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Analysis of Environmental Impact of Disposal of Uranium Waste in Surface Landfill Facilities

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Abstract
Front-end nuclear fuel cycle facilities generate a significant amount of uranium waste during operation and decommissioning, characterized by long half-life and high toxicity. Locating disposal facilities near these sites poses challenges due to safety concerns. To address this issue, the Chinese government has approved the construction of a disposal facility in a sparsely populated area of Gansu Province, aiming to centralize the disposal of uranium waste from across the country and minimize disposal risks. This study focuses on assessing the long-term environmental impact post-closure of the landfill facility. By simulating uranium migration under actual hydrological conditions using a storage chamber model, the analysis evaluates whether the public dose constraint requirements can be met. Results indicate that radionuclides begin to enter the biosphere approximately 400,000 years after landfill closure, with the public dose peaking at 2.23×10^{-2} mSv/a after 2,000,000 years, meeting the dose constraint value of 0.25 mSv/a. Additionally, uncertainty analysis suggests enhancing the anti-seepage efficiency of the HDPE membrane and increasing the thickness of bentonite during landfill facility design and construction to mitigate environmental impact, along with improving water conductivity of overburden drainage sheets.

Keywords Uranium waste · Centralized disposal · Dose · Environmental impact assessment · Near-surface

1 Introduction

The front-end nuclear fuel cycle facilities refer to: uranium purification facilities, uranium conversion facilities, uranium enrichment facilities, and fuel fabrication facilities. Such facilities will generate a large amount of uranium waste during the operation and decommissioning process [1]. The radionuclides contained in the uranium waste are: ^{234}U, ^{235}U and ^{238}U, do not contain ^{226}Ra and other artificial nuclides [2]. According to the source item investigation, uranium mainly exists in uranium wastes in chemical forms such as U_3O_8, UO_2 and UF_6, and the activity concentration is generally lower than 10^3 Bq/g. According to the regulations of the International Atomic Energy Agency [3] and China, uranium wastes with an activity concentration surpassing 1 Bq/g cannot be released from control and should be managed as radioactive wastes [1].

Uranium waste, recognized for its extended half-life [4], numerous decay by-products, and high chemical toxicity (refer to Table 1), poses a significant challenge. Chinese nuclear facilities produce approximately 200 tons of uranium waste annually, accumulating a total of 7,000 tons. These wastes are dispersed across five provinces with robust economies and high population densities.

China has established a classification system for disposing of radioactive waste based on the activity concentration of radionuclides. This system categorizes waste into very low-level, low-level, medium-level, and high-level waste, corresponding to landfill disposal, near-surface disposal, medium-depth disposal, and geological disposal, respectively. However, this classification system does not address uranium waste or specify its disposal method. The main reason is that uranium is a natural nuclide [5], belongs to existing irradiation, and the half-life of uranium is very long [6]. From the perspective of protecting contemporary and future generations, the closed uranium waste disposal facili-

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Table 1 Radioactive characteristics and decay daughters of U-238, U-235 and U-234

Uranium isotopes	Half-life (years)	Activity concentration (Bq/g)	Intake dose factor (Sv/Bq)	Mass percentage	Main decay daughter
^{238}U	4.47×10^9	1.24×10^4	5.7×10^{-6}	< 98.3%	^{234}U
^{235}U	7.04×10^8	8.0×10^4	6.1×10^{-6}	0.72%-5%	^{231} Pa, ^{227}Ac
^{234}U	2.45×10^5	2.31×10^8	6.8×10^{-6}	> 0.0057%	^{230}Th, ^{226}Ra, ^{222}Rn, ^{210}Pb, ^{210}Po

ties need permanent surveillance. Consequently, attempts to landfill uranium waste at its point of origin have encountered site selection challenges and local opposition, leading to significant quantities of uranium waste being temporarily stored at production sites. However, the temporary storage capacity is insufficient, posing high radiation safety risks to the surrounding areas.

