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Assessment of radiation exposure in the settlements located in Stepnogorsk area

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The Stepnogorsk area Northern Kazakhstan has a long history mining activities. Mining activities have lots of environmental and health impacts. The aims of this study were to characterizing the general radiological situation of the area and evaluate radiation exposure by scenarios in settlements. In this study radiological assessment was performed for critical group living in the territory contaminated with radionuclides; working and studying at school located on territory former mining site. The annual dose burden is 2.5 mSv y^{-1} in Zavodskoy, 1.9 mSv y^{-1} in Kvartsitka and 3.6 mSv y^{-1} in Aqsu; and exposure from radon is around 11 mSv y^{-1} at the ground floor, and for teachers - up to 12 mSv y^{-1}. At settlements, however, under the hypothesis that all food contaminated with radionuclides and vegetables is cultivated locally in the territories with high background level, exposure from ingestion is 9.1 mSv y^{-1} in Zavodskoy, 8.3 mSv y^{-1} in Kvartsitka and 11.5 mSv y^{-1} in Aqsu. The combined effects of environmental problems have culminated into health problems. There are such possibility of the higher prevalence of cardiovascular, digestive and respiratory systems so it is necessary to evaluate or protect people living in Stepnogorsk area.

Keywords: radiation exposure, mining activity, critical group, radiological assessment, disaster scenario.

Introduction

The Republic of Kazakhstan is located almost in the middle of the Eurasian continent. Oil, coal, various ore and non-metallic deposits are the priceless treasure of the republic. Some of these mineral resources make Kazakhstan famous in the world. They include chrome iron ore deposits, polymetallic deposits, copper, tungsten, molybdenum and uranium ores [1].

In Northern Kazakhstan mining viz., gold and uranium is considered the most development step of production. Special attention is paid to the settlements which located on the territory affected by mining activity. There are notice radiological risks both in terms of radiation doses and in the others factors affected [2, 3]. Key problems have been associated with the transport of Natural Occurring Radioactive Materials (NORMs) in aquatic and terrestrial ecosystems, where radionuclides are transferred from air, water, and soils into plants, animals and finally to man [4]. The long-term impact of gold mining or mining and Stepnogorsk Mining Chemical Combine tailings in these areas is not known, although health effects have been reported. Since the 2000s, several national and international teams have studied the potential risks for the population living in the immediate vicinity of tailing dumps in Northern Kazakhstan. Great concern has been raised, in particular for the settlements located near tailings with respect to safety problems related to contamination from radionuclides and heavy metals [5-8].

According to previous study total effective dose from radon exposure exceeding the worldwide range by an order of magnitude received by the public (critical group) at Aqsu school and settlements were evaluated [9-10]. In the frame of previous study several scenarios will be evaluated to reduce the radiological exposure of the population and to prevent environmental pollution by NORMs. Radiological assessment is performed for actual conditions and for a disaster scenario (hypothetic).

The aims of this study were to characterizing the general radiological situation of the area and evaluate radiation exposure by scenarios in settlements.

Material and Methods

Study area

The study area is a highly mineralized region, hosting underground that is endowed with quartz-veined deposits that may contain higher concentration of natural radionuclides deposits, and is located in the Stepnogorsk area Northern Kazakhstan. The map showing the study area is given in Figure 1.

The Stepnogorsk area comprises Aqsu, Zavodskoy and Kvartsitka settlements, where there is a small developing gold mine, and where copper and other mining activities have also been carried out in the past. Additionally, settlements are located < 5 km South East of Stepnogorsk Mining Chemical Combine tailings dump.

In order to evaluate the critical group characteristics at settlements of Stepnogorsk area, a questionnaire on occupancy times, local food crops and consumption habits. Following the survey, habitants, personals and schoolchildren were identified as the critical group, because of their supplementary exposure when working on contaminated workplaces. Habitants are supposed to cultivate all food and raise their animals locally. The dwellings and Aqsu school of the critical group are considered to be situated in territory of former mining site. It has been assumed that water from local wells of settlements is used by local population for a watering place of the cattle and watering of kitchen gardens.

