Technical report

Review of Performance Assessment for Engineered Barrier Systems to Support Future RD&D of Radioactive Waste Management in Japan

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Abstract

This paper is a state-of-the-art report on the performance assessment of cementitious and related materials as components of engineered barrier systems for radioactive waste management. In this paper, (1) the concept of safety functions is reviewed as the engineering background of discussion, (2) an overview of the postclosure performance assessment for Belgian low- and intermediate-level short-lived radioactive waste disposal is provided, and (3) a modeling methodology for engineered barrier systems is analyzed using the concept of “mandala for durability mechanics”. According to these works, authors present technical suggestions for technical stakeholders of Japanese low-level radioactive waste disposal.

1. Introduction

In radioactive waste management and disposal, cementitious materials are used as tunnel support, mechanical plugs, backfill materials, buffer materials, and waste form [e.g., NAGRA (2002), ONSRAF/NIRAS (2011) and NUMO (2018)]. In radioactive waste disposal engineering, a fundamental scheme of performance assessment is presented in the safety case by the disposal operators. The safety case comprises the “safety strategy”; “assessment basis”; “evidence, analyses, and arguments”; and “synthesis” (OECD/NEA 2004, 2013a). The safety case includes an assessment strategy and methodology and the collation of a broad range of evidence and arguments [e.g., various scientific studies such as those of Haga et al. (2005), Lothenbach and Wieland (2006), Wieland et al. (2014), Kurumisawa et al. (2017), Yokozeki et al. (2003), Yamada et al. (2006), Nakarai et al. (2006), Lothenbach et al. (2019) and Kinomura and Iida (2020)]. Therefore, the safety case is a key input to support the decision making of stakeholders. The key targets to be assessed in a safety case are presented as “safety functions” such as physical containment, delay as well as spread of release, dilution as well as dispersion, and limited accessibility, [e.g., ONSRAF/NIRAS (2001)].

To learn the essence of safety cases, we review two technical reports supporting the safety case of Belgian low- and intermediate-level waste short-lived (abbreviated as LILW-SL). The documentation reviewed includes the OECD/NEA Peer Review of the Safety Case (OECD/NEA 2012). In this work, the “safety strategy” and “assessment basis” for the disposal systems of some Japanese low-level radioactive wastes (LLW) are discussed. First, safety functions used in this study are defined and their assignments to each barrier design of Japanese LLW are presented. Second, to develop the future RD&D of Japan, this work reviews the postclosure performance assessment of Belgian LILW-SL. Third, by referring to “mandala for durability mechanics” proposed by Sato et al. (2008), new mandala for durability mechanics of a multibarrier system are suggested. Some technical issues related to safety case development and system design improvement in the future are identified. In conclusion, two technical suggestions are presented for technical stakeholders of Japanese LLW disposal.

2. Review of safety functions of multibarrier systems

In the engineering design of radioactive waste facilities, the safety functions are one of the concepts connecting the safety requirements by a regulatory authority and the specific designs developed by a disposal operator. In the IAEA report (IAEA 2011a), five conceptual requirements have been stated for high-level radioactive waste: (1) importance of safety in the process of the development and operation of a disposal facility, (2) containment of radioactive waste, (3) isolation of radioactive waste, (4) multiple safety functions, and (5) passive means for the safety of the disposal facility. According to these requirements, waste classification and multibarrier systems have been developed in each member state. Table 1 and Fig. 1 show the Japanese waste classification and disposal scheme. Japanese LLWs are classified into five groups: L3, L2, L1, TRU, and U. L3 and L2 wastes are set to be managed in near-surface disposal facilities, whereas L1 and TRU wastes are in geological disposal facilities at various depths. In Japan, the disposal scheme...
for U waste has not been determined yet. Belgian LILW-SL waste, whose disposal concept is introduced in the next section, corresponds approximately to the Japanese L3 and L2 wastes [c.f., NEA’s summary for Belgium in 2013 (OECD/NEA 2013b)].

The concept of safety functions is closely related to IAEA requirements 2, 3, and 4 (IAEA 2011a). In Japanese LLW disposal, the long-term containment of waste (IAEA requirement 2) is not considered in the present scheme. Note that “long-term” used here indicates “during post-closure period” (definition of lifetime of a disposal facility is presented in Appendix 1). The RD&D of high-performance waste form and package only for a part of TRU wastes is an ongoing project aimed toward an alternative technology for future use. The long-term safety functions used herein are defined as follows [based on ONDRAF/NIRAS (2010), c.f., Mallants et al. (2008)]:

(1) Delay and attenuation of radionuclide release (function R) involve retaining the contaminants within the disposal facility for as long as required. The four subfunctions are defined as follows:

(i) Limitation of contaminant releases from waste forms (R1, equivalent to IAEA requirement 2),
(ii) Limitation of water flow through the disposal system (R2a),

(ii) Limitation of advection and diffusion through the contaminant retention barriers (R2b), and retardation of contaminant migration (R3).

