Preliminary performance evaluation on multi-barrier system for low-level radwaste

Évaluation des performances préliminaire sur système multi-barrière pour déchets radioactifs de faible activité

Chih-Chieh Lu
Geotechnical division, National Center for Research on Earthquake Engineering, R.O.C., chchllu@ncree.narl.org.tw

Po-Tsung Lin
Low-level Radioactive Waste Disposal Project, Sinotech Engineering Consultants, R.O.C.,

Fuchen Teng
Department of Civil and Construction Engineering, National Taiwan University of Science and Technology, R.O.C.,

ABSTRACT: Multi-barrier system is used in low-level radioactive waste (radwatse) disposal facility to confined and retard the radionuclide for hundreds to thousands of years. To ensure the achievement of safety functions of the disposal facility, safety assessment is always carried out to build public confidence for low level radwaste disposal. A reference low-level radwaste disposal site was selected to demonstrate the safety assessment process suggested by International Atomic Energy Agency (IAEA). The study mainly focused on the evaluation of the biosphere dose rate with various multi-barrier system (MBS) properties. The analyses results of annual effective dose were compared to the regulation limit for general public (i.e. 0.25 mSv/y) to demonstrate the safety of the disposal facility. The sensitivity analyses were conducted to quantify the influences of parameters uncertainty on the safety assessment. The concerned parameters include leaching rate of metal waste, absorption and diffusion effect of multi-barrier. The results shown that the calculated dose rates at all scenarios were below the regulation limit. Variations of dose rates were less than 10^2 for various MBS properties.

RÉSUMÉ : Le système à barrières multiples est utilisé dans les installations d'élimination des déchets radioactifs de faible activité (radwatse) à confiner et retarde le radionucléide pendant des centaines à des milliers d'années. Afin d'assurer la réalisation des fonctions de sûreté de l'installation d'élimination, l'évaluation de la sécurité est toujours effectuée afin de renforcer la confiance du public pour l'élimination des déchets radioactifs à faible niveau. Un site de rejet de déchets de faible activité de référence a été choisi pour démontrer le processus d'évaluation de la sécurité proposé par l'Agence internationale de l'énergie atomique (AIEA). L'étude a principalement porté sur l'évaluation du taux de dose de la biosphère avec diverses propriétés du système multi-barrière (MBS). Les résultats des analyses de la dose efficace annuelle ont été comparés à la limite de réglementation pour le grand public (soit 0,25 mSv / an) pour démontrer la sécurité de l'installation d'élimination. Les analyses de sensibilité ont été effectuées pour quantifier les influences de l'incertitude des paramètres sur l'évaluation de la sécurité. Les paramètres concernés comprennent le taux de lixiviation des déchets métalliques, l'absorption et l'effet de diffusion des barrières multiples. Les résultats ont montré que les taux de dose calculés à tous les scénarios étaient inférieurs à la limite réglementaire. Les variations des débits de dose étaient inférieures à 102 pour diverses propriétés de MBS.

KEYWORDS: Performance evaluation, multi-barrier system, radioactive nuclide migration, annual effective dose, Goldsim.

1 INTRODUCTION

Underground disposal with the concept of multi-barriers is employed for the final disposal of LLRW in Taiwan. The multi-barrier system considered both engineering and natural barriers including solidified waste, container, buffer, backfill, engineering barrier, and host rock, illustrated in Figure 1. The functions of those components are descripted as below:

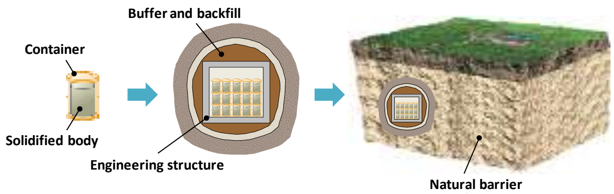

Figure 1. Conception of multi-barrier system

1. Solidified waste: Solidify the waste with a solidification agent to restrict the migration of the nuclides.
2. Container: Isolate the solidified waste from contact with water seepage from the external environment.
3. Engineering barrier: Engineering barrier for accommodating stacked waste containers (such as disposal vaults) shall be capable of isolating the waste containers from the seepage in the external environment.
4. Buffer and backfilling material: Buffer and backfilling materials shall have low permeability and high adsorbability to retard the migration of radioactive nuclide.
5. Natural barrier: Prevent nuclide migration from residential environment with sufficiently long time for the radioactivity of nuclide decaying to harmless levels.

