Scenarios of radiological impacts in the long-term safety analysis of radioactive waste disposal at the Vector Site located in the Chernobyl exclusion zone

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Abstract:

In Ukraine, at the Vector site in the Chernobyl exclusion zone, it is planned to dispose of large amounts of radioactive wastes, including those of Chernobyl origin, containing transuranium elements. The paper analyzes the main possible scenarios of radiological impacts of the Vector site for a long-term period after expiration of its active administrative control taking into account location of the Vector site in the exclusion zone. In the paper, assessment of total activities that can be disposed of on site is demonstrated, based on non-exceeding of admissible radiological impacts.

INTRODUCTION

According to the Radioactive Waste Management Strategy in Ukraine [1], facilities for long-term storage and disposal of radioactive waste (RW) are being constructed at the Vector site in the Chernobyl exclusion zone. It is planned to transfer almost all Ukrainian RW to the Vector site. Taking into account significant volumes and streams of RW that differ substantially by the level of activity, radionuclide composition and other characteristics, it is necessary to apply an integrated approach for treatment and subsequent placement of RW for safe storage and disposal at the Vector site.

One of the main issues of the strategy for RW disposal at the Vector site is to determine what are the maximum total activities of radionuclides that may be disposed of at the Vector site. This issue is analyzed in the paper.

The period of passive administrative control is considered, when the exclusion zone that is gradually reducing performs the barrier function (restricted access area – RAA) [2].

In this period, engineering barriers of the storage facilities are degrading, their maintenance is not performed. The only barrier for population to get to the Vector site may be existence of RAA. After RAA ceases to exist, population may reside also directly on site.

The above-mentioned period of passive control with barrier function of RAA, as well as the period after termination of existence of RAA, may be considered as the most critical for assessment of total activities of long-lived radionuclides in RW that may be disposed of at the Vector site.

The following dose constraints are applied: for scenarios of normal evolution – 0.3 mSv/year, for alternative scenarios – 1 mSv/year [2, 3].

For the period of existence of RAA, it is necessary to define and consider scenarios that lead to the maximum doses for population residing outside RAA in case of spreading of radioactive substances by groundwater and air.

Analysis of total activities of RW that may be disposed of at the Vector site is carried out for radionuclide composition of Chernobyl origin RW, because such waste comprises the majority both by volume and activity.

It is assumed that RW of Chernobyl origin whose total activity reaches 5% in the total activity of fuel of destroyed ChNPP Unit 4 of, i.e. about $2.5 \cdot 10^{16}$ Bq, will be subjected to near-surface disposal at the Vector site. It is the majority of generated RW of Chernobyl origin in the exclusion zone and, partially, low- and intermediate-level waste from the Shelter.

1 SCENARIOS OF RADIONUCLIDE MIGRATION WITH GROUNDWATER

The Vector site is located at the watershed of Prypyat' and Uzh rivers at a distance of 8 km and 18 km, respectively [4]. According to the available data [4], level of the first watershed is observed at a depth from 15 to 21 m. Water table incline is to the north-east to Prypyat' river. The main source of aquifer recharge is atmospheric precipitations. Water-containing rocks include sands of various grain-size composition with sublayers of loams and sandy loams. The first aquifer is bedded by marl (marl thickness is 12 m), under which the second aquifer is located (thickness of the second aquifer is 35 m, confined). In the marl aquiclude, there are sand lenses, through which a hydraulic link between the first and second aquifers is possible (filtration coefficient of marl clays is from 10^{-2} to 10^{-4} meters per day).

For the facility constructed for disposal of conditioned RW of ChNPP, migration of radionuclides with ground waters to the places of discharge near Prypyat' river was analyzed, as well as doses for the critical groups of population residing at this territory were estimated [5]. In [5], taking into account existing uncertainties in characteristics of geological layers, two hydrogeological models were developed (modeling region covered the territory between Prypyat' and Uzh rivers with the area of about 160 km^2 and the depth of about 100 m). In the first model, the layer of marl clays that was assumed as impermeable was considered as the lower boundary of the model. In the second model, possible interrelation between the first and second aquifers, which may take place due to inclusions of sand lenses with high filtration coefficient in the aquiclude, was taken into account. In the latter case, watershed of the second aquifer was accepted as the lower boundary of the model.