(2) Isolation (function I) involves isolating the waste from humans and the biosphere for as long as required. Two subfunctions are defined as follows:

(i) Reduction of the likelihood of inadvertent human intrusion and the possible consequences (I1),
(ii) Ensuring stable conditions for the disposed waste and system components (I2).

These safety functions are assigned to the systems, structures and components (SSCs) of a design concept. Since safety functions expected to operate and their performance usually change according to degradation of engineered barriers, engineers who design a disposal facility have to firstly define lifetime of a disposal facility. Here, the lifetime during post-closure period is categorized into four phases [based on ONDRAF/NIRAS (2010), c.f., Jacques et al. (2010)]:

(1) Nuclear regulatory control phase (phase III);
(2) Isolation phase (phase IV): radionuclides are inside waste containers during this phase;
(3) Chemical containment phase (phase V): radionuclides are inside engineered barriers artificially-constructed during this phase;
(4) Retardation phase (phase VI): radionuclides are out-

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**Table 1 Waste classification and type of disposal site in Japan.**

| Category | Waste type | Type of disposal site | Main source of waste generation |
|----------|------------|-----------------------|--------------------------------|
| HLW      | Vitrified waste | Deep geological | Nuclear fuel cycle facilities |
| TRU      | Wastes containing transuranium elements | (will be classified depending on radioactivity) | Nuclear fuel cycle facilities |
| U        | Uranium waste | Intermediate depth geological (cavity type, underground) | Nuclear power plant Research institute, medical and industrial facilities |
| L1       | Low-level waste containing comparatively high radioactivity | Near surface (concrete pit) | (All facilities) |
| L2       | Low-level waste | Near surface (trench) | Recycling use |
| L3       | Very low-level waste | “isolated (strictly controlled) type” or “controlled type” | (All facilities) |

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**Fig. 1 Illustrative summary of Japanese waste disposal scheme.**

※In this figure, “TRU” refers to wastes containing transuranium elements, having relatively high radioactivity and corresponding to deep geological disposal.
In addition, the degree of contribution to performance of SSCs is defined as “attributes” of SSCs to clearly express time-dependent relationship between safety functions and SSCs [based on ONDRAF/NIRAS (2010), c.f., Jacques et al. (2010)]:

1. **Main (attribute M):** the SSC has to fulfill a safety function during a certain period of time. The contribution of this SSC to long-term safety is taken account in the safety scenario. In the case of Belgian LILW-SL disposal, ONDRAF/NIRAS has stated that there is a need to verify performance of the SSC having attribute M.

2. **Support (attribute S):** the SSC will support another SSC to perform a safety function.

3. **Contribute (attribute C):** the SSC has no specific requirement regarding a safety function. However, it will contribute in a “certain extent” to the fulfillment of a safety function. The contribution of this SSC to long-term safety is not taken into account in the safety scenario but it could be taken into account in other scenario and assessment cases.

4. **Not Contribute (attribute NC):** the SSC has no specific requirement regarding a safety function and will not contribute to the fulfillment of a safety function.

When engineers try to assign attributes to SSCs, keep in mind that SSCs should be appropriately classified in accordance with assessment strategy and methodology.

To support the future RD&D of Japan, this work selects two specific designs of a disposal facility. As an example of a near surface disposal facility, the design of the L2 disposal plan for Rokkasho Low Level Disposal Centre (operated by Japan Nuclear Fuel Limited, JNFL) is selected. Rokkasho Low Level Disposal Centre started its operation in 1992 (disposal facility No. 1 and No. 2). Recently, the application for permission to make changes mainly in the installation of an additional facility (No. 3) has just been examined and approved by the Nuclear Regulatory Agency (NRA) of Japan. The design of the L1 disposal plan of The Federation of Electric Power Companies of Japan (FEPC) is chosen as an example of a geological disposal facility. The licensing application for this plan is currently being prepared. Assuming the state just before regulatory release of the site (i.e., at the end of phase III), this work compares disposal designs of the Belgian LILW-SL and Japanese L2 and L1 (Fig. 2). According to the definition of safety functions of the Belgian LILW-SL case, the assignment of the safety functions is presented. Based on previous studies, attributes of the SSCs have been presented with narrowing

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**Fig. 2** Specific designs of (a) Belgian LILW-SL at Dessel, (b) Japanese L2 at Rokkasho, and (c) Japanese L1. The long-term safety functions, which are expected to be operated in “phase III” (at before regulatory release), are assigned herein. L1 disposal site would be gradually released, therefore a state just before construction of mechanical plug of a disposal gallery has been considered here. Parentheses imply that the functions are only partially effective.
down target to the key SSCs: the multilayer cover for Belgian LILW-SL disposal design [Table S1 of Supplementary Materials, according to Mallants et al. (2008) and Jacques et al. (2010)]. The attributes of Japanese L2 and L1 disposal designs will be presented in Section 4, as a summary of this review. The assignments of the Japanese L2 and L1 disposal designs are just examples considered by the authors for comparison with the Belgian case.

