Technical Data

Dose Reconstruction for Residents Near the Former Semipalatinsk Nuclear Test Sites with a Focus on the Study of Radiation Health Effects

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A study on radiation health effects for residents around the Semipalatinsk Nuclear Test Site has been conducted by REA of Japan and NNC of the Republic of Kazakhstan. In this study, we established a new cohort. The present paper describes the method for individual dose estimation relevant to the consequences of nuclear tests for residents in 10 villages around the test site and presents part of the results. External doses were calculated based on air dose rates reported in the literature soon after the nuclear tests. Internal doses due to inhalation were estimated based on the air concentration of radionuclides calculated from the air dose rate. Internal doses due to ingestion were estimated based on the ground deposition of radionuclides calculated based on the air dose rate. The external dose was much higher than the internal dose. The total dose varied by village, with the highest dose observed in Chermushki followed by Dolon, Sarjal, Karaul, and Akbulak. These results are in reasonable agreement with doses reported by others so far.

KEY WORDS: Semipalatinsk Test Site, dose reconstruction, reference residents, external dose, internal dose by inhalation, internal dose by ingestion.

I INTRODUCTION

The epidemiological study of radiation health effects requires a correct assessment of the doses received by the affected population; however, this is not easy to do in cases where the doses occurred a long time ago. A good example is the Semipalatinsk Test Site (STS) in the Republic of Kazakhstan, where 456 nuclear tests were carried out from 1949 to 1989 when the site was part of the former Soviet Union.^{1, 2)} Of these tests, 111 were atmospheric or ground surface explosions performed between 1949 and 1963. The STS and its vicinity were contaminated with radioactive material, and the inhabitants in these areas suffered from radiation exposure and resulting radiation health effects.

The Radiation Effects Association (REA), Tokyo, Japan, has been engaged in a study on radiation health effects on residents around the STS, in cooperation with the National Nuclear Center (NNC) of the Republic of Kazakhstan, since

2001. In the study, a cohort was established and the overview of the cohort has been introduced in a previous publication.³⁾ The purpose of the present paper is to describe the method used for dose reconstruction and the resulting doses for an individual member of the cohort, which is the basis of the dose assessment used in our study on radiation health effects. In this paper, we provide information about the doses for the reference residents of the cohort.

II MATERIALS AND METHODS

1. Nuclear test data

The villages studied in the present paper are Dolon, Kinar, Karaul, Znamenka, Akbulak, Chermushki, Kanonerka, Mostik, Sarjal, and Ust-Kamenogorsk in the Former Semipalatinsk oblast of Kazakhstan. They are shown in **Fig. 1** except for Ust-Kamenogorsk which is located about 150 km east from Semey (formerly named; Semipalatinsk).

Nuclear test data, including the date of each nuclear explosion, yield of explosion (q in kt), height of explosion, wind speed (V in km/h) at the time of explosion, distance (X in km) from the site of the explosion to the point of interest, and radiation exposure dose rate (P_{24} in R/h, where $R = 2.58 \times 10^{-4} \text{C/kg}$) at 24 hours after the explosion at the measurement point were collected from published literature.⁴⁻⁷⁾ Related data were also provided for the present study with the help of the NNC. Portions of these data are included in **Table 1**.

We reconstructed the doses using the Russian Dose Calculation Method⁸⁾ (hereafter referred to as the Russian

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[†] They passed away during the preparation of this paper. They remain authors as a reflection of their substantial and valued contribution.

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Fig. 1 Map of STS and target villages for dose reconstruction.

Table 1 Nuclear test data and external radiation dose for reference residents.