In order to establish confidence of the public, the technique to evaluate the performance of multi-barrier system is a critical issue. A technical evaluation framework for the safety of disposal is summarized in Figure 2. Each technical field should be carefully evaluated and have a good communication with others to ascertain the safety of disposal facility. The study mainly focused on the evaluation of the biosphere dose rate with various multi-barrier system (MBS) properties. A reference low-level radwaste disposal site was selected to demonstrate the performance evaluation process for the MBS suggested by International Atomic Energy Agency (IAEA). The analyses results of annual effective dose were compared to the regulation limit for general public (i.e. 0.25 mSv/y) to demonstrate the safety of the disposal facility. The sensitivity analyses were conducted to quantify the influences of parameters uncertainty on the safety assessment. The concerned parameters studied include leaching rate of metal waste, absorption and diffusion effect of multi-barrier. Note that the other sub-technical fields including inventory of source term as well as site characteristics would be based on assumption.

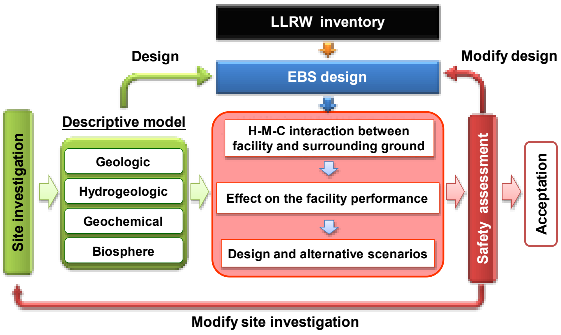

Figure 2. The relationship among LLRW disposal techniques

2 SITE CHARACTERISTICS OF THE EXAMPLE SITE

2 .1 *Geological condition*

The reference site is located on the southeast Taiwan island. The host rock is composed of sandstone, interbedded sandstone and argillite, argillite, mudstone, as well as conglomerates dispersed in various parts. The area is subject to ground stress along the east-west direction, forming a series of north-south anticlinorium structure stretching westwards. Degree of metamorphism increases gradually from the west to the east, forming mildly metamorphic slate or argillite. In this study, the land uplift due to the convergence of the Eurasian plate (EUP) the Philippine Sea plate (PSP) was assumed to have the same rate of erosion, which means that the the topography will not change during the considered evaluation period.

2 .3 *Hydrogeological condition*

The hydrogeological model included argillite zone and potential conductor zone. Ground surface observations revealed dense fracture distribution in the argillite zone. The attitudes of the fractures follow no particular order, and were therefore assumed to be composed of homogeneous permeable porous media. Generally, fracture intensity decreases with depth and hydrogeological parameters change as consequence. This study assumed that the model was composed of 3 hydrogeological units. The potential conductor zone was regarded as area with higher degrees of permeability. Angles for the potential conductor zone were assumed to be 90 degrees. The width, on the other hand, was set to 200 meters of homogeneous materials. Please refer to Table 1 for detailed parameter settings. Besides, this study assumed the climate in the cosidered evaluateion period will be similar to the current state according to prediction of IPCC (2013), and therefore, deduced the constant sea level. Based on above information, the change of the hydrogeological condition was ignored in the analysis, and the numerical mesh as well as flow field simulation results are shown in Figure 3.