The Belgian LILW-SL disposal has a vault-type design and is situated above ground [Fig. 2(a)]. Rainwater deposition is the origin of water infiltrating into cementitious barriers; therefore, performance of the multilayer cover is important in minimizing water percolation into the modules. According to Mallants et al. (2008) and Jacques et al. (2010), classification of components of the multilayer cover and those attributes have been presented (Table S1). The inspection rooms allow the monitoring of the system performance on the basis of humidity measurements, sampling of drainage fluids, and observation of cracking. The Japanese L2 disposal has a vault-type design, but it is situated underground and beneath the water table [Fig. 2(b)]. With the installation of the multilayer cover (upper, lower, and low-permeability layers) and placement of the disposal site within the bedrock, the concern is water infiltration from the bedrock instead of rainwater deposition. To address chemical degradation due to the adjacent cementitious materials, an additional low-permeability cover is set to be installed between the lower cover and the cementitious partition facility. The initial water permeability of the low-permeability cover is designed to be low enough relative to that of the bedrock (Takahoko Formation) and the adjacent lower cover. In the case of the Japanese L1 disposal [Fig. 2(c)], the repository site is a horizontal cavity type ("rock cavern", c.f., SKB (2011)) and is located underground (depth > 70 m). The waste is surrounded by bentonite-cement composites, and the long-term safety function of R2b (and/or R2a) is assigned. In contrast to near-surface disposal concepts, the groundwater flow system around the geological disposal site is usually complicated. At this point in Japan, the geological disposal site is undecided, we should select a conservative groundwater flow model and allocate a large safety margin to the site depth. Nonetheless, to strengthen the safety argument and ensure "defense in depth" [c.f., IAEA's SSR-5 (IAEA 2011b)], degradation modeling and performance assessment as faithful as possible are even important from an engineering aspect.

To compare the engineered barrier system designs for Belgian LILW-SL and Japanese LLW (L2 and L1), this study has defined the safety functions used in the Belgian LILW-SL case and has assigned to the Japanese L2 and L1 cases, as described above. In the next section, the assessment workflow for the Belgian LILW-SL disposal concept is introduced as a point of comparison with the Japanese L2 and L1 disposal concepts.

3. Overview of assessment workflow of the Belgian LILW-SL disposal concept

In 2011, ONDRAF/NIRAS (the Belgian National Agency for Radioactive Waste and Enriched Fissile Material) submitted a safety case in preparation for the application for the construction and operation of a near-surface repository at Dessel. The Belgian Federal Public Service of Economy and Energy requested the NEA to organize a peer review of the key aspects of the safety case. The review results have been presented in the OECD/NEA report (OECD/NEA 2012). The international review team was asked to consider the agreement of the safety case international best practices in the following areas: (1) long-term safety strategy; (2) proposed disposal system design; (3) quality of scientific and technical bases for safety assessment, particularly in the area of concrete phenomenology; and (4) long-term safety assessment methodology as well as results. The long-term phenomenological behavior of concrete was highlighted as an important issue in the safety case. In the current work, two technical reports assessing cement degradation and sorption performance to support the safety case are selected and their workflows are reviewed as useful references for the future development of a safety case of Japanese radwaste disposal.

One of the technical reports reviewed herein is that by Jacques et al. (2009), which is focused on the assessment of cement degradation in the LILW-SL disposal at Dessel. The workflow of Jacques et al. (2009) is shown in Fig. 3(a). Correspondence with the safety case is expressed by symbols [A-#, B-#, C, and D, Fig. S2 of Supplementary Materials and background colors (light orange, pale blue, and pale green)]. The work begins by describing the barrier system concepts, presented as a bluish text box labeled as “W1. (B-I System concepts).” The system concepts of Belgian LILW-SL at Dessel are reviewed in the former chapter [Fig. 2(a)]. Subsequently, the approach of the assessment is described and is presented as a light orange rectangle labeled as “W2. (A-3 Assessment strategy).” To simulate the chemical degradation of concrete barriers (focused on modules), this work separately models the (1) (micro)biological and geochemical weathering processes in multilayer cover (external factors for the modules) and (2) geochemical degradation processes in concrete (internal factors for the modules). The outlines are presented in W3–6 and W8 and W9. The details of the methodology and outcomes are reviewed in the next section. The main outcomes of the report of Jacques et al. (2009) are indicated in the light green rectangle (W7 and W10).

