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A Gradient of Radioactive Contamination in Dolon Village Near the SNTS and Comparison of Computed Dose Values with Instrumental Estimates for the 29 August, 1949 Nuclear Test

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External dose/Retrospective dosimetry/Semipalatinsk/Nuclear tests/Fallout.

Spatial distributions of soil contamination by ^{137}Cs (89 sampling points) and $^{239+240}Pu$ (76 points) near and within Dolon village were analyzed. An essential exponential decrease of contamination was found in Dolon village: the distance of a half reduction in contamination is about 0.87–1.25 km (in a northwest-southeast direction from the supposed centerline of the radioactive trace). This fact is in agreement with the available exposure rate measurements near Dolon (September 1949 archive data): on the basis of a few measurements the pattern of the trace was estimated to comprise a narrow 2 km corridor of maximum exposure rate. To compare computed external doses in air with local dose estimates by retrospective luminescence dosimetry (RLD) the gradient of radioactive soil contamination within the village was accounted for. The computed dose associated with the central axis of the trace was found to be equal to 2260 mGy (calculations based on archive exposure rate data). Local doses near the RLD sampling points (southeast of the village) were calculated to be in the range 466–780 mGy (averaged value: 645+/–70 mGy), which is comparable with RLD data (averaged value 460+/–92 mGy with range 380–618 mGy). A comparison of the computed mean dose in the settlement with dose estimates by ESR tooth enamel dosimetry makes it possible to estimate the "upper level" of the "shielding and behavior" factor in dose reduction for inhabitants of Dolon village which was found to be 0.28+/–0.068.

INTRODUCTION

It is now widely accepted that reliable estimates of radiation dose are needed for epidemiological studies to investigate the health effects attributed to the effects of radiation exposure arising from nuclear tests at the Semipalatinsk nuclear test site (SNTS). Calculated values of dose are available for affected populations around the SNTS, but they are subject to significant uncertainties in settlements where the distribution of fallout was heterogeneous, being based largely on sparse monitoring data gathered following the test. This is the reason why instrumental methods of retrospective dosimetry (RLD with quartz grains in bricks and ESR dosimetry with human tooth enamel) are very important for verification of any computed values of dose. The analysis of the spatial heterogeneity of soil contamination data by long-lived ^{137}Cs and $^{239+240}Pu$ radionuclides can provide data that are useful for the comparison of computed dose values with instrumental estimates and for the interpretation of existing discrepancies. Such analysis, performed for Dolon village, Kazakhstan, is discussed in this paper. The village of Dolon is one of the most affected inhabited settlements within the regions of highest radiation dose as a result of nuclear tests

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in the SNTS.

According to the available and published archive data,[1,2] the radioactive trace of the 29 August, 1949 nuclear test in the SNTS is located just north-west- (NW) of the village of Dolon, Kazakhstan. On the basis of aerial and ground exposure rate measurements during 5–13 September, 1949 (published archive data[1]), the pattern of the fallout deposition near Dolon village had been estimated as a narrow corridor about 2 km in width, having a maximum dose, and a strong spatial reduction in dose rate value over a distance of 3–4 km across the trace's central axis. Later measurements of ^{137}Cs and $^{239+240}Pu$ soil contamination in the vicinity of and within Dolon village[3–6] supported this overall picture, but, as the exact locations of these measurements had not been well described, it was not possible to produce accurate estimations of the gradient of fallout in Dolon village. However, additional data concerning ^{137}Cs and $^{239+240}Pu$ soil contamination near and within Dolon village[7–10] are now available together with supporting geographical coordinates that provide the location of each measurement. These data make it possible to estimate the spatial parameters of the gradient of soil contamination to the SE of the village (in relation to the central axis of the radioactive trace). Using these results, similar values for parameters may be suggested for the spatial distribution of external dose across the village. This enables values of local dose in the village to be calculated and compared with the results of instrumental retrospective dose estimations that have been obtained by retrospective luminescence dosimetry (RLD) for several fixed locations and by ESR dosimetry using tooth enamel from several human donors.

