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Safety assessment of Beishan pre-selection area for geological disposal of high-level radioactive waste in China

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Abstract

A safety assessment was conducted for Beishan region of Gansu, China, the results show that Se-79 and Cs-135 are the key nuclides released in the near field between 1000 and 4000 years after the closure of the repository. After 4000 years, Tc-99, Np-237 and U-235 are the key nuclides released in the near field. Within 5000 years after the closure of the repository, Se-79 is the key nuclide released from the dominant water fractures, and its peak release rate is 1×10^5 mol/m^3, peak time 4000 a. At 20,000 years after the closure of the repository, Cs-135 is the key nuclide, and its peak release rate is 5×10^6 mol/m^3, with a peak time of 100,000 a.

Keywords Safety assessment · Geological disposal · Beishan · Database · Dose

Introduction

Safety assessment technology is an important link and one of the difficult technologies in the research and development process of high-level radioactive waste (HLW) geological disposal. The safety assessment report is an indispensable material for the national competent authority to conduct an assessment, and it is also one of the primary foundations for step-by-step decision-making. The development of assessment models and the establishment of assessment methods is the core work of safety assessment research [1]. The importance of safety assessment in the geological disposal of HLW can be summarized as a prerequisite for national approval, a rationale for public acceptance, a symbol of waste safety system engineering comparable to nuclear power safety, a ligament for the intrinsic connection between multiple disciplines in scientific and technological research, a means to achieve overall optimization of complex multi-barrier systems, and a basis for determining the performance requirements of the system components [2].

According to China's geological disposal system research and development plan, geological disposal of HLW research and development should focus on site selection and site assessment, repository concept design, safety assessment, and related basic research. These three elements should be interdependent, coordinated, mutually reinforcing, and developed collaboratively around the engineering goals. Site selection and site assessment are the prerequisites and foundation, and site parameters are the prerequisites for engineering design and safety assessment, which will provide basic site data for the design and construction of the repository and safety assessment. The repository engineering design is based on the site conditions while at the same time providing data requirements to it. In addition, the repository design serves as the foundation for the safety assessment effort, which in turn receives feedback from the safety assessment results, resulting in design optimization. The safety assessment is based on the site conditions and the repository design. In turn, the results of the safety assessment effectively guide the site assessment work to make it more focused, and provide feedback for the repository design, providing a basis for modifying and optimizing the repository design and its final approval. The safety assessment work is iterative with the development of the disposal project cycle, and as knowledge of geological disposal safety assessment improves, the corresponding safety assessment

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work requires further refinement and improvement [3, 4]. The site safety evaluation serves as the foundation for the subsequent site investigation of the candidate site in the pre-selected area of Beishan, the preferred pre-selected area for geological disposal of HLW in China, and is also the core work to confirm the safety and suitability of the site. Therefore, this paper carries out a safety evaluation for the pre-selection area of Beishan, with a view to providing a certain basis for the engineering design of the repository and subsequent design optimization.

Methods and techniques for safety assessment

Feature, event, and process screening

Based on the systematic digestion and analysis of the list of characteristics, events and processes of the Organization for Economic Co-operation and Development/Nuclear Energy Agency (OECD/NEA) (FEPs version 2.1) [5, 6], through analysis and comparison of the screening process of FEPs in countries such as the United States, Sweden and Japan, and mastering the corresponding analysis methods and technical means, and then taking the reference design of the geological repository for high release waste in China and the site of the pre-selection area in Beishan as the object, through the collection Then, by analyzing the results of research on various systems such as glass curing bodies of HLW, packaging containers, buffer materials, lithosphere and biosphere in China, and based on the necessary external events, the screening of FEPs list in the planning and site selection stage was carried out based on the corresponding screening guidelines and expert judgment, etc.

Safety features and safety indicators

Investigate relevant studies on safety standards, safety functions, safety requirements, and safety indicators for geological disposal of HLW. Start from six barrier systems, namely glass curing body, packaging container, buffer material, perimeter rock disturbance zone, lithosphere, and biosphere, collect and summarize the safety functions, safety characteristics and their characterization indicators that each barrier system should have, and then classify and grade the safety indicators for the purpose of safety evaluation [7].

