopsy Registry give a unique possibility to apply the direct approach for the reconstruction of ^{90}Sr

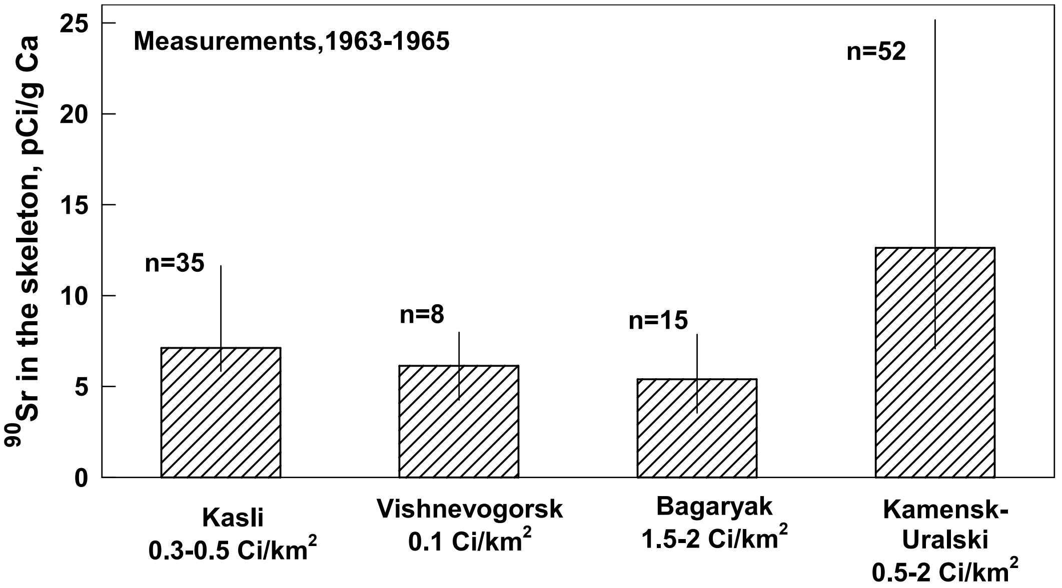

Fig. 6. Geometric means of ^{90}Sr concentration in the skeleton in adult residents of several settlements located on territories with different ^{90}Sr-contamination density. Bars indicate geometric standard errors.

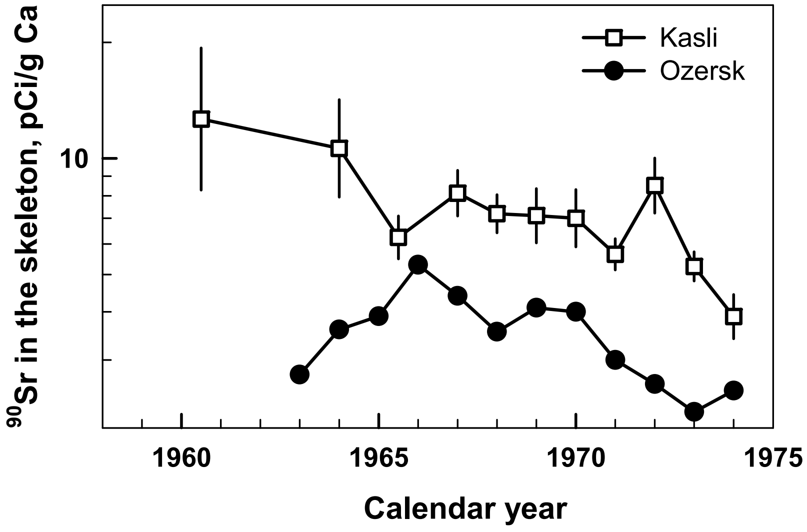

Fig. 7. The dynamics of ^{90}Sr concentration in the skeleton in adult residents of Kasly and Ozersk. Data for Ozersk were kindly provided by K.G. Suslova.

intake for residents of the EURT settlements, where measurements on ^{90}Sr-concentrations in the skeleton are available.

2.2.3 Reconstruction of ^{90}Sr intake for referent settlements on the basis of data on ^{90}Sr in bones

The reconstruction of radionuclide intake with use of measurements of ^{90}Sr in bones is based on estimating the ^{90}Sr content in the skeleton with use of a biokinetic model for strontium and dynamics of dietary intake of the radionuclide. The dynamics of dietary ^{90}Sr intake were estimated in detail for referent settlements based on numerous measurements of total-beta activity and ^{90}Sr specific activity in local foodstuffs. Thus, the reconstruction of dietary intake of radionuclides using data on measured ^{90}Sr concentration in the skeleton was performed for residents of the referent settlements. This allows comparison of the estimates obtained using two methods for reconstruction of ^{90}Sr intake.

For reconstruction of ^{90}Sr intake on the basis of radiochemical measurements of ^{90}Sr concentration in the skeleton for residents of the referent settlements, data on ^{90}Sr concentration in the skeleton have been extracted from the Autopsy Registry for adults. These data (as pCi ^{90}Sr per g Ca) were converted to ^{90}Sr content in the skeleton per unit ^{90}Sr-contamination density of a settlement where a person lived with use of data on Ca content in the skeleton dependent on age and gender of a person (Shagina et al. 2002) and data from the reference book on ^{90}Sr-contamination density of EURT villages (Peremyslova et al. 2004).

The other two significant components for reconstruction of ^{90}Sr intake based on measurements of the radionuclide in the skeleton are a biokinetic model for strontium and the dynamics of dietary ^{90}Sr intake in referent settlements. Previous estimates (Tolstykh et al. 2002) were based on use of a retention function of strontium in bone developed by Degteva and Kozheurov (1994). This model did not account for gender differences in strontium metabolism and only considered the skeleton, which is the main site of strontium retention. Recently, a new age and gender-dependent biokinetic model for strontium was developed by Shagina et al. (2002). This newer model is now used for calculation of ^{90}Sr content in the skeleton for reconstruction of radionuclide intake. The dynamics of dietary ^{90}Sr intake (i.e., relative intake) was used as evaluated for referent settlements (Tables 10 and 12). Estimated ^{90}Sr contents in the skeleton with use of the two models for strontium metabolism and the dynamics of the radionuclide intakes in referent settlements are shown in Fig. 8 in comparison with measured ^{90}Sr in the skeleton for adult residents of the referent settlements. It is seen in Fig.8 that predicted values of ^{90}Sr content in the skeleton based on different models are very similar. The slightly higher values obtained with the new model can be explained by its taking into account strontium recycling in the human body.

The time-dependence of ^{90}Sr-content in the skeleton for residents of five referent settlements with peak value in the first period after the accident (1959–1960) and further significant drop in subsequent years (Fig. 8) is comparable with data obtained for residents of other villages [for example, for residents of Kasly (Fig. 7)] or residents of the territories with different ^{90}Sr-contamination density (Fig.4).

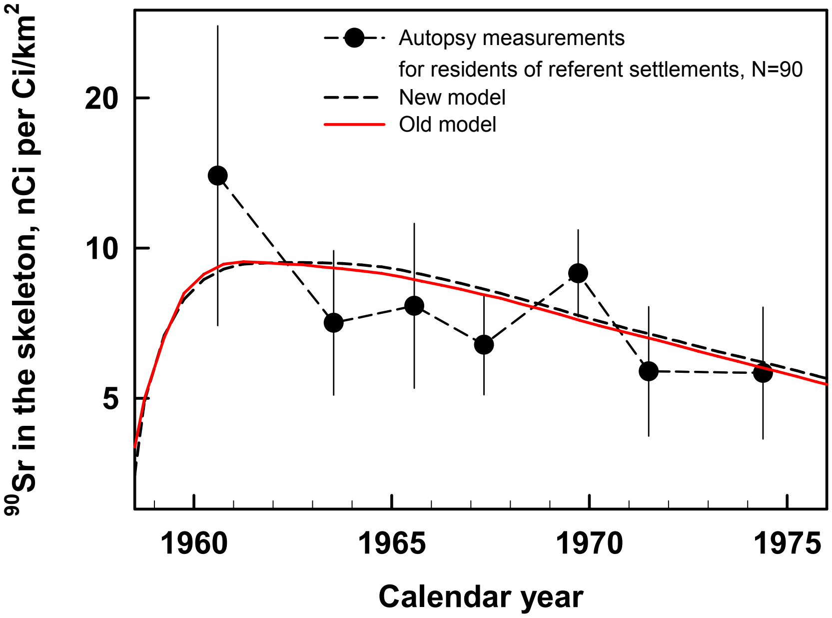

Fig. 8. ^{90}*Sr content in the skeleton calculated on the basis of the dynamics of estimated dietary intake (this report) and two models for strontium retention in humans (model of Degteva and Kozheurov 1994, referred as "old" model and model of Shagina et al. 2002, referred in as "new" model) fitted to measured values of* ^{90}*Sr for residents of five referent settlements. Measured values are given as geometric means with standard errors.*

Nevertheless, the absence of a sufficient number of measurements obtained in 1957–1960 makes it very difficult to describe precisely the dynamics of ^{90}Sr content in the skeleton for this period. The observed dynamics of ^{90}Sr content in the skeleton implies that there could be a significant reduction in the levels of ingested ^{90}Sr in 1960 compared to the previous period. The possibility of such reduction could be reasonable, because:

1. During the first period after the accident the main source of ^{90}Sr intake was bread baked at home using flour made of grain acquired from local collective farms, i.e., locally produced grain. In 1957–1958, contamination of local grain occurred as a result of fallout during passage of the radioactive cloud. As shown by measurements of total-beta activity in bread and grain performed in this period in some villages, contamination of grain and of baked bread was very heterogeneous with the values varying over two orders of magnitude. In subsequent years contamination of grain was mainly due to soil-root uptake, although migration of radionuclides with wind occurred. In 1960, substitution of imported products for contaminated grain started in EURT settlements, which resulted in a significant reduction in levels of ^{90}Sr intake.
2. Measurements of the total activity of locally produced foodstuffs were performed in 1957–1960 in the absence of radiochemical measurements, which started only in 1960. For this period the contribution of ^{90}Sr to the activity in different foodstuffs was assumed on a theoretical basis.

3. The impact of the implementation of countermeasures that commenced in 1958 were more intensive in 1959–1960.

For these reasons, four different dynamics of ^{90}Sr intake were assumed, as illustrated in Fig. 9. Each of them considers high ^{90}Sr-intake during the first period after the accident and significant reduction of the intake before 1960 or in 1960:

Assumed Dynamics-I: Significantly high intake from the beginning of intake until May 1958, i.e., during the period of surface contamination, with steep drop in the levels of intake when the soil-root route of contamination prevailed. The same dynamics of ^{90}Sr intake in 1958–1960 as of the estimated intake followed by a 10-fold decrease in 1960; the same dynamics of ^{90}Sr intake as of the estimated intake after 1960.

Assumed Dynamics-II: Significantly high intake from the beginning of intake until May 1958. A smaller decrease in the intake in 1958 compared to Dynamics-I, and a continuous drop in the intake levels until the end of 1960; a second steep drop in the levels of ^{90}Sr intake in 1960 and the same dynamics of ^{90}Sr intake as of the estimated intake after 1960.

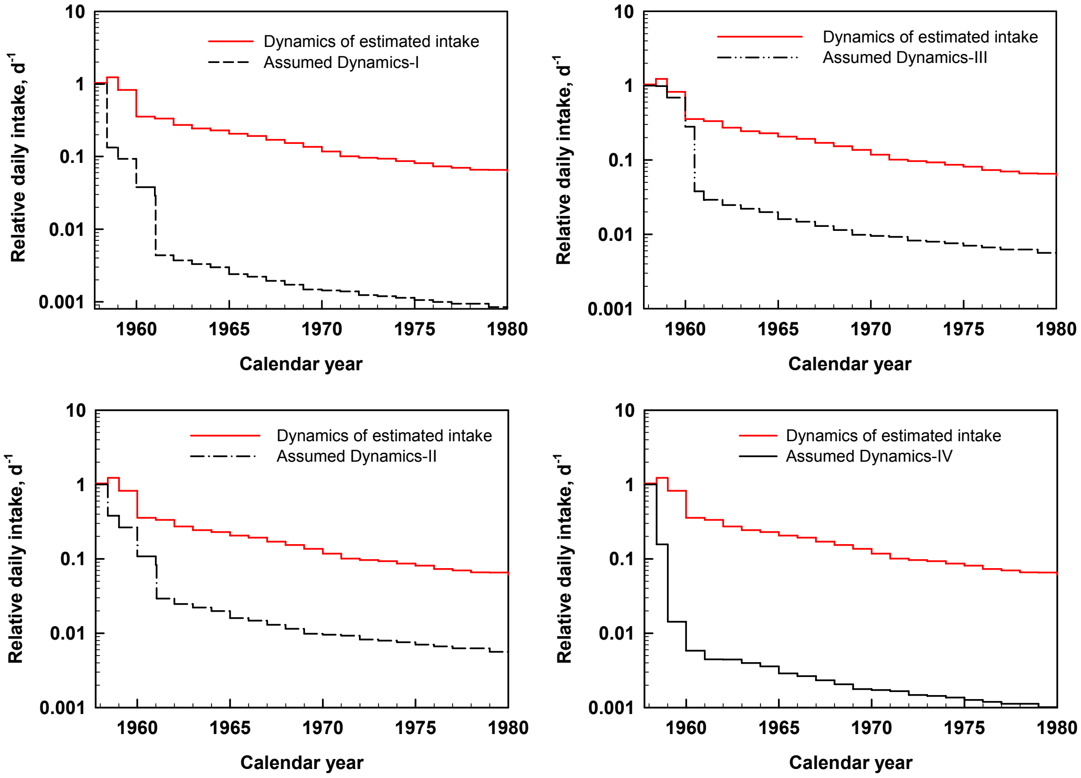

Fig. 9. Four assumed dynamics of relative ^{90}Sr intake compared to the relative ^{90}Sr-intake estimated on the basis of measurements of local foodstuffs (Tables 10 and 12). These dynamics of relative ^{90}Sr-intake are used for fitting ^{90}Sr-content in the skeleton to measured values (Fig. 10).

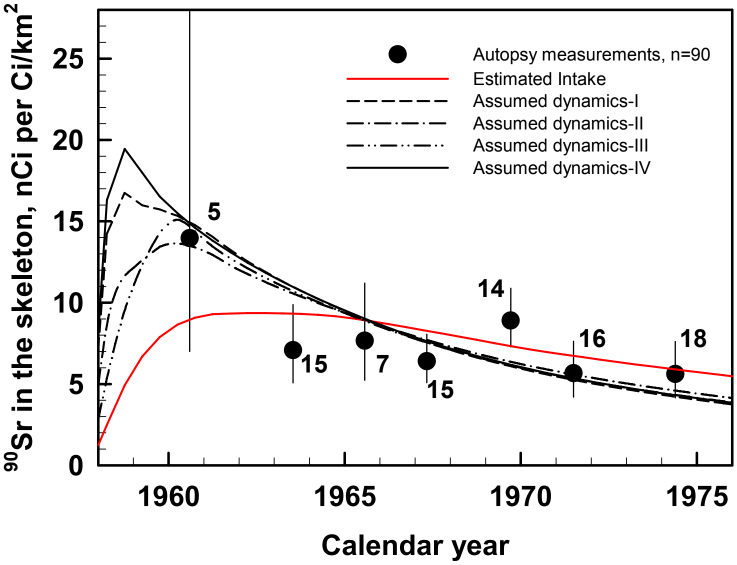

Fig. 10. Comparison of fitted ^{90}Sr contents in the skeleton obtained on the basis of four assumed dynamics of ^{90}Sr intake with measured ^{90}Sr in the skeleton in adult residents of five referent settlements.

Assumed Dynamics-III: Significantly high intake during the first three years after the explosion, 1957–1960. Two steep drops in the levels of intake in the beginning and in the middle of 1960; the same dynamics of ^{90}Sr intake as of the estimated intake after mid-1960.

Assumed Dynamics-IV: Significantly high intake from the beginning of intake until May 1958 during the period of surface contamination, two steep drops in 1958 and in 1959; the same dynamics in ^{90}Sr intake as estimated from contamination of local foodstuffs commencing from 1960.

These assumed dynamics of relative ^{90}Sr-intake were used for fitting ^{90}Sr contents in the skeleton obtained with use of the new biokinetic model (Shagina et al. 2002) to measured values. Fig. 10 shows fitted ^{90}Sr contents in the skeleton obtained on the basis of these dynamics of radionuclide intake. It is seen in Fig. 10 that assumptions of higher intakes of ^{90}Sr before 1960 result in a reasonable time dependence in calculated ^{90}Sr contents in the skeleton compared to measured values. The model predictions obtained for the first period after the accident lie in the range of uncertainties in measured values.