MATERIALS AND METHODS

The first nuclear test in the former Soviet Union (FSU) was conducted on 29 August, 1949 within the SNTS at 7 am local time.[1] The 22 kt nuclear device was placed on the tower at a height of 30-m.[1,2] The distance between ground zero and Dolon village (located to the NE from ground zero) is 109.4 km and the height of the top of the radioactive cloud was estimated to be about 9 km above ground level.[1,2] The wind speed to the northeast on the morning of 29 August, 1949 was about 47–60 km per hour.[1,11] It also rained intermittently during the day. No protective measures were taken for the population during or after this test because of lack of previous experience and the absence of data on the possible

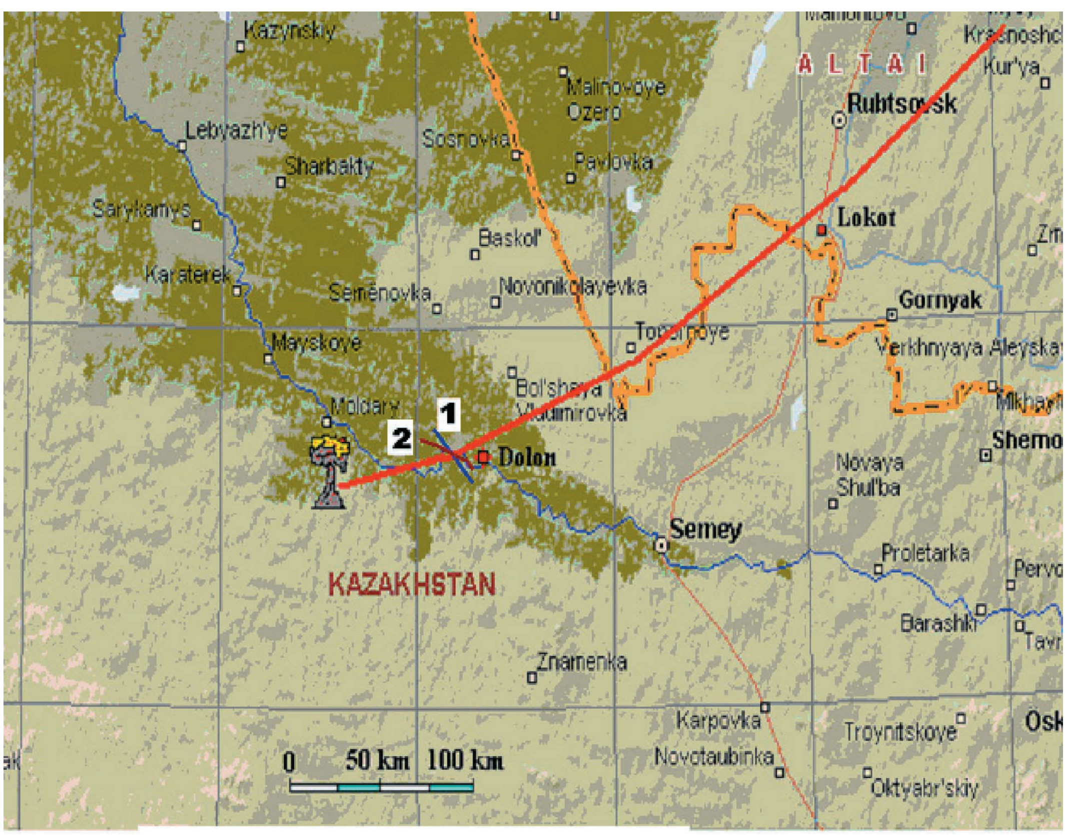

Fig. 1. Regional map showing the SNTS and populated areas. The solid thick line represents the roughly estimated central axis of the radioactive trace of the 29 August, 1949 nuclear test[1]; 1 represents the cross section of aerial exposure rate measurements near Dolon village[1]; 2 represents the cross section of ground exposure rate measurements near Dolon village[1].

scale of radioactive contamination following a surface nuclear test.[1] However, both ground and aerial exposure rate measurements were performed along the radioactive trace and near some villages, including the village of Dolon[1,2] (see Fig. 1), during the period 5–13 September, 1949.

The results of the aerial and ground exposure rate measurements can be used to calculate the accumulated external dose in air from the 29 August 1949 nuclear test. The following parameters (Stepanov *et al.*,[11] Gordeev *et al.*,[12,13]) were taken into account when calculating the cumulative external dose in the air near the village of Dolon and applied using the model of Gordeev *et al.*[13] They include: fallout arrival time (2.5 h), duration of fallout deposition (2 h), exposure rate at time H+24 (1100 mR/h). Also accounted for in the calculations were: the total yield of the explosion, the date and time of the explosion, the height of the top of the radioactive cloud, the height of detonation above ground surface, and wind speed, averaged over the height of the radioactive cloud. The time dependence of the exposure-rate in air was applied according to that given by Leipunski.[14] The dose rates along the central axis of the radioactive trace near Dolon village were taken from the available results for ground and aerial exposure rate measurements during the period September 5 to September 13, 1949.[1,2] To convert historical exposure rate units (mR/hour) to absorbed dose rate in air (mGy/hour), a conversion factor 8.7×10^{-3} mGy/mR was used.