According to local executive bodies the population of Stepnogorsk area of the beginning of 2019 is 68.1 thousand people, where including:

Stepnogorsk city – 45.917 thousand people; Aqsu – 4.027 thousand people (1989 male and 2038 female); Zavodskoy – 3.964 thousand people (2012 male and 1952 female) and others settlements – 14.144 thousand people.

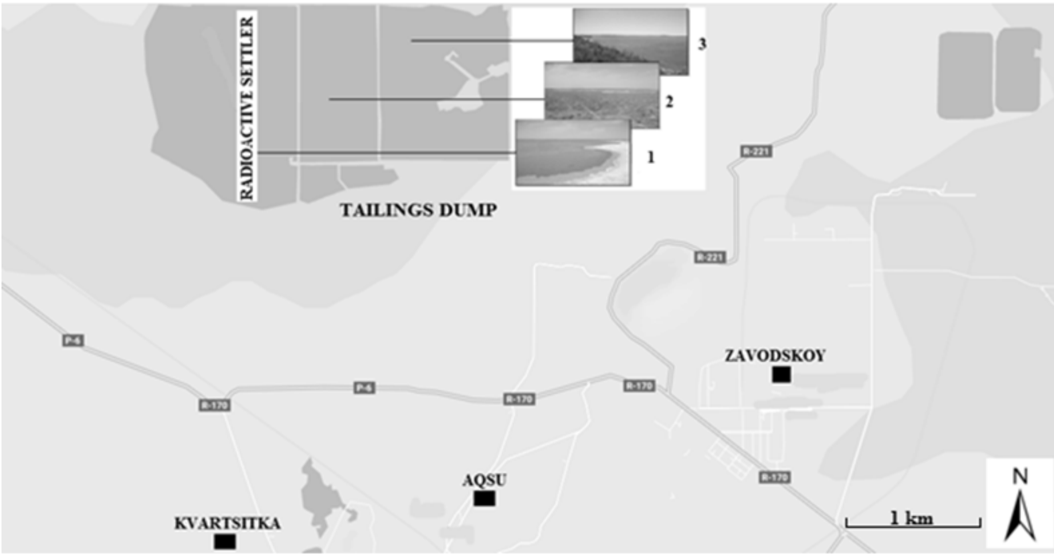

Figure 1. Scheme showed settlements location near the HMP tailings site, where 1 - tailings dump evaporation pond; 2 - pond 2; 3 - pond 3.

Gamma absorbed dose measurements

The ambient gamma absorbed dose rates $(H(10))$ were measured in all sampling locations in the settlements using DKSAT-1123 (ATOMTEX Scientific Production Unitary Enterprise, Republic of Belarus) and RKS-01-SOLO (SOLO LLP, Republic of Kazakhstan). The measuring cycle is 40 seconds for the ambient gamma dose rates in the range from 0.05 to 10 μSv h $^{-1}$ for DKS-AT-1123; RKS-01-SOLO is 0.01 to 15 106 μSv h $^{-1}$. The measurement uncertainty of the unit for gamma rays is $\pm$ 15%. All measurements were carried out according to International Atomic Energy Agency (IAEA) Guidelines [11]. The gamma radiation levels were measured both inside and outside the dwellings at 1 m above the ground. Once operated, the dosimeter gives a radiation dose rate value after few minutes. The mean value was calculated and recorded for each pair of measurements. About 46 readings were taken at different points in each location. These measurements were carried out during spring season.

Radon measurements

Equivalent equilibrium volume activity (EEVA) of radon in indoor and outdoor air was measured with automatic compact radiometers of radon and thoron Ramon-02 and Ramon-02A (SOLO LLP, Republic of Kazakhstan). Measurements were carried out in accordance to ASTM D6327-10 [12]. Measurements were performed in the dwellings and social objects.

