PRELIMINARY STUDY OF POST-CLOSURE SAFETY ASSESSMENT IN THE NUMO SAFETY CASE

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Abstract

NUMO has developed a generic safety case for the geological disposal in Japan. This safety case provides the multiple lines of arguments and evidences to demonstrate the feasibility and the safety of the geological disposal, which will encourage stakeholder confidence in the safe implementation of geological disposal and will provide a basic structure for a safety case which will be applicable to any potential site. The key distinguishing features of the safety assessment are "application of the risk-informed approach", "scenario development with comprehensiveness, traceability and transparency", and "realistic radionuclide migration model reflecting the repository design". For the purpose of optimization of protection, the disaggregated approach, as one of risk-informed approaches, which makes it possible to evaluate a potential impact of a future event and its probability separately, is applied as a frame of the safety assessment. Developed scenarios are classified into 4 categories on the basis of their probabilities; "Likely scenario", "Less likely scenario", "Very unlikely scenario" and "Human intrusion scenario". The methodology of the scenario development results from a desire to combine a bottom-up what is called FEP-based approach and a top-down method based on the safety functions, appropriate to risk-informed assessment. The scenarios considered to be "likely" are developed to be as realistic as possible, representing comprehensive current understanding of relevant FEPs in terms of extent and rate of impact on radionuclide containment and eventual release and transport. The methodology consisting of overall procedure and associated toolkits is aiming to increase traceability and transparency. For a rational repository design, it is important that the assessment model can show the difference of the performance among candidate designs, such as the panel layout and the disposal galleries. Then NUMO's model is based on the 3D particle tracking method which can effectively describes the radionuclide migration behavior reflecting the repository design.

1. Introduction

The results from R&D carried out over 20 years was integrated into a generic safety case for the geological disposal in Japan and published in the H12 report[1] in 1999 in order to demonstrate the generic feasibility of geological disposal of high-level radioactive waste (HLW) in Japan. This provided the technical basis to formulate the Final Disposal Act, which established the Nuclear Waste Management Organization in Japan (NUMO) as the implementer of geological disposal of specified waste. A generic study on safe geological disposal for intermediate-level waste generated from reprocessing of spent nuclear fuel and mixed–oxide fuel fabrication (termed TRU waste in Japan) was also issued in 2007 (TRU-2 report[2]) and the Act was amended to include TRU waste in the NUMO geological disposal program.

NUMO has been promoting a stepwise siting process based on a volunteering approach[3] and, in parallel, carrying out an intensive R&D program focusing on technical issues identified from H12 and TRU-2 in order to increase both the technical reliability and also public confidence in the safety of geological disposal. As no volunteer site has yet appeared, such R&D has been conducted without reference to any specific candidate site or host rock type. Taking into account the progress in scientific and technical knowledge resulting from this R&D, NUMO is now developing an updated generic safety case (NUMO-SC) that builds on H12 and TRU-2 to demonstrate technical feasibility and safety of geological disposal in Japan on the basis of state-of-the-art scientific knowledge and identify important future R&D issues.

In line with the international manner (e.g. IAEA[4] and OECD/NEA[5]), the general purpose and context of the NUMO safety case is explicitly specified in terms of the background outlined above and the progress to date in defining required post-closure performance goals. The potential settings for a volunteer geological disposal project in Japan also set key boundary conditions, requiring a safety strategy that includes realistic assessment of pre- and post-closure safety to allow both comparison of sites and also possible repository concepts that could be tailored to them[6,7,8].

The geological environments of a range of potential candidate sites are represented as site descriptive models (SDMs), which have been developed as realistically as possible based on recent progress in geosciences and site characterization technology[7]. Appropriate repository concepts are then developed by tailoring them to such siting environments on the basis of a comprehensive set of Design Factors, as described in Goto et al[8].

This paper focuses on the approach and methodology for scenario development and radionuclide migration modelling in the NUMO-SC.

2. Risk informed approach

Safety regulations for geological disposal have yet to be formulated in Japan. Safety criteria and other relevant requirements for safety assessment have therefore been assumed based on international standards.

Although it is impossible to precisely predict the future, estimates of doses and/or risks over very long time periods can be derived for bounding future evolution scenarios within a performance assessment and compared with appropriate criteria to support the post-closure safety. Referring to international standards and guidelines, it has been recommended that the likelihood of such scenarios should be determined (qualitatively and/or quantitatively) and incorporated into the assessment by either an aggregated or disaggregated approach[4,9]. These recommendations have already been reflected in safety regulations in some countries (e.g. Germany[10], the UK[11] and Sweden[12, 13]).