Settlement	Date	q	X	V	t_0	Δt	t_c	P_{24}	Housing	D_{cloud}	MF_{cloud}	E_{cloud}	$D_{fallout}$	$MF_{fallout}$	$E_{fallout}$	Total E	Total E
	y/m/d/h	kt	km	km/h	h	h	h	R/h		R		R	R		R	R	Sv
Dolon	49/8/29/07	22	118	60.0	1.97	1.64	3.61	1.300	Wooden	24.13	0.86	20.75	197.60	0.53	104.73	125.48	0.77
Kainar	51/9/24/13	38	150	26.4	5.68	4.51	10.19	0.304	Saman	4.40	0.50	2.20	36.23	0.45	16.30	18.50	0.11
Karaul	53/8/12/7.5	400	195	85.7	2.28	2.16	4.43	0.809	Saman	14.44	0.79	11.41	117.27	0.45	52.77	64.18	0.39
Znamenka	56/8/24/6.3	27	131	86.4	1.52	1.33	2.84	0.075	Wooden	1.49	0.86	1.28	12.04	0.52	6.26	7.54	0.05
Akubulak	51/9/24/13	38	155	26.4	5.87	4.65	10.52	0.707	Saman	10.16	0.50	5.08	83.60	0.46	38.46	43.54	0.27
Chermushki	49/8/29/07	22	76	60.0	1.27	1.13	2.40	1.800	Wooden	37.55	0.86	32.29	300.55	0.52	156.29	188.58	1.15
Kanonerka	49/8/29/07	22	135	60.0	2.25	1.85	4.10	0.240	Wooden	4.31	0.86	3.70	35.42	0.52	18.42	22.12	0.13
Mostik	49/8/29/07	22	90	60.0	1.50	1.30	2.80	0.107	Wooden	2.13	0.86	1.83	17.24	0.52	8.97	10.80	0.07
Sarjal	53/8/12/7.5	400	110	85.7	1.28	1.30	2.59	1.292	Saman	26.60	0.79	21.01	211.99	0.46	97.52	118.53	0.72
U. Kamenogorsk	56/8/24/6.3	27	342	86.4	3.96	3.14	7.10	0.071	Brick	1.11	0.80	0.89	9.22	0.46	4.24	5.13	0.03

method). In this method, the individual doses were calculated based on the exposure dose rate measured at 24 hours after an explosion (P_{24}). In cases where dose rates were not recorded at 24 hours after an explosion, the P_{24} values were calculated from the radiation dose rate determined at t_1 hours after the explosion (P_{t_1}) using a power function of time with the exponent of -1.2 . The P_{24} values are shown in Table 1. We collected nuclear test data for 36 cases after 13 tests, and in this paper we calculated doses for reference residents in 10 villages after 4 major nuclear tests (performed on 29 August 1949, 24 September 1951, 12 August 1953, and 24 August 1956), as also shown in Table 1. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) reported that the 4 major nuclear tests contributed 85% of the

total collective effective dose from all STS tests combined.¹⁾

2. Outline of the dose calculation

The method for individual dose calculations in the present paper is based on the Dose Evaluation Methodological Handbook^{8, 9)} and others^{10, 11)} developed by Gordeev, with various modifications in accordance with the information obtained in the present study.

Residents received doses through many exposure pathways, so we calculated doses through external irradiation and internal irradiation separately. An external dose consists of exposure from radiation released from the radioactive cloud and exposure by radiation from radioactive fallout deposited on the ground surface. An internal dose consists of doses received

through inhalation of radioactive particles in the atmosphere and by ingestion of foods contaminated with radioactive fallout.

For the dose calculation, we assumed the reference resident who was an adult born in a village around the STS before the time of the nuclear tests and had lived there for the whole period of the dose calculation.

We calculated the external dose by the Russian method by determining the whole-body dose of the reference resident in each village, taking into consideration factors such as the transit time of radioactive plumes, the time spent outside houses, and the shielding factor of houses for each test, and the dose rate at 24 hours after a nuclear explosion (P_{24}) within each village.