The basic principles of the Chinese government and the IAEA regarding uranium waste disposal are consistent, namely that it is not advisable to adopt excessively costly methods to dispose of uranium waste. Therefore, the Chinese government agrees to carry out uranium waste disposal work in areas with good site conditions and to implement instituted control for more than 30 years after the disposal facility is closed.

To solve the problems of uranium waste disposal and promote the sustainable development of the nuclear industry, the Chinese government has decided to build a uranium waste disposal facility in Gansu Province, a sparsely populated province in China, to centrally dispose the uranium wastes in China's developed provinces, and carry out ecological compensation to Gansu Province. According to the latest requirements of the International Atomic Energy Agency, uranium in the front-end nuclear fuel cycle facility belongs to plan exposed and should be managed as artificial nuclides [7]. Therefore, the design requirements for this disposal facility are aligned with those of very low-level waste landfill facilities, which are near-surface disposal facilities. The environmental impact of the disposal facility is mainly caused by the migration of radionuclides into the biosphere through groundwater. Therefore, it is necessary to carry out an environmental impact analysis to demonstrate whether the impact on the public can be accepted in a long time scale after waste disposal [8], and whether the disposal of uranium containing waste in this area is appropriate.

2 Materials and Methods

2.1 Location and Design of Landfill facilities

The landfill facility is located in Jinta County, Jiuquan City, Gansu Province. This area is a Gobi landform with no mineral resources and tourist attractions around. There are no natural villages and no permanent residents within a radius of 5 km of the facility. The population density within 10 km is 7 persons/km^2. The closest settlement to the facility is a farm 7 km away, and the farm's drinking water is drawn from groundwater. The groundwater of the site is buried in pores with a depth of 11 m. The direction of groundwater flow is from northwest to southeast. The geographical location of the project site is shown in Fig. 1.

The total disposal scale of the landfill facility is 1.5×10^5 m^3, which is divided into 6 landfill units. After investigating the radioactivity level of uranium waste in China, the activity concentration of uranium in the waste to be received is less

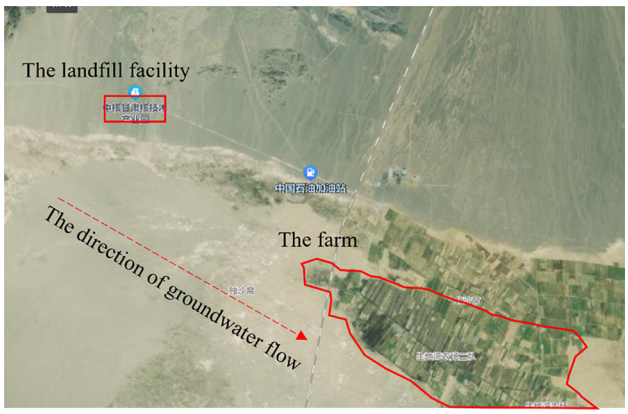

Fig. 1 Schematic diagram of the geographical location of landfill facilities

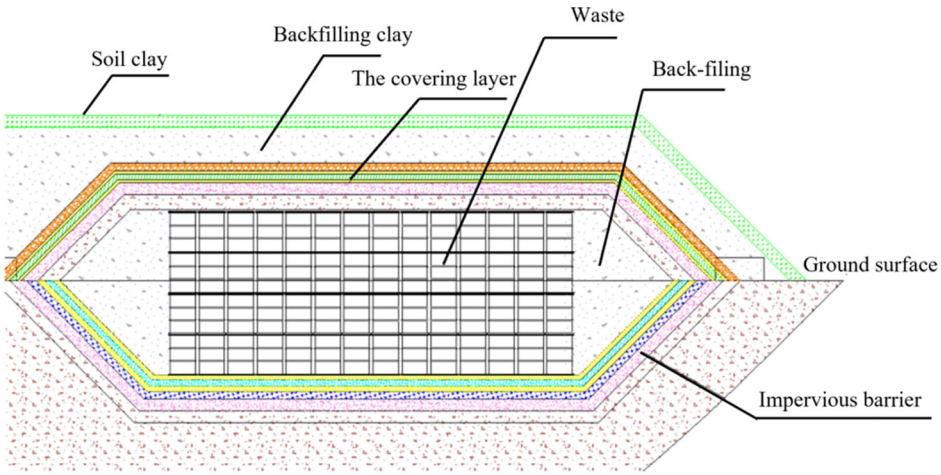

Fig. 2 The design of landfill facilities

than 50 Bq/g, with an average value of 5.6 Bq/g. Therefore, the uranium activity concentration limit is set at 50 Bq/g for this landfill facility, and the total radioactivity of acceptable uranium is 2.25×10^{13} Bq.