The resulting levels of daily ^{90}Sr intake in referent settlements obtained by fitting to measurements of ^{90}Sr in bones are shown in Fig. 11. It is seen that average levels of ^{90}Sr intake lie within a range of an order of magnitude after 1959. Therefore, the selection of an appropriate intake for the calculation of doses is very important for persons who migrated to EURT settlements after 1959.

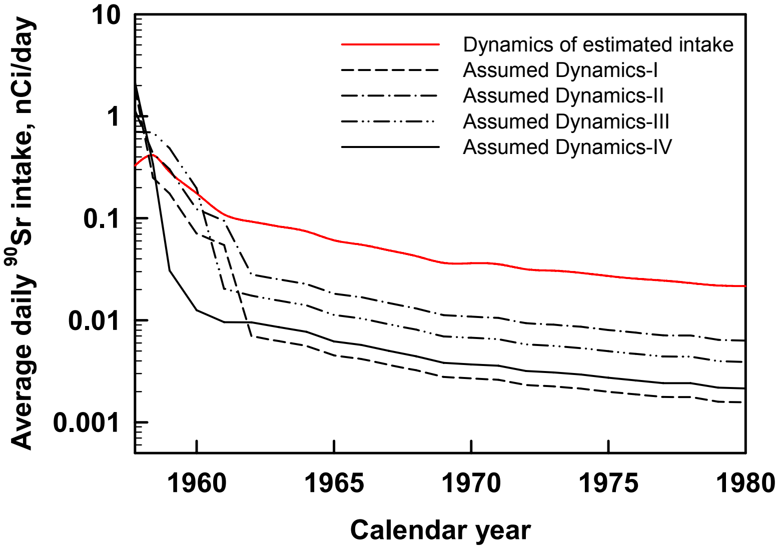

Fig. 11. Levels of daily ^{90}Sr intake obtained on the basis of measured contents in bones and dynamics of estimated ^{90}Sr-intake function (this report) and assumed dynamics of ^{90}Sr intake (shown in Fig.10). These data could be applied for the estimation of the uncertainties in levels of ^{90}Sr ingestion for residents of the EURT settlements.

2.2.4. Reconstruction of ^{90}Sr intake for other non-evacuated settlements on the basis of available data on ^{90}Sr in bones

Because the direct approach ultimately results in more reliable estimates, the same approach was used to derive the intake function on the basis of measurements of ^{90}Sr-body burdens for rural residents living in other settlements located on the EURT. This approach is based on the assumption that the dynamics of radionuclide intake in other villages was the same as in referent villages. The evidence for the same dynamics of ^{90}Sr intake in EURT villages could be demonstrated by considering the dynamics of ^{90}Sr-body burdens in the skeleton. Fig. 12 shows the time dependence in ^{90}Sr contents in the skeleton for adult residents living in villages located on territories with different initial ^{90}Sr-contamination densities: the group of residents living in highly contaminated villages (>0.6 Ci km^{-2}) and the group of residents living in villages with intermediate contamination densities (0.2–0.6 Ci km^{-2}).

It is seen in Fig. 12 that the dynamics of ^{90}Sr content in the skeleton in adult residents living on territories with different ^{90}Sr-contamination density are similar and are characterized with a peak value soon after the accident and a slower decrease at later times. A similar pattern in the content of ^{90}Sr in the skeleton is observed for residents of Kasly (Fig. 7). This suggests the same dynamics of ^{90}Sr intake in EURT villages.

Modelled ^{90}Sr burdens in the skeleton were estimated by fitting calculations based on different relative dynamics of the radionuclide intake as assumed for residents of the referent settlements (Fig. 9). Fig. 12 shows comparison of calculated ^{90}Sr content in the skeleton with

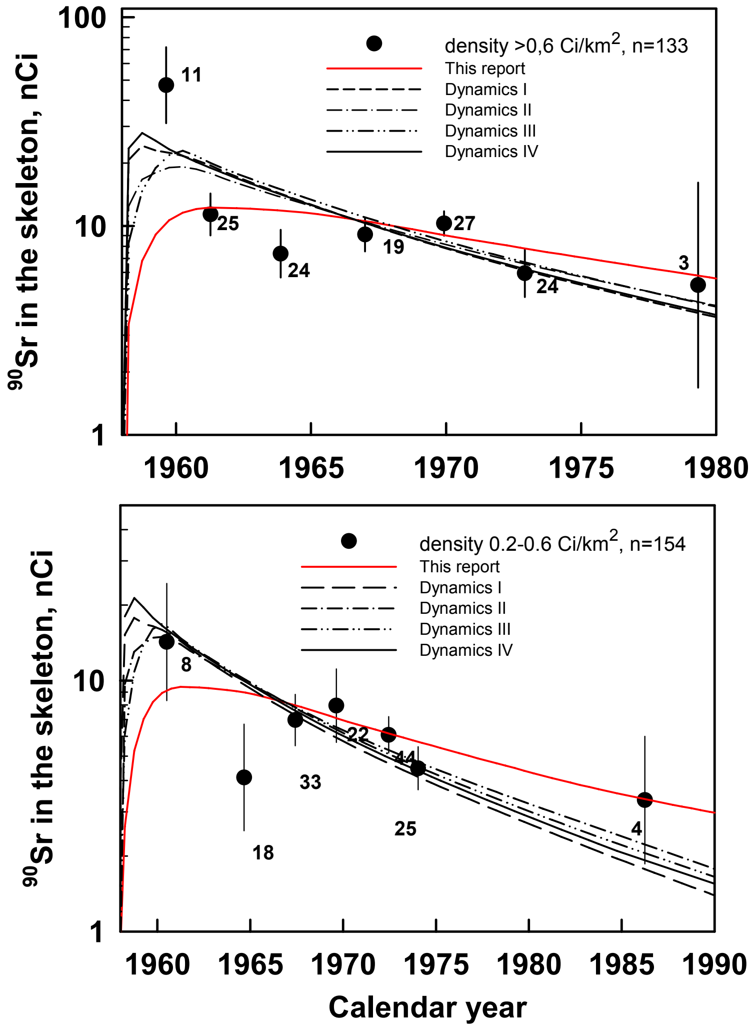

Fig. 12. The content of ^{90}Sr in the skeleton of residents living in EURT villages located on territories with different contamination densities (>0.6 Ci km^{-2} and between 0.2 and 0.6 Ci km^{-2}) dependent on time after the accident in comparison with calculated values obtained using different dynamics of radionuclide intake. The numbers beside each point indicate the number of data points.

values derived from measurements of ^{90}Sr concentration in bones obtained for residents of villages located on areas with different levels of ^{90}Sr-contamination density. For residents living in villages with ^{90}Sr-contamination density 0.2–0.6 Ci km^{-2} model calculations based on different assumed dynamics of the radionuclide intake satisfactorily describe measured ^{90}Sr in the skeleton. However, for residents living in villages with ^{90}Sr-contamination density >0.6 Ci km^{-2}, model calculations are lower for the first period after the accident than the levels actually observed. Moreover, because the dynamics of estimated intake do not imply a significant reduction in radionuclide intake as observed in ^{90}Sr-burden during the first period after the accident, calculated ^{90}Sr contents in the skeleton were fitted to measurements obtained after 1960.

Therefore, for residents living in villages located on the EURT territory the same dynamics of ^{90}Sr intake can be used as for residents of the referent settlements. For residents who lived in cities the dynamics of ^{90}Sr intake could be different, because they are supplied by foodstuffs imported from other regions. However, if a city is provided by bread or milk from collective farms of adjacent territories, the same dynamics in ^{90}Sr intake could be assumed. Nevertheless, Fig. 6 represents data obtained both for rural and urban populations (Kamensk-Uralsk, Kamyshlov, Kasly) and the same dynamics in ^{90}Sr content in the skeleton is observed for a larger group of residents.

Table 15 shows estimates of the total ^{90}Sr intake in 1957–1970 obtained by fitting calculated ^{90}Sr-burdens in the skeleton to actual measured values for residents of the EURT villages located on territories with different contamination densities. It is seen from Table 15, that the total ^{90}Sr-intake estimated for four different dynamics are closer to each other and about 30% higher that the total intake obtained under assumption of the relative dynamics of radionuclide intake derived from measurements of foodstuffs in referent settlements. As shown in Fig. 12, predictions of ^{90}Sr in the skeleton obtained for these dynamics don't satisfactorily describe the first period after the accident.

Evidence for the same dynamics of ^{90}Sr intake in villages located on the EURT territory as in the referent settlements makes possible the reconstruction of village-specific ^{90}Sr-intake functions for those villages having a sufficient number of donors with measured values of ^{90}Sr concentration in the skeleton.

2.3 COMPARISON OF ^{90}Sr-INTAKE ESTIMATES OBTAINED BY DIFFERENT METHODS

Fig. 13 shows estimated ^{90}Sr content in the skeleton using our biokinetic model for strontium (Shagina et al. 2002) and estimates of ^{90}Sr-intake obtained by different methods: a) on the basis of measurements of local foodstuffs (Tables 10 and 12) and b) by fitting the dynamics

Table 15. Estimates of total-^{90}Sr intake for adult residents of EURT villages located on territories with different contamination densities over the period 1957–1970.

Versions of ^{90}Sr intake	Total ^{90}Sr intake, nCi (^{90}Sr-contamination density >0.6 Ci km^{-2})	Total ^{90}Sr intake, nCi (^{90}Sr-contamination density 0.2–0.6 Ci km^{-2})
Dynamics of ^{90}Sr intake based on measurements of local foodstuffs	780	600
Assumed dynamics I	980	720
Assumed dynamics II	960	740
Assumed dynamics III	1045	765
Assumed dynamics IV	975	745

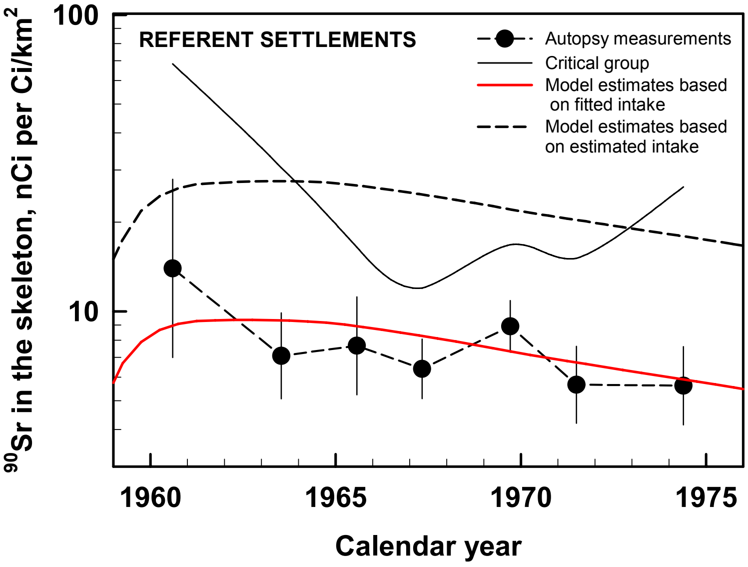

Fig. 13. Comparison of calculated values of ^{90}Sr content in the skeleton based on dietary intake estimated from measurements of local foodstuffs (dashed line) and from measurements of ^{90}Sr concentration in bones (red line). Black points represent geometric means of ^{90}Sr content in the skeleton (with standard errors) derived from autopsy measurements of ^{90}Sr concentration in bones obtained for adult residents of referent settlements.

of estimated ^{90}Sr-intake to measurements of ^{90}Sr in bones (shown by red curve in Fig.13) in comparison with ^{90}Sr content in the skeleton for adult residents of referent settlements derived from measurements of ^{90}Sr concentration in bones.

As can be seen, measured levels of ^{90}Sr in the skeleton are significantly lower than calculated values based on measurements of ^{90}Sr-intake with local foodstuffs. These results can be explained by natural reasons, because the following assumptions were made for the calculation of ^{90}Sr content in diet:

1. The basic diet consists of foodstuffs of local production with measured ^{90}Sr concentration. Therefore, account has not been taken for the rejection and replacement of contaminated foodstuffs by non-contaminated ones and the use of non-local foodstuffs;
2. The loss of ^{90}Sr during cooking was ignored (the actual loss is suspected to be about 20%);
3. Estimates of ^{90}Sr in local foodstuffs for the first period after the accident (September 1957–April 1958) were obtained with great uncertainty; estimates based on measurements of total-beta activity during the period before 1960 were not obtained reliably in the absence of radiochemical measurements of specific radionuclides in food samples;
4. Sampling during the first period after the accident was not sufficient and mostly performed in villages with high contamination; and

5. Contamination of the territories within a village was very heterogeneous.

The results shown in Fig.13 confirm that the estimation of dietary intake based on measurements of ^{90}Sr activity in local foodstuffs is reliable for about 15% of the adult population (so called critical group) with maximal levels of the intake.

It was shown in Peremyslova et al. (2004) that ^{90}Sr-intake functions were evaluated by many authors at different times after the accident. Early estimates of ^{90}Sr intake were based on direct measurements of local foodstuffs in specific (the same) settlements (Bournazyan 1974); while later estimates were based on normalized values of ^{90}Sr intake (per unit of ^{90}Sr-contamination density) and estimated contamination density (Ternovsky et al. 1985; Romanov et al. 1997). These estimates, summarized in Peremyslova et al. (2004) and shown in left panel of Fig. 14, were used for the calculation of ^{90}Sr content in the skeleton to compare with measured ^{90}Sr in the skeleton for adult residents of referent settlements (right panel of Fig. 14).

It is seen in Fig.14 that all model predictions based on different ^{90}Sr-intake functions are higher than actually observed levels of the radionuclide in the skeleton. The model predictions based on different ^{90}Sr-ingestion functions are very similar in dynamics but none of the model predictions satisfactorily describe the dynamics of measured ^{90}Sr in bones.

Previous analysis (Tolstykh et al. 2002) performed using the intake function estimated in (Peremyslova et al. 2001) and an age-dependent model for strontium retention in human bone (Degteva and Kozheurov 1994) showed that the intake levels, which correspond to geometric means of ^{90}Sr content in the skeleton, are about 3.5 times lower than values estimated on the basis of measurements of local foodstuffs. This value is slightly higher than the value obtained in this analysis, if the same scaling approach is used (measured levels are 3 times lower than model predictions). This is explained by the fact that new estimates of the ^{90}Sr-intake function

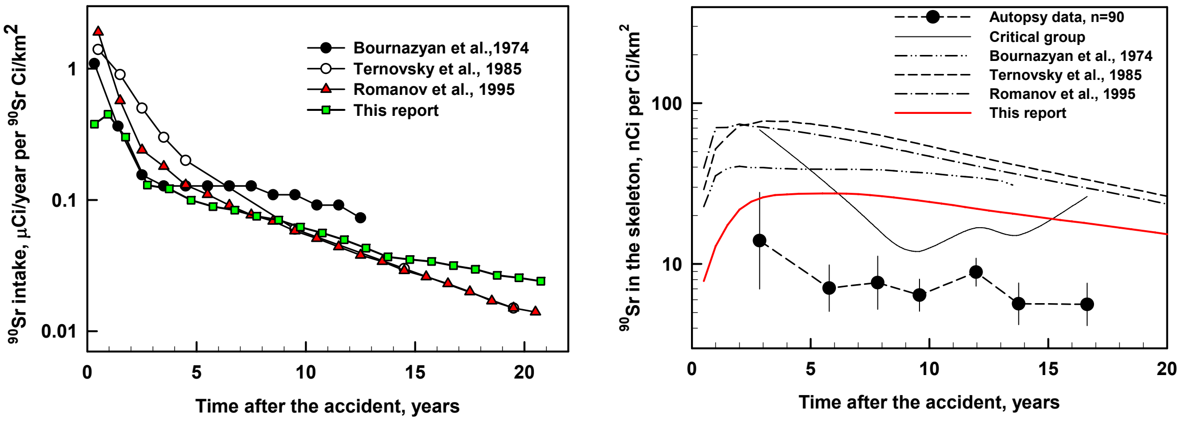

Fig. 14. Strontium-90-intake function normalized per unit of ^{90}Sr-contamination density according to different authors (left panel) and derived estimates of ^{90}Sr content in the skeleton compared to measured values for adult residents of referent settlements (right panel).

are based on more reliable assumptions on ^{90}Sr contribution to total-beta activity of bread and milk measured during the first period after the accident.

Table 16 presents estimates of the total-^{90}Sr intake per unit ^{90}Sr-contamination density in 1957–1970 obtained by different authors on the basis of environmental measurements and the estimates obtained by fitting calculated ^{90}Sr burdens in the skeleton to actual measured values for residents of five EURT referent settlements.