Table 1. The parameters for the site scale hydrogeological model

Unit	Layer distribution		K_h(m/d)	K_z(m/d)	Sy	n
Potential conductor zone	1	Ground surface to EL. -600 m	1.5	4.5	0.25	0.30
Argillite zone	1	200m	0.03	0.09	0.30	0.40
	2	200m	0.003	0.009	0.25	0.30
	3	Beyond layer 2 to the depth of EL.-600m	0.00003	0.00003	0.02	0.05

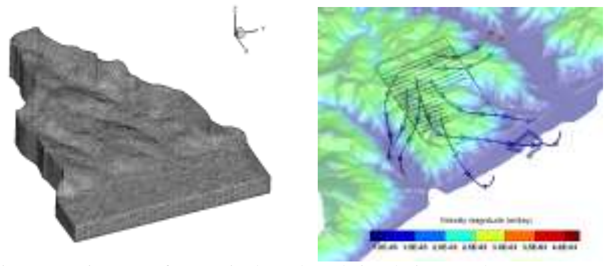
Figure 3. Diagram of numerical mesh and simulation results

2 .4 *Geochemical condition*

Before constructing the disposal facility, the surrounding rocks would be in reduction state. When the disposal tunnel is excavated, atmospheric gas will be introduced into the tunnel and spread out over the surrounding ground, which turns the surrounding ground to oxidation state. Once the disposal facility is backfilled, groundwater flow may re-saturate the surrounding bedrock and make it return reduction state. Given the trends of decreasing sea level, the groundwater system at the reference site should remain as a freshwater system with similar pH values and chemical characteristics.

2 .5 *Biosphere condition*

The studied site is in coastal area, and the possible routes of human ingestion, inhalation, and exposure of radioactive nuclides are shown in Figure 4. Based on the assumption in this study, the climate will not change for 100,000 years after close the disposal facility. Surface ecosystem in the future was therefore expected to be similar to those of the current state.

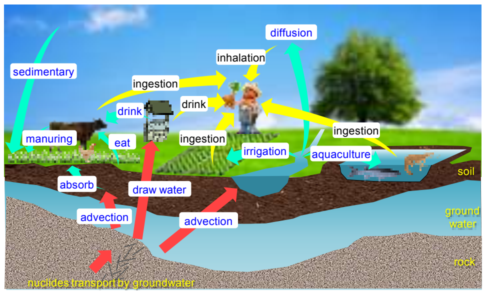

Figure 4. Concept of nuclide migration in coastal ecosystem

3 CONCEPTURAL DESIGN

The conceptual design of disposal facilities should take operational and decommissioning low level radioactive wastes into account, which include class A, class B, class C. This study assumed that the disposal site will receive about 750 thousand 55-gallon drums of low level radioactive waste, which the amount of 75 thousand waste drums is for class B and C, and the amount of 675 thousand is for class A. The designed multi-barrier system considered its long-term safety function of isolation and containment to mitigate the release of nuclide. The layout of the disposal facilities is planed as shown in Figure 5.To engineering barrier design, this conceptual design adopted roughly spherical cross section due to geological conditions of the site and operation demand. The design of multi-barrier system for near field is shown in Figure 6. Since Class B/C LLRW are more radioactive, the designed disposal vault wall is thicker. Also more reliable material of buffer is also deployed to ensure that long-term nuclide transfers within the disposal facility.