The landfill facility adopts a semi-underground design, as shown in Fig. 2. The floor of the landfill facility is composed of rammed clay, bentonite, geotextile, HDPE membrane, and will be covered after the waste is filled, and the covering layer is composed of rammed soil, geotextile, drainage sheet, geotextile and gravel.

2.2 Parameters and Scenarios of Nuclide Migration

The main parameters considered in the evaluation include: infiltration, nuclide distribution coefficient (K_d value) and hydrological data. The infiltration amount was 6 mm/a; the Kd value in each medium was taken from "Derivation of activity limits for the disposal of radioactive waste in near surface disposal facilities" (IAEA-TECDOC-1380) [9]. The main hydrological data used in the evaluation are shown in Table 2.

The assessment primarily focuses on the environmental effects of nuclide migration under typical scenario post closure of the landfill [10], neglecting to assess the repercussions of intrusion incidents. According to the recommended scenario development requirements by the International Atomic Energy Agency [11], the primary nuclide migration scenarios (events) that should be analysised in the environmental impact assessment of the landfill facility are: following the closure of the landfill facility, as the structure deteriorates, rainfall infiltrates the site, interacting with the waste, leading to the leaching of nuclides by rainwater. These nuclides then permeate through the unsaturated zone and eventually infiltrate the aquifer. Subsequently, they migrate towards the farmland along with groundwater flow, with a conservative assumption that the local populace consumes this groundwater [12].

2.3 Evaluation Model

Ecolego software was used to calculate the nuclide migration. When simulating the nuclide migration process, the system is

Table 2 Hydrological data around the landfill facility

Name	Medium	Thickness (m)	Length (m)	Dry density (kg/m^3)	Effective porosity	Actual velocity	Degree of dispersion
Landfill unit	Concrete, crushed stone, etc	7	–	3000	0.3	Infiltration divided by effective porosity	Non
Unsaturated	Slightly weathered rock	10	–	2000	0.15	Infiltration divided by effective porosity	Non
Aquifer	Strongly weathered rock	40	6000	2000	0.28	140 m/a	600 m

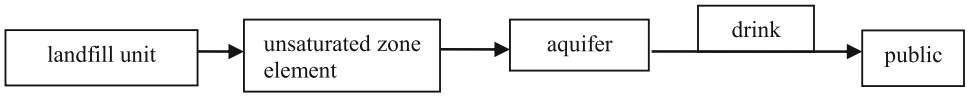

Fig. 3 The migration pathways of uranium

divided into a series of chambers according to the conceptual model [13]. Each chamber is a space with a certain boundary. It is assumed that the pollutants are mixed immediately after entering the chamber, so that the concentration of the entire chamber is uniform. The migration process is represented by a migration ratio. The migration ratio refers to the ratio of the activity of a certain nuclide lost or obtained by the chamber A due to migration in the t period to the total activity of the nuclide [14].

Assuming that the total amount of radionuclide N in the storage chamber i during t period is N_i(Bq) [15], for the number i chamber, the rate of change of the total amount of radionuclide N in the storage chamber with time satisfies the following first-order linear differential equation:

$$\frac{dN_i}{dt} = \left[\sum_{j\neq 1} \lambda_{ji} N_i + \lambda_M M_i + S_i\right] - \left[\sum_{j\neq 1} \lambda_{ij} N_i + \lambda_N N_i\right] \tag{1}$$

where i, j-chamber; N, M-the amount of radionuclides, N and M (N is a daughter of M) in the chamber, Bq; S-other external sources and drains of radionuclide N, Bq/a; S-the decay constant of the nuclide N, a^{-1}; λ_N-the decay constant of the radionuclide M, a^{-1}; λ_M-migration ratio of radionuclide N come from chamber j, a^{-1}; λ_{ji}-migration ratio of radionuclide N out from chamber i, a^{-1}.