Landscape analysis

An analysis was performed using methods such as fault trees or event trees on the basis of the screened list of FEPs and the developed safety functions and safety indicators, and evaluation scenarios were identified [8]. The proposed scenarios were divided into major scenarios (design basis evolution scenarios, over-design basis evolution scenarios with different boundary conditions such as early breakage of waste packages, failure of buffer materials, etc.) and disturbance scenarios based on the list of FEPs (human intrusion scenarios, extreme geological re-construction scenarios, extreme climate change scenarios).

Technical options, conditions and parameters for the safety assessment

Technical options for modeling the release of nuclide source terms

The analysis of the aqueous system of silicate glass curing body was carried out as part of the investigation of the mechanism related to the release of nuclides in glass curing body, and the source term release model was combined with the partial release scenario and full release scenario of nuclides proposed by the US. In the previous work, we studied the solubility of glass solidified body and the release rate of nuclides under different temperature and pH conditions [9]. Considering that the temperature in the underground repository is not higher than 60 ℃, and the pH value of groundwater is generally in the range of 6 ~ 10, the temperature of 60 ℃ and pH = 6 are taken as the research conditions. The calculation program of the release of nuclides in glass curing body under the two scenarios was written in MATLAB software, and then the effect of dissolution rate, temperature, and pH on the release rate of nuclides in glass curing body was analyzed [10, 11].

The migration of several typical nuclides with large packing capacities (Cs-135, Pu-239, Np-237, Am-241, and U-238) was calculated, and the results revealed that the mass release rate of nuclides in glass-cured bodies were in the order of 10^{-10} ~ 10^{-3} g/a, but considering the solubility factor, the release rate of the vast majority of nuclides should be in the relatively small order of magnitude. The release rate of Cs-135 is on the order of 10^{-5} ~ 10^{-4} g/a, because Cs-135 is completely dissolved in groundwater. And from the radioactivity release rate, the release rate is in the range of 1 ~ 10^{5} Bq/a under the assumption of complete release, as shown in Fig. 1.

Technical options for modelling the diffuse migration of nuclides in buffer/backfill materials

The diffusion migration of nuclides in buffered backfill materials is simulated using the compartment model, which is currently in common to use internationally. According to the reference conceptual design of the geological repository for HLW in China, the geometrically homogeneous

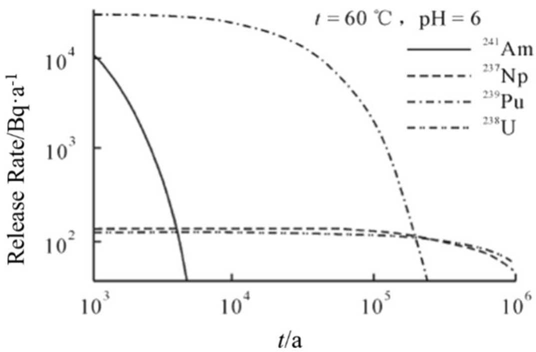

Fig. 1 The release rates of different nuclides calculated with the reaction kinetic models

equivalence method and the medium dispersion method are used to classify the chamber in the near field, respectively [12]. The geometric uniform equivalence method is mainly applicable to the case of uniform corrosion of the disposal vessel and relatively uniform surrounding medium, while the medium dispersion method is mainly applicable to the case of non-uniform corrosion of the disposal vessel (such as initial defects or pitting corrosion, etc.) and diffusion of nuclides in different directions, and the key sensitive areas in the migration process of nuclides can be considered. Using the above model, a theoretical model containing key parameters such as percolation coefficient, pressure, effective diffusion coefficient, nuclide partition coefficient, effective porosity of bentonite, bentonite scale parameters, nuclide decay constants, etc., is established to describe the macroscopic migration behavior of nuclides in bentonite, which is solved by substituting different nuclide-related property parameters to give quantitatively the macroscopic migration behavior of nuclides on long time scales (Pu-239, U-238, Np-237, Am-241. Cs-135, Tc-99, Se-79, Cl-36, and I-129) in the bentonite, some results are shown in Fig. 2. The results show that the migration rate of different nuclides varies greatly and bentonite has a good deterrent effect on the migration of nuclides in groundwater, and the activity of nuclides decreases by about 2–3 orders of magnitude after passing through bentonite.