It is seen from Table 16 that the total-^{90}Sr intake over the period of 1957–1970 per unit ^{90}Sr-contamination density estimated by fitting calculated ^{90}Sr burdens in the skeleton obtained on the basis of different dynamics of radionuclide intake and the biokinetic model of strontium metabolism are very close and they are about 3 to 6 times lower compared to estimates based on measurements of local foodstuff contamination. Therefore, the estimation of internal doses due to ingested ^{90}Sr should be based on direct measurements of the radionuclide in the human body. For residents of the EURT settlements further analysis is required for selection of the appropriate intake function.

It is seen in Table 16 that in spite of different dynamics of ^{90}Sr-intake, the total intake of the radionuclide during 1957–1970 is very close (less than 10% difference between the dynamics of estimated intake based on environmental measurements and assumed dynamics). Functions describing average-^{90}Sr intake in referent settlements shown in Fig. 10 represent the possible range of uncertainties in the intake function.

Table 16. Estimates of the total-^{90}Sr intake per unit ^{90}Sr-contamination density over the period 1957–1970 derived from different approaches.

Approach	Versions of ^{90}Sr intake	Total ^{90}Sr intake nCi (Ci km^{-2})$^{-1}$
Estimation of ^{90}Sr intake on the basis of measurements of local foodstuff (Fig. 5)	Skryabin et al. (1985)	2700
	Romanov et al. (1997)	3500
	Peremyslova et al. (2001)	2050
	Tables 10 and 12 of this report	1690
Estimation of ^{90}Sr intake on the basis of measurements of ^{90}Sr-burdens in the skeleton in couple with assumed dynamics of intake (Fig. 6)	Dynamics of ^{90}Sr intake based on measurements of local foodstuff	565
	Assumed dynamics I	580
	Assumed dynamics II	575
	Assumed dynamics III	555
	Assumed dynamics IV	575

2.4 AN APPROACH TO ^{90}Sr-INTAKE RECONSTRUCTION FOR SETTLEMENTS WITH ABSENCE OR PAUCITY OF DATA ON ^{90}Sr IN BONES

Due to the fact that ^{90}Sr intake for residents of EURT settlements cannot be reliably estimated for the first period after the explosion due to the absence of radiochemical measurements of ^{90}Sr in local foodstuffs and deficient environmental monitoring and other factors outlined in the previous section, this may result in conservative estimation of ^{90}Sr retention in the human skeleton and of the doses from internal exposure. For this reason, measurements of ^{90}Sr concentration in the skeleton are very valuable for reconstruction of radionuclide intake.

Bone sampling was conducted in many settlements (both in villages and in towns) located on the EURT territory. Overall, the Autopsy Registry contains information on about 1,500 donors who lived in 146 EURT settlements. However, bone sampling was intermittent and within a particular village only a small number of samples was obtained. For some villages there is a sufficient number of measurements of ^{90}Sr concentration in bone samples of deceased residents (for example, bone samples were taken from 65 donors of Bagaryak for measurements), while for other villages the number of measurements is negligibly small (for example, only three samples for Allaky). Table 17 shows statistics on the number of measured donors from different settlements located on the EURT territory. Therefore, some criteria must be established in order to estimate a settlement-specific ^{90}Sr-intake function on the basis of measurements of ^{90}Sr concentration in the skeleton. Two criteria were chosen: 1) the number of measurements should be more than five, preferably obtained at a minimum of two time points and 2) the precision in estimating average intake should be met. The second criterion is based on consideration of the confidence interval desired for the estimation of average-^{90}Sr-intake function and variability in the population.

Because the intake function is reconstructed on the basis of measured ^{90}Sr concentrations in the skeleton, the desired confidence interval in ^{90}Sr-intake estimates should be propagated through confidence intervals in ^{90}Sr contents in the skeleton and then compared with variability of measured values. To estimate the desired variability in estimated ^{90}Sr contents in the skeleton

Table 17. Statistics on the number of measured donors in settlements located on EURT areas.

Number of measured donors	Number of settlements	Total number of measured donors
1–4	98	183
5–9	23	150
10–14	11	131
15–20	3	53
More than 20	11	979
Total	*146*	*1496*

a Monte-Carlo simulation was applied. A simplified model, combining power and exponential functions, is used to describe strontium retention in adult humans for the period from one month to 30 years after a single ^{90}Sr intake characterized by desired precision:

$$R(t) = I \cdot f_1 \cdot P \cdot t^{-b} \cdot e^{-\lambda \cdot t} \ , \tag{1}$$

where I is the amount of ^{90}Sr ingested (a case of single intake is considered here), f_1 is a parameter describing strontium absorption from the gastrointestinal tract, P is the fraction initially retained in the skeleton, b is the slope of the power function, and λ is the strontium-elimination rate.

This simplified retention function numerically coincides with the biokinetic model for adults used in TRDS-2000 for ^{90}Sr-dose calculations. The estimated distributions for individual parameters were based on literature data and historical URCRM results (Degteva et al. 1999). The types of distributions accepted for model parameters are presented in Table 18.

Measurements of milk samples collected from individual farms in specific settlements showed that the distribution of ^{90}Sr concentration in milk within a particular village tends to be lognormal. Therefore, it could be assumed that the reconstructed estimate of ^{90}Sr-intake is log-normally distributed with the desired 95%-confidence intervals set to be varied by a factor of two.

The resulting uncertainties in calculated ^{90}Sr contents in the skeleton are provided in Table 19; the variability is best described by lognormal functions; therefore, geometric standard deviations are shown.

The number of measured bone samples sufficient to estimate ^{90}Sr intake with the established confidence intervals (Table 19) can be evaluated with use of the following equation:

$$n = \frac{s^2 t^2_{\alpha(2),(n-1)}}{d^2} \tag{2}$$

Table 18. Range and distribution type for parameters used to estimate uncertainties in calculated ^{90}Sr content in the skeleton based on single ^{90}Sr-intake with desired confidence intervals.

Parameter	Range	Distribution
I, nCi	0.61–1.63	Lognormal
f_1, unitless	0.13–0.42	Lognormal
P, unitless	0.72–0.87	Normal
b, unitless	0.14–0.24	Normal
λ, year^{-1}	0.01–0.07	Lognormal

Table 19. Variability in estimated ^{90}Sr content in the skeleton at different times after intake.

Time after intake, years	Variability in estimated ^{90}Sr content in the skeleton, σ_g
1	1.67
5	1.73
10	1.80
15	1.90
20	2.01

In this equation, s^2 is the sample variance, estimated with n-1 degrees of freedom, d is the half-width of the established confidence intervals, and 1-α is the confidence level for the confidence interval. This equation is correct for the normal distribution. Nevertheless, because ^{90}Sr concentration in the sample is log-normally distributed (Schubert and Brodsky 1964), this equation can be applied to logarithmic values of ^{90}Sr concentration in the skeleton.

Because the variability in calculated ^{90}Sr content in the skeleton depends on time after intake (Table 19) and bone samples were collected at different times after the accident, weighted sample variances and half-widths were estimated. Because the critical values of Student's t depend on n, the unknown sample size, the solutions were achieved by an iterative process. The analysis was applied to 146 settlements, where bone sampling had been performed, and revealed that only for 19 settlements could the reconstruction of the ^{90}Sr-intake function rely on direct measurements. For other villages, even with a sufficient number of measurements, direct reconstruction is not possible because of the large variability in measured concentrations of ^{90}Sr in the skeleton.

Therefore, subsequent analysis will be based on grouping the settlements located close to each other, which are characterized with similar features of soil contamination, food supply and life style (a similar grouping was performed for residents of the referent settlements). This will allow the estimation of group-averaged ^{90}Sr-intake functions based on combined data on measured ^{90}Sr concentration in the skeleton. This analysis is now underway and should be complete by September 2006.

3. RECONSTRUCTION OF ^{90}Sr INTAKE FOR EVACUATED RESIDENTS OF THE EURT

For residents of evacuated settlements the same approach on the reconstruction of ^{90}Sr intake is applied by using data on measured ^{90}Sr-body burdens. This approach is not dependent on the relative dynamics of ^{90}Sr intake, because residents of such settlements were evacuated during relatively short periods of time after the accident, and therefore a single intake approximation is applied.

The schedule of evacuation is presented in Table 20. The residents of three settlements (Berdyanish, Satlykovo, and Galikaevo), located in closest proximity to the site of the explosion (1100 persons) were quickly evacuated (within 7–14 days after the accident), essentially because of high levels of external exposure rate. Evacuation of other settlements took place later, but was due to high levels of ^{90}Sr-contamination density (more than 2–4 Ci km^{-2} of ^{90}Sr) (Romanov et al. 1997). Thus, the population of Rus.-Karabolka, Yugo-Konevo, and some other nearby settlements (2,280 persons in total) were evacuated 250 days after the accident. Later (within 330 to 670 days after the accident) another 8,300 persons were removed from territories with contamination density >2Ci km^{-2} of ^{90}Sr.

3.1. AVAILABLE DATA ON ^{90}Sr IN HUMANS FROM EVACUATED SETTLEMENTS

Since 1974, some EURT residents have been examined for their ^{90}Sr-body burden with a whole-body counter (WBC). Table 21 presents information about the data sets (number of residents measured, etc.) for persons from evacuated EURT settlements. These data allow estimation of the ^{90}Sr-body burdens as a function of time after the accident and allow reconstruction of the ^{90}Sr-intake function independently of measurements of local foodstuffs and contamination density. The estimates of the intake of ^{90}Sr for residents of evacuated settlements were obtained in earlier work (Tolstykh et al. 2002).

Analysis of the WBC data for residents of evacuated settlements has shown that for most of them the measured ^{90}Sr-body burdens were lower than WBC detection limits (Kozheurov et al. 2002). Tables 22 and 23 show statistical characteristics of measured ^{90}Sr-body burdens for different age groups of residents of evacuated settlements obtained by two methods: radiochemical and WBC. These data can be used for the reconstruction of the ^{90}Sr intake.

Table 20. The schedule of evacuation from contaminated EURT territories.

Time of evacuation, days after accident	Settlements	^{90}Sr-contamination density, Ci km^{-2}	Population
250	Alabuga, Gorny, Igish, Troshkovo, Rus.-Karabolka, Yugo-Konevo	8–65	2,300
330	Boevka, Bryukhanovo, Fadino, Gusevo, Krivosheino, M.Shaburovo, Melnikovo, Skorinovo	4–18	5,200
670	Kazhakul, Chetyrkino, Klyukino, Tygish	2–6	3,100

Table 21. Number of persons from selected Urals settlements measured for ^{90}Sr-body burdens.

Settlements	Settlement characteristics[a]	Number of persons measured	Period of measurements
Berdyanish, Satlykovo, Galikaeva	Axis of EURT, evacuated during 7–10 days; initial ^{90}Sr-contamination density was 375–650 Ci km^{-2}	209[b]	1964–1997
Alabuga, Yugo-Konevo	Axis of EURT, evacuated through 250 days; initial ^{90}Sr-contamination density was 8–10 Ci km^{-2}	140[c]	1964–1997

[a] Initial contamination density of settlement area according to Ternovsky et al. (1985) and Romanov et al. (1997); the territory of life-support for the different settlements can vary significantly.

[b] Data include radiochemical measurements (7 persons) and WBC measurements (202 persons).

[c] Data include radiochemical measurements (11 persons) and WBC measurements (129 persons).

Table 22. Statistical characteristics of measured ^{90}Sr-body burdens for different age groups of residents evacuated 10 days after the accidents from Berdynish, Satlykovo and Galikaevo.

Age group	Method	Number of persons	Period of measurements	Geometric mean, nCi	Geometric standard deviation
Adults	Autopsy	4	1964–1967	105	5.7
	WBC	12	1976–1982	0.6	40.8
Teenagers	WBC	6	1985–1988	107	1.8
Children	WBC	19	1985–1986	27.4	6.7

Table 23. Statistical characteristics of measured ^{90}Sr-body burdens for different age groups of residents evacuated 250 days after the accident from Alabyga and Yugo-Konevo.

Age group	Method	Number of persons	Period of measurements	Geometric mean, nCi	Geometric standard deviation
Adults	Autopsy	6	1967–1974	6.6	1.2
	WBC	11	1982–1989	15.8	9.1
Teenagers	Autopsy	3	1965–1969	47	4.7
	WBC	9	1985	18.5	12.7
Children	WBC	10	1985	9.7	9.1

It is seen from Tables 22 and 23 that data on measured ^{90}Sr-body burdens obtained by the WBC for almost all groups of residents were below detection limits and have high variability. The only set of WBC data that could be used for the reconstruction of a reliable ^{90}Sr-intake function was obtained for a group of teenagers whose ^{90}Sr retention in the whole body was maximal. Data obtained at *post mortem* measurements of ^{90}Sr concentration in the skeleton for adult residents of evacuated settlements and teenagers from Alabuga and Yugo-Konevo settlements are also being used for the reconstruction of the ^{90}Sr-intake function.

3.2. RECONSTRUCTION OF ^{90}Sr INTAKE

Data on measured ^{90}Sr-body burdens many years after the accident allow reconstruction of the ^{90}Sr intake independently of measurements of local foodstuffs and contamination density. Principles of the reconstruction are the following: (1) ^{90}Sr intake can be assumed as an acute intake, because a considerable amount of time has passed between the intake and the measurements; (2) average-^{90}Sr content in the skeleton or total body at the time of measurements can be reconstructed on the basis of an age- and gender-dependent biokinetic model for strontium (Shagina et al. 2002); (3) ^{90}Sr intake is reconstructed on the basis of reliable WBC measurements for adolescents of Bergyanish, Satlykovo and Galikaevo settlements and autopsy measurements for other age groups; (4) and the range in the estimates of ^{90}Sr intake is determined by variability in individual measurements (Tables 22 and 23). Fig. 15 shows the principles of ^{90}Sr-intake reconstruction for the evacuated settlements. The results are outlined in Table 24.

It is seen in Table 24 that the estimates of ^{90}Sr intake based on autopsy measurements of adults and WBC measurements of teenagers and children evacuated from Berdyanish, Satlykovo, Galikaeva are very close despite high variability and the small number of measurements for adults. Therefore, this estimate is considered as a reliable estimate of ^{90}Sr intake for residents of

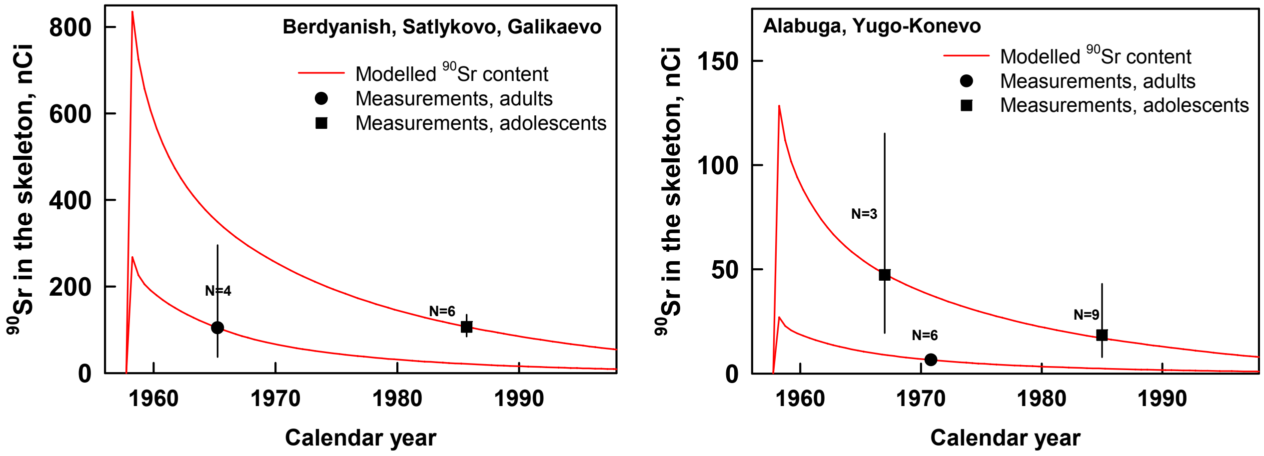

Fig 15. ^{90}Sr contents in the skeleton fitted to actual measurements of radionuclide content in residents of Berdyanish, Satlykovo and Galikaevo evacuated 10 days after the accident (left panel) and in residents of Alabuga and Yugo-Konevo evacuated 250 days after the accident (right panel). Measurements were obtained by radiochemical and WBC methods.

Table 24. Average-^{90}Sr intake for persons in evacuated settlements o the EURT as estimated from measurements of ^{90}Sr in the skeleton or whole body.