We calculated the internal doses due to the inhalation pathway by first calculating the concentration of radioactivity in the atmosphere based on the P_{24} value and then using these values to calculate the radioactivity inhaled. Finally, we calculated the individual dose from the radioactivity and the inhalation dose coefficients of radionuclides defined by the International Commission on Radiological Protection (ICRP).¹²⁾

We calculated the internal doses due to ingestion of radionuclides by first calculating the ground deposition of radionuclides based on the P_{24} values and then calculating the individual dose using the ground deposition and the conversion coefficients from deposition to dose developed in the UNSCEAR report; these coefficients had been derived for global fallout from past atmospheric nuclear tests.²⁾

3. Calculation of the external dose

We calculated the external dose designated as the external whole body dose (effective dose) by the Russian method by combining the doses from the radioactive cloud and from radioactive fallout deposited on the ground. We assumed that the dose rate decays as a function of time after explosion with the exponent of -1.2 .

External doses consist of air doses from the radioactive cloud (D_{cloud}) and those from fallout deposited on the ground surface (D_{fallout}). We assumed that D_{cloud} was delivered during the time (Δt) that the cloud passed between the start time (t_0) of the explosion and the completion time (t_c). By contrast, D_{fallout} was delivered during the time between t_c and 10 years after the explosion. The duration of 10 years was taken here because radiation doses from the fallout from nuclear testing are predominantly delivered during the first several years and the dose rate become negligible or less significant at 10 years after explosion.

We calculated the external doses (E_{cloud} and E_{fallout}) actually received by individual residents by taking into account the time spent outside the houses as well as the shielding effect of the houses.

We determined the time spent outside the houses for exposure to the radioactive cloud by dividing it into two types: daytime and night time. In cases when the cloud passed during the daytime, we assumed that 2/3 of the exposure time (Δt) was outside the houses and 1/3 was inside. Similarly, in

cases when the cloud passed during nighttime, we assumed that 1/5 of the exposure time was outside the houses and 4/5 inside. Exposure to radioactive fallout was determined by the NNC, who carried out a survey through interviews to obtain information about the time spent outside, based on the age and occupation of each residents. However, this information was not available for all residents. The present dose reconstruction for exposure to radioactive fallout considered the time spent outside in cases where the occupation was known. The time spent outside is not shown in this paper.

The shielding effect of houses or buildings from external radiation sources varies depending on the construction materials and wall thicknesses; consequently, the exposure doses vary among individuals. Wood, adobe, or bricks were used as construction materials in the main types of houses in these regions. We assumed that shielding factors (K_{cloud} : the ratio of the dose rate at outside of house to the dose rate at inside of house) of wooden, adobe, and brick houses for external radiation from the radioactive cloud were 1.3, 4.0, and 3.0, respectively, based on the Handbook values. (The Handbook does not show 1.3 for a wooden house, but we calculated this value from the Handbook.) Unfortunately, information on type of house lived in by each resident was not available, but the dominant house in each village was reported by the NNC and is shown in **Table 1**. Wood is the most commonly used construction material in Dolon, adobe is common in Kainar, and brick is common in U. Kamenogorsk. Taking into account the diversity of the actual construction materials in a village, we assumed that in Dolon, 60% of the houses were wooden, 20% were adobe, and 20% were brick; in Kainar, 60% of the houses were adobe, 20% were wooden, and 20% were brick. We then calculated the average shielding factor for housing in each village. The shielding factor for housing against the external dose due to the radioactive cloud was derived as 1.73 in villages where wooden houses were dominant, 2.70 in villages where adobe were dominant, and 2.48 in villages where brick was dominant. Finally, we calculated the modifying factor (MF_{cloud}) for D_{cloud} for each village from the shielding factor and time spent outside the house during the passing of the cloud. Values for MF_{cloud} are included in **Table 1**. External doses due to the radioactive cloud were calculated from D_{cloud} and MF_{cloud} .

From the Handbook, the shielding factors of wooden, adobe, and brick houses for external radiation from fallout deposited on the ground surface were 3.0, 13.0, 10.0, respectively. Shielding factors for housing for each village with wooden, adobe, and brick as the dominant housing materials were 4.25, 7.53, and 7.04, respectively. The modifying factors (MF_{fallout}) for D_{fallout} were calculated from the shielding factors, as well as from time spent outside the house. In this case, the time spent outside the houses was more carefully determined by taking into account the age or job of the individuals. Values for MF_{fallout} are shown in **Table 1**. External doses due to radioactive fallout can be calculated from D_{fallout} and MF_{fallout} .