The ^{137}Cs and $^{239+240}Pu$ soil contamination densities near and within Dolon and corresponding data on the geographical coordinates of each measurement were obtained from the data published by Dubasov *et al.*, Gastberger *et al*, Sakaguchi *et al.*[7–15] In total, the ^{137}Cs activity and Global Positioning System (GPS) location data for the 89 sampling points and corresponding ^{137}Cs and $^{239+240}Pu$ and GPS data for the 76 sampling points were analyzed below (see Table 1). Descriptions of the methodology of soil sampling and measurement of radionuclide activity are presented in the papers.[8–10,15] All ^{137}Cs activities were adjusted to 1992. The distances between different locations were estimated using software available at http://www.flymicro.com/records/recordcalc2.cfm.

Table 1. Number of soil sampling points with available measurements within and in the vicinity of Dolon village.

Number of sampling points with measured activities		References
^{137}Cs	$^{239+240}Pu$	
59	59	Dubasov *et al.*[7,15]
8	8	Gastberger *et al.*[8,9]
22	9	Sakaguchi *et al.*[10]
Total: 89	Total: 76	–

The coordinates of buildings in Dolon village, where bricks were used to estimate the local accumulated external dose by RLD,[16] are given by Sakaguchi *et al.* [10]

The equation of the putative central axis of the radioactive trace (Fig. 3) was obtained using the geographical coordinates of ground zero of the 29 August 1949 nuclear test (50°26'50" N, 77°48'40" E),[7] coordinates of the center of sampling points near Dolon village associated with the center of the axis,[10] and the position of maximum exposure rate measured in September 1949 close to Dolon.[1]

The non-linear approximation of experimental data by the Gaussian function by the least squares method was performed by Origin 6.1 software (OriginLab Corporation, USA).

RESULTS AND DISCUSSION.

Based on the available results of exposure dose rates,[1] the pattern of fallout deposition near Dolon village is estimated to be a maximum dose within a narrow corridor about 2 km wide with strong spatial reduction over a distance of 3–4 km across the central axis (Fig. 2).

As there are only a few points with exposure rate measurements in the vicinity of Dolon village (Fig. 2) with which to characterize the gradient of dose across the radioactive trace and because the exact coordinates of these measurements are not available, the width of the radioactive plume near Dolon and the position of the centerline of the

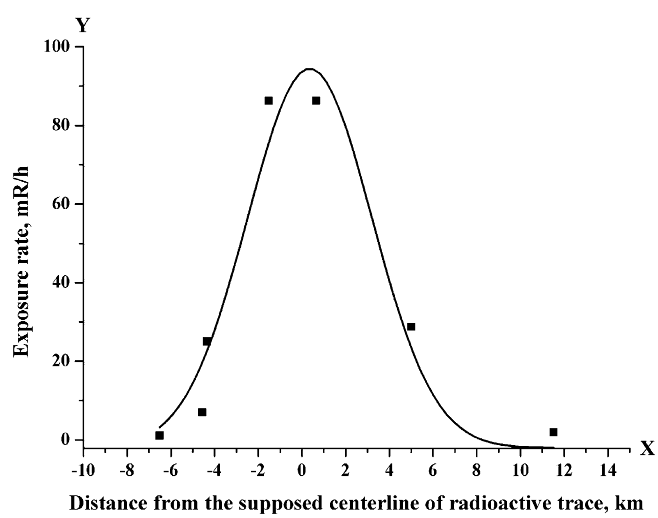

Fig. 2. The results of aerial and ground exposure rate measurements (filled squares) along the cross section of the radioactive trace near Dolon village (Y)[1] vs distance from the central axis of the radioactive trace. The solid curve is calculated using a non-linear approximation by Gauss function. The exposure rates are in historical units as obtained by instrumental measurements during5–13 September 1949, recalculated to 12 a.m., September 5, 1949. To convert to SI units (C kg^{-1} h^{-1}) the values shown should be multiplied by 2.58 10^{-7} (C kg^{-1} hr^{-1} per mR/h).

trace are not known with a high degree of certainty. We sought more detailed information from the variation in soil activity with location of soil sampling within and in the vicinity of the village.

The locations of soil and brick sampling points and the supposed position of the centerline of the radioactive trace are indicated in Fig. 3. For further analysis the distances from sampling points orthogonal to the centerline were calculated.