The vertical downward migration rate of nuclides due to rainfall infiltration (λ_{inf}, a-1) is given by the following equation:

$$\lambda_{\text{inf}} = \frac{q}{L\theta_w R} \tag{2}$$

where q-Darcy flow velocity through landfill unit (m/a); L-the total length of radionuclide migration (m), that is the height of the landfill unit; θ_w-effective porosity of the medium in the landfill unit; R-retention coefficient of nuclides in landfill unit medium, its value is given by the following formula:

$$R = 1 + \frac{\rho K_d}{\theta_w} \tag{3}$$

where ρ-density of landfill unit medium (kg/m^3), K_d-distribution coefficient of nuclides in landfill unit (m^3/kg).

The decay, adsorption, convection and dispersion are considered, when the nuclides leaking from the unsaturated zone enter the aquifer. In the calculation, it is assumed that: (1) there is no other leakage source term, $S(t)$ is constant 0, (2) The nuclides are mixed evenly in the vertical direction, (3) ignore molecular diffusion, (4) consider the decay of nuclides, (5) consider the migration of nuclides along the groundwater flow direction. The migration of nuclides in aquifers can be expressed by the following formula:

$$R\frac{\partial C}{\partial t} = \frac{D_X}{\theta_w}\frac{\partial^2 C}{\partial x^2} - \frac{q}{\theta_w}\frac{\partial C}{\partial x} - R_T \lambda_T C_p \tag{4}$$

where x-the distance that the nuclide migrates along the groundwater flow direction, m; t-time since closing, a; C-nuclide concentration in groundwater, Bq/m^3; q-darcy velocity of groundwater, m/a; θ_w-effective porosity of aquifer, q/θ_w- actual velocity of groundwater, m/a; D_x-longitudinal dispersion coefficient, m^2/a, $D_x = a_x q/\theta_w$; a_x-longitudinal dispersion, m; λ_T-decay constant of nuclide, a^{-1}.

When calculating the migration of nuclides in the aquifer, ecolego software considers the advection transport and dispersion of groundwater flow. For advection transport, it can be expressed by the migration ratio of advection, and for dispersion, it can be expressed by the migration ratio of dispersion:

$$\lambda_{A,ij} = \frac{q}{\theta_w L_i R} \tag{5}$$

$$\lambda_{D,ij} = \frac{a_x}{\Delta x}\lambda_{A,ij} \tag{6}$$

where L_i-length of chamber in aquifer, m; Δx-longitudinal migration distance of nuclide in medium, m (Fig. 3).

The scale of the facility is 150,000 m^3, the waste density is 3000 kg/m^3, the average activity concentration of uranium is 50 Bq/g, and the abundance of uranium is considered at 5%. The radioactivity of uranium isotopes in the waste is shown in Table 3. Considering the decay of ^{238}U and ^{235}U, the two decays are connected as follows:

Table 3 Total activity of uranium isotopes in landfill facility

Nuclide	Half-life (a)	Activity concentration (Bq/g)	Total activity (Bq)
^{234}U	2.44×10^5	44	1.98×10^{13}
^{235}U	7.04×10^8	1.5	6.75×10^{11}
^{238}U	4.47×10^9	4.5	2.03×10^{12}
Total		50	2.25×10^{13}

Table 4 Peak concentrations of nuclides released from the bottom of the landfill facility and their occurrence time

Nuclide	^{235}U	^{238}U	^{231} Pa	^{227}Ac	^{234}U	^{226}Ra	^{210}Pb	^{210}Po
Maximum release rate (Bq/a)	5.43×10^6	1.63×10^7	1.77×10^5	2.12×10^5	1.69×10^8	3.78×10^6	6.83×10^6	1.23×10^7
Corresponding time (a)	3×10^1	3×10^1	7.0×10^4	7.0×10^4	3×10^1	1.02×10^5	1.02×10^5	1.02×10^5