The calculations performed in [5] made it possible to determine pathways of ground waters and places of their discharge and calculate time of ground water movement. Radionuclides are transferred with ground waters from the Vector site to the direction of Prypyat' river through the first aquifer (CHE1 scenario) or through the first and second aquifers (CHE2 scenario).

According to the scenarios, as a result of water infiltration through the upper waterproofing level of the disposal facility and RW package, radionuclides are leached and contaminate the transferring medium – water. Then, through artificial and natural foundation of the disposal facility, water contaminated with radionuclides is moved down to the unsaturated area and to the aquifer. The aquifer is considered as the only source for contamination of biosphere.

In [5], the following assumptions were made:

- atmospheric precipitations get to the disposal facility through the cap;
- infiltration increases with time and will be equal to 100% after 500 years;
- artificial foundation of the disposal facility is considered as one element that ensures additional sorption of radionuclides and increases time of their transfer with water to geological medium;

- radionuclides are transferred through the near field only in vertical direction, i.e. condition of preservation of water flows that pass through elements of the near field (cap, disposal module, artificial foundation, natural foundation) to the aquifer is fulfilled;
- values of sorption coefficients are accepted according to general reference data in [4];
- radionuclides are transferred through the saturated area by one geosphere level (CHE1) or by 5 geosphere levels (CHE2) up to the discharge to the surface.

During modeling of biosphere, all dose pathways for members of the critical group residing in the places of ground water discharge were considered.

In these scenarios, the critical group of population is located at a distance of about 7000 m from the Vector site. Therefore, this distance may be considered as the size of RAA.

The estimates obtained in [5] were used to analyze possible radiological impacts under the assumption that Chernobyl origin RW with the total activity of $A_0 = 2.5\cdot10^{16}$ Bq would be disposed of at the Vector site, where activities of the main dose-forming long-lived radionuclides are estimated as: ^{90}Sr – $5.2\cdot10^{15}$ Bq, ^{137}Cs – $11.6\cdot10^{15}$ Bq, ^{239}Pu – $6.8\cdot10^{13}$ Bq.

For the scenario of radionuclide spreading from the Vector site by the first aquifer, maximum impact of ^{90}Sr at a distance of ≈ 7000 m is observed in ≈ 220 years, and dose for the critical group of population at ^{90}Sr activity of $5.2\cdot10^{15}$ Bq is estimated as ~ 52 mSv/year, at ^{137}Cs activity of $11.6\cdot10^{15}$ Bq in ≈ 300 years, and dose is ~ 8.8 mSv/year.

The above-mentioned estimates exceed the criteria for permissible impact on the critical group of population (0.3 mSv/year) approximately by 200 times. However, these estimates are made with a high degree of conservatism.

The estimates that take into account the second aquifer have shown that radiological impact of ^{90}Sr and ^{137}Cs becomes negligible.

Apart from this, it is expected that time interval of up to 500 years will belong to the active control of the Vector site (≈ 200 years – operation of facilities and 300 years of active control), when cap integrity is maintained, contamination of the environment is monitored, etc. Within this period, it is unlikely that the area of existing exclusion zone will be reduced significantly.

Therefore, safety of 90Sr and ^{137}Cs disposal for a long term may be ensured taking into account measures of active control and barrier function of RAA. However, to justify this, it is necessary to carry out detail studies on properties of engineering and natural barriers, scenarios for migration of nuclides.

For the scenario of spreading of radionuclides from the Vector site by the first aquifer, maximum impact of ^{239}Pu at a distance of ≈ 7000 m is observed in ≈ 17400 years, and dose for the critical group of population at activity of $6.8\cdot10^{13}$ Bq is estimated as ~ 160 mSv/year.

The above-mentioned estimates exceed the criteria for permissible impact on the critical group of population (0.3 mSv/year) approximately by 500 times. However, the same as for ^{90}Sr and ^{137}Cs, these estimates are made with a high degree of conservatism. The estimates that take into account the second aquifer show that radiological impact of ^{239}Pu becomes negligible.

Contrary to ^{90}Sr and ^{137}Cs, during the period when significant impact of ^{239}Pu is expected, there will be no active control of the Vector site.