Water sample collection and processing

Water samples were taken at the settlements local wells at randomly chosen houses. Water samples were preserved by adding 0.5-1 ml L^{-1} HNO^{3}. Samples were collected at May 2018. Water samples were analyzed for total alpha and uranium in the supernatant after 48 h sedimentation (to mimic people's habit: if wells water is used for human consumption, people allow sediments to settle). Total alpha was measured using alpha beta radiometer UMF 2000. Identification of Ra and U isotopes was done with preliminary radiochemical treatment of water and soil samples. Minimum detectable specific activities in standard geometry are: 0.01 Bq l^{-1} for ^{226}Ra; 0.05 Bq l^{-1} for ^{234,238}U [13].

Soil sample collection and measurement of radionuclide activity concentration

Soil was sampled at locations with elevated gamma radiation at territory of Aqsu school and randomly chosen houses of settlements and at background locations. Soil samples were collected within the 5 cm depth. In areas with highest levels of gamma dose rate at soil surface soil cores were taken to a depth of 30 cm. The cores were divided into 0–5, 5–10, 10–20, 20–30, and 30–40 cm fractions.

Radionuclide activity concentration of ^{232}Th, ^{226}Ra and ^{40}K was measured with Progress-BG beta– gamma spectrometer using a NaI detector with no more than 30% relative efficiency. The detector has energy resolution of 10% at 662 keV ^{137}Cs energy peak. Calibration of the NaI(Tl) detection system was done using the standard samples ^{137}Cs, ^{226}Ra or ^{232}Th with activity concentration from 1000 to 3000 Bq/kg and density $0.8 \div 1.2$ kg/l supplied by SIE Dosa instruction manual [14]. The background activity was determined by remove the control sample from the detecting unit and start the spectrum acquisition in the background measurement mode and the duration of measurement was 3600 seconds. During the measurement, the program displays the count rate values in the control intervals for the measured background spectrum on the monitor. The same time was used for spectral data. Minimum detectable specific activities in standard geometry are 8 Bq kg^{-1} for ^{232}Th and ^{226}Ra; 40 Bq kg^{-1} for ^{40}K [15].

Food samples

Food was collected at settlements from local people or on the market. Meat, vegetable, milk and water samples were collected to obtain an overall idea of the contaminant intake by ingestion. Samples were analyzed for uranium and total alpha following procedures described before. For the critical group it has been assumed that they consume the average diet of the local population (Table 1) and with all food originating from local contaminated territory.

Table 1.
Human consumption averaged data for settlements.

Product name	Milk	Meat	Fish	Potato
Consumed quantity, kg/year	300	70	10	20

Radiological assessment

Consider several main scenarios for evaluation of dose burden of the public from NORMs. Examination of a large number of scenarios from around the world revealed that the limiting cases for a significant number of radionuclides could be reduced to a few scenarios. Within these scenarios, different exposure pathways may account for the total exposure. These relevant exposure pathways are summed for each scenario to yield the total dose.

The assessment of scenarios depends on several parameters, such as exposure time, concentration of the radionuclide used in the exposure pathways and timing of the scenario with respect to radioactive decay. On the basis of these observations from specific and detailed scenarios, the following scenarios are used in the calculation of activity concentration values [16]:

Scenarios Resident near and landfill or other facility (RL)-Child and RL-Adults.

Scenario RL considers individuals living near a landfill or other facilities who are exposed through contaminated dust released at the landfill or facility. In addition, it is assumed that the residents harvest foodstuffs in a private garden on the site that has become contaminated through the deposition of contaminated material.

Scenario Resident using water and ingestion (food).

The presence of contaminated material may lead to a release of radionuclides into a groundwater aquifer. This may affect downstream wells, which may lead to the ingestion of contaminated drinking water or of contaminated foodstuffs produced in a private garden if the well water is used for irrigation.