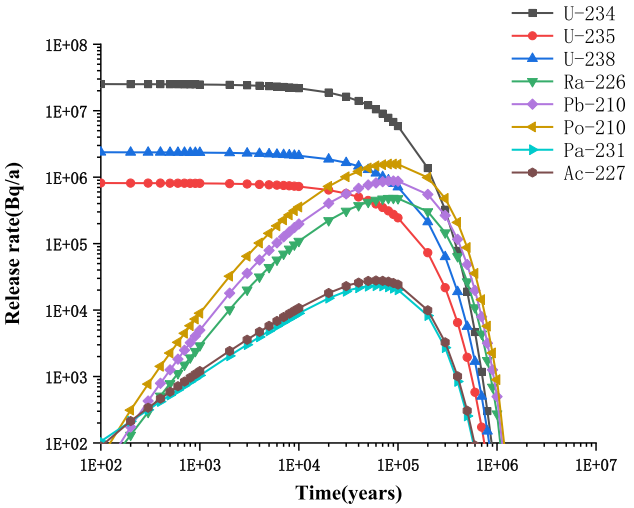

Fig. 4 Relationship between release rate and time of nuclides from the bottom of the landfill unit

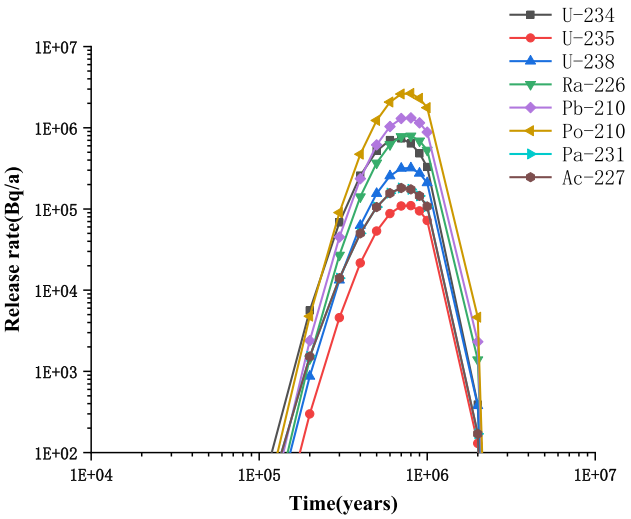

Fig. 5 Relationship between release rate and time of nuclide from unsaturated zone

^{235}U $\rightarrow^{231}$ Pa $\rightarrow^{227}$ Ac;

^{238}U $\rightarrow^{234}$ U $\rightarrow^{226}$ Ra $\rightarrow^{210}$ Pb $\rightarrow^{210}$ Po.

3 Results and Discussion

3.1 Calculation Results

Table 4 and Fig. 4 show the peak concentration and peak occurrence time of nuclides released from the bottom of the landfill facility. Table 5 and Fig. 5 show the peak concentration and peak occurrence time of nuclides released from the unsaturated zone. Table 6 and Fig. 6 show the maximum concentration of nuclides in the well water and the time of

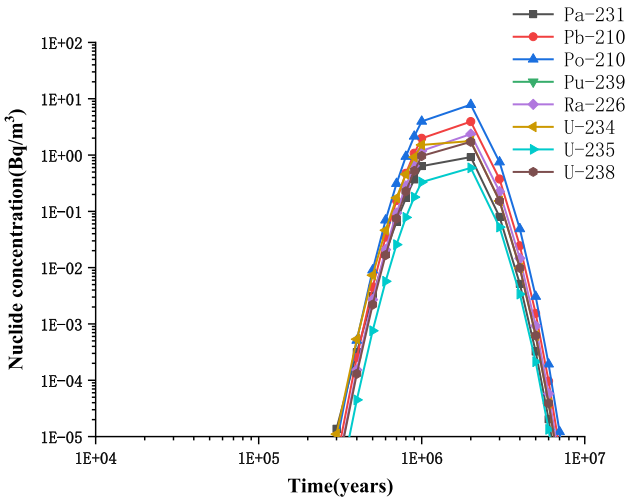

Fig. 6 Relationship between nuclide concentration and time in well water

Table 5 Peak concentrations of nuclides released from the unsaturated zone to the saturated zone and their occurrence time