Excavation disturbance zone (EDZ) nuclide migration model building technique scheme

EDZ is characterized by two properties of pore medium and fracture medium, and the migration of nuclides in EDZ is characterized by two migration modes of diffusion and convection. According to the characteristics of nuclide migration in EDZ, the mathematical models (equivalent compartment model for pore medium and network model for fracture medium) of granite surrounding rocks were established by GoldSim and COMSOL software respectively to simulate the migration process of nuclides in EDZ.

Based on the relationship between the groundwater flow rate and the subsurface hydraulic gradient, and the permeability of the subsurface medium and the fracture pore size in EDZ, under the assumption that the subsurface hydraulic gradient is taken as 0.001, the fracture length is 1 m (the thick of the disturbed area around the borehole is taken as 1 m), and under the condition that the probability distribution function of the permeability of the surrounding rock satisfies log-norm (mean = − 9.5, sd = 0.5, min = − 11.0, max = − 8.0), the data of penetrating fractures in the fracture network model were measured. Part calculation results are listed in Table 1. The calculation results show that there is no order of magnitude difference between the near-field radionuclide release rates calculated by the equivalent

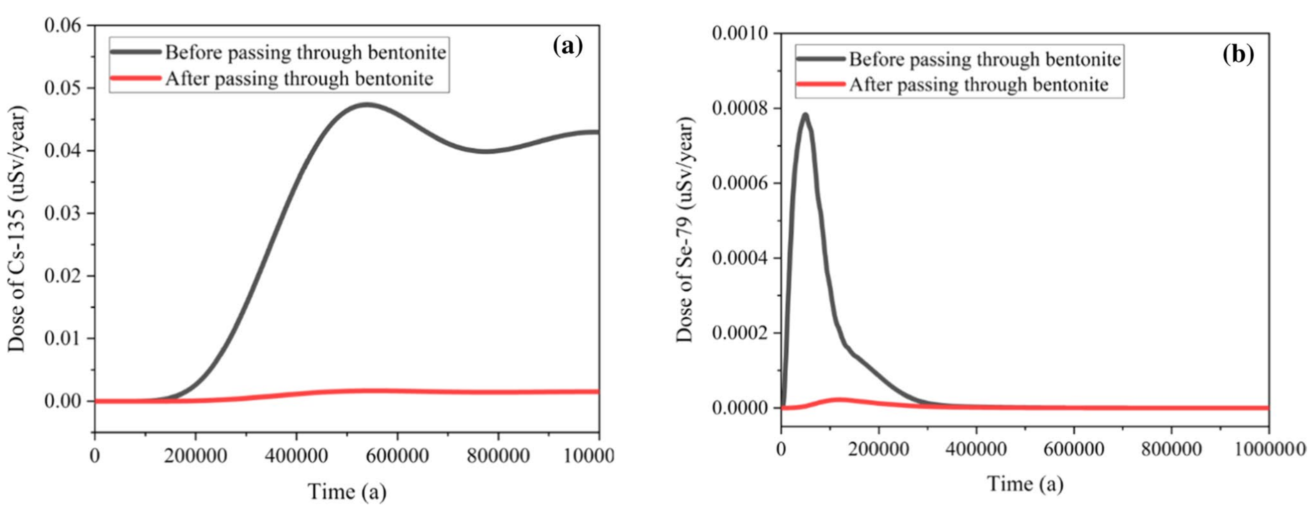

Fig. 2 Dose comparison of **a** Cs-135 and **b** Se-79 before and after passing through bentonite

Table 1 Comparison of calculation results of fracture network model and equivalent compartment model

Time	1e4 a		1e5 a		1e6 a	
Model	FNM	ECM	FNM	ECM	FNM	ECM
Cs-135 (Bq/year)	3266.01	3155.03	16,037.36	15,955.69	3517.03	3436.21
Se-79 (Bq/year)	57.0	56.36	23.18	22.82	1.63e-3	1.62e-3
Tc-99 (Bq/year)	2484.05	2072.88	2484.05	2421.46	2484.05	2421.46