Annual effective dose of radiation of residents of the settlement at the expense of all natural sources of radiation which is defined sum of all its components:

$$E_{eff} = E_{ext} + E_{ext,Rn} + E_w + E_{ing}, \tag{1}$$

where, E_{ext} – annual external dose radiation from natural radionuclides; $E_{(ext,Rn)}$ – annual effective doses of external radiation from radon isotopes in air; E_w – annual effective dose of internal radiations of adult inhabitants at the expense of long-living natural radionuclides in drinking water; E_{ing} – annual effective dose of internal radiation of adult inhabitants from ingestion at the expense of natural radionuclides [17].

Results and discussion

Gamma dose exposure

External radiation exposure to members of the public is due to terrestrial and cosmic radiation. It varies from place to place with altitude and latitude and also with surface mineralization. The average $H(10)$ was at Aqsu (0.4 ± 0.1 µSv h $^{-1}$), at Kvartsitka (0.15 ± 0.04 µSv h $^{-1}$) and at Zavodskoy (0.16 ± 0.05 µSv h $^{-1}$), respectively. The highest $H(10)$ values ≈ 2.87 µSv h $^{-1}$ were detected in the Aqsu school territory which slightly higher than the control readings for this region. Figure 2 shows frequency distributions of these measurements. Data of outdoor dose rates were found normally distributed at 95% confidence level.

Indoor measurements of average of $H(10)$ at floors and at 1 m height in the center of the room of dwelling were performed. The mean $H(10)$ were equal to 0.19 ± 0.06 µSv h $^{-1}$, 0.16 ± 0.05 µSv h $^{-1}$ and 0.15 ± 0.06 µSv h $^{-1}$ in Kvartsitka, Aqsu and Zavodskoy, respectively. There were no statistically

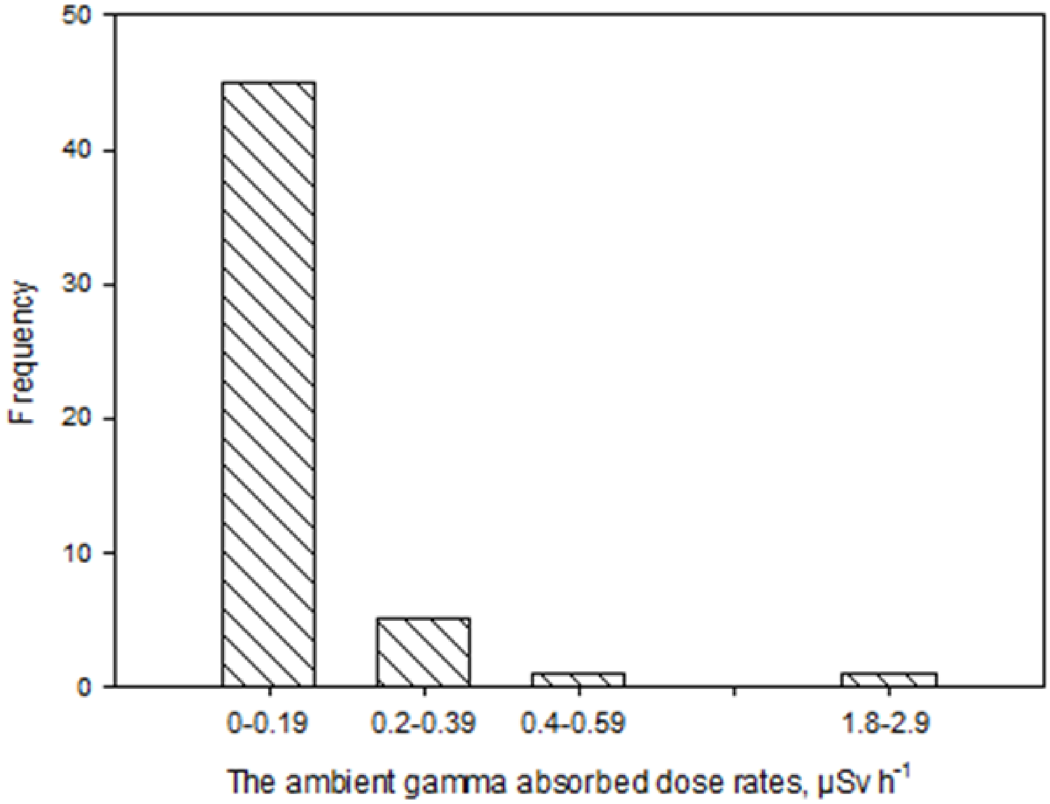

Figure 2. Frequency distribution showing dose rate for outdoor measurements.