Settlement	Evacuation, days after accident	^{90}Sr intake based on measurements for adults, μCi	^{90}Sr intake based on measurements for adolescents, μCi		^{90}Sr intake based on measurements for children, μCi
Berdyanish, Satlykovo, Galikaevo	10	7.4 (2.6–20.9)	7.5 (6.0-9.5)		7.0 (4.5–10.9)
Alabuga, Yugo-Konevo	250	0.75 (0.7–0.8)	1.1 (0.5–2.7)	1.4[a] (0.6–3.2)	Measurements are below WBC detection limits

[a] Geometric mean of the WBC data for teenagers who lived in Alabuga and Yugo-Konevo was slightly lower than the WBC detection limits; the pooled estimate of ^{90}Sr intake based on autopsy and WBC measurements for adolescents is 1.3 μCi with wide CI (0.5–3.1).

the settlements evacuated at short periods after the accident. For Alabuga and Yugo-Konevo settlements, the value obtained for adolescents is slightly higher than for adults and has higher variability. Nevertheless, estimates obtained for adolescents on the basis of autopsy and WBC data are very close and the pooled estimate is 1.3 μCi with the range from 0.5 to 3.1 μCi. With consideration of the wide CI the estimate of ^{90}Sr intake based on measurements for adolescents is not significantly different from the estimate based on measurements for adults.

The reconstruction of intake functions for evacuated settlements was also estimated by different authors (see Peremyslova et al. 2004) by consideration of total-ß-activity measurements in local foodstuffs . A comparison of estimates of average daily ^{90}Sr intakes for persons in settlements located on the axis of the EURT obtained by different methods (based on diet and direct measurement of ^{90}Sr in bones) is presented in Table 25.

Table 25. Daily ^{90}Sr intakes for adult residents of the EURT area according to Bournazyan (1974), Ternovsky et al. (1985a), and Romanov et al. (1997) estimated on measurements of the local foodstuffs and ^{90}Sr intakes estimated on measurements of the radionuclide in bones according to this study.

Settlement	Evacuation, days after accident	Average daily ^{90}Sr intake, μCi			
		Bournazyan (1974)	Ternovsky et al. (1985)	Romanov et al. (1997)	This study (estimates for adults)
Berdyanish	10	3.0	2.6	3.9	1.2
Satlykovo	10	1.5	1.6	2.4	0.6
Galikaevo	10	2.1	1.6	2.4	0.8
Yugo-Konevo	250	0.1	0.04	0.1	0.003

As seen in Table 25, the estimates differ significantly from each other. It should be noted that the values described by Bournazyan (1974) were calculated on the basis of direct measurements of local foodstuffs in specific (the same) settlements (although rejection of some foodstuffs was not taken into account). Estimates performed later (Ternovsky et al. 1985 and Romanov et al. 1997) are based on normalized values of ^{90}Sr intake (per unit of ^{90}Sr-contamination density) and estimated contamination density. It is seen in Table 25, that for settlements evacuated in 10 days after the accident, the actual average ingestion of the radionuclide is about factor of 3 lower than the estimates calculated from local foodstuffs. For Yugo-Konevo, evacuated 250 days after the accident, the difference is one to two orders of magnitude. Therefore, the normalized values of radionuclide intakes and contamination density are very important parameters for the reconstruction of internal dose.

The new estimates differ from the earlier estimates obtained by Tolstykh et al. (2002): 3.5–4.0 μCi ^{90}Sr for residents Berdyanish, Satlykovo and Galikaevo and 1.3–1.6 μCi ^{90}Sr for residents of Alabuga and Yugo-Konevo. The new estimates are considered to be more reliable as they were obtained by direct intake input into the biokinetic model and reliable WBC measurements are used for evacuated residents.

4. RECONSTRUCTION OF THE INTAKE OF NON-^{90}Sr RADIONUCLIDES FOR RESIDENTS ON THE EURT

4.1. RECONSTRUCTION OF THE INTAKE FUNCTION FOR NON-EVACUATED SETTLEMENTS

For evaluation of radionuclide-specific intake functions it is assumed that the radionuclide composition (Table 6) was the same throughout the EURT territory. For short-lived radionuclides the reconstruction of intake is performed for the first three years after the accident (due to rapid decay of these radionuclides the intake in subsequent years is considered to be negligibly small). Analysis of data on contamination of local food products (Peremyslova et al. 2004) has shown that the most important foodstuff in the first three years after the accident was bread (the contributions of other products were very small). Therefore, the data outlined in Table 7 allow estimation of the intake functions for the short-lived radionuclides considered.

It is obvious that the intake of short-lived radionuclides with bread was significant during the first period after the accident (October 1959–November 1958), due to the high surface contamination of grain and high contribution of the radionuclides to the total activity. In subsequent years, due to prevalence of the root route of contamination and extremely low transfer from soil into plants, the intake of short-lived radionuclides with bread was much lower.

The intake of ^{95}Zr, ^{95}Nb, ^{106}Ru and ^{144}Ce with milk and meat due to ingestion by cows of contaminated forage or grazing on contaminated territories for a short period of time before winter period should be negligibly small, because the transfer of these elements through biological barriers is low (Peremyslova et al. 2004). Therefore, if the same surface contamination of grain and forage is assumed, the contamination of milk and meat cannot be significant compared to contamination of bread.

In subsequent years, the contamination of milk and meat by short-lived radionuclides depended on the following processes: radioactive decay; migration from soil to plants, and discrimination against in the gastrointestinal tract of milk- and meat-producing animals. Because of the small migration of these radionuclides through the chain "soil–cow milk (meat)" and the significant contribution of their intake with bread during the first period after the accident, the intake of these radionuclides with milk and meat is neglected. For the same reasons indicated above for milk, the ingestion of short-lived radionuclides with vegetables is ignored.

The discrimination against long-lived ^{137}Cs in cows is small; therefore, the transfer of this radionuclide from contaminated forage to milk and meat is high. Nevertheless, because the contribution of this radionuclide to total-beta activity of fallout was negligibly small (0.0036%), the intake of ^{137}Cs is ignored.

Average estimates of radionuclide-specific contamination of bread in 1958–1960 (mainly as a result of radionuclide migration from soil into grain) are shown in Table 26. It is seen from Table 26 that over 95% of the radionuclide-specific intake with bread occurred during the first period after the accident (October 1957–November 1958).

Table 26. Estimates of the intake of non-^{90}Sr radionuclides with bread for the first period after the accident (1957–1960).

Period	Radionuclide	Estimated specific activity in bread		Estimated daily intake with bread	
		Bq kg^{-1}	nCi kg^{-1}	Bq d^{-1}	nCi d^{-1}
October, 1957 to May 1, 1958	^{144}Ce	584.6	15.8	374.1	10.1
	^{95}Zr(^{95}Nb)	110.3	3.0	70.6	1.9
	^{106}Ru	34.6	0.94	22.1	0.60
	^{137}Cs	0.42	$1.1\cdot10^{-2}$	0.27	$7.3\cdot10^{-3}$
May 1, 1958 to November 1, 1958	^{144}Ce	361.0	9.8	231.0	6.2
	^{95}Zr(^{95}Nb)	12.4	0.33	7.9	0.21
	^{106}Ru	34.6	0.94	22.1	0.60
	^{137}Cs	0.41	$1.1\cdot10^{-2}$	0.26	$7.1\cdot10^{-3}$
November 1, 1958 to November 1, 1959	^{144}Ce	8.4	0.23	5.4	0.15
	^{95}Zr(^{95}Nb)	$4.5\cdot10^{-2}$	$1.2\cdot10^{-3}$	$2.9\cdot10^{-2}$	$7.8\cdot10^{-3}$
	^{106}Ru	0.81	$2.2\cdot10^{-2}$	0.52	$1.4\cdot10^{-2}$
	^{137}Cs	$3.5\cdot10^{-2}$	$9.5\cdot10^{-3}$	$2.3\cdot10^{-2}$	$6.2\cdot10^{-3}$
November 1, 1959 to November 1, 1960	^{144}Ce	2.0	$5.2\cdot10^{-2}$	1.2	$3.4\cdot10^{-2}$
	^{95}Zr(^{95}Nb)	$1.2\cdot10^{-3}$	$3.3\cdot10^{-5}$	$7.7\cdot10^{-4}$	$2.1\cdot10^{-5}$
	^{106}Ru	0.18	$4.9\cdot10^{-3}$	0.12	$3.1\cdot10^{-3}$
	^{137}Cs	$1.2\cdot10^{-2}$	$3.3\cdot10^{-4}$	$7.7\cdot10^{-3}$	$2.1\cdot10^{-4}$

As an example, Fig. 16 shows estimates of the reconstructed ^{144}Ce intake in comparison with data obtained by other authors. The approaches used by the other authors were previously described in our milestone report (Peremyslova et al. 2004).

It is seen in Fig.16 that the reconstruction of ^{144}Ce intake based on measurements of the total-beta activity in bread and taking into account radioecological characteristics of radionuclide transfer in food chains resulted in lower estimates compared with results of other authors.

As noted above, locally produced bread was baked from flour made from grain grown by collective farms. Therefore, contamination of bread in a specific village is not dependent on the village-specific ^{90}Sr-contamination density. As a result, further work on the estimation of short-lived radionuclide intake will be directed to grouping of villages according to the territory of supply by collective farm and estimating the weighted average-^{90}Sr-contamination density. The total intake of short-lived radionuclides per unit ^{90}Sr-contamination density for the period of 1957–1960 is presented in Table 27.

4.2 RECONSTRUCTION OF THE INTAKE FUNCTION FOR EVACUATED SETTLEMENTS

Residents of Berdyanish, Satlykovo and Galikaevo settlements were evacuated during the first 10 days after the explosion. During this period intake of radionuclides occurred with bread due to surface contamination of local grain stored in open buildings. Therefore, intake of short-lived radionuclides can be obtained on the basis of estimates of ^{90}Sr intake derived from measurements of its content in the skeleton and the radionuclide composition of fallout (Table 6). Estimates of the intake of short-lived radionuclides for residents of Berdyanish, Satlykovo and Galikaevo are presented in Table 28.

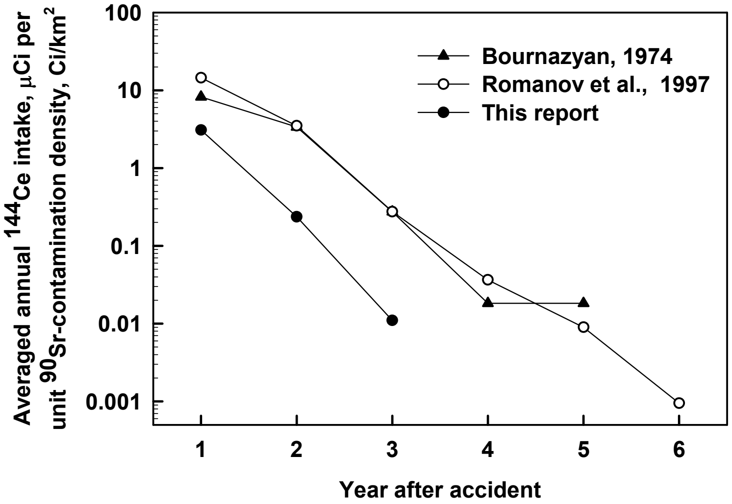

Fig. 16. Comparison of the estimates of ^{144}C- intake function for referent villages (^{90}Sr-contamination density in the villages is considered to be equal to 1 Ci km^{-2}) with estimates obtained by different authors normalized per unit ^{90}Sr-contamination density.

Table 27. The total intake of short-lived radionuclides per unit ^{90}Sr-contamination density for the period of 1957–1960.

Period of intake	Radionuclide-specific intake for the indicated periods					
	^{144}Ce		^{95}Zr (^{95}Nb)		^{106}Ru	
	Bq	nCi	Bq	nCi	Bq	nCi
October 1957 to May 1, 1958	79310	2140	14970	400	4690	130
May 1, 1958 to November 1, 1958	41580	1120	1420	38	3980	110
November 1, 1958 to November 1, 1959	1970	55	11	0.3	190	5.1
November 1, 1959 to November 1, 1960	440	12	0.28	0.01	45	1.2

Table 28. Average intake of ^{90}Sr and short-lived radionuclides for residents of Berdyanish, Satlykovo and Galikaevo; these villages were evacuated during the first 10 days after the accident.

Radionuclide	Contribution to the total activity of fallout, %	Total intake, nCi
^{90}Sr	2.7	7420
^{95}Zr(^{95}Nb)	12.5	34130
^{106}Ru	1.9	5120
^{144}Ce	33	90520
^{137}Cs	0.02	52

Residents of Alabuga and Yugo-Konevo were evacuated within 250 days after the explosion (May 1958), i.e., before the beginning of the first pasture period. Therefore, radionuclide intake occurred as a result of surface contamination of grain, forage, etc., and the intake of short-lived radionuclides occurred mostly with contaminated bread. The same path of intake was characteristic for ^{90}Sr. For this reason, estimates of the total intake of short-lived radionuclides for residents of Alabuga and Yugo-Konevo can be reconstructed from ^{90}Sr intake derived from measurements of ^{90}Sr concentration in the skeleton (Table 24). The radionuclide composition during the considered period slightly changed due to decay of short-lived radionuclides, especially of ^{95}Zr/^{95}Nb. Thus, in calculations the radionuclide composition of the fallout corresponding to the middle point of the evacuation period (120 days) was used. Estimates of the intake of short-lived radionuclides for residents of Alabuga and Yugo-Konevo are presented in Table 29.

There have not been measurements of ^{90}Sr concentration in bone samples obtained for residents evacuated 330 days after the accident. Therefore, the intake of short-lived

Table 29. Average intake of ^{90}Sr and short-lived radionuclides by residents of Alabuga and Yugo-Konevo evacuated during the first 250 days after the accident.

Radionuclide	Contribution to the total activity of fallouts, %	Total intake, nCi
^{90}Sr	4.2	750
^{95}Zr(^{95}Nb)	5.3	950
^{106}Ru	2.3	410
^{144}Ce	38.3	6900
^{137}Cs	0.03	5

radionuclides for this group of residents can be obtained from estimates normalized per unit ^{90}Sr-contamination density (Table 27).

4.3. VALIDATION OF THE INTAKE FUNCTION BY MEASUREMENTS OF RADIONUCLIDE CONTENT IN HUMAN EXCRETA

Validation of the intake of short-lived radionuclides for residents of EURT settlements is one of the important tasks in dose reconstruction, because the contribution of these radionuclides in fallout was significant. According to estimates of Romanov et al. (1997), the main contribution to total internal dose was from ^{144}Ce. Validation of the estimates of intake of short-lived radionuclides intakes can be performed with use of information on beta-activity measurements in feces. This is possible because the absorption of short-lived radionuclides in the gastro-intestinal tract (GIT) is negligibly small (10^{-2}–10^{-4}); thus, the total-beta activity of feces directly reflects the current intake of radionuclides.

4.3.1. Available data on total-beta activity of excreta

The URCRM archive contains registration journals on results of measurements of total-β activity excreted with urine and feces for residents of several settlements located on the EURT territory. These measurements were performed in 1958–1959 during expeditions of URCRM staff to EURT settlements or during observations of residents in URCRM clinics. The most interesting are results obtained during expeditions and during the first day of hospitalization in URCRM clinics. A Registry of total-β-activity measurements in excreta was created on the basis of archival data. The Registry contains individual data (system number and/or family name and the name of a person), place of residence on EURT territory, and the results of measurements of total-β activity in excreta (with subtraction of activity due to natural ^{40}K). Table A1.4 presents detailed characteristics of available data on measurements of excreted total-β activity.

The Registry includes 213 measurements obtained for 200 persons who were residents of 16 EURT settlements in 1958–1959. A significant number of measurements were obtained in 1958 for residents of EURT villages evacuated 330 days after the explosion (*n* = 62). In addition, there are measurements for residents of referent settlements obtained in 1958–1959. It should be noted that among residents of Bagaryak village measured in 1958, there are residents who took part in liquidation of the consequences of the explosion; therefore, for these residents the intake differed from that characteristic for residents of referent settlements. However, measurements obtained for residents of Bagaryak village in 1959 can be used for validation purposes. Data contained in the Registry were used for validation of the intake function with local foodstuffs.

4.3.2. Comparison of daily intake obtained from data on excreta contamination with other estimates

Analysis of the estimates of dietary intake of radionuclides derived from measurements on the contamination of local foodstuffs shows that in 1957–1958 the contribution of short-lived radionuclides to the total daily intake was significantly higher than the contribution of ^{90}Sr (by a factor of 8). Therefore, the contribution of short-lived radionuclides to the total-beta activity in feces was determinative in 1958, which allows the use of data on total-beta activity for validation of the intake of short-lived radionuclides. In 1959 the contribution of ^{90}Sr to the total intake of radionuclides was dominant (about 80%), and data on total-beta activity in feces obtained in 1959 can be used for validation of the intake of both ^{90}Sr and short-lived radionuclides.