4. Calculation of internal doses due to inhalation

In the present calculation of inhalation doses, radioactive

iodine, strontium, cesium, and related elements were targeted, since they made a major contribution to the total dose experiences by the residents.

Inhalation of radioactivity can be considered to occur just during the time of passing of the radioactive cloud (Δt), so dose rates in air at the time of $t_0 + \Delta t/2$ can be considered a good approximation of the dose rate during Δt . The dose rate was calculated based on the P_{24} .

The radionuclide concentration ($\bar{C}_{a\Delta t}$, Bq/m³) in the air can be derived from the dose rate in air using the following formula from the Handbook.⁸⁾

$$\bar{C}_{a\Delta t} = \frac{0.75 \times 24^n \times K_{Bq/\gamma} \times K_a \times P_{24}}{E_\gamma \times \bar{n}_\gamma \times q^{0.04} \times t_c^n}$$

where,

$K_{Bq/\gamma} = 3.7 \times 10^4$ conversion coefficient of passage from the gamma radiation rate to the volume radioisotope activity contained in the air (Bq × h)/(m³ × mR)

K_a radiation fraction of aerosol fission products at the atmospheric bottom layer.

E_γ average energy of the gamma radiation (MeV)

$\bar{n}_\gamma$ average photon yield at the gamma radiation (photon/Bq/s)

In the present paper real values are not known for K_a , E_γ and $\bar{n}_\gamma$, so they are assumed to 1 as suggested in the Handbook. For details of the formula, please refer to the formula 5.22 in the Handbook.

The total inhaled radioactivity was calculated from the concentration of radioactivity during the time (Δt), the biologically available fraction (η) of the total radioactivity, the length of the time, and the breathing rate during that time. The inhaled radionuclide was derived from the total inhaled radioactivity and the fraction of radioactivity based on the decay of each radionuclide at the time of passing of the cloud. For the breathing rate of the reference resident, 1.2 and 0.45 m³/h were assumed for daytime and nighttime, respectively. Each inhalation dose was calculated from the inhaled radionuclide and inhalation dose coefficients (Sv/Bq) for the radionuclide obtained from ICRP Publication 72.¹²⁾

The biologically available fraction was developed in the Handbook to correct for the radioactivity actually inhaled by taking into account the biologically significant fraction of particles. Important factors affecting the value are yield and height of the explosion, the distance between the explosion and the site of interest, and the wind speed at the time of the explosion. The biologically available fraction was calculated by the formula:

$$\eta_{d \leq 50} = 1 - [1 - 0.6 \times (H_{\max} \times \bar{V})^{-0.9}] \times \exp(-4 \times X_a^3)$$

where, $X_a = X/X_{cr}$ is adjusted distance which serves as a non-dimensional criterion for particles (with size not exceeding 50 micron) distribution at the radioactive trace of fallouts. Generally X_a means the distance X normalized by critical distance X_{cr} at which aerosol particle is transferred from the explosion zone with the average wind velocity ($\bar{V}$, km/h) and settling from the height of radioactive cloud uppermost edge ($H_{\max}$, km) with the speed (W_{50} km/h). The adjustable distance

is equal to

$$X_a = \frac{W_{50} \times X}{H_{\max} \times \bar{V}}$$

The value of W_{50} is equal to 0.73 km/h for the real lifting of radioactive cloud at the surface nuclear explosion.

For details of the formula, please refer to the formula 5.11 in the Handbook.