significant differences between values obtained at different height that indicate no contribution of floor construction materials. The difference between settlements was also not found. Similar measurements at walls were in average equal to 0.22 ± 0.07 µSv h $^{-1}$, 0.18 ± 0.06 µSv h $^{-1}$ and 0.16 ± 0.05 µSv h $^{-1}$ in Kvartsitka, Aqsu and Zavodskoy, respectively. These values were 1-2 µSv h $^{-1}$ higher than $H(10)$ at floor of the same premises. This systematic difference can be explained by the impact of concrete construction materials of walls.

In this study, we obtained of indoor/outdoor ratio dose rate for each dwelling, which is also normally distributed with range 0.8–1.5. The average indoor/outdoor ratio was 1.2 ± 0.3. A world median value for indoor/outdoor ratio varies in the range 0.6–2.3 with mean 1.3. The ratio of indoor/outdoor for settlements dwellings was lower than the world median value.

The data obtained from the survey meter reading were used to estimate the dose ratio. The ratio of indoor to outdoor gamma ray doses, in normal radiation background areas in India, is found to be approximately 1.2, particularly in dwellings which have cemented floors and concrete walls.

Indoor radon concentration

Radon is present everywhere in the air in varying concentrations. Radon gas contributes relatively little to the dose to the lung. The indoor radon concentration level at Aqsu found to vary from 8 to 858 Bq m $^{-3}$ with a mean value of 143 ± 30 Bq m $^{-3}$, at Zavodskoy from 10 to 313 Bq m $^{-3}$ with a mean value of 107 ± 10 Bq m $^{-3}$, at Kvartsitka from 20 to 501 Bq m $^{-3}$ with a mean value of 87 ± 9 Bq m $^{-3}$, respectively. As is apparent from results, some radon concentration values were found to be higher than the maximum permissible level of 200 Bq m $^{-3}$, which is the implemented by ICRP, 37 for dwellings [18]. The higher indoor radon concentration was shown in dwelling at Kvartsitka which located near the sump (probably, it referential to former gold-mining site).

According to previous study there is found high radon concentration on the ground floor at Aqsu school. There is a decrease in radon concentration from the ground to first floor level. The primary reason for this is the higher convective flow of soil gas into the ground classrooms, as they are not protected by a basement. The Aqsu school is located on territory of former mining site.

Summary statistics of the radon concentration measurements in classrooms are presented in Table 2.

Table 2.
Results of the survey at Aqsu school.

Levels (floors)	Radon range (Min/Max)	Arithmetic mean	Geometric mean	>400 Bq m^{-3}	<400 Bq m^{-3}	$H(10)$, μSv h^{-1}
Ground	153-4703	860	583	2 (25%)	6 (75%)	0.23
First	109-415	284	255	5 (100%)	-	0.19

As it can be seen from Table 1 most (75%) of the radon concentration in workplaces at ground floor were higher the worldwide range. The values of 400 Bq m^{-3} is the action level proposed by the European Commission (EC, 1999) for new buildings and existing buildings respectively [19]. The results show that radon concentration at first floor was in normal values, the radon concentrations are below worldwide range, which is the recommended by EC, 1999. The limited number of classrooms in the second floor might have induced a slight imprecision in the means calculated for this floor.

Water contamination

Table 3 presents the results of the radiochemical analysis of drinking water contamination in a private well and in the centralize sources of Kvartsitka and Aqsu.

The study of centralize water sources of Aqsu and Kvartsitka shows no excess of permissible levels for all measured parameters. In the water, which are collected from the well of Kvartsitka (the source of kitchen-garden watering), the total activity of alpha emitters exceeds the level of intervention [HR, 2015] by 2 orders of magnitude; the total activity of the beta emitters are exceeding by an order of magnitude [20].