The other technical report reviewed herein is Wang et al. (2009), which provides an assessment of the sorption properties of cementitious barriers. [Fig. 3(b)] illustrates the workflow. In the case of the sorption properties of cementitious barriers, the understanding and knowledge of radionuclide sorption on cementitious materials are not comprehensive enough for a thorough discussion.
Therefore, the establishment of a scientific basis is a good starting point for discussion. The main objective is to quantify safety function $R_3$ and its long-term evolution. In line with this objective, six scientific issues have been raised as follows: (1) degradation mechanisms and evolution of cementitious engineered barrier components, (2) treatment of Kd as a function of time in view of alteration of phases, (3) treatment of Kd as a function of cement composition; (4) geochemical evolutionary path, (5) impact of organic compounds and their potential degradation products on radionuclide behavior, and (6) impact of other potentially perturbing components. Issues (1) and (4) were addressed by Jacques et al. (2009), and they correspond to $W_5$ in Fig. 3(b). Based on the outcomes, a database of sorption values is established and three technical assessments are presented as follows [$W_7$ in Fig. 3(b)]: radionuclide and chemical inventories; redox conditions; and degradation as well as impact of organic compounds. As a result, benchmark Kd values are suggested [$W_{10}$ in Fig. 3(b)], reported in detail by Fig. 3(a) Workflow of Jacques et al. (2009).
Compared with the assessment works of the Belgian LILW-SL case, technical works would have not adequately reported on a phenomenological interpretation of elementary processes of barrier system degradation (e.g., volumetric change, water infiltration mechanism, chemical interaction mechanism, and reaction kinetics) and/or estimation of the site-specific parameters required to assess barrier performance in Japan (e.g., variation of groundwater composition, climatological conditions such as temperature, humidity, solar radiation, rain water and fallen snow amount, rain water composition, and so on). The state-of-the-art performance assessment of the Japanese LLW disposal is expected to be introduced elsewhere (e.g., previous research programmes towards the Japanese LLW disposal are reviewed by a Research Task Force “Application of cement and concrete technology to industrial and radioactive waste management” of Japan Concrete Institute). In the next section, the modeling methodology of the Belgian case is analyzed by applying the concept of “mandala for durability mechanics”.

### 4. Analysis of modeling methodology in accordance with the concept of “mandala for durability mechanics”

Before exploring analysis of modeling methodology, this work introduces the concept of “mandala” in durability mechanics. The concept of durability mechanics was originally proposed by Coussy and Ulm (2001) as a transdisciplinary science. Durability mechanics comprises three types of studies as follows: (1) kinetics of degradation reactions; (2) coupled chemical and physical modeling from the viewpoint of material sciences; and (3) preventive maintenance, diagnosis, and future as-

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**Fig. 3(b) Workflow of Wang et al. (2009).**

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essment. To express the concept of durability mechanics, Sato et al. (2008) suggested a “mandala for durability mechanics”, which represents the governing equations and complex relationships among materials, potentials, space, and time. Their approach is useful for scientists and engineers to describe the time-dependent behaviour of multiscale concrete system (from material to structure), and it can be extended to other composite materials used in Civil engineering, Geosystem engineering and so on. Herein, inspired from the study by Sato et al. (2008), drafts of mandala for engineered barrier system describing modeling methodology of the Belgian LILW-SL and Japanese L2 and L1 disposal systems are newly presented, and the remaining technical issues are discussed.

Drafts of mandala of engineered barrier systems are drawn in Figs. 4, 5, and 6. The format focusing mainly on reaction modeling is shown in Fig. S3 of Supplementary Materials. The right side of the mandala (white background) denotes the coordinate system and the focused degradation factor(s) of the targeted barrier(s). For multiscale modeling, the focused material is analyzed from various engineering aspects. At the bottom of the coordinate system, the general classification of water chemistry is presented as water infiltration is a major factor of degradation of barrier materials in disposal sites. The left

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**Fig. 4(a) Draft of mandala of the barrier system of the Belgian LILW-SL design prepared by the authors on the basis of the work of Jacques et al. (2009).**
side of the mandala (black background) denotes the technical information that is essential in model development and demonstration. In the mandalas for Japanese L2 and L1, future works to be addressed are also indicated.

Figure 4(a) shows the mandala for the Belgian LILW-SL disposal. The interactions in the multilayer cover and the modules are modeled via two approaches. In the multilayer cover, the geo(bio)chemical interaction is modeled according to a single-layer simple mass balance approach (coupling of chemical and transport processes, as a simplification). The model formulations are shown in Fig. 4(b). The chemical composition of water infiltrating into the modules, $X_{\text{inflow}}$, is the unknown parameter. $X_{\text{outflow}}$ indicates the supply from rainwater, and is equal to $X_{\text{wetdep}}$. $X_{\text{sink}}$ and $X_{\text{source}}$ are the parameters depending on weathering reactions in the soil and clay layers. These required data are based on the knowledge of environmental assessment in Europe. Eight main cases (three water types: rain, soil, and clay) are calculated. The outputs are shown in Table S2 of Supplementary Materials. These outputs are used as input parameters for the modeling of the modules. Figure 4(c) shows the modeling flow of the modules. The flow comprises two models (the decoupling of the chemical and transport processes): batch reaction model (in order to determine degradation state boundaries) and one-dimensional transport model (in order to determine alteration front velocities). Based on several preliminary considerations, such as those of Jacques (2009), a properly simplified methodology for batch chemical modeling is selected [see also Fig. 4(a), e.g., Fe$_2$O$_3$-free reaction system (no effect in pH evolution) and ideal solid solution between ettringite and tricarboaluminate (with