5. Calculation of the internal dose due to ingestion

The internal dose due to ingestion of radionuclides can be calculated by methods similar to those used to calculate the inhalation dose. However, very few parameters necessary for this dose calculation were available, so we abandoned this approach and adopted a new approach, which was developed in the report by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR Model).²⁾ The model consists of 5 compartments, (1) air, (2) soil, (3) diet, (4) body, and (5) dose. Parameters connecting each compartment (including deposition on the ground surface) to the internal dose due to ingestion are included in the report.

In the present dose calculation of the ingestion pathway, the dose contribution by short-lived radionuclides is not significant, so we calculated the dose only for the radionuclides of strontium, iodine, cesium, and barium.

The density of the total radioactivity; $R(t)$ (Bq/m²) deposited on the ground surface at the moment t after formation of radioactive trace t_c can be calculated based on the P_{24} using the following formula in the Handbook:

$$R(t) = 3.7 \times 10^6 \times 24^{1.2} \times P_{24} \times t^{-1.2}$$

The density of each radionuclide can be derived using the fraction of each of the radionuclide, as well as the decay of the radioactivity with time. The derived density of total radionuclides, as well as the resulting dose calculated from the density and the parameters for each radionuclide provided by UNSCEAR, are shown in **Table 3**.

Conversion coefficients from the deposition to the dose for radionuclides in the ingestion pathway, P_{2345} (nSv/Bqm⁻²), were 0.08 for ⁸⁹Sr, 53 for ⁹⁰Sr, 4.3 for ¹³¹I, 55 for ¹³⁷Cs, and 0.013 for ¹⁴⁰Ba.²⁾ We calculated the 10-year doses following deposition using 29.5 and 46.2 for ⁹⁰Sr and ¹³⁷Cs, respectively.

III RESULTS

1. Result of the external dose calculation

External radiation doses for the reference residents of 10 villages around the STS, calculated on the basis of the radiation exposure rate in air as well as on the modifying factor obtained from the shielding factors of houses and the time spent inside houses, are shown in **Table 1**. We used $6.1 \cdot 10^{-3}$ mSv/mR as a conversion coefficient from radiation exposure in air to the effective dose to human body, as provided in the Handbook.⁷⁾

In the case of the nuclear test on 28 August 1949, the explosion was at 7 AM and resulted in an air dose (D_{cloud}) of 24.13R according to the radioactive cloud during the time of passing and the precipitation of radioactivity (1.64 hours starting at about 9 AM and ending at about 40 minutes past 10

Table 2 Internal dose by inhalation.

Settlement	Date y/m/d/h	Sr-90		I-131		Te-132		Ca-137		Inhalation
		Activity	Dose	Activity	Dose	Activity	Dose	Activity	Dose	Total dose*
		Bq	mSv	Bq	mSv	Bq	mSv	Bq	mSv	mSv
Dolon	49/8/29/07	8.04E+00	1.93E-04	1.77E+04	1.31E-01	7.05E+04	1.27E-01	2.08E+01	9.59E-05	8.28E-01
Kainar	51/9/24/13	2.11E+01	5.06E-04	5.03E+04	3.72E-01	1.77E+05	3.19E-01	5.48E+01	2.52E-04	1.84E+00
Karaul	53/8/12/7.5	1.11E+00	2.65E-05	2.51E+03	1.86E-02	9.67E+03	1.74E-02	2.87E+00	1.32E-05	1.12E-01
Znamenka	56/8/24/6.3	1.50E-01	3.61E-06	3.12E+02	2.31E-03	1.33E+03	2.39E-03	3.86E-01	1.78E-06	1.61E-02
Akubulak	51/9/24/13	5.45E+01	1.31E-03	1.30E+05	9.62E-01	4.58E+05	8.27E-01	1.15E+05	6.53E-04	4.73E+00
Chermushki	49/8/29/07	2.55E+00	6.11E-05	4.97E+03	3.68E-02	2.25E+04	4.05E-02	6.53E+00	3.00E-05	2.75E-01
Kanonerka	49/8/29/07	2.50E+00	5.99E-05	5.66E+03	4.19E-02	2.18E+04	3.93E-02	6.48E+00	2.98E-05	2.53E-01
Mostik	49/8/29/07	2.61E-01	6.26E-06	5.42E+02	4.01E-03	2.30E+03	4.15E-03	6.70E-01	3.08E-06	2.79E-02
Sarjal	53/8/12/7.5	3.81E-01	9.14E-06	7.70E+02	5.70E-03	3.36E+03	6.06E-03	9.74E-01	4.48E-06	4.12E-02
U. Kamenogorsk	56/8/24/6.3	4.71E+00	1.13E-04	1.12E+04	8.26E-02	4.05E+04	7.29E-02	1.23E+01	5.65E-05	4.49E-01