ECM equivalent compartment mode , *FNM* fracture network model

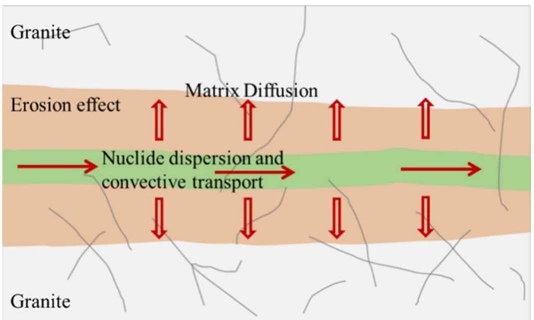

Fig. 3 Schematic diagram of nuclide migration in the lithosphere

compartment model and those calculated by the network model, for example, the maximum annual release rate of Cs-135 calculated by the equivalent compartment model is 1.6×10^5 Bq/a, while the result of the fracture network model is 2.4×10^5 Bq/a. And the result of Se-79 is 62.17 Bq/a and 61.04 Bq/a, the result of Tc-99 is 2484.05 Bq/a and 2421.46 Bq/a.

Technical options for modeling nuclide migration in the surrounding rock

The Ecolego software was used for preliminary trial calculations of Cs-135, Se-79, and Sn-126 to obtain the maximum occurrence time of the key nuclides, and then the more refined software GMS10.1 and COMSOL were used to calculate the nuclide concentration and spatial distribution of nuclide concentration in granite fissure water of the Beishan pre-selection area, in order to simulate and predict radionuclide migration in the geological body. The migration process of nuclides throughout the lithosphere in the reference scenario is shown in Fig. 3. The conceptual modeling process assumes that the perimeter rock length around each disposal unit is 100 m and the dominant water fissure length is 500 m, the same as the aquifer beneath the sedimentary layer. Interactions between radionuclides released from other disposal units were ignored. For the surrounding rock, a single fissure one-dimensional multi-path solute migration model was used, which means that the distribution of all fissures in the surrounding rock was determined first, and then the fissures were discretized according to the size distribution (the probability distribution of the constant logarithm of the hydraulic conductivity coefficient is used in the mathematical model processing, and the hydraulic conductivity coefficient is proportional to the square of the gap width) according to the requirements of calculation accuracy [13].

Biospheric nucleotide transfer modeling technology program

The final part of the safety evaluation of geological disposal of high-level radioactive waste is the biosphere, which focuses on the migration processes of radionuclides in various media of the biosphere (e.g., water, soil, plants and animals, etc.) and the associated exposure pathways to human doses. Since the time scale of the safety evaluation is very long (generally more than 10,000 years), it is difficult to predict the future human environment and lifestyle, so the biosphere has the largest uncertainty compared to the near-field and far-field.

In this paper, the recommended methods and steps of IAEA BIOMASS reference biosphere were used to collect and organize the existing environmental information around the pre-selected site in Beishan, and a preliminary reference biosphere radionuclide transport model for the pre-selected area in Beishan was established. The biosphere radionuclide transport and dose evaluation was carried out in the following three steps: (1) analyze the migration process of radionuclides in various environmental media of the biosphere, identify the environmental media that mainly have an impact on human dose, and divide the reservoir chamber according to its size, type and interrelationship; (2) determine the main exposure pathways according to specific human habits and lifestyles; (3) based on the reference human Determine the relevant parameters and calculate the radiological consequences of geological disposal for humans (expressed in terms of