The difference between the centralized and well water is due to the difference of the source term. The centralize water systems transfers the clean drinking water from Stepnogorsk Reservoir and the absence of alpha and beta emitters indicates the absence of penetration (diffusion) of radium and/or radon through system defects. The activity concentration of ^{228}Ra in the private well of Kvartsitka was slightly higher than in centralized water systems. Therefore, the activity concentration of ^{228}Ra was at the limited of detectable amount and also below the permissible levels.

Table 3.
Results of the radiochemical analysis of samples of water; NDA – non-detectable amount.

No	Name of samples	Total specific activity, Bq L^{-1}		Activity concentration of radionuclides, Bq L^{-1}		
		beta	alpha	^{228}Ra	^{234}U	^{238}U
1	W -1 (centralize) Aqsu	0.41	0.08	0.0124±0.0011	NDA	NDA
2	W-1(centralize) Kvartsitka	0.39	0.09	0.0136±0.0012	NDA	NDA
3	W-2(well) Kvartsitka	2.83*	20.8*	0.0345±0.0012	0.55±0.12	0.67±0.23
Level of interventions for drinking water**		1.0	0.2	0.2	2.8	3.0

* Values exceeding the level of intervention;
** HR (2015)

Soil and food samples

Radionuclide activity concentrations of the soil samples varied within the study area due to the not significant differences of geological structures. Table 4 gives the average radionuclide concentrations in soil. When we compare the soil concentrations with the worldwide range for soils, the limits for thorium, radium and potassium are clearly exceeded at abnormal site [21]. However, all the samples were taken at locations with normal assumed 'background' and elevated gamma dose rate (territory of school), so this is certainly not a presentation of the average situation but rather worst case conditions.

Table 4.
Average activity concentration of ^{226}Ra, ^{232}Th and ^{40}K in soil samples studied settlements.

Settlements	Average activity concentration, Bq kg^{-1}		
	^{226}Ra	^{232}Th	^{40}K
Aqsu Abnormal site	37.5±2.5	21.5±2.2	177.5±4.5
	617.8±3.2	188.3±2.9	731.5±6.2
Kvartsitka	83.4±1.7	26.7±1.9	124.2±3.1
Zavodskoy	41.3±1.7	16.6±1.9	207.5±3.3
Worldwide range*	50	50	500

*UNSCEAR, 2000

According to previous study recorded alpha levels in food products viz., milk collected in surrounding settlements were lower than the worldwide range. The uranium concentration in the milk and some potatoes samples was below the detection limit for beta-gamma spectrometer; hence actual concentrations are below the local and international exemption limits.

According to Sofronova work, the study of the radionuclides concentration and heavy metals showed that in meat samples from Aqsu, the activity concentration of ^{238}U was 2.0 Bq/kg, which is higher than the control level (1.3 Bq kg^{-1}). The content of ^{232}Th in meat sample from Zavodskoy is exceeded worldwide range value by an order of magnitude, Aqsu is 500 times higher than the level indicated in the literature. The concentration of ^{226}Ra in meat sample from the Zavodskoy is 150 times, and Aqsu is 100 times higher than the control level (0.004 Bq kg^{-1}). The activity concentration of 210Pb in meat samples in the Zavodskoy is 3 times higher than the control level (0.9 Bq kg^{-1}). Thus, a sharp accumulation of long-lived isotopes ^{226}Ra and ^{323}Th is most typical for meat samples [22].

Radiological assessment

To assess the radiation doses to the population 3 scenarios have been developed, which differ in the ways of generating dose burden (Table 5).