*: Include doses from inhaled Sr-89, I-132, I-133, I-134, I-135, Ba-140 and La-140.

Table 3 Internal dose by ingestion calculated based on ground deposition.

Settlement	P_{24} R/h	Total activity	Sr-89		Sr-90		I-131		Cs-137		Ba-140		Total dose
		Bq/m ²	Bq/m ²	Sv	Bq/m ²	Sv	Bq/m ²	Sv	Bq/m ²	Sv	Bq/m ²	Sv	Sv
		Bq/m ²	Bq/m ²	Sv	Bq/m ²	Sv	Bq/m ²	Sv	Bq/m ²	Sv	Bq/m ²	Sv	Sv
Dolon	1.300	4.81E+09	3.85E+06	3.08E-04	2.89E+04	1.16E-03	5.77E+05	2.42E-03	9.62E+04	4.66E-03	4.91E+07	6.38E-04	9.19E-03
Kainar	0.304	1.12E+09	9.00E+05	7.20E-05	6.75E+03	2.71E-04	1.35E+05	5.67E-04	2.25E+04	1.09E-03	1.15E+07	1.49E-04	2.15E-03
Karaul	0.809	2.99E+09	2.39E+06	1.92E-04	1.80E+04	7.22E-04	3.59E+05	1.51E-03	5.99E+04	2.90E-03	3.05E+07	3.97E-04	5.72E-03
Znamenka	0.075	2.78E+08	2.22E+05	1.78E-05	1.67E+03	6.69E-05	3.33E+04	1.40E-04	5.55E+03	2.69E-04	2.83E+06	3.68E-05	5.30E-04
Akubulak	0.707	2.62E+09	2.09E+06	1.67E-04	1.57E+04	6.31E-04	3.14E+05	1.32E-03	5.23E+04	2.53E-03	2.67E+07	3.47E-04	5.00E-03
Chermushki	1.800	6.66E+09	5.33E+06	4.26E-04	4.00E+04	1.61E-03	7.99E+05	3.36E-03	1.33E+05	6.45E-03	6.79E+07	8.83E-04	1.27E-02
Kanonerka	0.240	8.88E+08	7.10E+05	5.68E-05	5.33E+03	2.14E-04	1.07E+05	4.48E-04	1.78E+04	8.60E-04	9.06E+06	1.18E-04	1.70E-03
Mostik	0.107	3.96E+08	3.17E+05	2.53E-05	2.38E+03	9.55E-05	4.75E+04	2.00E-04	7.92E+03	3.83E-04	4.04E+06	5.25E-05	7.56E-04
Sarjal	1.292	4.78E+09	3.82E+06	3.06E-04	2.87E+04	1.15E-03	5.74E+05	2.41E-03	9.56E+04	4.63E-03	4.88E+07	6.34E-04	9.13E-03
U. Kamenogorsk	0.071	2.63E+08	2.10E+05	1.68E-05	1.58E+03	6.34E-05	3.15E+04	1.32E-04	5.25E+03	2.54E-04	2.68E+06	3.48E-05	5.02E-04

AM) in Dolon, which was 118 km from the site of explosion. The modifying factor (MF) for D_{cloud} in Dolon is 0.86, so the actual dose (E_{cloud}) that resident received from the radioactive cloud became 20.75R. The air dose (D_{fallout}) due to radioactive fallout deposited on the ground surface during the time of the deposition and 10 years after the deposition in Dolon was 197.60R. Taking into account the modifying factors of 0.53 for D_{fallout} , the actual dose (E_{fallout}) that residents received from fallout was calculated as 104.73R. The total effective dose can be calculated as 0.77Sv in Dolon. The contribution of E_{cloud} and E_{fallout} to the total dose varies depending on the case, but in all cases, E_{fallout} is much larger than E_{cloud} .