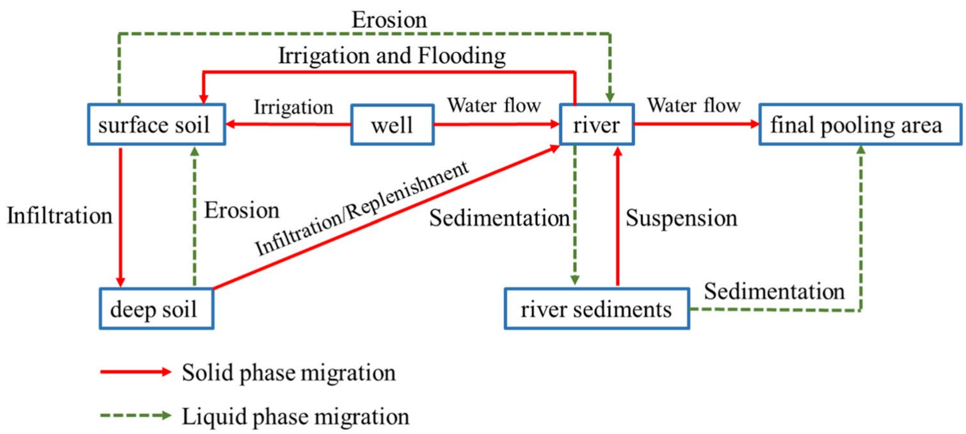

Fig. 4 The migration of radionuclides through the biosphere

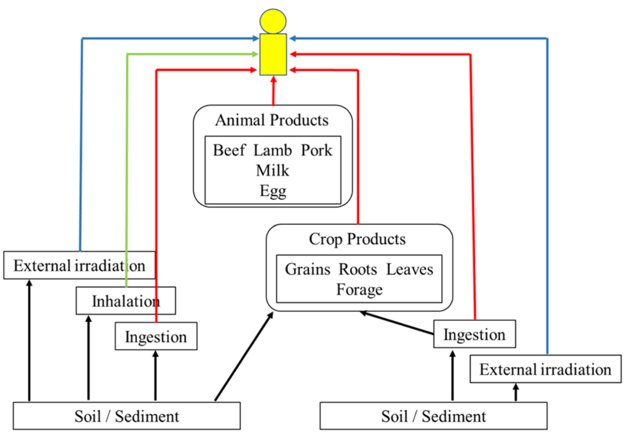

Fig. 5 The exposure pathway of radionuclides in the biosphere

annual effective dose to individuals). The migration process of radionuclides released from the lithosphere in the biosphere and the related exposure pathways are shown in Figs. 4 and 5.

Parameter sensitivity analysis and model uncertainty analysis

The geological disposal assessment model of HLW needs to predict the migration of radionuclides and the impact on the human environment over an extremely long time scale and a large spatial scale, and due to the complexity of the research object, it is particularly important to quantify the uncertainty of the assessment results to improve its credibility. The uncertainty of key parameters has a large impact on the uncertainty of results. Using the parameter sensitivity analysis method to analyze the key parameters affecting nuclide migration, the obtained results are feed back into the safety assessment to provide confidence in the results.

Some results of the parametric sensitivity analysis are briefly illustrated below with the near-field Cs-135 nuclide release rate, and the solubility limits of nuclides in water are not considered in order to enhance the calculation speed. The calculated sensitivities of the parameters associated with the near-field nuclide release rate were ranked as follows: water flow rate near the disposal disturbance area > effective diffusion coefficient (buffer material) > distribution coefficient (buffer material) > disposal vessel failure time > glass curing body dissolution rate, as shown in Fig. 6.

Results and analysis of the safety assessment

Taking the conceptual design of China's disposal repository and the site characteristics and regional environment of Beishan preselection area as the object, collect and summarize the research results in disposal chemistry and surrounding rock characteristics, combined with thedeveloped scene, established subsystem models and obtained performance evolution data of engineering barrier materials, and use COMSOL and ArcGIS software for modeling, The safety of the preselected site in Beishan, Gansu Province was evaluated.

Results and analysis of the near-field assessment

As is shown in Fig. 7, the release rates of single disposal canister in near field of fission activated nuclides, 4N(the mass number of nuclide in this series is an integral multiple of 4, thorium-series), 4N + 1(the mass number of nuclide in this series is an integral multiple of 4 plus 1, neptunium-series), 4N + 2(the mass number of nuclide in this series is an integral multiple of 4 plus 2, uranium-series), 4N + 3(the mass number of nuclide in this series is an integral multiple