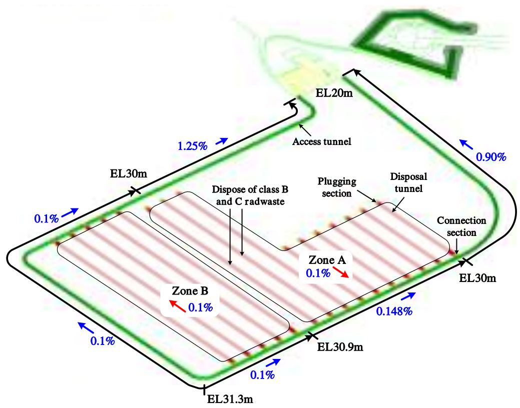

Figure 5. Layout of waste disposal facilities

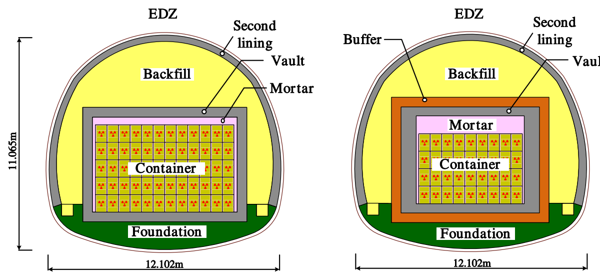

Figure 6. Conceptual design for the engineering barrier system

4 PERFORMANCE ASSESSMENT

Refer to conceptual design, 1D system level conceptual models planned for the reference disposal site are shown in Figure 7. A mathematical analysis model generated by GoldSim according to the aforementioned conceptual model is shown in Figure 8. In the model, dozens of Cell elements are used to simulate diffusion as well as advection mechanism for near field barriers. Pipe elements in document of Far_Field simulate different flow paths from disposal tunnel to biosphere. Some other numerical considerations are introduced below.

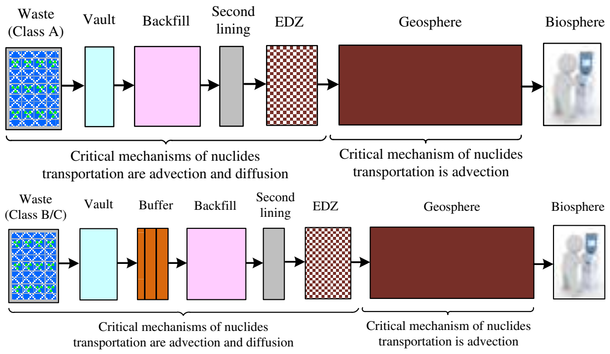

Figure 7. Conceptual model for the nuclide migration

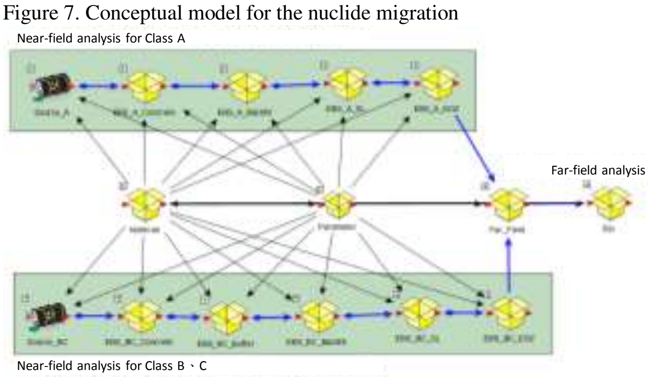

Figure 8. Analysis model of GoldSim

1. Source term consideration

The analyzed unit is one disposal vault, and all wastes in the vault are contained by 55-gallon drum. In the initial stage of analysis, the spaces (pores) between wastes were assumed to be filled with water. The nuclides in non-metallic waste are completely soluble in water. To nuclides in metallic waste, the release rate follows JAEA's suggestion. Legally stipulated nuclides are used for the setting of source term, and the legally stipulated maximum radioactivity of each class waste was adopted for conservative bias, and the considered decay chains are shown in Figure 9.

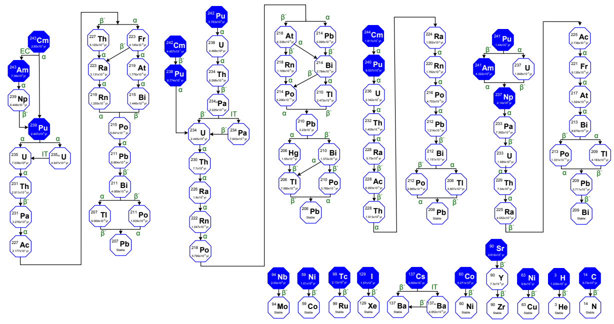

Figure 9. Decay chains of legally specified nuclides

2. Near-field consideration

According to the flow field analysis and current conceptual designs, flux rate per unit length is 0.0133 m^3/m/yr in Class A LLRW disposal tunnels and 0.0046 m^3/m/yr in Class B/C LLRW disposal tunnels prior to engineering barrier deterioration. After deterioration of the engineering barrier, the flux rate in the disposal facilities will increase, thus further accelerating the mechanism of advection. Refer to the approach used in SKB(2014), the study adjusted hydraulic conductivities of the engineering barriers to simply consider the deterioration of EBS. Table 2 shows hydraulic conductivity ratio considered in different periods.