Nuclide	^{235}U	^{238}U	^{231} Pa	^{227}Ac	^{234}U	^{226}Ra	^{210}Pb	^{210}Po
Maximum release rate (Bq/a)	4.34×10^5	1.31×10^6	7.14×10^5	7.14×10^5	1.39×10^6	1.54×10^6	2.58×10^6	5.15×10^6
Corresponding time (a)	1.8×10^6	1.8×10^6	1.77×10^6	1.77×10^6	1.75×10^6	1.82×10^6	1.82×10^6	1.82×10^6

Table 6 Peak concentrations of nuclides in well water and their occurrence time

Nuclide	^{235}U	^{238}U	^{231}Pa	^{227}Ac	^{234}U	^{226}Ra	^{210}Pb	^{210}Po
Concentrations in well water (Bq/m^3)	1.37	4.13	2.25	2.25	4.27	4.76	7.91	$1.58E \times 10^1$
Corresponding time (a)	1.98×10^6	1.98×10^6	1.94×10^6	1.94×10^6	1.94×10^6	2.03×10^6	2.03×10^6	2.03×10^6

peak value. Table 7 and Fig. 7 show the relationship between dose and time caused by nuclide.

3.2 Uncertainty Analysis

Due to the complexity of the environmental impact assessment of radioactive waste disposal, it is necessary to minimize the uncertainty in the assessment. Then, the uncertainty of parameters is a very important factor affecting the evaluation results. In this study, the single parameter change method is used to analyze the parameter uncertainty include: rainfall infiltration, groundwater velocity, vadose zone thickness and nuclide distribution coefficient (K_d value). Sensitivity analysis was carried out for these parameters, and the analysis results are shown in Table 8.

From the results of sensitivity analysis and calculation, the influence of various parameters on the results is ranked as follows: rainfall infiltration > K_d value in facility > groundwater velocity > thickness of vadose zone > K_d value in aquifer > K_d value in vadose zone.

3.3 Data Analysis

After the landfill facility is closed, due to rainfall infiltration, uranium moves down with the rainwater, passes through the facility floor and enters the unsaturated zone, then enters the aquifer and reaches the farm through the aquifer. The dose caused by the public drinking groundwater begins to increase around 41,000 years after the facility is closed, and reaches the peak at 2 million years, which is 2.23×10^{-2} mSv/a, less than the dose constraint value of 0.25 mSv/a. The key nuclide is ^{210}Po (the daughter of ^{238}U). In 10 million years, with the diffusion and decay of radionuclides, the dose to the public was close to zero.

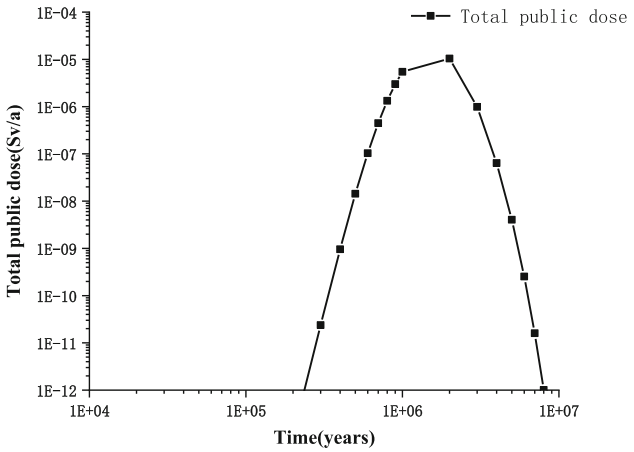

Fig. 7 Relationship between total public dose and time due to various nuclides

4 Conclusion

From the perspective of environmental impact assessment, the northwest region with sparse landfill facility is located in the northwest region with sparse population. After the closure of the facility, the maximum dose to the public from uranium released through groundwater migration is 2.23×10^{-2} mSv/a, which is below the dose limit (0.25 mSv/a). When the activity concentration limit of uranium in the facility is set at 50 Bq/g and the total activity is set at 2.25×10^{13} Bq, the impact on the environment is acceptable. The centralized disposal strategy and construction of landfill facility in Gansu Province can solve China's uranium waste disposal problem and reduce the pressure on the operation of nuclear fuel cycle facilities.