Referring to “the Commission considers that although a similar level of protection can be achieved by these two approaches, more information may be obtained to reach risk-informed decisions from separate consideration of the probability of occurrence of a particular situation giving rise to a dose, and the resulting dose.” in ICRP Pub.122[9], which recommends the regulatory framework of the geological disposal, the disaggregated approach is applied to the safety assessment of NUMO-SC.

To define scenario categories and target doses for geological disposal, the following assumptions were made:

- The depth for geological disposal largely mitigates the effects of natural processes and human activities relevant to near surface and sub-surface disposal;
- Perturbing natural events (extreme events) which could cause significant degradation on the safety functions of repository system should be effectively excluded by the stepwise siting process;
- The residual probability of extreme events that cannot be precluded by siting is regarded as very low, even over the long-term.

The scenario categories and target doses are defined as follows:

- “likely scenario”: 10 μSv/y
- “less-likely scenario”: 300 μSv/y
- “very unlikely scenario”: 20 - 100 mSv for the first year, 1 -20 mSv/y after the first year.
- “human intrusion scenario”: 20 - 100 mSv for the first year, 1 -20 mSv/y after the first year.

3. Scenario development methodology

In the late nineties, scenario development was often described as a bottom-up process[14], whereby scenarios were developed in essence from FEP databases. Nowadays, it is recognized that, in practice, the approaches actually adopted are better described as top-down or "hybrid", taking as their starting-point an integrated (top-down) understanding of the system under consideration, including uncertainties in the initial state[5]. A bottom-up element remains to the extent that FEP databases or FEP catalogues are still used, but the focus is generally on checking completeness, which occurs parallel to the main assessment process. Based on this perspective, NUMO has developed a hybrid methodology, combining top-down (approach using safety functions) and bottom-up (FEP-based approach) approaches in a complementary manner (Fig. 1).

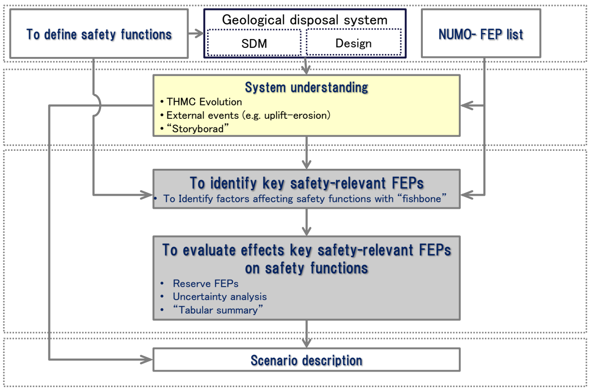

Figure 1 Overview of scenario development

The evolution of safety functions and the interaction between them is developed based on the system understanding which is closely linked to the site and the design. It is described with “storyboard” in NUMO-SC to understand the evolution of the geological disposal system. The safety functions have the role of identifying the key safety-relevant processes/phenomena.

In addition, in parallel with the top-down approach, a comprehensive and NUMO FEP catalogue is derived from referencing generic FEP lists provided by OECD/NEA[15], taking account of other FEP activities such as Japan Atomic Energy Agency FEPs

(JAEA[16, 17]) and geological disposal repository in the NUMO-SC.

The relationship between the safety functions and key relevant FEPs which could perturb such properties of the safety functions can be presented thought "state variable", which defines the state of the safety function on "fishbone diagram" (Fig. 2). As a result, FEPs that need to be considered can explicitly be selected for classifying and checking completeness of scenarios and extracting the key safety-relevant uncertainties.

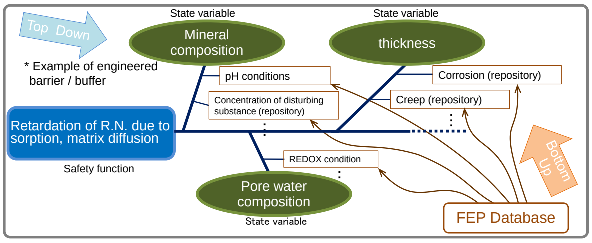

Figure 2 Structure of fishbone diagram

Each fishbone diagram is associated with a summary of knowledge-base consisting of descriptions of phenomenological understanding of the FEPs that could drive system evolution and uncertainties together with handling them through the scenario analysis. An example for a part of buffered safety function ("Retardation of nuclide migration by sorption") is shown in Table 1 which is called "tabular summary". The uncertainty and probability of scenarios are also discussed in the analysis to classify scenarios into defined categories based on the best current understanding of the FEPs and uncertainties summarized as in Table 1. The likely scenario consists of most probable evolutions of safety functions, leading to be realistic.

In addition to the hybrid approach which ensures the completeness and comprehensiveness, the recording materials, such as fishbone diagram and tabular summary, make it possible to ensure traceability and transparency.