2. Internal dose due to inhalation

The concentration (Bq/m³) of radionuclides in the air was calculated from the dose rate in air (P_{24}) at the time of passing of the radioactive cloud. The total inhaled radioactivity was calculated from the concentration of the radionuclides in the air, the time of passing of radioactive cloud (Δt), the biologically available fraction, and the breathing rate. The inhaled radioactivity of the 4 radionuclides, as well as their resulting doses, are shown in **Table 2**. The total inhalation dose values shown in the table indicate the total dose due to ⁸⁹Sr, ⁹⁰Sr, ¹³¹I, ¹³²I, ¹³³I, ¹³⁴I, ¹³⁵I, ¹³²Te, ¹³⁴Cs and ¹³⁷Cs, ¹⁴⁰Ba and ¹⁴⁰La. In many cases, the internal doses due to inhalation were much lower than the external doses. Generally, radioiodine

contributed the largest dose and was closely followed by ¹³²Te. The contributions were much lower from ⁹⁰Sr and ¹³⁷Cs than from radioiodine.

3. Internal dose due to ingestion

The density (Bq/m²) of total radioactivity on the ground surface at the time of the end of the passing of the radioactive cloud (t_c) was calculated from the air dose rate (P_{24}) and is shown in **Table 3**. The density of each radionuclide was then calculated and used to determine the internal doses due to ingestion for ⁸⁹Sr, ⁹⁰Sr, ¹³¹I, ¹³⁷Cs and ¹⁴⁰Ba using the parameters developed by UNSCEAR. Among these radionuclides, ¹³⁷Cs contributed the largest dose in many villages, followed by ¹³¹I and ⁹⁰Sr. The total ingestion doses in the table express the total of doses for the 5 main radionuclides. Generally, the internal dose due to ingestion of radionuclides is in the same order as those due to inhalation, and both are much lower than the external dose.

4. Total dose received by residents from the nuclear tests

Table 4 shows the total of external and internal doses from inhalation and ingestion of radioactivity caused by nuclear tests for the residents in various villages around the STS. In many cases, and especially in villages where substantial doses were delivered, the major part of the doses was contributed

Table 4 Total dose received by reference residents.

Settlement	Date y/m/d/h	External	Internal		Total
			Inhalation	Ingestion	
		Sv	Sv	Sv	Sv
Dolon	49/8/29/07	0.76542	0.00083	0.00919	0.77543
Kainar	51/9/24/13	0.11286	0.00184	0.00215	0.11685
Karaul	53/8/12/7.5	0.39150	0.00011	0.00572	0.39733
Znamenka	56/8/24/6.3	0.04602	0.00002	0.00053	0.04656
Akubulak	51/9/24/13	0.26557	0.00473	0.00500	0.27530
Chermushki	49/8/29/07	1.15032	0.00028	0.01272	1.16332
Kanonerka	49/8/29/07	0.13494	0.00025	0.00170	0.13689
Mostik	49/8/29/07	0.06587	0.00003	0.00076	0.06665
Sarjal	53/8/12/7.5	0.72302	0.00004	0.00913	0.73219
U. Kamenogorsk	56/8/24/6.3	0.03130	0.00045	0.00050	0.03225

from external radiation. The contribution from inhalation and ingestion varied by village, but in a very general way, both were of the same order. The present study revealed that, among the villages studied, the reference residents of Dolon, Karaul, Chermushki, and Sarjal received several hundred mSv. The doses for residents in the other villages not mentioned were lower than in those four villages.