As can be seen from the release and migration of radionuclides in groundwater: (1) Due to the slow migration speed of uranium and its daughters, the dose peak time appears in hundreds of thousands of years; (2) Of all radioactive

Table 7 The time of occurrence for the maximum dose caused by each nuclide

Nuclide	^{235}U	^{238}U	^{231}Pa	^{227}Ac	^{234}U	^{226}Ra	^{210}Pb	^{210}Po
Dose (Sv/a)	4.69×10^{-8}	1.35×10^{-7}	1.17×10^{-6}	1.81×10^{-6}	1.53×10^{-7}	9.70×10^{-7}	3.99×10^{-6}	1.39×10^{-5}
Corresponding time (a)	1.98×10^4	1.98×10^6	1.94×10^6	1.94×10^6	1.94×10^6	2.03×10^6	2.03×10^6	2.03×10^6

Table 8 Sensitivity analysis and calculation results of main parameters

Parameter	Value	Maximum dose		Early/late
		(Sv/*a*)	Growth rate (%)	
K_d value in the facility(m^3/ kg)	4	8.82×10^{-6}	− 49.90	Late
	8	4.40×10^{-6}	− 75.00	Late
Rainfall infiltration (mm/a)	13	3.85×10^{-5}	118.80	Early
	26	7.64×10^{-5}	334.10	Early
vadose zone K_d (L/kg)	7.5	1.75×10^{-5}	− 2.30	Late
	75	1.58×10^{-5}	− 10.20	Late
aquifer K_d (L/kg)	7	1.61×10^{-5}	− 8.50	Late
	70	9.58×10^{-6}	− 45.60	Late
Groundwater velocity (m/a)	55	8.89×10^{-6}	− 49.50	Early
	110	4.73×10^{-6}	− 73.10	Early
Thickness of vadose zone (m)	10	1.55×10^{-5}	− 11.90	Late
	20	1.43×10^{-5}	− 18.80	Late
Original value		2.23×10^{-5}	–	

nuclides, ^{238}U's daughter ^{210}Po has the highest concentration and dose contribution at the groundwater outcrop point; (3) If the assumptions in the evaluation are confirmed within a 1000-year scale, then the evaluation results are true within a human predictable timescale.

To further reduce the environmental impact after the closure of the landfill facility, according to the results of uncertainty analysis, improvements should be made in the design and construction requirements of the landfill facility from the following aspects: (1) At the bottom of the landfill facility, the anti-seepage performance of HDPE membrane should be strengthened, and the thickness of bentonite at the bottom should be further increased to improve the adsorption capacity of nuclides and block water flow; (2) Increase the thickness of the cover layer and further optimize the drainage plate in the cover layer to improve water conductivity; (3) Good quality assurance work for base material performance verification and construction can minimize uranium release within a limited scale.