In this period, it is likely that engineering barriers of the disposal facilities will be degraded, and long-term safety will be defined by the properties of hydrogeological medium.

For the period of time more than 10,000 years, it is not possible to rely on the existence of RAA and integrity of the disposal systems.

^{239}Pu migration will be determined by sorption capacity of sand and characteristics of aquifers. According to the estimates stated above, it may be expected that properties of natural barriers will be such that, on the one hand, they will limit ^{239}Pu migration to acceptable levels and, on the other hand, a sufficient level of ^{239}Pu "dilution" in geosphere outside the boundaries of the Vector site will be ensured during migration.

Therefore, concerning ^{239}Pu activity during disposal, safety will rely only on the properties of environment in the area of RW disposal, which does not comply with the generally accepted concept of defense-in-depth. However, at the moment, there are no other ways of isolating large amounts of low-level (and, partially, intermediate-level) RW of Chernobyl origin that may be implemented in practice.

The above-mentioned also necessitates a thorough study of hydrogeological conditions on the territory of the Vector site and comprehensive detailed modeling of ground water pathways for adequate analysis of the scenarios of long-term behavior of RW disposal systems for safety justification.

The demonstration assessments stated above show that, at the total activity of Chernobyl origin RW of $2.5 \cdot 10^{16}$ Bq, there are no evident (by several orders of magnitude) safety margins by dose indicators on the one hand. On the other hand, the possibility for disposal of low-level and a part of intermediate-level waste of Chernobyl origin at the Vector site cannot be excluded. This underlines the necessity for thorough studies of long-term safety to obtain justified confidence in adequate level of ecological safety for RW disposal at the Vector site within the boundaries of the exclusion zone.

2 SCENARIOS OF SPREADING OF RADIONUCLIDES WITH AIR

Spreading of radioactive substances with tornado leads to the most serious consequences.

Characteristics of tornadoes in the region of the exclusion zone are determined in [6]. Tornadoes of various intensity, up to tornado of F 3.0 class, happened and potentially may occur in this region. The probability of F 3.0 class tornado passing through a certain part of the territory is estimated as 10^{-6}/year (for F 1.5 class tornado – 10^{-5}/year). The path width of F 3.0 class tornado is 290 m.

The scenario of transfer of radioactive substances with tornado is studied in [7] as applied to the ChNPP Shelter. In case of F 3.0 class tornado, dust and various objects (up to vehicles, etc.) encountered on the tornado path are drawn into the funnel of tornado.

For the Shelter, a scenario in which 500 kg of fuel dust with total activity of $1.2 \cdot 10^{15}$ Bq is drawn into the funnel of F 3.0 class tornado (in case of destruction of the Shelter roof), further elevated to the height of ≈ 1000 m, spread in the atmosphere and precipitated to the territory was considered in [7].

Also, for passing of tornado through the Vector site, it should be supposed that all radioactive substances on surface and in the near-surface layer of the site (due to erosion processes) will be drawn into the funnel of tornado.

In [7], modeling of dust spreading was based on scenarios of meteorological situation in the area of ChNPP using numerical regional model of weather forecast MM5, adapted for calculation of meteorological fields over the territory of Ukraine. The dispersion of radioactive cloud was calculated using CALPUFF software.

The weather conditions that accompanied the F 3.0 class tornado on 11 June 2001 near the ChNPP (and from the Vector site) were taken as input meteorological data. The hypothetical source of release corresponded to coordinates and time of passing of this tornado. The contamination map obtained as a result of calculations was transferred so that the place of the release source coincided with the geographical coordinates of the ChNPP (in this paper – Vector site).

The results of calculations show that field of precipitated radioactive dust has 2 maxima: first one due to intense washout of radioactive substances near the source, and the second one due to gradual approach of the cloud to the surface resulting from turbulent diffusion and washout by the precipitations.

In [7], for activity of fuel dust of $1.2 \cdot 10^{15}$ Bq, the estimated maximum annual exposure dose for population is 670 mSv/year and is observed at a distance of ≈ 12 km. The second dose maximum of 88 mSv/year is observed at a distance of ≈ 90 km.