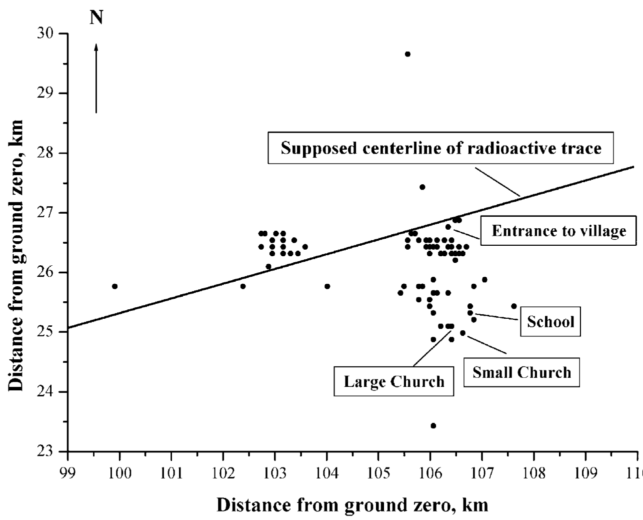

Fig. 3. Locations of soil and brick sampling points (filled circles), in relation to the supposed position of the centerline of the radioactive trace (solid line).

Gradient of radioactive soil contamination in Dolon village.

The distributions of soil contamination by ^{137}Cs and $^{239+240}Pu$ are plotted in Fig. 4 and Fig. 5 as a function of distance orthogonal to the central axis of the trace. The significant dispersion in the contamination values prevents the fitting of a Gaussian function to the experimental data. Possible reasons of this scatter include: a) heterogeneous distribution of fallout; b) soil disturbance due to human activity and natural processes (removing of soil by wind etc.) following the August 1949 nuclear test. However, apart from these uncertainties, the clustering of high contamination values near the central axis of the trace is remarkable. It should be noted that the global fallout level of ^{137}Cs was not subtracted from the data shown in Fig. 4.

To provide analysis of spatial distribution of contamination within Dolon village, the soil contamination data were averaged over 0.5 km intervals in a SE direction from the supposed position of the centerline of the radioactive trace and orthogonal to this centerline (see Fig. 6 and Fig. 7). A value of about 2 kBq/m^2 for ^{137}Cs global fallout in the Semipalatinsk region was subtracted from the values shown in Fig 6 on the basis of ^{137}Cs soil contamination data presented

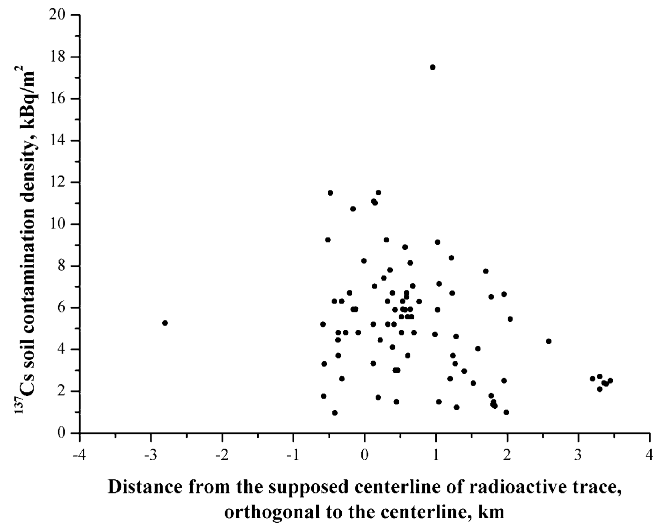

Fig. 4. Distribution of ^{137}Cs soil contamination density vs distance from the supposed position of the centerline of the radioactive trace. The positive and negative values of distance correspond to locations SE and NW of the trace centerline respectively.

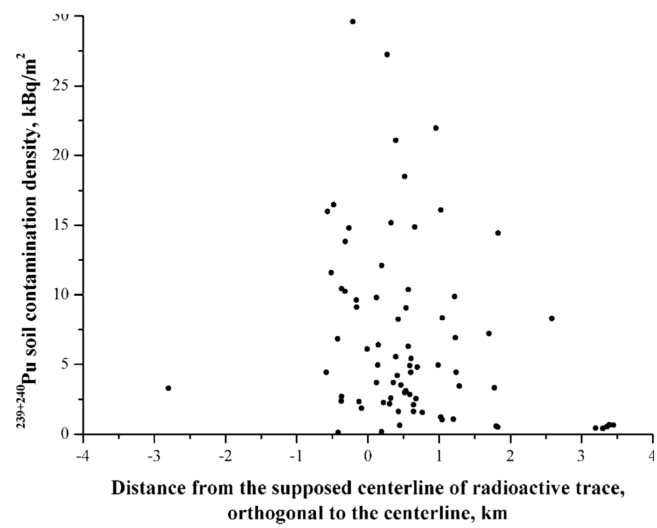

Fig. 5. Distribution of $^{239-240}Pu$ soil contamination density vs distance from the supposed position of the centerline of the radioactive trace. The positive and negative values of distance correspond to locations SE and NW of the trace centerline respectively.