For validation purposes, measurements for residents evacuated 330 days after the explosion (in August–September 1958) from settlements located on areas with ^{90}Sr-contamination density of 4–18 Ci km^{-2} were selected. Measurements of total-beta activity of feces were performed in April–June 1958 for adult residents of these settlements. The results for residents from non-evacuated referent settlements are available for 1959 only. Characteristics of the total-beta activity in feces used for validation are given in Table 30.

As discussed above, the absorption of ^{144}Ce, ^{95}Zr, ^{95}Nb, and ^{106}Ru in the GIT is negligibly small (10^{-2}–10^{-4}); thus, daily excretion of these radionuclides with feces directly reflects the current level of intake. So, the median daily intake of these radionuclides per unit of ^{90}Sr contamination density in April–June 1958 for the first group of settlements indicated in Table 30 is equal to 4.4 nCi day^{-1}. It must be noted that the contribution of ^{90}Sr in this period was one order of magnitude lower than the contribution of short-lived radionuclides and can be considered as negligible.

In May–November 1959, the contribution of ^{90}Sr to total-beta activity of the diet became significant: 1.66 nCi day^{-1} of ^{90}Sr+^{90}Y (Table 10) and 0.33 nCi day^{-1} of short-lived radionuclides including their daughters (Table 26). Because the GIT absorption of ^{90}Sr is 23.6%, 76.5% of ingested ^{90}Sr is eliminated with feces. This gives us a value of daily excretion of ^{90}Sr+^{90}Y with feces equal to 1.27 nCi day^{-1}. On the basis of these estimates, the relative contributions of ^{90}Sr and short-lived radionuclides to the total-beta activity of feces are 0.8 and 0.2, respectively. Applying this ratio to the measured value of daily fetal excretion we receive for short lived radionuclides 0.16 nCi day^{-1}.

Table 31 summaries data on daily intakes of short-lived radionuclides estimated using three different approaches.

Table 30. Statistical characteristics of total-beta-activity measurements in feces for residents of two groups of EURT settlements.

Settlements[a]	Average ^{90}Sr-contamination density, Ci km^{-2}	Date of measurements	*n*	Total-beta activity of feces, without ^{40}K, nCi day^{-1}				
				Mean and standard deviation	Percentiles			
					25th	50th	75th	95th
Boevka, Bryukhanovo, Fadino, Gusevo, Krivosheino, Melnikovo	9.5	April–June 1958	69	63±74	12	42	87	183
Allaky, Bagaryak, Yushkovo, Tat.-Karabolka	1.2	May–November 1959	44	1.4±1.5	0.38	1.05	1.90	4.19

[a] The first group includes residents evacuated 330 days after the explosion, the second group includes residents of referent (non-evacuated) settlements

Table 31. Comparison of the intake of short-lived-radionuclides estimated for 1958 and 1959 on the basis of different approaches.

Method of intake assessment	Daily short-lived radionuclide intake per unit of ^{90}Sr-contamination density, nCi day^{-1} per Ci km^{-2}	
	April–June 1958	May–November 1959
Based on measurements of total-beta activity in local foodstuffs (Table 26)	18.6	0.34
Based on measured ^{90}Sr in the skeleton and radionuclide composition in fallout (Fig. 13)	6.2	0.11
Based on measurements of total-beta activity of excreta[a]	4.4 (0.04–19.3)	0.16 (0.024–0.87)[b]

[a] Median value with 90% CI in parentheses.

[b] The contribution of short-lived radionuclides to total beta-activity of feces is 20%.

As can be seen in Table 31 there is good agreement between estimates derived from measurements of radionuclides in feces and bones. Therefore, close agreement of the estimates of the intake of short-lived radionuclides (and of ^{90}Sr in 1959) are obtained on the basis of two independent sets of available data on humans. It is seen from Table 31 that estimates of the intake of short-lived radionuclides derived from measurements of local foodstuffs are overestimates. It should be noted that measurements of the total-beta activity in feces obtained in 1958 are more reliable for validation of the intake of short-lived radionuclides, because by 1959 a considerable amount of short-lived radionuclides had decayed. This increases uncertainties in estimation of their intake in 1959, because of the significant contribution of ^{90}Sr-intake to total-beta activity in feces.

Analysis of data outlined in Table A1.4 on measurements of the total-beta activity in feces shows that a significant number of measurements were obtained for residents of ONIS settlement. Residents of Metlino, located in the upper Techa River region, were evacuated to this village (Tables A3.1 and A3.2). According to Romanov et al. (1997) the ^{90}Sr-contamination density of ONIS was 1.5 Ci km^{-2}. It should be emphasized that ONIS has a special position among other EURT settlements. This settlement is located close to Ozersk and was generally supplied by the same imported foodstuffs as Ozersk; nevertheless, the contribution of local foodstuffs into diet was presumably higher in ONIS than in Ozersk. These factors create additional uncertainty in estimation of radionuclide intake for residents of ONIS and restrict the validity of application of referent intake function normalized per unit ^{90}Sr-contamination density. For this reason, measurements of the total-beta activity in feces obtained for residents of this village are extremely important for the reconstruction of radionuclide intake for ONIS settlement, because of the lack of necessary data on ^{90}Sr measurements in bones.

Measurements of the total-beta activity of feces of persons in ONIS were conducted during expeditions that took place in 1958; at later times, residents were invited to URCRM for medical and dosimetric observations. As shown above, the data of 1958 are of primary interest. The measurements of 1958 and 1959 were selected for validation purposes. The statistical characteristics of measurements of the Metlino residents relocated to ONIS are presented in Table 32.

Table 32. Statistical characteristics of the total-beta activity measurements in feces for Metlino residents relocated to ONIS.

Period of measurements	Number of people	Total beta activity of feces, nCi day^{-1}				
		Mean and standard deviation	Percentiles			
			25th	50th	75th	95th
August–September, 1958	24	5.8±9.8	1.9	3.2	4.9	13.7
November–December, 1958	5	4.2±6.4	0.9	1.5	2.6	12.9
June–December, 1959	31	1.1±1.2	0.3	0.8	1.6	2.9

It is seen from Table 33 that differences between estimated values are significant for the period of August–September 1958; for this period estimates derived from measurements of local foodstuffs and measurements of the total-beta activity excreted in feces differ by a factor of six. For later periods these differences become smaller and close to a ratio of three. Therefore, it is presumed that the intakes of radionuclides normalized per unit ^{90}Sr-contamination density could be lower in ONIS than in other EURT settlements, because of the higher contribution of imported foodstuffs in the local diet.

Another data set very useful for the validation of the estimated intake of short-lived radionuclides are the measurements of total-beta activity in excreta of EURT residents, which were performed in October–December 1957–1959 by specialists of the Southern Urals Biophysics Institute (SUBI). This set of data contains information on about 1000 measurements of excreta for the residents of the more contaminated areas of the EURT. These data could be very valuable to validate the intake of short-lived radionuclides in Berdyanish, Satlykovo, Galikaevo and R. Karabolka. Unfortunately, our plans to involve SUBI scientists in our work on this subject was curtailed by the significant budget cuts we have received.

5. RECONSTRUCTION OF RADIONUCLIDE INTAKES FOR RESIDENTS OF THE KARACHAY TRACE

The territories of the EURT and the KT partially overlap each other. Therefore, residents living on EURT areas had additional intake due to windblown activity from Karachay Lake. Environmental monitoring was conducted by URCRM specialists in five settlements at different distances from the source of contamination, but on territory contaminated predominantly due to the KT (Table 34). Most extensive investigations have been carried out in Sarykulmiak, which is the most contaminated settlement on the KT area. In the other five settlements sampling was conducted occasionally. Permanent monitoring was performed until 1985; after 1999, sampling was performed in three settlements.

Table 33. Comparison of the estimated intakes of short-lived-radionuclides for residents of ONIS estimated for 1958 and 1959 on the basis of different approaches.

Period of measurements	Daily intake of short-lived radionuclide per unit of ^{90}Sr contamination density, nCi day^{-1}	
	Based on measurements of total-β activity of local foodstuffs and data on ^{90}Sr-contamination density (Table A1)	Based on excreta data
August–September 1958	19.0	3.2 (1.9–4.9)
November–December 1958[a]	0.5	0.3 (0.18–0.52)
June–December 1959[a]	0.5	0.16 (0.06–0.32)

[a] The contribution of short-lived radionuclides to total-beta activity of feces is 20%.

Table 34. Characteristics of the villages located on the KT area where sampling was performed.

Settlement	Contamination density of ^{90}Sr, Ci·km^{-2}, 1967	Contamination density of ^{137}Cs, Ci·km^{-2}, 1967	Period of sampling
Kainkul	0.9	2.6	1967–2000
Karagaikul	0.4	1.7	1967–2001
Sarino	0.5	1.4	1967–1985
Sultayevo	0.3	1.0	1967–1972
Sarykulmiak	1.5	4.4	1967–2001

In these settlements the basic foodstuffs (milk, meat, potatoes, etc.) were produced on private farms. The first sampling of local foodstuffs commenced soon after the radionuclides settled on the soil (Tables A2.1-3). As a result, a complete set of data necessary for the reconstruction of dietary intake of radionuclides is available. Estimation of intake is based on the same composition of local diet (Table 5) and the same approaches applied for reconstruction of dietary intake for residents of EURT settlements.

Contrary to the situation on the EURT, the main radionuclide that determined contamination on the KT was ^{137}Cs; its contribution to the fallout was three times that of ^{90}Sr. Because cesium easily penetrates biological barriers, the content of ^{137}Cs in humans could be significant.

As shown in previous sections, estimation of ^{90}Sr intake on the basis of measurements of local foodstuffs resulted in overestimation of its actual intake, and, therefore, overestimation of its content in the human body. However, this approach satisfactorily describes the contents of ^{90}Sr in the skeleton for the most highly exposed part of a population (15%). In general, measurements of radionuclides in exposed individuals are very important and lead to more reliable estimates of intake. Measurements of ^{137}Cs-body burden were conducted for residents of referent settlements on the KT at different times after contamination. These results can be used for validation of the intake as estimated on the basis of measurements of local foodstuffs.

5.1. ESTIMATION OF THE DIETARY INTAKES OF ^{137}Cs AND ^{90}Sr

Principles of ^{137}Cs intake reconstruction on the KT are the same as applied for ^{90}Sr-intake reconstruction on the EURT (Section 2.2). Intake of radionuclides on the KT territory commenced in May 1967. During the first period after the contamination (1967–1969) the sampling of milk and other foodstuffs was conducted each month during the growing season and twice during wintertime. This allowed estimation of monthly intake, which was further averaged over a year. After 1969, samples of milk and other foodstuff were taken during the summer and served as a basis for the assessment of average annual intake of radionuclides (Tables A2.1-2).

Table 35 shows estimates of ^{137}Cs and ^{90}Sr dietary intake in the referent settlement Sarykulmiak. The same estimates, but normalized per unit ^{90}Sr-contamination density, are shown in Table 36.

Sampling of actual rations (duplicate rations) of adults and children was performed in Sarykulmiak at different times after the beginning of contamination. Table 37 shows data on ^{90}Sr and ^{137}Cs contents in actual rations for adult residents. It is seen that estimates are 2.5 higher on average than actual contents in duplicate rations (a similar fact was noted for estimates of ^{90}Sr intake for residents on the EURT, and reasons for this were discussed in Section 2.13). However, the estimated values are within the upper 95%-CI of radionuclide content in actual rations.

Additionally, sampling of actual rations was performed for children of preschool age (3–7 years old) and for children of school age (7–15 years old). Table 38 shows ratios of geometric means of ^{90}Sr and ^{137}Cs contents in actual rations for children to those for adults for residents of Sarykulmiak.

Table 35. Estimates of ^{137}Cs and ^{90}Sr intakes in Sarykulmiak.

Calendar year	^{90}Sr, nCi year^{-1}	^{137}Cs, nCi year^{-1}	Calendar year	^{90}Sr, nCi year^{-1}	^{137}Cs, nCi year^{-1}
1967	75	180	1977	27	50
1968	58	157	1978	22	26
1969	59	128	1979	22	26
1970	35	119	1980	21	26
1971	30	92	1981	20	26
1972	27	73	1982	25	28
1973	24	72	1983	18	25
1974	24	71	1984	18	24
1975	23	69	1985	21	24
1976	23	67			

Table 36. Daily ^{137}Cs and ^{90}Sr intake normalized per unit ^{90}Sr-contamination density.

Calendar year	Intake, pCi day^{-1}		Calendar year	Intake, pCi day^{-1}	
	^{90}Sr	^{137}Cs		^{137}Cs	^{90}Sr
1967	82	334	1977	26	93
1968	55	291	1978	19	49
1969	63	236	1979	19	48
1970	25	220	1980	17	48
1971	22	170	1981	17	47
1972	18	135	1982	27	51
1973	13	134	1983	19	47
1974	15	131	1984	20	45
1975	16	128	1985	25	44
1976	17	124			

Table 37. Comparison of actual and estimated ^{90}Sr and ^{137}Cs contents in rations of adult residents of Sarykulmiak village (values are given in pCi day^{-1}).

Date of investigations	^{90}Sr				^{137}Cs			
	Number of samples	Estimate	Actual (duplicate rations)		Number of samples	Estimate	Actual (duplicate rations)	
			$\bar{x}_g$	σ_g			$\bar{x}_g$	σ_g
August 1967	22	120	165	2.1	22	400	290	2.5
May 1968	22	150	100	2.7	21	580	245	2.6
December 1968	18	160	50	2.8	22	310	80	2.3

Table 38. Ratios of ^{90}Sr and ^{137}Cs intakes for children of different ages to those for adults.

Age, years	Radionuclide	Date of investigations			Average value
		August 1967	May 1968	December 1968	
3–7	^{90}Sr	0.5	0.6	0.7	0.6
	^{137}Cs	0.8	0.6	0.3	0.5
7–15	^{90}Sr	1.3	1.0	1.0	1.2
	^{137}Cs	0.7	1.0	-	0.9

It is seen from Table 38 that the average ratio of dietary intake of radionuclides for 3–7-year old children and adults is between 0.5 and 0.6 and for older children (7–15 years) it is closer to unity.

The intake of radionuclides was calculated for villages located on the KT according to data shown in Table 36 and information on ^{90}Sr-contamination density available in our Reference Book (Peremyslova et al. 2004). At any time after the accident, the intake of radionuclides was lower than the limits of annual intake in place at that time.

5.2. VALIDATION OF ^{137}Cs INTAKE BY WBC MEASUREMENTS

Measurements of ^{137}Cs-body burdens for residents of Sarykulmiak were performed in 1969 and 1977. Measurements of the radionuclide in 10 children were performed in January and August 1969 at the Biophysics Institute (Moscow) on a whole body counter (WBC) SICH-2.2. The median ^{137}Cs-body burden for children aged 10–14 years in 1969 was 22.5 nCi (832 Bq).

Measurements of ^{137}Cs in 20 adult residents of Sarykulmiak were performed in August 1977 at the URCRM on WBC SICH-9.1. Statistical characteristics obtained for this group of subjects are given in Table 39. As can be seen, the median ^{137}Cs-body burden in 1977 was 12 nCi (462 Bq), and the average value was 525 Bq (14.2 nCi).

Table 39. Statistical characteristics of ^{137}Cs-body burdens in 20 adult residents of Sarykulmiak village measured in August 1977 at URCRM.

Statistical characteristic	^{137}Cs-body burden	
	Bq	nCi
Mean	525	14
Standard deviation	229	6
Median	462	12
95th percentile	895	24
Geometric mean	477	13

The measured values of ^{137}Cs-body burdens could be compared to values calculated using estimates of radionuclide intake. For this purpose the age-dependent model for cesium presented in ICRP Publication 56 (ICRP 1989) is used. As shown in Table 38, the intake of ^{137}Cs for children aged 10–14 years is close to the adult value. Therefore, calculations of ^{137}Cs-body burdens were performed with use of data on average annual intake (Table 37) and the ICRP model for children of referent ages. Calculated values of ^{137}Cs-body burden were from 18 nCi (age 10 years) to 45 nCi (age 15 years). It is seen that calculated values are in agreement with values measured in children in 1969. The estimated ^{137}Cs-body burden in adult persons with use of data on radionuclide intake (Table 37) and the ICRP model for adults is 750 Bq in 1977, which is also in agreement with measured values. The ratio of the geometric mean of measured ^{137}Cs-body burden in adult residents of Sarykulmiak village and the estimated value (based on average annual intake) is 1.4.