Table 1 Tabular summary of the issues associated with buffer performance

State variable	Reference FEP	Knowledge about the effects	Uncertainties to be considered	Definition of handling through the scenario analysis
Mineralization	pH condition (repository)	When the pH rises, secondary minerals such as iron hydroxide and CSH gel increase. The pH and secondary minerals react commutatively.	• Although there is an uncertainty in the change of mineral composition, it is shown by the analysis that the gap clogging by the secondary mineral localizes the affected area to the boundary. • It is shown by the analysis that, even if the gap clogging is not caused, the change of most buffer materials requires 10 thousand years or more.	For the likely and less-likely scenarios, parameters are set in consideration of the impact variation range.
	Redox condition (repository)	Under the oxidizing atmosphere reducing agents such as pyrite oxidizes and the mineral composition changes.	• It is shown by the analysis that migration of the oxidation-reduction front by the alpha radiolysis is suppressed by the reaction with the reducing agent, such as pyrite in the buffer material. • The time of migration is limited after the overpack opening even if the occurrence is assumed.	The change of redox condition resulting from the waste body radiation and the oxidizing groundwater penetration from the outside are not dealt with by the likely and less-likely scenarios.
	perturbing species' concentration (repository)	For the co-disposal, the high pH plume originated from the TRU disposal facility reaches to likely cause a deterioration by dissolution or secondary-mineral precipitation. (Refer to FEP sheet "3.2.4.1-H pH condition (repository)")	The impact can be disregarded by sufficient separation of the HLW and TRU facilities in the case of co-disposal.	It is not dealt with by the likely and less-likely scenarios.
	corrosion (repository)	The Fe ion produced by receptacle corrosion causes phenomena, such as ion exchange of the bentonite, dissolution of the montmorillonite and secondary-mineral precipitation, to change the mineral composition. But, the composition change is localized by clogging of the gap between the bentonite and overpack.	• The analysis shows that the gap clogging at the iron-bentonite boundary limits the affecting area and that the change from the initial mineral composition in the region of most buffer materials is small. • The time when the possibility of a tychopotamic loss due to the buffer-material change by the iron impact cannot be denied thoroughly is after tens of thousands years (based on the quantitative ratio of the iron cumulative supply by the receptacle corrosion and the buffer material).	For the likely and less-likely scenarios, parameters are set in consideration of the impact variation range.

4. Realistic radionuclide migration modeling reflecting the repository

It has been assumed to be important for dose calculation that groundwater is media for radionuclide migration because of its relatively higher probability. Therefore, its assessment, which is required more realistically than any other, is focused on in this report.

4.1. Approach of safety assessment

Taking account of both geometry and size of components of the geological repository, the migration regions from the waste to biosphere are divided into 4 regions; near-field scale, repository scale, regional scale and biosphere (Fig. 3). The smaller scale is provided boundary conditions from the larger scale and gives calculated radionuclide flux at its boundary to the larger. In case of regional scale and biosphere, their boundary conditions are based on nationwide information in Japan.

As the near-field scale targeting more safety functions than others requires more realistic assessment, it is focused on in this report.

4.2. Radionuclide migration model

NUMO has developed a three-dimensional "PARTRIDGE" (Particle tracking in deep geological environment)[18] that allows random-walk simulation of nuclide transport in a spatially-heterogeneous flow field. This is intended to evaluate differences among repository design options and host rock characteristics.

PARTRIDGE consists of a groundwater flow module and a mass transport module. The groundwater flow module can deal with a deterministically-defined high permeability zone such as a fault, a statistical discrete fracture network and also engineered structures, including access tunnels and the EBS (Fig. 4). These are expressed as an equivalent heterogeneous hydraulic conductivity tensor, using the Crack Tensor method and numerically solved by using FEMWATER code[18]. The Darcy velocity obtained from FEMWATER is distributed among the fractures and rock matrix (in case of hard rock, flow in the matrix is assumed to be zero). Thereafter, the pore velocity in fractures is evaluated and used in the nuclide transport analysis.

Based on the groundwater flow analysis, 3-D mass transport from the individual waste packages is analyzed by the random-walk method considering advection, dispersion and matrix diffusion in the mass transport analysis module. Transport of nuclides is simulated by an instantaneous pulse source of particles (Fig. 4).

PARTRIDGE is a powerful tool to realistically describe the radionuclide migration behavior. However, it is unsuitable for a large number of radionuclide migration calculations at present, because the calculation cost is too huge and improvements are required to handle chemical reactions and radioactive decay.