by Yamamoto *et al.*[17], which are related to the territories near Almaty (Kazakhstan) located far from the SNTS. The global fallout level of $^{239+240}Pu$ was neglected in the data shown in Fig. 7.

The data shown in Fig. 6 and Fig. 7 were fitted to the following exponential function:

$$q = A + B \times \exp(-X/C) \quad (1)$$

where –

q – ^{137}Cs or $^{239+240}Pu$ soil contamination density, kBq m^{-2};

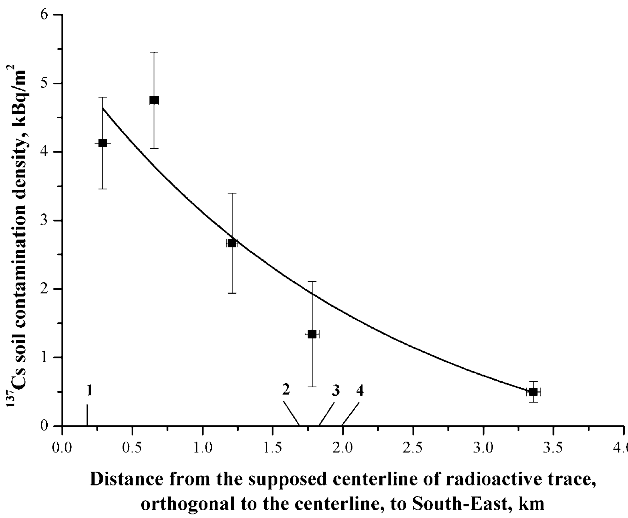

Fig. 6. Dependence of ^{137}Cs soil contamination density in Dolon village vs distance from the supposed centerline to the SE (the distance "0" corresponds to the supposed centerline of the trace). The filled squares are experimental data and errors are given at a 68% level of confidence. The solid line represents an approximation obtained by non-linear fitting of exponential function to experimental data (Eqn. 1), as described in the main text. The numbers indicate various locations where "1" is the entrance to village (0.193 km), "2", "3", "4" are the school (1.7 km), large church (1.83 km) and small church (1.93 km) respectively, and correspond to locations where brick samples were obtained for testing by the RLD method.[16)]

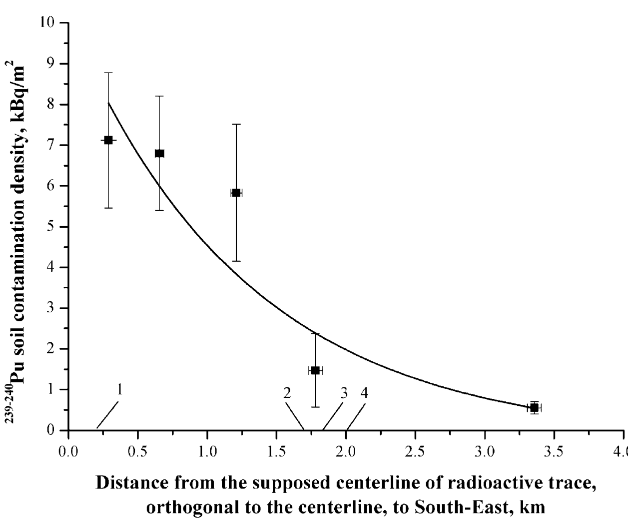

Fig. 7. Dependence of $^{239+240}$Pu soil contamination density in Dolon village vs distance from the supposed centerline to the SE (the distance "0" corresponds to the centerline of the trace). The filled squares are experimental data and errors are given at a 68% level of confidence. The solid line represents an approximation obtained by non-linear fitting of exponential function to experimental data (Eqn. 1), as described in the main text. The numbers indicate various locations where "1" is the entrance to village (0.193 km), "2", "3", "4" are the school (1.7 km), large church (1.83 km) and small church (1.93 km) respectively, and correspond to locations where brick samples were obtained for testing by the RLD method.[16)]

X – distance in km from the supposed centerline of radioactive trace, orthogonal to the centerline, to the southeast;

The values of parameters A, B, C are: i) for ^{137}Cs soil contamination, A= –0.955 kBq m^{-2}, B = 6.302 kBq m^{-2}, C = 2.226 km, (R^2 = 0.955) and ii) for $^{239+240}$Pu soil contamination, A= – 0.222 kBq/m^2, B = 10.323 kBq m^{-2} and C = 1.293 km, (R^2=0.931).