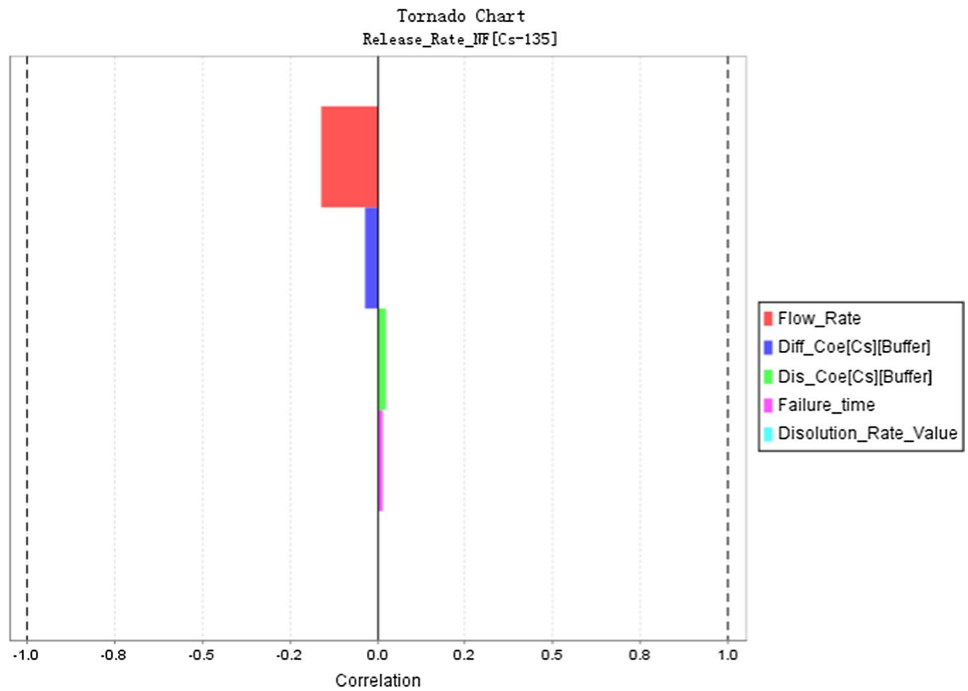

Fig. 6 Sequencing of parameter sensitivity related to the release rate of Cs-135

of 4 plus 3, actinide-series) series nuclides were calculated. The results show that between 1000 and 4000 years after the closure of the repository, Se-79 and Cs-135 are key nuclides released in the near field, and Tc-99, Ra-226 and Pd-107 also contribute to it. In about 4000 ~ 10,000 years, the release concentration of Sn-126, Np-237, U-235, Th-229, Np-94 and other nuclides began to increase rapidly. Tc-99, Np-237, U-235, Pd-107, Sn-126 and other nuclides were the key nuclides released in the near field 100,000 years after the closure of the repository. Between 30,000 and 70,000 years, the release concentrations of radionuclides such as cm-245, Am-241, Pu-239 and zr-93 began to increase rapidly. Because Se-79 and Cs-135 are long-lived nuclides with low adsorption, high solubility, and a large diffusion coefficient, they have a relatively strong migration ability and can reach peak release sooner [14].

Results and analysis of the far-field assessment

The results of far-field assessment in Fig. 8 show that Se-79 is the key nuclide released from the dominant water fractures within 5000 years after the closure of the repository, and its peak release rate is 1×10^5 mol/m^3, peak time 4000 a. At 4000 a, the release concentration of Cs-135 began to increase rapidly. In about 20,000 years, it exceeded Se-79 and became the key nuclide, with a peak release rate of 5×10^6 mol/m^3 and a peak time of 100,000 years. For nuclides with large adsorption coefficient in the lithosphere (such as 237Np), it has a large blocking force on nuclide migration, resulting in a significant lag in the time of the peak release rate compared with Se-79 and Cs-135, and the peak release rate is reduced by 2 ~ 4 orders of magnitude.

Conclusions

In this paper, we take the granite section of the Beishan pre-selection area in China as the engineering background and the normal evolution of the repository as the assessment basis, and initially establish a systematic safety evaluation method in the planning and site selection stage, including the safety function and safety requirements, the list of FEPs and the scenery screening method, the sensitivity and uncertainty analysis method, and the procedures of near-field source term release, far-field nuclide migration, and biosphere nuclide transfer. The research results have been applied in the site screening, underground laboratory site screening, and design work conducted by the Beijing Research Institute of Uranium Geology and in the repository concept design work conducted by China Nuclear Power Engineering Co., Ltd.