IV DISCUSSIONS

The dose reconstruction for residents around STS in this study was conducted based on reported data of the dose rates actually measured in the air after the nuclear tests. Unfortunately, all details are not described in the reports. The reported values can be considered to be representative of a given village, and the dose rates can be considered higher than the average in the villages. If it is the case, the calculated dose in this study would be the highest in the villages.

We assumed that the dose rate decays as a function of time after explosion with the exponent of -1.2 . We checked this value based on the decay of radionuclides in the source term calculated with the "ORIGEN-2.2 nuclide annihilation/production code," and we took it as a good approximation that expressed the time change of the air dose rate due to the radionuclides. SIMON et al. proposed a 10-term exponential function instead of the power function based on American nuclear tests and reported that this exponential function can provide better estimates of the external dose.¹³⁾ This point should be kept in mind.

In our study, we have used the residential history of 131,723 residents who were registered in our registry. Among them, 41,543 residents have a complete residential history for the period from 1949 to 1963. This means that we can calculate doses for 40 thousand residents, although we need more information other than just life histories. In this paper, we calculated doses for reference residents who had lived in a village for the whole period of dose calculation.

The calculation of the internal dose for reference residence due to inhalation was conducted by determining the concentration of the radioactivity in the air during passing of the radioactive cloud using P_{24} . We have no better method with

reliable data, so we consider that the doses determined by this method are reasonable. Reduction factor of housing for the radioactivity concentration in the air may affect the dose. But the factor was not used in the dose calculation in the present paper because we did not have proper information regarding the factor.

In the present study, the internal dose through ingestion was calculated based on the ground deposition derived from P_{24} and the transfer coefficients used in the UNSCEAR model. The UNSCEAR model and parameters were developed based on global fallout after atmospheric nuclear explosions and assume a global lifestyle; therefore, more specific parameters reflecting local ecological and social conditions are desirable for the dose calculation. In spite of this, we consider that the present calculation can provide reasonable values for the ingestion doses of the residents.

However, we consider that much room for improvement remains for the accuracy of the dose calculations. For instance, we used the dose rates in air at the time of the nuclear tests for the external dose as well as for the internal dose. Therefore, we needed to make efforts to reconstruct the doses for residents in villages where the data for the measured air dose rate were not available. In this sense, further efforts aimed at ecological studies of radionuclides in this region are very important.

At present, many studies have been reported regarding the dose reconstruction for residents around the STS. For example, BAUER et al.¹⁴⁾ studied the radiation dose due to local fallout from nuclear tests in Kazakhstan for the Semipalatinsk Historic Cohort and reported a range of cumulative effective radiation dose estimates in this cohort from 20 mSv to 4 Sv. Similarly, STEPANENKO et al.¹⁵⁾ reported an overview of the main results presented at the Dosimetry Workshop in Hiroshima in 2005. Their results for the external air dose in Dolon village calculated by different methods are 2,260–2,300 mGy on the trace of the radioactive cloud and 500–645 mGy as an average in the village. LAND et al.¹⁶⁾ studied thyroid nodule prevalence and radiation dose from fallout around STS and reported an average individual thyroid dose from external and internal radiation sources of 0.04 Gy (range 0–0.65) and 0.31 Gy (0–9.6), respectively. GROSCHE et al.¹⁷⁾ studied mortality from

cardiovascular diseases in the Semipalatinsk historical cohort in relation to radiation exposure. Dosimetry was determined based on the method developed by the National Cancer Institute for 7,705 exposed individuals living in Dolon, Kainar, Kanonerka, Karaul, Sarzhal, and Znamenka. They reported that radiation dose estimates in this cohort ranged from 0 to 0.63 Gy, with a mean dose of 0.09 Gy. These facts show that the dose estimates vary with the reports, which may reflect such factors as the targeted population and the method of dose assessment. Nevertheless, the results of the present paper are in good agreement with these previous papers, and especially the ones reported recently.

We consider that our methods for dose reconstruction are promising for future epidemiological studies of the residents near the former STS.

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