The distances of a half reduction of maximum contamination (at X = 0) are 1.25 km and 0.87 km for ^{137}Cs and $^{239+240}$Pu respectively. The gradients of soil contamination shown in Fig. 6 and Fig. 7 can be used for comparison of computed dose values with local dose values estimated by the RLD method. In the present study we suggest that spatial distribution of external dose across the village from NW to SE is similar to the spatial distribution of soil contamination.

Comparison of computed dose values with RLD data.

By applying the model of Gordeev *et al.*[13)] and using parameters presented in the section "Material and methods" of this paper (see above), the cumulative external dose in the air near Dolon village was estimated to be 2260 mGy. It should be noted that this value represents a maximum value associated with the center of the radioactive trace, since it is based on the use of the exposure dose rate measured close to the central axis.[1)] Since, on the basis of the discussion the trace is presumed to be narrow, the calculation of the relationship between the maximum dose along the axis of the trace and the *local* dose in Dolon village (1.7–1.93 km from the centerline of the trace) needs to take into account the spatial distribution of radioactive contamination in Dolon village. This is required if calculated local dose values are to be compared with experimental RLD dose estimates for the same locations.

There are two ways in which this calculation can be performed: i) using exponential functions (Fig. 6 and Fig. 7) fitted to experimental data, and ii) using the ratio of measured values of local soil contamination density to the maximum measured value of contamination close to the centerline. Both approaches were used to estimate the local doses at distances between 1.7 km and 1.93 km from the centerline of the axis to the SE, within which area the brick-sampled school, large church and small church are located. The results of doses estimations by calculations are shown in Table 2. The RLD data are shown in Table 3.

The values of the local dose (Table 2) recalculated based on the maximum dose in the centerline of the trace (2260 mGy) and the gradient of contamination within the village, range from 466 mGy to 780 mGy (average 645 ± 70 mGy). This overlaps with the range of 380 mGy to 618 mGy (average 460 ± 92 mGy) obtained by RLD (Table 3). The mean external dose in the air for Dolon, estimated in this study as an average dose over the distance from the entrance to the village to 3.5 km in a SE direction within the village, is equal to 775 ± 40 mGy (this averaging was performed using

Table 2. Calculated values of external accumulated dose in air at different locations in Dolon village.

Method of dose estimation	Distance from the supposed centerline of radioactive trace, to SE, orthogonal to the centerline	Accumulated dose of external irradiation in the air	References
Calculation *)	0	Dose in the centerline of the trace: 2260 mGy	Present work
	0	2300 mGy	Gordeev *et al.*[12] – **)
Recalculated dose in Dolon - exponential contamination distribution (1) ***)	1.82 km - average distance over three RLD sampling locations: school, large church, small church	Local calculated dose on the base of ^{137}Cs contamination near 3 locations: 780 ± 43 mGy	Present work
		Local calculated dose on the base of $^{239+240}Pu$ contamination near 3 locations: 510 ± 36 mGy	Present work
	1.82 km – average distance, as above.	Average calculated local dose over six above mentioned dose values: 645 ± 70 mGy	Present work
Recalculated local dose in Dolon - measured soil contamination ****)	1.78 km – average distance over all locations of contamination measurements in the range 1.5–2.0 km	Local calculated dose on the base of ^{137}Cs contamination: 678 ± 60 mGy	Present work
		Local calculated dose on the base of $^{239+240}Pu$ contamination: 466 ± 30 mGy	Present work

*) – Calculations based on maximum archive exposure dose rate measurements to the northwest from Dolon village (September, 1949), maximum exposure dose rate is assumed to be associated with the centerline of radioactive trace.
**) – Estimated based on data presented in this paper; the value of dose is assumed to be associated with the radioactive trace.
***) Recalculation based on the value of 2260 mGy for the centerline of radioactive trace; assuming that the maximum contamination value is determined by an exponential model (1) at distance "0", and local contamination is determined by an exponential model (1) at various distances within the village.
****) Recalculation based on the value of 2260 mGy for the centerline of the radioactive trace, assuming that the maximum contamination value corresponds to the maximum measured value close to "0" distance and that local contamination corresponds to the value of contamination at a distance of 1.78 km (close to RLD sampling locations).

an exponential model of spatial distribution of contamination (see Eqn.1)).