References

1. Skoko, B.; Marović, G.; Babić, D.; Šoštarić, M.; Jukić, M.: Plant uptake of 238U, 235U, 232Th, 226Ra, 210Pb and 40K from a coal ash and slag disposal site and control soil under field conditions: A preliminary study. J. Environ. Radioact. **172**, 113–121 (2017). https://doi.org/10.1016/j.jenvrad.2017.03.011
2. Payne, T.E.; Harrison, J.J.; Cendon, D.I.; Comarmond, M.J.: Radionuclide distributions and migration pathways at a legacy trench disposal site. J. Environ. Radioact. **211**, 106081 (2020). https://doi.org/10.1016/j.jenvrad.2019.106081
3. International Atomic Energy Agency (IAEA): Application of the concepts of exclusion, exemption and clearance. IAEA-RS-G-1.7. IAEA, Vienna. (2004) https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1202_web.pdf.
4. International Atomic Energy Agency (IAEA): CLASSIFICATION OF RADIOACTIVE WASTE. IAEA-GSG-1 IAEA, Vienna. (2009) https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1419_web.pdf
5. Hughes, C.E.; Cendón, D.I.; Harrison, J.J.; Hankin, S.I.; Johansen, M.P.; Payne, T.E.; Vine, M.; Collins, R.N.; Hoffmann, E.L.; Loosz, T.: Movement of a tritium plume in shallow groundwater at a legacy low-level radioactive waste disposal site in eastern Australia. J. Environ. Radioact. **102**(10), 943–952 (2011). https://doi.org/10.1016/j.jenvrad.2010.05.009
6. International Atomic Energy Agency (IAEA): Management of Residues Containing Naturally Occurring Radioactive Material from Uranium Production and Other Activities. IAEA-SSG-60 IAEA, Vienna. (2021) https://www-pub.iaea.org/MTCD/Publications/PDF/PUB1883_web.pdf
7. Pavliuk, A.O.; Kotlyarevskiy, S.G.; Bespala, E.V.; Zakharova, E.V.; Ermolaev, V.M.; Volkova, A.G.: Experience of on-site disposal of production uranium-graphite nuclear reactor. J. Environ. Radioact. **184–185**, 22–31 (2018). https://doi.org/10.1016/j.jenvrad.2018.01.005
8. McGuire, C.; Dale, P.; Copplestone, D.; Wilson, C.; Tyler, A.: Characterising radium-226 particles from legacy contamination to support radiation dose assessments. J. Environ. Radioact. **212**, 106127 (2020). https://doi.org/10.1016/j.jenvrad.2019.106127
9. International Atomic Energy Agency (IAEA): Derivation of activity limits for the disposal of radioactive waste in near surface disposal facilities. IAEA-TECDOC-1380 IAEA, Vienna. (2003) https://www-pub.iaea.org/MTCD/Publications/PDF/te_1380_web.pdf
10. Kim, J.H.; Hornibrook, C.; Yim, M.-S.: The impact of below detection limit samples in residual risk assessments for decommissioning nuclear power plant sites. J. Environ. Radioact. **222**, 106340 (2020). https://doi.org/10.1016/j.jenvrad.2020.106340
11. International Atomic Energy Agency (IAEA): The Long Term Stabilization of Uranium Mill Tailings, IAEA-TECDOC-1403. IAEA, Vienna. (2004) https://www-pub.iaea.org/MTCD/Publications/PDF/te_1403_web.pdf
12. International Atomic Energy Agency (IAEA): Handbook of Parameter Values for the Prediction of Radionuclide Transfer to Wildlife. Technical Reports Series No. 479.IAEA, Vienna. (2014) http://www-pub.iaea.org/MTCD/Publications/PDF/Trs479_web.pdf

13. Hilal, M.A.; Attallah, M.F.; Mohamed, G.Y.; Fayez-Hassan, M.: Evaluation of radiation hazard potential of TENORM waste from oil and natural gas production. J. Environ. Radioact. **136**, 121–126 (2014). https://doi.org/10.1016/j.jenvrad.2014.05.016
14. Bushuev, A.V.; Kozhin, A.F.; Zubarev, V.N.; Aleeva, T.B.; Petrova, E.V.; Glagovskii, E.M.; Rudenko, V.S.; Girke, N.A.: Radioactive contamination of spent reactor graphite. Atom. Energy **117**(3), 196–200 (2015). https://doi.org/10.1007/s10512-014-9910-4
15. Wareing, A.; Abrahamsen-Mills, L.; Fowler, L.; Grave, M.; Jarvis, R.; Metcalfe, M.; Norris, S.; Banford, A.W.: Development of integrated waste management options for irradiated graphite. Nucl. Eng. Technol. (2017). https://doi.org/10.1016/j.net2017.03.001