**Static mass balance model of the multilayer cover**

- Mass balance of an element $X$ in a given soil volume,

$$X_{\text{outflow}} = X_{\text{inflow}} - X_{\text{sink}} + X_{\text{source}},$$

- Charge balance in water leached from the soil volume,

$$\begin{align*}
&= 2(SO_4^{2-}) + (Cl^-) + (NO_3^-) + (HCO_3^-) + 2(CO_3^{2-}) + (OH^-) + (RCOO^-) \\
&\text{"(X)" means "concentration of X in moles per 1 kg of water (= molality), here.}
\end{align*}$$

- The concentration of leached water from the soil,

$$X_{\text{soilwater}} = X_{\text{outflow}} / P^*$$

- The inflow of an element at the top of the soil is only by wet deposition in the rainwater,

$$X_{\text{inflow}} = X_{\text{wetdep}} = (X)_{\text{rainwater}} P^*$$

- Additional assumptions for the specific elements,

Cl, S: constant at leaching process, $X_{\text{outflow}} = X_{\text{inflow}} = X_{\text{wetdep}}$;
base cations (Na; K; Ca; Mg), Al: affected by weathering, $X_{\text{outflow}} = X_{\text{wetdep}} + X_{\text{weathering}}$;
$X_{\text{weathering}}$ was defined as a function of texture class and parent material class;
N: affected by nitrogen cycle in soil, organic matters and atmosphere, $X_{\text{outflow}} = N_{\text{wetdep}} - N_{\text{denitrification}}$.

- Required input parameters,

$X_{\text{wetdep}}$: the total yearly deposition;
$P^*$: the yearly amount of water leaving the soil;
$BC_{\text{weathering}}$: the yearly weathering amount of base cations (= BC), and the distribution on the mineral phase;
$A_{\text{weather}}$: the yearly Al weathering amount;
$N_{\text{immobilization}}$: the yearly N immobilization in soil organic matter;
$N_{\text{denitrification}}$: the yearly N denitrification to the atmosphere;
P$_{\text{CO2}}$: partial pressure of CO$_2$ in the soil air (buffered by microbial activity).

**Note 1:** [M/L/T] means “yearly total moles of a leaching element per unit area of a soil layer”, here.

**Note 2:** [L/T] means “yearly total depth of water per unit area of a soil layer”, here.

Fig. 4(b) Summary of modeling methodology of Jacques et al. (2009) for the multilayer cover of the Belgian LILW-SL concept at Dessel.
only minor effects on sulfur concentration and initial amounts of hydrates). As the result of such thermodynamic simulation, the aqueous and mineral compositions of cementitious barriers are quantitatively modeled depending on the cumulative amount of leached water [Fig. S4(a) in Supplementary Materials]. Under the assumption of homogeneous concrete with constant porosity, one-dimensional (reactive) transport calculation can be performed. The calculation provides the velocities of the alteration front [Fig. S4(b) in Supplementary Materials]. Sensitivity due to infiltrating water composition and porosity is considered and reported as part of the revised manuscript [for the purpose of facilitating knowledge management, the control numbers given by ONDRAF/NIRAS are assigned as follows: NIROND-TR 2008-24E for Jacques et al. (2009), and NIROND-TR 2008-24E Version 2 for the revised manuscript written by Jacques and Mallants (2011)].

In the Japanese L2 design [Fig. 2(b)], the potential pathways of water infiltration would be through (1) part of the multilayer cover and roof or wall of the partition facility and (2) floor of the partition facility, during regulatory control phase (phase III, probably 300-400 years in Japan). Overview of the infiltration paths is presented in Fig. S5(a) of Supplementary Materials. There are three infiltration paths: rainwater infiltration through the multilayer cover (Case-1); groundwater infiltration through part of the multilayer cover (Case-2); groundwater infiltration through floor of the partition facility (Case-3). The coordinate system and related technical information for the path of Case-1 are described in Fig. 5(a), assuming an approach similar to that by Jacques et al. (2009). As shown in Fig. 4(b), Jacques et al. (2009) has developed a static mass balance model of the multilayer cover. This model development is strongly supported by the study of Jacques et al. (2010), who assessed the water redistribution processes in the multilayer cover, chemical composition of the multilayer cover and gradual degradation processes under the site-specific climate. Such assessment work with replacing the assessment target to the multilayer cover of the Japanese L2 design will quantitatively give important

**Soil-type (case 3) and clay-type (case 5) water infiltration**

**Reaction model of concrete-water interaction**

Consider a total of $N_c$ species in the system with $N_s$ master species and $N_t$ ($=N_c - N_s$) secondary species.

- **Mass balance of $N_s$ species,**
  
  \[ \frac{\partial M_i}{\partial t} = m_{H2O} \left( c_i + \sum_{j=1}^{N_s} v_{ij}c_j \right) \]

  $M_i$: the mass of the $i$th primary species ($i=1, ..., N_s$);
  $m_{H2O}$: the mass of water; $c_i$: the concentration of the $i$th primary species; $v_{ij}$: the stoichiometric coefficient of the $i$th primary species for the $j$th secondary species.