It should be noted that the conversion of maximum dose at the axis to local dose in the village was performed assuming that the gradient of contamination was similar to the gradient of exposure rate in the village. These two quantities are not necessarily equivalent; the gradient of soil contamination is expected to be steeper in comparison with the gradient of exposure rate because of the fractionation of different radionuclides, radioactive particles, and rare gases. For example, Fig. 8 shows a notable tendency for the fraction of $^{239+240}Pu$ soil contamination to increase relative to ^{137}Cs close to the centerline of the radioactive trace. This is the reason why the local dose was recalculated using contamination data for both radionuclides – ^{137}Cs and $^{239+240}Pu$.

Finally it should be noted that although a wide spatial distribution (similar to a Gaussian function) of soil contamination near Dolon village has been reported in one paper,[21] the analysis in this paper pools soil contamination data from not only Dolon but also from other more distant settlements

Table 3. Values of external accumulated dose at different locations within Dolon village as estimated by the RLD method in the four bricks.

Method of dose estimation	Distance from the supposed centerline of radioactive trace, to SE, orthogonal to the centerline	Accumulated local dose of external irradiation (natural background dose is subtracted)	References
RLD	1.82 km – average distance over three RLD sampling locations: school, large church, small church	Doses at the 10 mm depth in the four measured bricks: 190 mGy, 194 mGy, 222 mGy, 210 mGy	Goeksu *et al.*[18] – *)
		Doses at the 10 mm depth in the four measured bricks: 248 mGy, 309 mGy, 222 mGy, 217 mGy	Sato *et al.*[19]
		Dose at the 10 mm depth in the bricks averaged over all above mentioned Labs/Authors and over all bricks and sampling locations: 230 ± 40 mGy	–
		Local accumulated external dose in the air:**) 460 ± 92 mGy (range: 380-618 mGy)	–

*) – Averaged values of the results from 4 laboratories of European supported measurement group: GSF (Germany), MRRC (Obninsk, Russia), Helsinki University (Finland), Durham University (UK).
**) Local dose estimated in the air assuming that the value of conversion factor from the dose at 10 mm depth in the brick to the dose in the air is equal to 2 ± 0.25; it is to note for comparison, that according Bailiff *et al.*[5] and according Simon *et al.*[20] local RLD doses in the air near the same locations are equal to 475 ± 110 mGy and 420 ± 120 mGy, consequently.

(Mostik, Cheremushki, Budene, Chagan). Consequently the analysis discussed in this paper has relevance to the wider group of settlements down wind of the fallout and is not confined only to Dolon village and its environs.

Comparison of computed dose values with ESR data

The latest data from ESR tooth enamel dosimetry[22,23,24] (see Table 4) make it possible to estimate the combination of "shielding and behavior" factors for the inhabitants of Dolon village.

The dose values estimated by the ESR teeth enamel dosimetry method are essentially lower in comparison with computed dose values and with RLD estimates. This difference can be explained by the shielding from exposure, which occurred when residents stayed indoors, and by the behavior factor, that is the relocation and migration of the people from the village.

For the analysis, persons were only eligible whose tooth enamel had already formed before 29 August 1949, who were permanent inhabitants of the village at 29.08.1949 and who had not been subject to medical and professional irradiation (Table 4).

The average dose obtained by the ESR teeth enamel dosimetry method for 16 inhabitants of Dolon village is Dex = 156 ± 37 mGy. Comparison of this value with the calculated average external accumulated dose in air for Dolon village (Dair = 775 ± 40 mGy) allows estimation of the "shielding and behavior" factor (F) for inhabitants of Dolon village:

$$F = R1/R2 \times (Dex/Dair) = (1.05/0.75) \times (156/775) = 0.28 \pm 0.068 \quad (2)$$

Where:
R1 = 1.05 mSv/mGy – ratio of the whole body effective dose to the dose in tooth enamel in a case of external gamma irra-