Therefore, estimates of the intake of radionuclides obtained from measurements of local foodstuffs can be used for dose estimates for residents of the KT area.

6. DISCUSSION

The main purpose of this report is to develop methodological approaches for the reconstruction of intake of radionuclides for residents of the EURT and KT areas. The EURT and the KT covered significant territory, which included a number of settlements where people had been relocated from the Techa River. As a result, 4,000 members of the ETRC and 1,300 members of the TROC received additional exposure due to their subsequent residence in areas contaminated by the EURT in 1957 and the KT in 1967.

Long-lived ^{90}Sr is considered as a referent radionuclide for soil contamination and intake reconstruction in the EURT and KT areas. Settlements located on the territories of the EURT and/or KT with ^{90}Sr-contamination density >0.1 Ci km^{-2} are considered in this report. Maximal levels of contamination were observed in 1957 in three settlements located on the EURT and amounted to 400–650 Ci km^{-2}. The residents of these settlements were evacuated within 10 days after the accident. Later, the populations of areas with ^{90}Sr contamination density >2 Ci km^{-2} were evacuated. Additional levels of soil contamination in 1967 in areas of human residence did not exceed 1.5 Ci km^{-2}, but the KT plume was superimposed on areas already contaminated in 1957.

There are two basic approaches that can be applied to the assessment of the dietary radionuclide intake for a population living in areas contaminated by radioactive fallout:

1. Intake is derived from the measurements of local foodstuff contamination and/or modeling of food chains; or
2. Intake is derived from measurements of the concentration of radionuclides in human body, tissues and excreta with the use of models describing behavior of radionuclides in a human body.

Usually, these approaches are used together with one of them prevailing. The latter approach is favorable, because it is strongly based on actual data on radionuclide-body burden. The second approach was mainly used for internal dose estimation for the members of the ETRC and TROC. This approach has also been applied in the Chernobyl situation because estimates of ^{137}Cs and ^{90}Sr intakes are based on numerous WBC measurements of ^{137}Cs in human body performed after the accident (e.g., Likhtarev et al. 2000). This current report describes and analyses the results obtained by both approaches and describes a combined approach for the derivation of reconstructed intake for evacuated and non-evacuated EURT residents, as well as KT residents.

Previous to the present report, internal dose assessments for EURT residents were based on the first approach only (Romanov et al. 1997). During recent years a unique database on measurements of ^{90}Sr in bone samples has been compiled at the URCRM that allows more reliable estimation of radionuclide intake using the second approach (Peremyslova et al. 2004). Nevertheless, as discussed in Section 2.2, for the early period of the accident the number of “human measurements” is low. As a result, data contained in the Autopsy Registry are not sufficient for estimation of the dynamics and levels of ^{90}Sr accumulation in the skeleton during the period of major intake (1957–1960). The findings obtained in this report (Section 2.3) have shown that there are significant contradictions between estimates of ^{90}Sr intake obtained using above two approaches (Table 16). Fig. 13 demonstrates that measured levels of ^{90}Sr in the skeleton are significantly lower than values calculated on the basis of measurements of ^{90}Sr in local foodstuffs. The results shown in Fig. 13 confirm that the estimation of dietary intake obtained on the basis of measurements of ^{90}Sr in local foodstuffs is reliable for about 15% of population with maximal levels of the intake (the so-called critical group) and overestimate real intake for the majority of people. This is mainly explained by the following reasons:

- Such countermeasures as rejection and replacement of contaminated foodstuffs by non-contaminated ones were not taken into account in the calculations;
- The loss of ^{90}Sr during cooking was ignored (i.e., loss of about 20% of ^{90}Sr);
- Estimates of ^{90}Sr in local foodstuff for the first period after the accident (September 1957–April 1958) have large uncertainties;

- Sampling during the first period after the accident was not sufficient and was mostly performed in villages with high contamination; and
- Contamination of the territories within a village area was very heterogeneous.

There are uncertainties in the dynamics of ^{90}Sr intake for residents of the EURT territories. Several possible versions of intake dynamics were considered in Section 2.3. Tables 15 and 16 show that estimates of the total ^{90}Sr intake for different possible dynamics are very close. For adult residents at the time of the accident the dynamics of radionuclide intake are not very significant in estimation of the cumulated dose, it will only affect the dose rate. However, for children and adolescents, the dynamics of radionuclide intake is very important, because levels of ^{90}Sr intake determine its retention in the skeleton. So, the uncertainty in the intake dynamics should be taken into account in the process of evaluation of the total uncertainty in internal doses.

Table 40 summaries the results of ^{90}Sr-intake reconstruction with use of all available data and different methodological approaches. A comparison of the estimates of ^{90}Sr intake is given for different time periods.

First of all, Table 40 shows a comparison of daily ^{90}Sr intake during the first period after the accident (0–250 days) normalized per unit ^{90}Sr-contamination density for residents of the evacuated villages of Yugo-Konevo and Alabuga. These values are derived from measurements of ^{90}Sr in bones (see Table 24) with estimates obtained for residents of five referent settlements by fitting ^{90}Sr content in the skeleton to measured data (on the basis of different dynamics of radionuclide intake). Secondly, Table 40 represents estimates of ^{90}Sr intake derived from measurements of total-beta activity excreted in feces in comparison with other estimates. Thirdly, Table 40 contains data on measured daily ^{90}Sr intake with rations at later periods after the accident (1961, 1964) obtained for residents of Allaki, Bagaryak and Boulzi settlements compared to fitted values.

It is seen in Table 40 that levels of ^{90}Sr intake estimated on the basis of local foodstuff measurements with consideration of the composition of local diet are higher by a factor of 2.5–3 compared to estimates derived from human data (measurements of the total-beta activity of feces and ^{90}Sr concentration in bones). Consideration of different versions of relative dynamics (time schedule) of ^{90}Sr intake implies that the ^{90}Sr-intake dynamics reconstructed from measurements of local foodstuffs is the most appropriate. Other assumed versions of dynamics did not result in significant improvements of the intake estimates.

For the EURT settlements with an insufficient number of measured residents two approaches for ^{90}Sr-intake reconstruction will be applied. Bones for donors who lived in settlements located close to each other and characterized by similar soil contamination and life style will be grouped to derive village-grouped ^{90}Sr-intake functions. For settlements where the information on soil contamination is available, a ^{90}Sr-intake function will be estimated on the basis of ^{90}Sr-bone data for referent settlements and village-specific ^{90}Sr-contamination density. As indicated in Section 2.4, the resulting ^{90}Sr contents in the skeleton, and, therefore, the internal doses from ^{90}Sr will be dependent upon the reliability of assessments of ^{90}Sr-contamination density.

Table 40. Comparison of normalized values of daily ^{90}Sr intake derived from data obtained in referent settlements and with use of different approaches to intake reconstruction.

Calendar year	Method of ^{90}Sr-intake reconstruction	Daily ^{90}Sr intake, nCi day^{-1} per Ci km^{-2}
1957–1958	Based on ^{90}Sr-in-bone data and the assumption of acute intake for evacuated settlements[a]	0.28
	Based on measurements of local foodstuffs	1.0
	Based on ^{90}Sr-in-bone data and the assumptions on the schedule of intake for non-evacuated settlements:	
	• The dynamics estimated from measurements of local-foodstuffs	0.37
	• Assumed dynamics, I-IV (Fig. 11)	0.46–1.42
1959	Based on measurements of the total-beta activity of feces	0.32
	Based on measurements of local-foodstuffs	0.83
	Based on ^{90}Sr-in-bone data and the assumptions on the schedule of intake for non-evacuated settlements:	
	• The dynamics estimated from measurements of local foodstuffs	0.27
	• Assumed dynamics, I-IV (Fig. 11)	0.03–0.43
1961	Based on measurements of ^{90}Sr concentration in duplicated diets[b]	0.11–0.12
	Based on measurements of local-foodstuffs	0.33
	Based on ^{90}Sr-in-bone data and the assumptions on the schedule of intake for non-evacuated settlements:	
	• The dynamics estimated from measurements of local-foodstuffs	0.11
	• Assumed dynamics, I-IV (Fig. 11)	0.01–0.09
1964	Based on measurements of 90Sr concentration in duplicated diet[c]	0.16 (0.04–0.8)
	Based on measurements of local-foodstuffs	0.23
	Based on ^{90}Sr-in-bone data and the assumptions on the schedule of intake for non-evacuated settlements:	
	• The dynamics estimated from measurements of local-foodstuffs	0.074
	• Assumed dynamics, I-IV (Fig. 11)	0.006–0.023

[a] Alabuga and Yugo-Konevo only

[b] Allaki and Bagaryak only

[c] Boulzy only.

The task of reconstruction of intake of short-lived radionuclides on the EURT has been given special attention in this report (Section 4). Unique data on measurements of the total-beta activity in feces obtained for residents of EURT settlements during the first period after the explosion were used for validation of the estimated intakes (Section 4.3). This report presents for the first time the description and analysis of these data that were kept in URCRM registration journals. The data on excreta contamination obtained in 1958 and 1959 were used for validation of the intake of short-lived radionuclides. As shown in Section 4.3.2, estimates of daily intakes derived from measurements of bone samples and feces are in good agreement. It should be emphasized that good agreement among the results obtained with use of independent sets of data indicates the reliability of assumptions used for the reconstruction of the intake of short-lived.

It should be noted that the intake of additional ^{90}Sr by members of the ETRC evacuated to the EURT territory has different significance for people of different ages. For example, residents who lived in the upper Techa River in 1950–1952 and then exposed while in their teens due to residence on EURT area with ^{90}Sr-contamination density of 1 Ci km^{-2}, would have a 10% increase in their body-burden. For residents who lived in the upper Techa River in 1953–1956 and were then exposed due to residence on the EURT area with ^{90}Sr-contamination density of 1 Ci km^{-2} while in their teens, would result in a 30% increase in their body-burden.

For short-lived radionuclides, their contribution to the total internal dose can also be significant. Table 41 represents a comparison of the intakes of short-lived radionuclides in Metlino (located on the upper Techa River) and in settlements located on the EURT. It must be noted that Metlino was the nearest settlement on the Techa River to the site of releases (7 km downstream) and the Metlino residents were relocated to territories later contaminated by the EURT. It is known that some of these persons moved to Berdyanish (650 Ci km^{-2}) and were evacuated in 1957, but the majority of people moved to ONIS (1.5 Ci km^{-2}) where they lived in 1957–1960.

As can be seen from Table 41, the additional intakes of short-lived radionuclides obtained by adult Metlino residents are significant only for those who moved to Berdyanish. As for children born in Metlino, the intake of short-lived radionuclides and corresponding exposure of the GIT obtained in the EURT after the relocation from the Techa River exceeded the levels obtained before 1957.

The detailed analysis of potential contributions from different sources of confounding exposure for referent persons from the ETRC and TROC will be performed during the next step of our project. Such analysis will include the contributions of external exposures and will be done in order to establish finally the best conceptual approach to the reconstruction of individualized doses due to residence on the contaminated territories of the EURT and the KT.

On the basis of the results of the current report an algorithm for the calculation of individual internal doses due to residence within the EURT and the KT areas will be developed. This algorithm will be incorporated into the new version of the dose-reconstruction system and will also provide dosimetric support for the epidemiological studies of the Techa River cohorts (ETRC and TROC) as well as for the cohort of EURT residents. Then, individualized doses due to residence on the contaminated territories for the members of the ETRC and TROC will be

Table 41. Comparison of the total intake of short-lived radionuclides by residents of Metlino from the Techa River and from residence on the EURT.

Settlement	Period of intake	Total intake of short-lived radionuclides, 10^{-6} Ci
Metlino (Techa River):		
• Adults	1950–1956	100
• Children born in 1951	1951–1956	10
• Children born in 1952	1952–1956	0.4
Berdyanish (EURT, 650 Ci km^{-2})	29 September– 9 October 1957	164
ONIS (EURT, 1.5 Ci km^{-2})		
• Derived from local foodstuffs	1957–1959	6.8
• Derived from excreta contamination		2.3

reconstructed by combining settlement-specific intake functions with individual-residence histories within the contaminated areas.

CONCLUSIONS

The main purpose of this report was to develop methodological approaches to the reconstruction of radionuclide intake for residents of the EURT and KT areas. The EURT and KT covered significant territory including a number of settlements with compact habitation of people removed from the Techa River. So, 4,000 members of the ETRC and 1,300 members of the TROC were exposed additionally due to the residence on the areas contaminated in 1957 (EURT) and 1967 (KT).

It was shown that a considerable number of both environmental radionuclide examinations and measurements of ^{90}Sr in human-bone samples collected at autopsy were performed at the URCRM since 1958 for the territories of the EURT and KT. The dose-reconstruction process for the EURT and KT areas is based extensively on measurements of food-stuff contamination and exposure in humans for “referent” settlements that serve as sites of long-term monitoring. For other settlements deposition density-to-dose-conversion-factors are derived.

Several methodological approaches to the reconstruction of intake are considered in this report. The analysis has shown that the choice of the best approach depends on the data available and differs for different groups of evacuated and non-evacuated settlements located on the EURT as well as for the area of the KT.

For the first time the estimates of ^{90}Sr intake were derived from measurements of this radionuclide in human bones and the whole body. The findings have shown that there are significant contradictions between estimates of ^{90}Sr intake calculated on the basis of measurements of ^{90}Sr in local foodstuffs and those based on other measurements. The estimates based on measurements of foodstuffs are reliable only for about 15% of population with maximal levels of intake; for the majority of people the estimates are too high So, the estimates of intake obtained on the basis of “human data” and based on measurements of ^{90}Sr in duplicated diet are preferable.

The task of the reconstruction of the intake of short-lived radionuclides for persons on the EURT was given special attention. This report presents for a first time the description and analysis of unique data on measurements of the total-beta activity in feces obtained for residents of EURT settlements during the first period after the explosion. The data on excreta contamination obtained in 1958 and 1959 were used for validation of the intake of short-lived radionuclides. The estimates of daily intakes derived from measurements of bone samples and feces are in good agreement. It should be emphasized that good agreement among the results obtained with use of independent sets of data indicates the reliability of assumptions used for the reconstruction of the intake of short-lived radionuclides.

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Appendix 1

CONTAMINATION DENSITY OF THE URALS SETTLEMENTS COVERED BY THE EURT AND KT

Table A1. Contamination density of the Urals settlements covered by the EURT and KT.