(1) The systematic safety assessment method and nuclide transport model were applied to the safety assessment of the Beishan pre-selection site, and the results of the

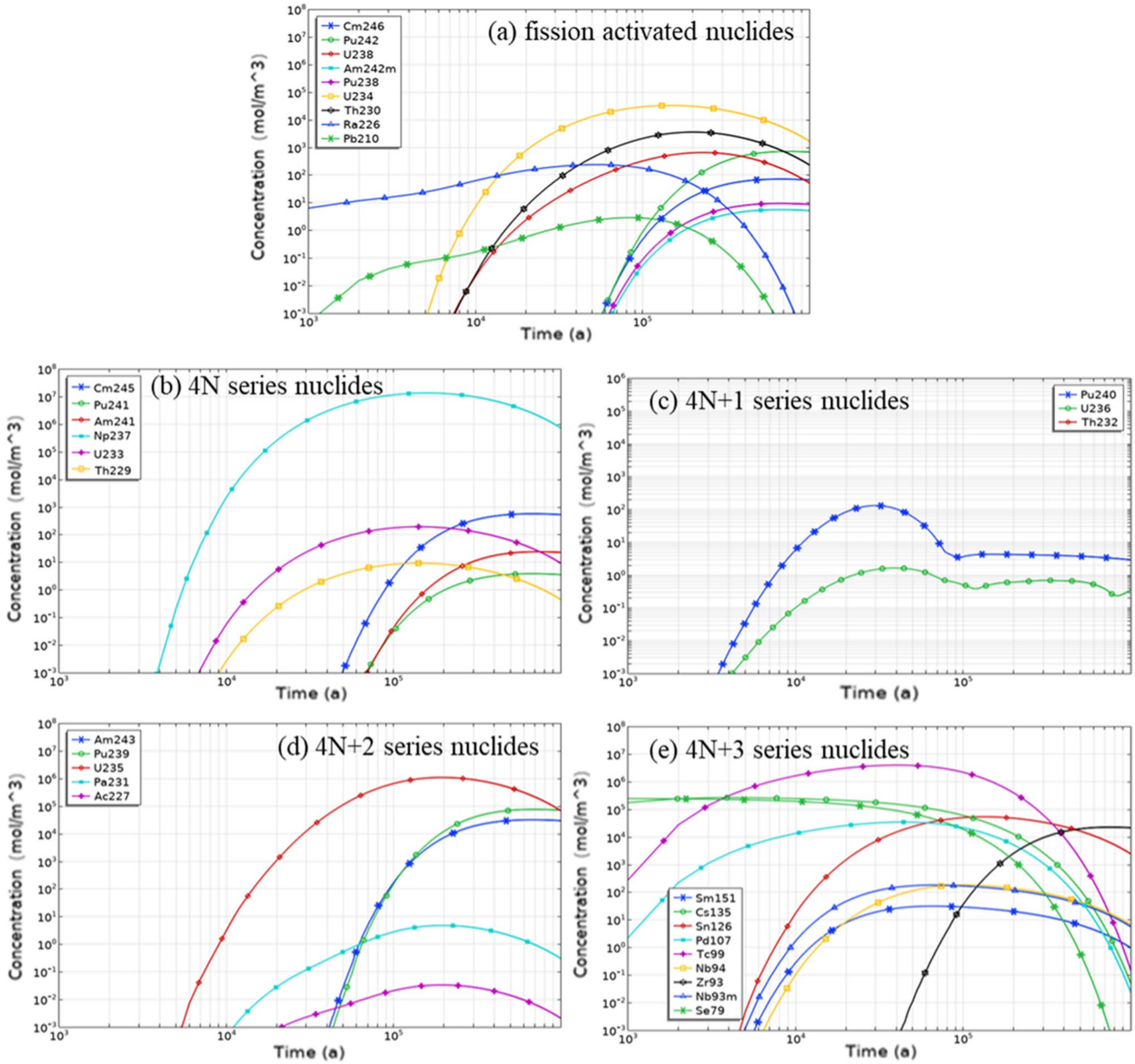

Fig. 7 The release rates of single disposal canister in near field of **a** fission activated nuclides; **b** 4N series nuclides; **c** 4N + 1 series nuclides; **d** 4N + 2 series nuclides; **e** 4N + 3 series nuclides

near-field and far-field nuclide transport were obtained, demonstrating that the assessment method and models are feasible and practical, and that proprietary lists and scenarios can be developed for specific sites and scenarios, making the evaluation method and model universally applicable.

(2) Se-79 and Cs-135 are the key nuclides released in the near field between 1000 and 4000 years after the closure of the repository; After 4000 years, Tc-99, Np-237 and U-235 are the key nuclides released in the near field. Within 5000 years after the closure of the repository, Se-79 is the key nuclide released from the dominant water fractures, and its peak release rate is 1×10^5 mol/m^3, peak time 4000 a. At 20,000 years after the closure of the repository, Cs-135 is the key nuclide, and its peak release rate is 5×10^6 mol/m3, with a peak time of 100,000 a.