The resulting contribution to the dose is made by internal exposure due to ingestion of food contaminated with aerosols during the year and inhalation uptake of aerosols secondarily raised to the air [7].

The estimates in [7] are carried out under the assumption that spreading of radioactive substances by the tornado takes place at the present time.

The activity of Chernobyl origin RW will decrease with time due to natural decay of radionuclides and, accordingly, if spreading of these RW with tornado will take place after a long time, doses for population will be lower.

To estimate dose reduction, let us use the data of paper [8], where, for specific initial activity of RW, doses for population are calculated depending on time after closure of the facility with disposed RW of Chernobyl origin. In particular, the scenarios “inhalation uptake of radionuclides” and “ingestion of small fragments of waste substance” are considered, which analyze pathways of human exposure that make a decisive contribution to the above-mentioned estimates for the scenario of spreading of radioactive substances with tornado.

The time dependence of dose reduction for both scenarios is similar. The reduction of dose in 10,000 years will be about 4 times, in 100,000 years about 100 times.

Let us assume that, with time, due to erosion, some part of activity of RW that may be drawn into the funnel of tornado will release to the surface and into near-surface layer of the Vector site. This part of activity is denoted by coefficient K. Then the K value can be roughly estimated under the assumption that:

– height of stock piles of RW packages disposed of in the facility is ≈ 10 m;

– cap of the facility is completely degraded (in particular, due to erosion) and RW are on the surface layer;

– concentrations of radionuclides in RW in the near-surface layer have decreased by ≈ 10 times due to mixing of initial RW with the material of the cap by surrounding soils, due to washout of radionuclides, etc.;

– during passage of the tornado, subsurface layer with thickness of 20 cm is drawn into the funnel.

Under such assumptions, K value is roughly estimated as:

$$K = \frac{0.2m}{10m} \times 0.1 = 2 \cdot 10^{-3}$$

For disposal of Chernobyl origin RW with estimated activity of $A_0 = 2.5 \cdot 10^{16}$ Bq at the Vector site and for the above K value, using data from [8] described above, the dose of potential exposure at a distance of 12 km from site may be estimated as:

– for the period of 10,000 years – 6.9 mSv/year;

– for the period of 100,000 years – 0.27 mSv/year.

Therefore, if the abovementioned condition of the disposal facilities on the Vector site is achieved after 10,000 years, the estimated dose of potential exposure of 6.9 mSv/year exceeds the criteria of admissible dose of 1 mSv/year; after the period of 100,000 years, this criterion is not exceeded.

The above-mentioned demonstration analysis shows that, for scenarios of spreading of radionuclides in the atmosphere (the same as for the scenarios of spreading of radionuclides with ground waters) at total activity of $2.5 \cdot 10^{16}$ Bq of Chernobyl origin RW, there are no evident (by several orders of magnitude) safety margins by dose indicators on the one hand. On the other hand, the possibility for disposal of low-level and some part of intermediate-level waste of Chernobyl origin at the Vector site cannot be excluded. Therefore, it is necessary to carry out detail studies and analysis of natural processes that may lead to release of RW to the surface of the site.

It should be noted that RAA does not “protect” directly from the scenario of spreading of radioactive substances with tornado from the Vector site because the maximum exposure dose for population is assessed at quite a significant distance from the site, about 12 km. However, RAA protects the site from unintentional intrusion with destruction of the RW cap and, therefore, promotes prevention of the scenario considered above.

CONCLUSIONS

Based on the existing data on modeling of radionuclide migration from the RW disposal system through the hydrogeological medium to the accessible biosphere, approximate estimates of radiological impacts for the critical groups of population at a distance of about 7000 m from the Vector site have been conducted.

The estimates for spreading of radioactive substances in the atmosphere by the scenario of their drawing into the tornado funnel and appropriate radiological impacts are adapted to the RW disposal systems.

Assessments of radiological impacts show that, for disposal of low-level and partially intermediate-level RW of Chernobyl origin, there are no evident (by several orders of magnitude) safety margins by dose indicators on the one hand. On the other hand, the possibility for disposal of these RW at the Vector site cannot be excluded. It is necessary to carry out thorough studies of long-term safety to obtain justified confidence in adequate level of ecological safety for RW disposal at the Vector site within the boundaries of the exclusion zone.

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