Table 2. Hydraulic conductivity ratio of EBS

Engineering Barrier (Class A)	Time After Closure			
	0 yrs	50 yrs	300 yrs	> 700 yrs
	Hydraulic Conductivity Ratio			
Waste, vault, and backfill	1	1.5	5	10
Secondary lining and EDZ	1	2	8	10
Engineering Barrier (Class B/C)	Time After Closure			
	0 yrs	50 yrs	300 yrs	> 700 yrs
	Hydraulic Conductivity Ratio			
Waste, vault, and buffer	1	1	1.5	2
Backfill	1	1.5	5	10
Secondary lining and EDZ	1	2	8	10

3. Far-field and biosphere consideration

Since the disposal facility covers a large area, the outflow of whole facility may distribute over many catchments and affect the dose calculation of critical population. Therefore, the particle tracking skill is adopted in this research to trace the pathway of each monitoring points. Figure 9 describes the particle tracking points and outflow locations established for this site. The area covered by red dots in the figure shows the flow field toward Daren river. The area covered by green box shows the flow field towards the Pacific Ocean in the eastern side, while the area covered by blue dots shows the flow field towards the Tawa river. Note that this analysis would only consider critical populations at Daren river and Tawa river watersheds. The flow pathes toward the Pacific is not considered due to the less usage of salt water for human and the dilution effect of seawater. Hoever, further analysis may need for clarification purpose. Since the critical populations live in coastal area, the nuclide migration in coastal ecosystem shown in Figure 4 is considered in dose analysis.

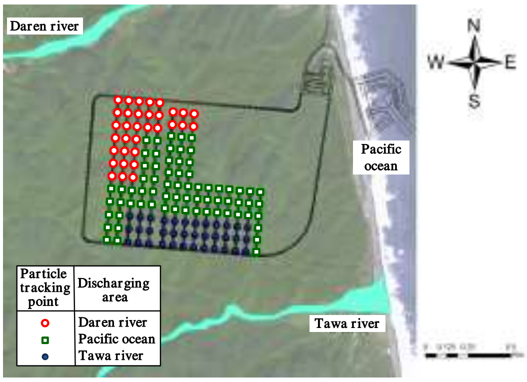

Figure 9. Particle tracking monitoring points and outflow locations

4. Sorption consideration

This study used the simplified linear sorption model to simulate sorption mechanism, and the linear partition coefficient is one of the important factors. To this, the sorption data base provided by JAEA (2013) was used in this study. For long-term considerations, the distribution coefficients of engineering barrier materials may be affected due to the effects of chemical decay (IAEA, 2004). Hence, sorption of engineering barrier is set to drop to 10% of the original value after an analysis timespan of 500 years.

4 .1 *Analysis results of basic scenario*

Figures 10 show the outcomes of dose analysis for various nuclides in Tawa watershed. The results of Daren river watershed are not shown since the critical population in this analysis located on Tawa river watershed. Note that the graph only shows the nuclides with significant doses contribution. Results indicate that annual effective dose per individual is far lower than the required regulation limit (0.25 mSv). For critical population living in the downstream region of Daren river, the peak annual effective dose per individual under this scenario was 0.00026 mSv, occurring 5,130 years after closure of the facility. For critical populations living in the downstream region of Tawa river, the peak annual effective dose per individual under this scenario was 0.001 mSv, occurring 5,470 years after closure of the facility. The critical nuclide considered for these assessments was C-14 in both cases.