Code	Settlement	Oblast	Status	^{90}Sr-contamination density [a], Ci km^{-2} 1957	^{90}Sr-contamination density [b], Ci km^{-2} 1967	^{137}Cs-contamination density [c], Ci km^{-2} 1967
8	Abdyrova	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
18	Akbasheva	Chelyabinsk	Exist	0.1	<0.12	<0.37
36	Allaky	Chelyabinsk	Exist	0.9	0.30	0.37–0.93
41	Amineva	Chelyabinsk	Exist	0.5	0.45	0.93–1.87
45	Anbashskaya	Chelyabinsk	Exist	0.2	0.62–1.24	1.87–3.73
59	Argayash	Chelyabinsk	Exist	0.1	0.17	0.37–0.93
75	Bagaryak	Chelyabinsk	Exist	2	0.12–0.31	0.37–0.93
76	Bazhikaeva	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
91	Barakova	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
95	Bashakul	Chelyabinsk	Exist	0.4	0.38	1.87–3.73
97	Bayazitova	Chelyabinsk	Exist	0.1	0.12–0.12	0.37–0.37
113	Berdyanish	Chelyabinsk	Evacuated in 1957	650	0	0
116	Beregovoy	Chelyabinsk	Exist	0.3	0.15	0.37–0.93
125	Berezovka	Chelyabinsk	Exist	0.1	<0.12	<0.37
136	Bigardy	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
138	Bizhelyak	Chelyabinsk	Exist	0.4	0.33	0.93–1.87
154	B. Taskino	Chelyabinsk	Exist	0.3	0.60	1.87–3.73
164	B.Tyulyakovo	Chelyabinsk	Exist	0.2	0.12–0.31	0.37–0.93
167	B. Kuyash	Chelyabinsk	Exist	0.5	1.60	1.87–3.73
169	Borisovka	Chelyabinsk	Exist	0.1	0.20	0.37–0.93
173	Borovoe	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
188	Bulatova	Chelyabinsk	Exist	0.1	0.15	3.73–9.30
190	Boulzy	Chelyabinsk	Exist	0.8	0.25	0.37–0.93
193	Burino	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
199	Bukharino	Chelyabinsk	Exist	0.1	<0.12	<0.37
226	Vetka	Chelyabinsk	Exist	0.5	0.31–0.62	0.93–1.90
231	Vishnevogorsk	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
237	Vozdvizhenka	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
245	Voskresenskoye	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
258	Gaevo	Chelyabinsk	Exist	1.3	0.12–0.31	0.37–0.93
267	Golubinka	Chelyabinsk	Exist	0.4	0.88	1.87–3.73
284	Grigoryevka	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
306	Dolgoderevenskoye	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
309	Druzhny	Chelyabinsk	Exist	0.2	0.30	0.37–0.93
336	Zhukovo	Chelyabinsk	Exist	0.2	0.12–0.31	0.37–0.93

Table A1. (Continued)

Code	Settlement	Oblast	Status	^{90}Sr-contamination density [a], Ci km^{-2} 1957	^{90}Sr-contamination density [b], Ci km^{-2} 1967	^{137}Cs-contamination density [c], Ci km^{-2} 1967
341	Zavarukhino	Chelyabinsk	Exist	0.1	<0.12	<0.37
368	Znamenka	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
373	Zotino	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
375	Zyryankul	Chelyabinsk	Exist	0.34	0.10	0.37–0.93
377	Ibragimova	Chelyabinsk	Exist	0.35	0.60	1.87–3.73
382	Iksanova	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
393	Ishalino	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
396	Kabanskoe	Chelyabinsk	Exist	0.2	0.12–0.31	0.37–0.93
405	Kainkul	Chelyabinsk	Exist	0.5	0.90	2.60
414	Kalinovsky	Chelyabinsk	Exist	0.2	0.29	3.70–9.30
432	Kanzafarova	Chelyabinsk	Exist	0.25	0.27	0.37–0.93
437	Karagaikul	Chelyabinsk	Exist	0.3	0.40	1.70
443	Karakulmiak[1]	Chelyabinsk	Exist	0.2	0.50	0.37–0.93
444	Karakulmiak[2]	Chelyabinsk	Exist	0.1	0.31–0.62	0.93–1.90
451	Karino	Chelyabinsk	Exist	0.1	0.43	0.37–0.93
460	Kasly	Chelyabinsk	Exist	0.35	0.12–0.31	0.37–0.93
482	Kisegach	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
487	Klepalovo	Chelyabinsk	Exist	0.2	0.12–0.31	0.37–0.93
509	Kolpakovo	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
511	Komsomolsky	Chelyabinsk	Exist	0.15	0.16	1.90–1.90
546	Krasnoe Pole	Chelyabinsk	Exist	0.1	<0.12	<0.37
555	Krasny Partizan	Chelyabinsk	Exist	0.5	0.12–0.31	0.37–0.93
567	Kubagusheva	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
572	Kuznetskoe	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
581	Kuluzhbaeva	Chelyabinsk	Exist	0.2	0.20	0.93–1.87
583	Kulmyakovo	Chelyabinsk	Exist	0.17	0.12–0.31	0.37–0.93
590	Kunashak	Chelyabinsk	Exist	0.3	0.31–0.62	0.93–1.87
604	Kyzylbulyak	Chelyabinsk	Exist	0.1	0.29	3.70–9.30
605	Kyzylova	Chelyabinsk	Exist	0.2	0.12–0.31	0.37–0.93
606	Kyrmyskaly	Chelyabinsk	Exist	0.27	0.40	1.87–3.73
607	Kyshtym	Chelyabinsk	Exist	0.1	0.17	0.37–0.93
610	Larino	Chelyabinsk	Exist	0.15	0.12–0.31	0.37–0.93
648	M. Kazakbaeva	Chelyabinsk	Exist	0.2	0.12–0.31	0.37–0.93
667	M. Kunashak	Chelyabinsk	Exist	0.4	0.46	1.87–3.73
668	M. Kuyash	Chelyabinsk	Exist	0.35	0.35	0.93–1.87

Table A1. (Continued)

Code	Settlement	Oblast	Status	^{90}Sr-contamination density [a], Ci km^{-2} 1957	^{90}Sr-contamination density [b], Ci km^{-2} 1967	^{137}Cs-contamination density [c], Ci km^{-2} 1967
671	Mansurova	Chelyabinsk	Exist	0.15	0.10	0.37–0.93
672	Marzhinbaeva	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
683	Mayak	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
690	Mediak	Chelyabinsk	Exist	0.1	<0.12	<0.37
729	Moskvina	Chelyabinsk	Exist	0.7	0.12–0.31	0.37–0.93
737	Murino	Chelyabinsk	Exist	0.1	0.20	0.37–0.93
738	Musakaeva	Chelyabinsk	Exist	0.9	0.30	0.93–1.90
774	Nizhnyaya	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
782	N. Soboleva	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
783	N. Techa	Chelyabinsk	Exist	0.2	0.17	1.87–3.73
793	Novoburino	Chelyabinsk	Exist	0.1	0.31–0.62	0.93–1.87
798	Novogorny	Chelyabinsk	Exist	0.4	0.29	3.73–9.33
799	N. Kurmanovo	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
834	Norkino	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
838	Ognevskoe	Chelyabinsk	Exist	0.4	0.12–0.31	0.37–0.93
843	Ozersk	Chelyabinsk	Exist	0.35	–	–
908	Podkorytova	Chelyabinsk	Exist	0.15	0.12–0.31	0.37–0.93
913	Poldnevo	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
931	Porokhovoe	Chelyabinsk	Exist	0.2	0.10	0.37–0.93
939	Pribrezhny	Chelyabinsk	Exist	0.2	0.30	0.37–0.93
951	Prudny	Chelyabinsk	Exist	0.1	<0.12	<0.37
957	Pyankova	Chelyabinsk	Exist	1.3	0.12–0.31	0.37–0.93
964	Razyezd No.2	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
990	Rus.-Karabolka	Chelyabinsk	Evacuated in 1958	65	0	0
999	Saitova	Chelyabinsk	Exist	0.1	<0.12	<0.37
1019	Sarino	Chelyabinsk	Exist	0.5	0.50	1.40
1022	Sarykulmiak	Chelyabinsk	Exist	0.5	1.50	4.40
1040	Selezny	Chelyabinsk	Exist	0.4	0.37	1.90–3.70
1043	Selyaeva	Chelyabinsk	Exist	0.1	<0.12	<0.37
1047	Serkino	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
1056	Sinarsky	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
1067	Slobodchikova	Chelyabinsk	Exist	0.6	0.25–0.31	0.75–0.93
1100	S. Soboleva	Chelyabinsk	Exist	0.1	0.31–0.62	0.93–1.90
1118	Suleymanovo	Chelyabinsk	Exist	0.6	0.50	0.93–1.90
1120	Sultaeva	Chelyabinsk	Exist	0.0	0.30	1.00

Table A1. (Continued)

Code	Settlement	Oblast	Status	^{90}Sr-contamination density [a], Ci km^{-2} 1957	^{90}Sr-contamination density [b], Ci km^{-2} 1967	^{137}Cs-contamination density [c], Ci km^{-2} 1967
1127	Surakovo	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
1129	Surtanysh	Chelyabinsk	Exist	0.4	0.40	1.87–3.73
1146	Tayginka	Chelyabinsk	Exist	0.1	0.31–0.62	0.93–1.87
1155	Tat.-Karabolka	Chelyabinsk	Exist	1.3	0.25	0.93–1.87
1160	Tahtalym	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
1190	Troshkovo	Chelyabinsk	Evacuated in 1959	16	0	0
1192	Trudovoy	Chelyabinsk	Exist	0.15	0.31–0.31	0.93–0.93
1203	Tyubuk	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
1208	Uvildy	Chelyabinsk	Exist	0.1	0.17	0.37–0.93
1230	Urukul	Chelyabinsk	Exist	0.2	0.50	0.93–0.93
1231	Usmanova	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
1234	Ust-Bagaryak	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
1235	Ust-Karabolka	Chelyabinsk	Exist	0.2	0.45	0.37–0.93
1243	Utyabaeva	Chelyabinsk	Exist	0.15	0.15	0.93–1.90
1248	Fadino	Chelyabinsk	Evacuated in 1958	8	0	0
1259	Halitovo	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
1267	Hudayberdinsky	Chelyabinsk	Exist	0.25	0.26	3.73
1276	Chapaevka	Chelyabinsk	Exist	0.1	<0.12	<0.37
1278	Chebakul	Chelyabinsk	Exist	0.6	0.50	0.93–1.87
1282	Chekurova	Chelyabinsk	Exist	0.15	0.61	0.37–0.93
1284	ONIS	Chelyabinsk	Exist	1.5	1.20	1.87–3.73
1309	Chishma	Chelyabinsk	Exist	0.2	0.31–0.62	0.93–1.87
1320	Shablish	Chelyabinsk	Exist	0.3	0.12–0.31	0.37–0.93
1322	Shaburovo	Chelyabinsk	Exist	0.35	0.12–0.31	0.37–0.93
1333	Shigaevo	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
1349	Yuzhnaya Kuznechiha	Chelyabinsk	Exist	0.1	<0.12	<0.37
1357	Yuldashevo	Chelyabinsk	Exist	0.2	0.31–0.62	0.93–1.87
1361	Yushkova	Chelyabinsk	Exist	0.7	0.12–0.31	0.37–0.93
1366	Yamantaeva	Chelyabinsk	Exist	0.2	0.31–0.62	0.93–1.87
1369	Yangi-Yul	Chelyabinsk	Exist	0.15	0.15	1.90–3.70
1375	Boevsky	Chelyabinsk	Evacuated in 1959	4	0	0
1377	Galikaevo	Chelyabinsk	Evacuated in 1957	400	0	0

Table A1. (Continued)

Code	Settlement	Oblast	Status	^{90}Sr-contamination density [a], Ci km^{-2} 1957	^{90}Sr-contamination density [b], Ci km^{-2} 1967	^{137}Cs-contamination density [c], Ci km^{-2} 1967
1378	Kazhakul	Chelyabinsk	Evacuated in 1960	2	0	0
1381	Krivosheino	Chelyabinsk	Evacuated in 1959	12	0	0
1383	Ostrovsky	Chelyabinsk	Destroyed in 1974	0.2	0.20	0.37–0.93
1388	Rependy	Chelyabinsk	Destroyed in 1970	1.4	–	–
1390	Yugo-Konevo	Chelyabinsk	Evacuated in 1958	10.8	0	0
1391	Sharapkulovo	Chelyabinsk	Exist	0.75	1.24–3.10	3.73–9.33
1392	Komsomolsky	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
1399	Akkul	Chelyabinsk	Destroyed in 1974	0.1	0.12–0.31	0.37–0.93
1402	Alabuga	Chelyabinsk	Evacuated in 1958	8	0	0
1404	Arykova	Chelyabinsk	Exist	0.1	0.36	0.37–0.93
1411	Bryukhanovo	Chelyabinsk	Evacuated in 1958	8	0	0
1416	Govorukhina	Chelyabinsk	Destroyed in 1974	0.1	0.12–0.31	0.37–0.93
1417	Gorny	Chelyabinsk	Evacuated in 1958	18	0	0
1418	Gusevo	Chelyabinsk	Evacuated in 1958	8	0	0
1420	Eremeevka	Chelyabinsk	Destroyed in 1974	0.5	0.62–1.24	1.90–3.73
1424	Igish	Chelyabinsk	Evacuated in 1958	32	0	0
1430	Kazakbaeva	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
1433	Karakaeva	Chelyabinsk	Destroyed in 1968	0.1	0.12–0.31	0.37–0.93
1435	Kirpichiki	Chelyabinsk	Evacuated in 1957	3	0	0
1442	M. Troshkovo	Chelyabinsk	Evacuated in 1958	24	0	0
1446	M. Irkabaeva	Chelyabinsk	Destroyed in 1975	0.1	0.12–0.31	0.37–0.93

Table A1. (Continued)

Code	Settlement	Oblast	Status	^{90}Sr-contamination density [a], Ci km^{-2} 1957	^{90}Sr-contamination density [b], Ci km^{-2} 1967	^{137}Cs-contamination density [c], Ci km^{-2} 1967
1448	M. Shaburovo	Chelyabinsk	Evacuated in 1958	4	0	0
1450	Melnikova	Chelyabinsk	Evacuated in 1958	18	0	0
1457	Novaya	Chelyabinsk	Destroyed in 1960	0.1	0.12–0.31	0.37–0.93
1469	Satlykovo	Chelyabinsk	Evacuated in 1957	400	0	0
1471	Svoboda	Chelyabinsk	Evacuated (1974)	0.1	0.12–0.31	0.37–0.93
1472	Skorinovo	Chelyabinsk	Evacuated in 1958	9	0	0
1476	Temryas	Chelyabinsk	Destroyed in 1978	0.2	1.00	0.93–1.87
1480	Chelyuskin	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
1489	Etbaeva	Chelyabinsk	Destroyed in 1972	0.15	0.30–1.24	0.93–3.70
1490	Yumangulova	Chelyabinsk	Destroyed in 1968	0.1	–	–
3009	Bayny	Sverdlovsk	Exist	2.1	0	0
3035	Galkinskoye	Sverdlovsk	Exist	0.2	0	0
3053	Kamensk-Uralsky	Sverdlovsk	Exist	0.6	0	0
3055	Kamyshlov	Sverdlovsk	Exist	0.5	0	0
3061	Klevakinskoe	Sverdlovsk	Exist	0.2	0	0
3077	Lebyazye	Sverdlovsk	Exist	0.1	0	0
3083	Maminskoe	Sverdlovsk	Exist	0.2	0	0
3112	Pozarikha	Sverdlovsk	Exist	1.5	0	0
3130	Sosnovskoe	Sverdlovsk	Exist	0.1	0	0
3187	Cheremkhovo	Sverdlovsk	Exist	3.1	0	0
3191	Rybnivskoe	Sverdlovsk	Exist	2.1	0	0
3194	Bogatenkova	Sverdlovsk	Exist	1.2	0	0
3214	Shcherbakovo	Sverdlovsk	Exist	2.7	0	0
3220	Klyukino	Sverdlovsk	Evacuated in 1959	2	0	0
3221	Tygish	Sverdlovsk	Evacuated in 1959	4	0	0
3222	Chetyrkino	Sverdlovsk	Evacuated in 1959	4	0	0

Table A1. (Concluded).

Code	Settlement	Oblast	Status	^{90}Sr-contamination density [a], Ci km^{-2} 1957	^{90}Sr-contamination density [b], Ci km^{-2} 1967	^{137}Cs-contamination density [c], Ci km^{-2} 1967
3242	Troitskoe	Sverdlovsk	Exist	0.2	0	0
4504	Moseevo	Chelyabinsk	Exist	0.1	0.12–0.31	0.37–0.93
4506	Korolevo	Chelyabinsk	Exist	0.37	0.12–0.31	0.37–0.93
	Belovodye	Sverdlovsk	Exist	1.8	0	0
	Chechyulina	Sverdlovsk	Exist	0.1	0	0
	Komarova	Sverdlovsk	Exist	0.8	0	0
	Novy Zavod	Sverdlovsk	Exist	1.5	0	0
	Shilova	Sverdlovsk	Exist	0.2	0	0
	Smolinskoe	Sverdlovsk	Exist	1.0	0	0

[a] Density of ^{90}Sr-contamination in 1957 is due to formation of the EURT.

[b] Density of ^{90}Sr-contamination in 1967 as a result of formation of the KT; the values are given by GN Romanov. If information on settlement ^{90}Sr-contamination was absent, the minimal and maximal values were derived from the maps of ^{137}Cs-contamination in 1994 (IDCRM1995b) by extrapolation to 1967 and using the ratio between ^{137}Cs and ^{90}Sr in soils. The map reflects cumulative contamination of the territories in 1994 due to the KT formation, fallout from the Chernobyl accident and operation of Mayak.

[c] Minimal and maximal values of density of ^{137}Cs contamination in 1967 as a result of formation of the KT; derived from the maps of ^{137}Cs-contamination in 1994 (IDCRM1995b). The map reflects cumulative contamination of the territories in 1994 due to the KT formation, fallout from the Chernobyl accident and operation of Mayak.

Appendix 2

TERRITORIAL DISTRIBUTION OF RESIDENCE LOCATIONS FOR MEMBERS OF THE ETRC AND TROC WITHIN THE EURT AND KT

Table A2.1. Statistics on the number of ETRC and TROC members exposed in EURT villages evacuated at different times after the explosion.