- **Mass balance of $N_t$ species,**
  
  \[ c_j = \frac{K_j}{R_j} \prod_{i} (y_{ij}c_i)^{\nu_{ij}} \]

  $K_j$: the mass action constant of the $j$th secondary species (at constant $P$ and $T$); $y_{ij}$: the activity coefficient of the $j$th secondary species.

- **Solution: the Newton-Raphson technique**

**1-D (reactive-)transport model of the modules**

Under the simplification for facilitating discussion (assuming the constant porosity during degradation),

- **Advection-reaction-dispersion equation,**

  \[ \frac{\partial C}{\partial t} = -\nu \frac{\partial C}{\partial x} + D_v \frac{\partial^2 C}{\partial x^2} - \frac{\partial q}{\partial t} \]

  Discretized grid of 0.1 m; $\nu$: $1.06 \times 10^{-8}$ (m/s), assumed by general drainage flux of a sandy loam soil; $D_v$: $D_v = D_a + a_d \nu$, $a_d$: 0 (m), $D_a$: $1 \times 10^{-10}$ (m²/s);
  $\frac{\partial q}{\partial t}$: mass balance of dissolution/precipitation.

Fig. 4(c) Summary of modeling methodology of Jacques et al. (2009) for the modules of the Belgian LILW-SL concept at Dessel.
technical information for assessment of concrete degradation, i.e., chemical compositions of water infiltrating into the concrete barrier. As shown in Fig. 5(b), mandala for the other two potential paths (Case-2 and -3) can be described. In these cases, degradation of the concrete barrier during post-closure period would be caused by groundwater infiltration. On the other hand, the degradation due to rainwater (including snowfall-origin water) infiltration during operational period seems to be still concerned [see Fig. 5(c)] because there is no roof for the concrete barrier before the multilayer cover installation in current JNFL’s design [according to JNFL (2020), c.f., a steel roof covering the entire disposal facility is designed in the latest plan of Belgian LILW-SL disposal, see Fig. S5(d) of Supplementary Materials]. Assessment assuming this situation would be important to review engineering design of the concrete barriers from the viewpoint of durability mechanics. As a summary of this analysis, SSCs classification and assignment of attributes of safety function are overviewed in Table 2 (see also Section 2, definition of safety functions and attributes).

In examination meetings of application for permission on the L2 disposal facilities of JNFL (meeting materials, video and minutes are disclosed only in Japanese at the website of NRA of Japan), assessment approach putting emphasis on hydraulic aspects seems to have been applied. An outline of the approach could be summarized as below. Based on the meeting materials [e.g., those of 334th Review Meeting held by NRA of Japan (JNFL 2020)], JNFL seems to consider that the transport property of bentonite is dependent on microstructures by reference to Ito and Mihara (2005) and JAEA-FEPC (2005). With this model, the chemical degradation of bentonite because of the attack of alkaline (high pH)
Table 2: The SSCs classification of the multilayer cover and concrete barrier of Japanese L2, during operational period. If we follow the Belgian case, the components from 2.1 to 2.4 can be called as “module”.

| Near surface disposal of Japanese L2                                                                 | R2a  |
|----------------------------------------------------------------------------------------------------|------|
| Components                                                                                         | Phase I | II |
| (Phase I = before installation of the multilayer cover)                                             |       |   |
| 1. Multilayer cover                                                                               |       |   |
| 1.1 Upper cover                                                                                   | M     |   |
| 1.2 Lower cover                                                                                   | M     |   |
| 1.3 Low-permeability cover                                                                         | M     |   |
| 2. Concrete barrier                                                                               |       |   |
| 2.1 Roof of partition facility                                                                     | M     |   |
| 2.2 Wall of partition facility                                                                     | C     |   |
| 2.3 Floor of partition facility                                                                   | C     |   |
| 2.4 Permeable layer (including sampling pipe & inspection room)                                    |       |   |
| 2.5 Filler                                                                                         | S or M|   |

* M: Main, S: Support, C: Contribute

Fig. 5(b) Draft of mandala of partial barrier system of the Japanese L2 design, for postclosure period. The chemistry of the groundwater infiltration process is overviewed.
Note 1: “B” means “total amount of binders (= cement + mineral admixtures)”. For Note 1, the discretized grid is not clearly shown (indicated as “??”) in JNFL (2020).

For Note 2, the detailed formulations on water permeability $k$ and dissolution rate of montmorillonite are indicated in Ito and Mihara (2005) (omitted for space considerations).