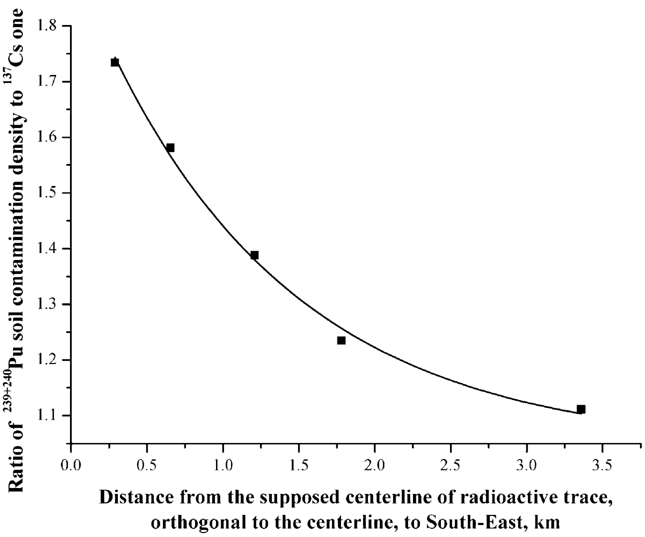

Fig. 8. Variation of the ratio of $^{239+240}$Pu soil contamination density to ^{137}Cs soil contamination density towards the southeast in Dolon village vs distance from the supposed centerline of the radioactive trace. The ratio was estimated using exponential models (Eqn. 1) of contamination gradient associated with both radionuclides.

Table 4. Results of ESR tooth enamel dosimetry for 16 inhabitants of Dolon village (D_{ex} – dose with background dose of 0.8 mGy per year subtracted).

N	Dex, mGy	Uncertainty of D_{ex}, mGy	Reference
1	0	66	Ivannikov *et al.*[22]
2	283	52	
3	29	29	
4	50	45	
5	64	39	
6	440	106	
7	72	28	
8	41	25	
9	54	40	
10	351	57	
11	430	93	
12	219	101	Ivannikov *et al.*[23]
13	198	61	
14	114	48	
15	60	47	Zhumadilov *et al.*[24]
16	87	33	

diation;[25)]
R2 = 0.75 mSv/mGy – ratio of the whole body effective dose for an adult person to the dose in the air in a case of external gamma irradiation.[26]

It should be noted that this is an estimation of the upper level of this coefficient, which will also include possible additional input to the dose in enamel from internal gamma and beta irradiation due to radionuclides ingested into the human body via food and inhalation. The ratios of effective dose in the whole body to the dose in enamel and to the dose in the air were accepted to be the same as at the Chernobyl incident (e.g. for gamma irradiation of ^{137}Cs). It is of note that for a more correct estimation of these ratios the real spectra of gamma irradiation from fission products following the 29 August 1949 nuclear test should be taken into account. However, the possible differences between the Chernobyl and SNTS ratios are not so important in that the time-averaged mean energy of the external gamma irradiation is similar in both of these situations (in the range 500–800 keV).[27]

CONCLUSIONS

Fallout from the 29 Augus 1949 nuclear test resulted in a narrow 2 km corridor of maximum exposure rate in the northwest vicinity of Dolon village, Kazakhstan, which is one of the most irradiated inhabited settlements near to the SNTS. The lack of available exposure rate measurements following the nuclear test and the absence of corresponding coordinates for measurements performed following the test, limits the accuracy with which the location of the central axis of the radioactive trace near Dolon can be determined. As a result, it is not possible to compare with confidence dose estimates based on archive exposure dose rate measurements with dose estimations obtained by experimental methods of retrospective dosimetry based on luminescence with bricks and electron spin resonance with tooth enamel. Such comparisons are essential given the large differences that currently exist between computed and instrumental estimates of dose.

Spatial distributions of soil contamination by ^{137}Cs (89 sampling points) and $^{239+240}$Pu (76 points) near and within Dolon village were analyzed. An essentially exponential decrease of contamination was found in Dolon village: the distance of a half reduction in contamination is about 0.87–1.25 km (in a northwest-southeast direction from the supposed centerline of the radioactive trace).

To compare computed external doses in the air with local dose estimates by retrospective luminescence dosimetry (RLD) the gradient of radioactive soil contamination within the village was accounted for. The computed dose associated with the central axis of the trace was found to be equal to 2260 mGy based on calculations using archive dose rate data. Local dose values for RLD sampling locations (in the southeast area of the village) were calculated at 466 mGy-780 mGy (average value 645 ± 70 mGy), which is consistent with the RLD data (averaged value 460 ± 92 mGy with the range 380–618 mGy). A comparison of the computed mean dose with dose estimates by ESR tooth enamel dosimetry allows estimation of an "upper level" for the "shielding and behavior" factor in dose reduction for inhabitants of Dolon village. This was estimated as 0.28 ± 0.068.

Finally, to obtain the width and position of the central axis of the fallout trace associated with the 29 August 1949 nuclear test at the STNS with greater precision, a more detailed investigation of soil contamination to the northwest of the village is desirable.

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