Settlement	Time of evacuation, days	^{90}Sr-contamination density, Ci/km^2	Number of ETRC members	Number of TROC members
Berdyanish	7	650	13	8
Satlykovo	7	400	2	
Alabuga	250	8	1	
Rus.-Karabolka	250	65	1	
Yugo-Konevo	250	10.8	6	
Boevka	330	4	6	
Melnikovo	330	18	1	
Skorinovo	330	4	4	
Kazhakul	670	2	10	3
Total			***44***	***11***

Table A2.2. EURT settlements where members of the ETRC and TROC cohorts lived during major exposure.

Settlement [a]	Density of ^{90}Sr-contamination in 1957 [b], Ci/km^2	Density of ^{90}Sr-contamination in 1967 [c], Ci/km^2	Density of ^{137}Cs-contamination in 1967 [d], Ci/km^2	Number of ETRC members	Number of TROC members
ONIS	1.5	1.2	1.9-3.7	1276	363
	0.1	0.1-0.3	0.4-0.9	784	303
Chishma	0.2	0.3-0.6	0.9-1.9	289	111
B. Taskino	0.3	0.6	1.9-3.7	218	91
Ozersk	0.35	0.15	-	151	25
Sarino	0.5	0.5	1.4	142	48
Kamensk-Uralsky	0.6	0	0	127	11
Bashakul	0.4	0.38	1.9-3.7	123	48
Argayash	0.1	0.17	0.4-0.9	67	11
B. Kuyash	0.5	1.6	1.9-3.7	55	12
Suleymanovo	0.6	0.5	0.9-1.9	48	21
Karagaikul	0.3	0.4	1.7	47	24
Hudayberdinsky	0.25	0.26	3.7	47	12
Larino	0.15	0.1-0.3	0.4-0.9	46	21
Borisovka	0.1	0.2	0.4-0.9	45	21
Surtanysh	0.4	0.4	1.9-3.7	43	19
Kyshtym	0.1	0.17	0.4-0.9	41	12
Kunashak	0.3	0.3-0.6	0.9-1.9	39	6
Chebakul	0.6	0.5	0.9-1.9	38	9
S. Soboleva	0.1	0.3-0.6	0.9-1.9	36	11
Tahtalym	0.1	0.1-0.3	0.4-0.9	36	4
Sultaeva	0	0.3	1.0	30	15
Dolgoderevenskoye	0.1	0.1-0.3	0.4-0.9	29	5
Novogorny	0.4	0.29	3.7-9.3	25	6
Vishnevogorsk	0.1	0.1-0.3	0.4-0.9	24	7
Karakulmiak	0.2	0.5	0.4-0.9	22	5
Kasly	0.35	0.1-0.3	0.4-0.9	22	5
Surakovo	0.1	0.1-0.3	0.4-0.9	21	6
Sarykulmiak	0.5	1.5	4.4	20	10
Ibragimova	0.35	0.6	1.9-3.7	18	13
N. Soboleva	0.1	0.1-0.3	0.4-0.9	17	4
Halitovo	0.1	0.1-0.3	0.4-0.9	17	9
Bagaryak	2.0	0.1-0.3	0.4-0.9	14	8
Krasny Partizan	0.5	0.1-0.3	0.4-0.9	14	1
Golubinka	0.4	0.88	1.9-3.7	10	2
Druzhny	0.2	0.3	0.4-0.9	10	0
Novoburino	0.1	0.3-0.6	0.9-1.9	10	3
Tat.-Karabolka	1.3	0.25	0.9-1.9	9	1

Settlement [a]	Density of ^{90}Sr-contamination in 1957 [b], Ci/km^2	Density of ^{90}Sr-contamination in 1967 [c], Ci/km^2	Density of ^{137}Cs-contamination in 1967 [d], Ci/km^2	Number of ETRC members	Number of TROC members
Allaky	0.9	0.3	0.4-0.9	4	0
Boulzy	0.8	0.25	0.4-0.9	1	0
Total				***4015***	***1283***

[a] Settlements were more than 100 ETRC or TROC members lived are shown in italics.

[b] Density of ^{90}Sr-contamination in 1957 is due to EURT formation (Appendix 1)

[c] Density of ^{90}Sr-contamination in 1967 as a result of formation of the KT; the values are given by GN Romanov. If information on settlement ^{90}Sr-contamination was absent, the minimal and maximal values were derived from the maps of ^{137}Cs-contamination in 1994 (IDCRM1995b) by extrapolation to 1967 and using the ratio between ^{137}Cs and ^{90}Sr in soils. The map reflects cumulative contamination of the territories in 1994 due to the KT formation, fallout from the Chernobyl accident and operation of Mayak.

[d] Minimal and maximal values of density of ^{137}Cs -contamination in 1967 as a result of the KT formation; derived from the maps of ^{137}Cs-contamination in 1994 (IDCRM1995b).

Appendix 3

DATA ON ^{90}Sr IN LOCAL FOODSTUFFS AND TOTAL BETA-ACTIVITY OF EXCRETA FROM PERSONS WITHIN THE EURT AREA

Table A3.1. Specific activity of ^{90}*Sr in milk sampled in referent settlements at different times after the explosion determined by radiochemical method (the geometric means are given in pCi* L^{-1}*)*[a].

Calendar year	Allaky			Bagaryak			Boulzy			Tat.-Karabolka			Yushkovo		
	$\bar{x}$	σ	*n*	$\bar{x}$	σ	*n*	$\bar{x}$	σ	*n*	$\bar{x}$	σ	*n*	$\bar{x}$	σ	*n*
1960	–	–	–	180	2.6	19	–	–	–	550	1.5	4	200	1.9	3
1961	80	1.5	3	200	2.1	11	–	–	–	–	–	–	60	1.1	3
1962							–	–	–	150	2.2	3			
1963	140	2.2	30	–	–	–	–	–	–				54	2.7	3
1964				120	2.4	10	110	1.6	28	150	1.5	29	130	2.2	33
1965	70	1.6	7	130	1.3	4	120	2.4	38	130	2.9	17	43	1.3	5
1966	57	1.5	5	120	1.3	5	51	1.4	5	160	4.2	105	57	1.6	5
1968	–	–	–	22	1.4	4	–	–	–	140	1.8	93	–	–	–
1969	120	1.8	13	150	3	21	–	–	–	120	1.8	115	–	–	–
1971	160	2.2	16	130	3	59	76	1.7	20	380	3	60	59	1.6	16
1981	–	–	–	–	–	–	38	2.3	51	–	–	–	43	1.7	12
1983	–	–	–	70	2.6	163	–	–	–	–	–	–	–	–	–
1984	57	1.8	93	68	2.7	69	30	1.9	44	–	–	–	30	1.7	33
1985	–	–	–	14	1.4	4	43	1.5	4	–	–	–	–	–	–
1993	–	–	–	68	2	32	–	–	–	41	2.3	65	–	–	–
1995	–	–	–	–	–	–	–	–	–	27	1.6	11	–	–	–
1997	35	1.6	37	82	2	37	14	2.1	21	27	1.7	31	–	–	–
1998	78	3.1	15	–	–	–	30	2.6	17	–	–	–	24	2.3	42
1999	–	–	–	35	2.4	35	–	–	–	–	–	–		-	-
2003	–	–	–	62	1.6	21	–	–	–	24	2.7	28		-	-

[a] Geometric mean $\bar{x}$, geometric standard deviation *σ,* and number of measured samples *n* are shown for each settlement

Table A3.2. Specific activity of ^{90}Sr in bread in referent settlements determined by the radiochemical method in 1961–1983 (data are given in pCi kg^{-1} per unit ^{90}Sr-contamination density, Ci km^{-2}).

Calendar year	Average specific activity of ^{90}Sr pCi kg^{-1} per Ci km^{-2}	Number of samples
1961	210±97	3
1962	220±150	3
1963	200±110	3
1964	210±20	2
1965	170±80	4
1966	160	1
1969	70±15	3
1971	24	1
1973	22	1
1974	19±8	4
1981	11±5	3
1983	11±5	3

Table A3.3. Specific activity of ^{90}Sr in potato determined by radiochemical method in 1963-2003 (geometric means are given in pCi kg^{-1}).[a]

Calendar year	Allaky			Bagaryak			Boulzy			Tat.-Karabolka			Yushkovo		
	$\bar{x}$	σ	*n*	$\bar{x}$	σ	*n*	$\bar{x}$	σ	*n*	$\bar{x}$	σ	*n*	$\bar{x}$	σ	*n*
1963	23	1.6	3	–	–	–	30	2.6	5	30	2.6	5	27	3.1	5
1964	13	1.47	5	78	1.3	4	19	1.1	25	19	1.4	4	–	–	–
1966	43	2.1	9	59	3.2	5	59	2.4	12	59	2.4	12	14	1.4	5
1967	–	–	–	–	–	–	–	–	–	41	2.6	145	–	–	–
1971	12	1.2	7	19	1.8	10	22	1.6	11	22	1.6	11	11	2.5	7
1973	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
1977	–	–	–	–	–	–	–	–	–	–	–	–		–	–
1981	–	–	–	–	–	–	–	–	–	–	–	–	5	2.8	5
1983	–	–	–	20	2.2	25	–	–	–	–	–	–	–	–	–
1984	19	1.8	24	–	–	–	–	–	–	–	–	–	11	2.3	21
1998	54	1.3	21	–	–	–	14	2.3	17	–	–	–	11	2.4	15
1999	–	–	–	–	–	–	–	–	–	11	2.7	20	–	–	–
2003	–	–	–	38	1.5	32	38	1.5	32	19	2.9	36	–	–	–

[a] Geometric mean $\bar{x}$, geometric standard deviation *σ,* and number of measured samples *n* are shown for each settlement.

Table A3.4. Statistical characteristics of specific activity of ^{90}Sr *in milk for the Bagaryak settlement. All data are given in pCi* L^{-1}.

Calendar year	Number of samples	Average	Median	Geometric mean	Standard deviation	95th percentile
1960	19	240	220	180	70	550
1961	9	250	280	190	59	960
1964	10	160	150	120	65	710
1965	4	130	130	130	35	170
1966	5	130	120	120	35	210
1968	4	22	24	22	11	46
1969	21	270	150	150	81	1550
1971	59	250	130	130	81	1080
1983	163	130	73	70	59	300
1984	69	110	62	68	73	520
1993	32	78	78	68	54	240
1997	37	100	81	82	54	340
1999	35	51	41	35	65	130
2003	21	68	65	62	43	89

Table A3.5. Characteristics of measurements of total-beta activity in feces for residents of EURT settlements during the first period after the explosion (1958–1959).

Settlement	^{90}Sr-contamination density, Ci km^{-2}	Time of evacuation, days	Period of measurements	Number of measurements
Allaky	0.9	–	Nov 1959–Oct 1959	6
Bagaryak	2	–	June 1958–July 1959	37
Boevka	4	330	Apr 1958–June 1958	19
Bryukhanovo	8	330	May 1958	8
Fadino	8	330	Apr 1958	3
Gusevo	8	330	Apr 1958	3
Krivosheino	12	330	May 1958–June 1958	30
Melnikovo	18	330	Apr 1958	6
ONIS	1.5	–	Aug 1958–Dec 1959	60
Tat.-Karabolka	1.3	–	May 1959 - July 1959	18
Yugo-Konevo	10.8	250	Apr 1958	4
Yushkovo	0.7	–	July 1958–Dec 1959	9
B. Kuyash	0.5	–	Apr 1958	1
Golubinka	0.4	–	Dec 1959	1
Kazhakul	2	670	June 1959	1
Ognevskoe	0.4	–	July 1959–June 1959	2

Appendix 4

DATA ON ^{90}Sr AND ^{137}Cs IN LOCAL FOODSTUFFS FROM THE KT AREA

Table A4.1. Statistical characteristics of the empirical distributions of specific activity of ^{90}*Sr in milk from the Sarykulmiak settlement (all values are given in pCi* L^{-1}*).*

Date of sampling		Average	Standard deviation	Median	Geometric mean	95th percentile	Number of samples
Year	Month						
1967	April	3800					2
	May	1350	820	1300	1200	2350	152
	June	610	205	580	581	970	52
	July	350	110	340	332	490	6
	August	240	190	130	135	400	10
	September	190	110	110	100	490	9
	October	270	160	95	90	380	9
1968	March	200	27	190	195	240	5
	April	140	70	140	122	220	10
	May	200	130	200	168	410	9
	June	110	43	110	97	160	6
	July	250	140	180	214	460	9
	August	200	108	180	170	380	10
	September	310	168	350	254	510	9
1969	March	220	97	220	197	380	12
	April	230	100	210	219	400	10
	May	310	162	270	289	600	13
	June	210	81	200	184	320	9
	July	190	54	180	189	270	11
	August	220	100	220	197	410	15
	September	200	95	210	157	300	15
1970	July	110	27	120	111	160	30
	December	150	176	120	116	410	13
1971	August	89	30	81	86	140	13
1972	April	110	32	97	105	160	10
	August	97	57	84	84	220	19
1973	July	78	8	70	70	150	25
1977	July	210	132	200	165	410	78
	August	92	38	76	86	160	9
1978	August	70	22	68	65	100	49
1979	March	100	41	97	65	170	36
1980	September	62	19	68	59	86	20
1985	August	70	22	70	68	110	25
1986	August	27					2
1999	March	32	24	27	27	68	17
	August	19	11	16	19	38	16
2000	August	24	16	19	22	51	15

Table A4.2. Statistical characteristics of the empirical distributions of specific activity of ^{137}Cs in milk from the Sarykulmiak settlement (all values are given in pCi L^{-1}).

Date of sampling		Average	Standard deviation	Median	Geometric mean	95th percentile	Number of samples
Year	Month						
1967	April	6410					2
	May	2680	954	2700	2500	4300	50
	June	1880	178	1800	1870	2120	6
	July	1600	635	1650	840	1890	4
	September	460	108	240	370	610	10
1968	February	410	168	460	380	490	6
	April	280	243	230	330	680	9
	May	1050	773	990	800	2220	8
	June	670	503	570	530	1430	7
	July	2600	3340	950	1230	8300	10
	August	2300	2592	970	990	6620	10
	September	1500	1424	1700	610	3410	9
1969	March	590	922	360	370	970	95
	April	330	184	290	300	650	11
	May	390	162	380	320	650	14
	June	490	338	390	390	1110	15
	July	870	803	380	580	2110	12
	August	1060	997	510	590	2540	16
	September	960	1208	490	500	2810	54
1970	May	1390	2103	450	630	6350	29
	July	780	522	670	670	1510	26
	December	330	268	210	260	840	13
1971	July	570	568	220	340	1510	13
1972	April	350	462	170	210	1110	10
	July	1160	414	1100	1080	1810	19
1973	July	450	59	460	330	950	24
1977	July	130	78	120	170	760	90
	August	350	178	330	320	650	9
1978	July	81	24	76	76	140	49
1979	March	68	59	62	59	150	36
1980	August	97	35	97	89	150	20
1985	July	200	162	160	65	510	26
1999	May	120	130	78	78	250	17
	July	41	35	22	30	70	16
2000	July	73	65	35	49	130	15

Table A4.3. Statistical characteristics of the empirical distributions of ^{90}Sr in adult rations, pCi day^{-1}.

Date of sampling	Number of rations	Statistical characteristics				
		Average	Standard deviation	Median	Geometric mean	95th percentile
August 1967	22	180	110	150	170	450
May 1968	22	160	160	120	97	380
December 1968	18	90	130	40	50	310

Table A4.4. Statistical characteristics of the empirical distributions of ^{137}Cs in adult rations, pCi day^{-1}.

Date of sampling	Number of rations	Statistical characteristics				
		Average	Standard deviation	Median	Geometric mean	95th percentile
August 1967	22	430	94	310	290	1460
May 1968	21	370	323	230	240	1040
December 1968	22	110	84	84	78	250

Table A4.5. Statistical characteristics of the empirical distributions of ^{90}Sr and of ^{137}Cs in rations of children aged 3–7 years, pCi day^{-1}.

Date of sampling	Number of rations	Statistical characteristics			
		Average	Median	Geometric mean	95th percentile
		^{90}Sr			
August 1967	14	140	70	78	500
May 1968	14	78	62	59	190
December1968	6	46	38	35	92
		^{137}Cs			
August 1967	14	270	240	220	400
May 1968	14	300	250	240	710
December1968	10	120	97	97	290

Table A4.6. Statistical characteristics of the empirical distributions of ^{90}Sr and of ^{137}Cs in rations of children aged 7–15 years, pCi day^{-1}.

Date of sampling	Number of rations	Statistical characteristics			
		Average	Median	Geometric mean	95th percentile
		^{90}Sr			
August 1967	13	490	140	210	1830
May 1968	12	130	100	100	320
December1968	9	100	65	73	200
		^{137}Cs			
August 1967	13	400	220	210	1280
May 1968	11	430	310	280	1210
December1968	10	150	140	120	290