In the first scenario, an assumption was formulated that the population consumes only food products produced in the territories contaminated with radionuclides. In this case, the internal exposure of the population is formed due to the consumption of meat and milk of cattle grazed in radiation-contaminated areas. Only water from a local well is used for watering animals. Another source of the formation of population internal exposure is vegetables grown in kitchen gardens of radiation-contaminated areas. In the summer, the water from the well is completely used for watering the kitchen gardens. The scenario described that the internal exposure of the population is formed as a result of the consumption of milk, meat and vegetables (root crops) grown in kitchen gardens. As it can be seen from Table 5 the population receives the highest dose burden from internal irradiation as a result of consumption of vegetables grown in kitchen gardens and watered with water from a well.

Table 5.
Predicted annual effective dose for critical groups in studied settlements, mSv y^{-1}.

Scenario	Settlements	Annual effective dose, mSv y^{-1}
Scenario RL	Aqsu	3.6
	Zavodskoy	2.5
	Kvartsitka	1.9
School scenario	Aqsu	7.7 to 10.81 for schoolchildren
		up to 12 for teachers
Scenario Resident using water and ingestion (food)	Aqsu	11.5
	Zavodskoy	9.1
	Kvartsitka	8.3

In the second scenario of radon exposure, it was assumed that the inhalation of radon concentration by a critical group (schoolchildren and teachers) includes one exposure way, which takes into account the inhalation of air both indoors and in the surface layer of atmospheric air in open areas. The frequency of exposure took into account the fact that teachers spend most of their time at school - about 60%. At the same time, the scenario took into account the constancy of the level of radon concentration at school throughout the academic year. The reason why it was necessary to accept these assumptions is that it is practically impossible to carry out a complete and correct reconstruction of the irradiation conditions during the 11-year training period even in the conditions of a rigorous epidemiological study. At the same time, the scenario did not take into account other natural sources of radiation, since their total contribution to the dose burden is significantly less than radon exposure (60-80%) and the influence of the factor of tobacco smoking.

In the third scenario ("hypothetical"), it was assumed that the population consumes food with the maximum content of radionuclides. This scenario can be realized if agricultural products are produced only in the most polluted area. This assumption makes it possible to estimate the maximum conservative dose of internal exposure to the population. The contribution to the internal dose of the population from meat is 31%, from milk - 30%, from vegetables - 39%.

The results indicated that the expected annual dose burden was exceeded for the critical groups. The influence of technogenic radiation factors on the morbidity of the population living in contaminated territory (more than 20-30 years) is not excluded, especially for diseases of the cardiovascular, digestive and respiratory systems [23].

Conclusion

Radiological impact assessment was done for settlements of Stepnogorsk area. Under current conditions, observed gamma dose rates and radon concentrations are exceptional for territory of Aqsu School and are of immediate concern.

Two scenarios and one disaster scenario were evaluated: the first scenario assumed that the population consumes only food products produced in the territories contaminated with radionuclides; the second scenario also assumes that the inhalation of radon concentration by a critical group (schoolchildren and teachers) includes one exposure way; the third disaster scenario ("hypothetical") population consumes food with the maximum content of radionuclides. For population living in the territories contaminated with radionuclides and consumed food from this territory the annual dose burden is 2.5 mSv y^{-1} in Zavodskoy, 1.9 mSv y^{-1} in Kvartsitka and 3.6 mSv y^{-1} in Aqsu.

For a critical group working and studying at Aqsu school the annual dose burden is ranges from 7.7 mSv y^{-1} to 10.81 mSv y^{-1} at the ground floor, and for teachers - up to 12 mSv y^{-1}. For schoolchildren on the second floor, this indicator ranges from 1.42 mSv y^{-1} to 2.21 mSv y^{-1}. For population living in the territories with high background level and consumed contaminated food the annual dose burden is 9.1 mSv y^{-1} in Zavodskoy, 8.3 mSv y^{-1} in Kvartsitka and 11.5 mSv y^{-1} in Aqsu.

Though the actual radiological situation is of no immediate concern for most of the population living in surroundings settlements. There are eminent radiological risk to critical group and the potential environmental contamination of school territory and radiological consequences calls for an urgent evaluation and potential application of effective remediation options.

Acknowledgments

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