Fig. 5(c) Draft of mandala of partial barrier system of the Japanese L2 design, for operational period. The chemistry of the rainwater infiltration process during operational period is overviewed.
solutions from cementitious materials is often numerically observed [e.g., Yamada et al. (2006)]. Based on numerical observation, time dependence of water permeability of the low-permeability cover would be estimated. Assuming at 1,000 year later from postclosure (long enough relative to the regulatory period), JNFL seems to propose settings of permeability required to conduct a two-dimensional steady groundwater flow analysis. Various patterns of setting are investigated, and as a result, JNFL seems to assess that water infiltration from the bedrock into the repository for at least 1,000 years is through the floors of the partition facility, as far as authors could see the meeting materials. This JNFL’s approach can be shown as e.g., Fig. 5(d) by authors. Note that JNFL (and NRA of Japan) seems to have recognized necessity of the other approach such as described in the previous paragraph [i.e., Figs 5(a), 5(b) and 5(c)] because there are many discussion records about countermeasures against rainwater infiltration during operational period, surveillance of drainage and maintenance plan of the partition facility. Authors expect that technical reports on outcomes of the examination meetings are published by the interested party, in the near future.

In a geological disposal concept (c.f., near-surface disposal), hydraulic assessment of water infiltration pathway is hard to conduct due to complex hydrological environment. Assessment methodology assuming after siting situation of Japanese L1 disposal mostly hasn’t been developed so far. Inspired from the analysis of Japanese L2 disposal, mandalas for durability mechanics of the engineered barrier are depicted by authors in Figs. 6(a) and 6(b). The coordinates and technical notes of selected SSCs are indicated. Figure 6(a) shows a part of barrier system around bedrock around an underground cavity. From geochemical aspects, the bedrock would be altered by oxidizing conditions. In addition, the near-field bedrock would be mechanically damaged by ground-pressure release. When assuming the assessment approach is similar to vault-type repositories (the Belgian LILW-SL and the Japanese L2), we can suggest some works for future safety assessment, for example, scientific study on chemical degradation process of the EDZ, as well as monitoring of the underground cavity, etc. Using some reference sites for a sedimentary rock environment in Japan, these works have been already done and/or ongoing, e.g., Chigira and Oyama (1999), Oyama and Chigira (1999) and the work at the Radioactive Waste Management Funding and Research Centre of Japan (RWMC 2014). In the geochemical approach for performance assessment, the safety function of R2a is regarded as important. Figure 6(b) shows mandala of the backfill and the composite barrier. Geochemical degradation of backfill would be important as a degradation factor of the bentonite barrier.

Under this approach, the priority of the material design of cementitious barriers can be presented as follows:

The main target to be assessed is the limitation of water infiltration through a chemical containment barrier. In this context, groundwater flow around the waste (groundwater flow in “near-field” and “chemical containment field”) is important. Therefore, the transport of water in the barrier system should be assessed. In accordance with this approach, the bentonite layer is regarded as a buffer material (“hydraulic buffer”). In this case, the material design of cementitious materials is optimized so as not to be harmful against the bentonite layer, while achieving the safety functions required at construction and operation phases in operational period (for the definition of “period” and “phases,” see Appendix 1 and Fig. S4 in Supplementary Materials).

On the other hand, we can propose the other approach attaching more importance to the safety function of R2b, i.e., chemical containment performance of the barrier system. For example, a Belgian design concept for spent fuel and vitrified waste (Belgian supercontainer concept) has been proposed according to this approach. In the concept, material design of the cementitious barriers can be determined as a following consideration:

The goal of this concept is to maximize the duration of the physical confinement of contaminants (it depends primarily on the performance of metallic overpack; see also Appendix 2 and Fig. S5 in Supplementary Materials). In this context, the required role of the buffer material is to provide a favorable chemical environment to delays overpack degradation. Therefore, cementitious materials (e.g., the cementitious layer, the pit, and the filler) serves as a buffer material (“chemical buffer”). In this case, the material design of cementitious materials can be optimized according to the safety function of “support of metallic overpack performance” (i.e., safety function of cementitious materials can be assigned to R1 having attribute of S for R1 of waste container, in the case of L1 design). Note that this approach is just on the assumption of designed R1 of waste container (it could be expected to some extent, even if the container would not be designed to have the special corrosion-resistance for long-term).

As a summary of this analysis, SSCs classification and assignment of attributes of the safety functions are overviewed in Table 3. Further discussion (possibly an improvement of design and/or concept suitable for Japan) based on the decision of the operator of the Japanese L1 disposal is expected in the near future.

Conclusions

Compared to the Belgian LILW-SL, there is room for improvement in performance assessment of Japanese LLW disposal from the viewpoint of safety cases. For technical stakeholders of Japan (e.g., JNFL, FEPC, NRA etc.), we present two suggestions on the categories of (1) design strategy and (2) assessment strategy, here. First, analysis of the design concepts should be re-considered to follow international good practices. Authors have introduced definition of safety functions and their attributes as well as SSCs classification of the Belgian
LILW-SL, and demonstration of the design analysis has been presented on Japanese L2 and L1 disposal concepts. In future examination meetings of a radioactive waste disposal facility, authors expect that the design will be classified as SSCs and assignments of the safety functions and the attributes will be presented by every technical stakeholder. Such works are only just an entrance of safety cases, but must lead smooth and constructive