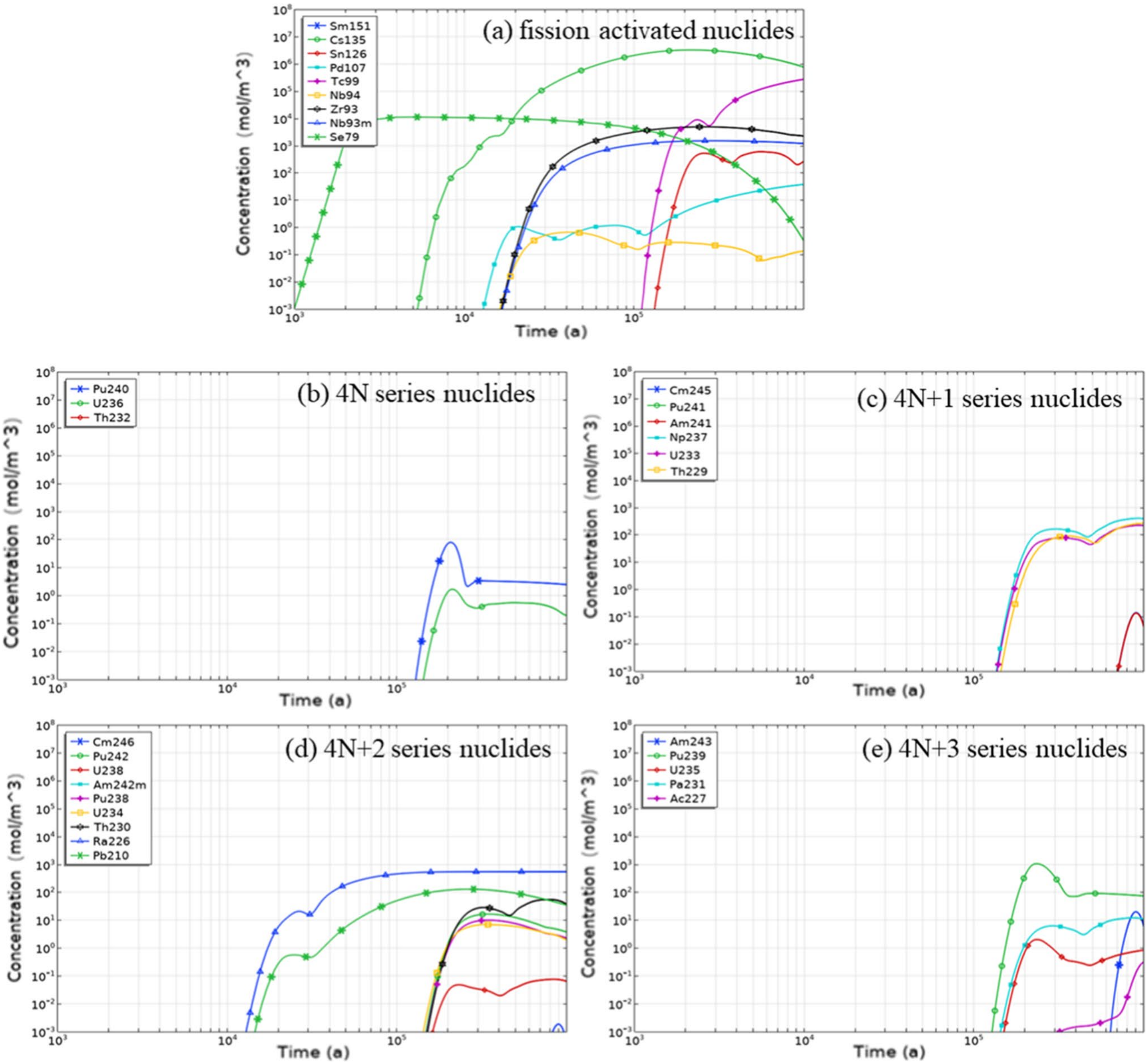

Fig. 8 The release rate in far field of **a** fission activated nuclides; **b** 4N series nuclides; **c** 4N + 1 series nuclides; **d** 4N + 2 series nuclides; **e** 4N + 3 series nuclides

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