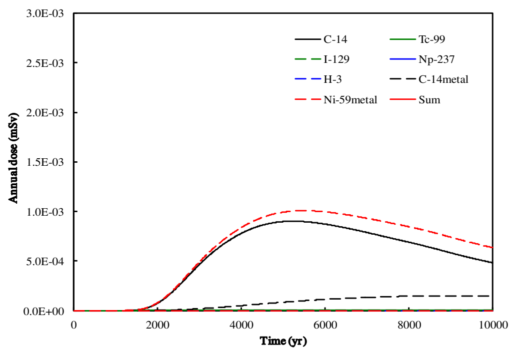

Figure 10. History of annual effective dose per individual in the design scenario (Tawa river watershed)

4 .2 *Parameter sensitivity analysis*

4.2.1 *Leaching rate*

To verify the impact of this parameter, this study assumed situations where nuclide leaching rates from metallic waste were 10 times, 100 times, and 1000 times the original setting and implemented subsequent analysis with the same procedure of the basic scenario. Analyzed results showed positive correlation between peak annual effective dose and diffusion coefficient. When diffusion coefficient was increased to 1,000 times original setting, the peak annual effective dose reached 0.012 mSv, which differed from the results obtained using original settings by about an order of magnitude. The critical nuclide would become $C\text{-}14_{metal}$.

4.2.2 *Distribution coefficient*

The materials' distribution coefficients for this study were based upon literature data, which were assumed to decrease to only 10% of original setting 500 years after closure. In the absence of additional information, conservative principle was adopted to verify the impact of the parameter. Outcomes of the analysis showed that the evaluated maximum annual effective doses of key populations were lower than the legal limit (0.25 mSv). Compared to the original settings, when sorption effect of engineering or natural barriers sorption was excluded, the resulting maximum annual effective dose of key populations increased by 16% to 45% and the peak doses occurring earlier as well. When engineering and natural barriers both lose their sorption effect, the maximum annual effective dose of key populations will increase by about about an order of magnitude. Note that when barrier sorption is excluded, the key nuclide of C-14 is replaced by Am-243.

4.2.3 *Diffusion coefficient*

This study assumed situations where the diffusion coefficient of engineering barriers were 10 times, 100 times, and 1000 times the original setting and implemented subsequent analysis according to the basic scenario. Analytical results show positive correlation between peak annual effective dose and diffusion coefficient. When diffusion coefficient was increased to 1,000 times the original setting, the resulting peak annual effective dose reaches 0.039 mSv, which is one or two orders of magnitude greater than the basic scenario. The occurrence of peak annual effective dose is 1,570 years after close the disposal facility, which is faster than the basic scenario.

5 CONCLUSION

This paper introduced the disposal concept for LLRWD and the framework for integrated techniques. A reference case was introduced to demonstrate the evaluation procedure for the performance of MBS. The analyses results of annual effective dose were compared to the regulation limit for general public (i.e. 0.25 mSv/y) in order to demonstrate the safety of the disposal facility. The sensitivity analyses were conducted to quantify the influences of parameters uncertainty on the safety assessment. The results shown that the calculated dose rates at all scenarios were below the regulation limit. Variations of dose rates due to different MBS conditions were less than 10^2. The proposed proceudre can apply to evaluate the performances of other LLRWD sites. Note that the study focus on the MBS performance evaluation. The consideration for other techniques including site investigation and source terms evaluation is simplified by some assumptions, and these issues are more complex in real case and should also be carefully evaluated.

6 REFERENCES (TNR 8)

IPCC. 2013. *Climate change 2013: the physical science basis: summary for policymakers*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Available at: http://www.ipcc.ch.

JAEA. 2013. *Development of the assessment tool for groundwater scenario concerning sub-surface disposal.* JAEA-Data Code 2013-015.

SKB. 2014. *Flow and transport modelling on the vault scale - Supporting calculations for the safety assessment SR-PSU.* SKB R-14-14, Svensk Kärnbränslehantering AB.