![Fig. 6 Drafts of mandala of partial barrier system of the Japanese L1 design: (a) The chemistry of the groundwater infiltration process is overviewed. (b) The geochemical degradation process of the composite barrier is overviewed.](image-url)
discussions between technical stakeholders as well as fruitful reviews by experts. Second, selection and validation of assessment approach should be considered in each technical stakeholder and be discussed between technical stakeholders. In this paper, current modeling methodology has been analyzed according to the concept of mandala for durability mechanics. Inspired from the study by Sato et al. (2008) and the review of the assessment work by Jacques et al. (2009), new mandalas for durability mechanics of engineered barrier systems have been proposed. Based on analysis using the new mandalas, two types of assessment approach for engineered barrier systems have been re-recognized: assessment approach giving priority to (1) safety function (and also (1), consequently). In consideration of the degree of the RD&D achievement at the time of each assessment, technical stakeholders have to discuss which approaches to be valid for safety argument.

Although it has been excluded in this review, the monitoring technology is an important factor in the context of safety cases. In the Belgian case, the prediction of service life based on a combined approach of numerical modeling and in-situ monitoring has been suggested as an assessment strategy by ONDRAF/NIRAS. This approach has been highly evaluated and encouraged by the International Review Team of NEA. The modeling and monitoring parameters are designed on the basis of the “durability indicators” developed by Baroghel-Bouny (2006) and Baroghel-Bouny et al. (2006). Note that the indicators suggested by Baroghel-Bouny (2006) are targeted at reinforced concrete. In Japanese industrial communities of infrastructural concrete, energetic RD&D for performance-based design has continued for a few decades, and fundamental knowledge of and technology for in-situ monitoring for service life prediction have been established [e.g., Shimomura (2011), Nakarai et al. (2019) and Frenzer et al. (2021)]. The following controversial problems remain for the in-situ monitoring of cementitious engineered barriers: (1) the functions of engineered barriers are not compromised in the course of monitoring as prerequisites established by IAEA (IAEA 2014); (2) following the prerequisites, what should be done and what should be monitored; and (3) the duration of the monitoring. These problems have been considered in Japan [e.g., focused on intermediate-depth geological disposal, as reported by RWMC (RWMC 2019)]. Internationally, good reviews have been reported about state-of-the-art RD&D of monitoring, especially for deep geological disposal, e.g., the final reports of the collaborative research project of “MoDeRn” from 2009 to 2013 and the subsequent project MoDeRn 2020. In Japan, the RD&D of monitoring technology is ongoing at, for example, Horonobe Underground Research Centre of JAEA and Low-Level Radioactive Waste Disposal Centre of JNFL. Future reporting is expected.

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| Component | R1 | R2a | R2b | R3 |
|-----------|----|-----|-----|----|
| 1. Bedrock (near-field) | III−IV | III | IV | V | VI |
| 1.1 Pristine (not damaged) zone | C | S | | | |
| 1.2 Excavation damaged zone (EDZ) | | | | C |
| 2. Disposal gallery | | | | |
| 2.1 Gallery support | C | C | | |
| 2.2 Backfill (top) | S | C | | |
| 2.3 Backfill (side, bottom) | S | C | | |
| 3. Bentonite-cement composite barrier | | | | |
| 3.1 Bentonite layer (low-permeability) | S or C | M | M | C | C | C |
| 3.2 Cementitious layer (low-diffusivity) | S | C | C | S or C |
| 3.3 Concrete pit | S | C | C | S or C |
| 3.4 Filler | S | C | C | S or C |
| 4. Waste | | | | |
| 4.1 Steel container | M | C | NC |
| 4.2 Waste matrix (Waste form) | C | | S or C |

M: Main, S: Support, C: Contribute, NC: Not Contribute
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Appendix 1 Definition of lifetime of a disposal facility

In the ONDRAF/NIRAS’ safety report in November 2011, the lifetime of a disposal facility defined by a Belgian regulatory authority (FANC, the Belgian Federal Agency for Nuclear Control), is used. The overview is presented in Fig. S1. This classification basically depends on license differences. The lifetime is divided mainly into two periods: “operational period” and “postclosure period.” Each period is further classified into several phases. The operational period is divided into construction phase, operation phase and closure phase, while the postclosure period includes the nuclear regulatory control phase and after (not defined). This definition has been prescribed as a Royal Decree of Belgium.

Appendix 2 Belgian “supercontainer” design

The Belgian supercontainer design is one of the reference designs for vitrified waste and spent fuel (heat-emitting waste) considered in the European community, as explained, for example, in the works of Bel et al. (2006) and Poyet (2008). The overview is presented in Fig. S6. Through the installation of a massive concrete layer consisting of ordinary Portland cement (OPC) around a watertight carbon steel overpack, the near-field environment can be buffered at a high pH condition. Under this condition, a low uniform corrosion rate can be guaranteed from an engineering aspect in the absence of aggressive species. That is, the long-term physical containment of radionuclides can be expected. The merit of this design has been discussed, e.g., Van Geet and Weetjens (2012). The detailed scientific information is accessible at the web site of the Belgian Nuclear Center (SCK-CEN 2021).

Supplementary Materials