Therefore, 1D multi-channel migration model is adopted for dose calculations as well as H12 and TRU-2. However, unlike fracture features observed at the bore hole surface were directly used for developing channels in those previous reports, fracture connectivity and geometries of artificial components are reflected on model using 3D particle tracking with non-sorbing particle as follows;

- Calculation of particle flux ($\phi_{3D}(t)$) at 100 m downstream from the gallery
- Approximation of $\phi_{3D}(t)$ by transmissibility coefficient ($T_{NFi}(t)$) and weighting factor W_i of each channel the channels of the host rock.

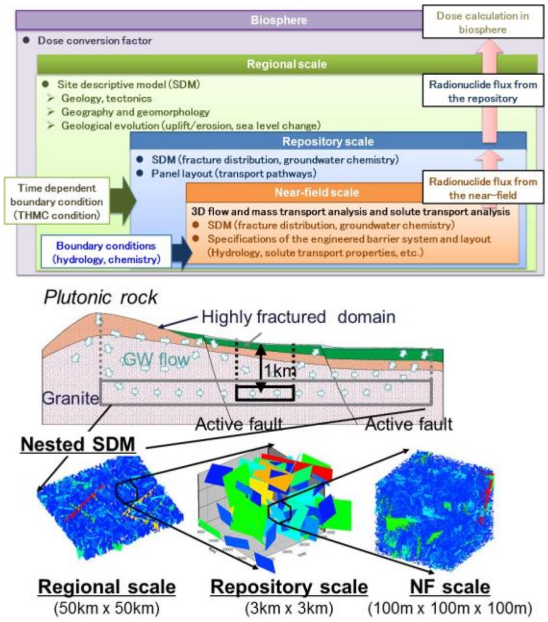

Figure 3 Relationship between 4 regions

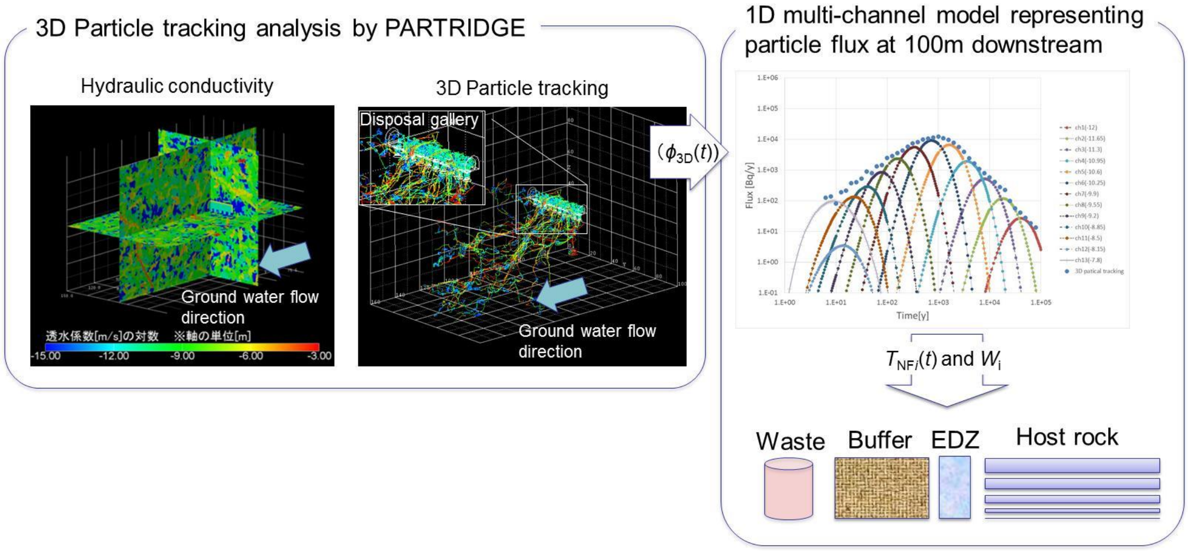

Figure 4 Framework of development of migration modeling

4.2. Migration parameter value setting

Several reactive transport analyses and thermal conductivity analyses have been conducted at the scenario development stage to understand the system evolutions, such as bentonite alteration, concrete structure alteration and thermal environment change around the wastes (Fig.5). "Solubilities", "K_ds" and

"D_es", are defined also using results from those analyses.

"Solubilities" are derived from pore water chemistry in HLW buffer and TRU mortar infilling material from thermodynamic calculations. To define the pore water of the HLW system, ion exchange reaction of montmorillonite, acid-base reactions of hydroxyl groups on montmorillonite surface, dissolution and precipitation reaction of accompanying minerals and reactions of iron corrosion products are taken into account. The Na-bentonite will persist for a long time on the basis of mass balance arguments, leading to chemical condition of the pore water can be defined as constant through the assessment time. In contrast, in the TRU system, the chemical condition is defined to evolve from Region I to Region II as alkali components are leached from the filler (mortar).

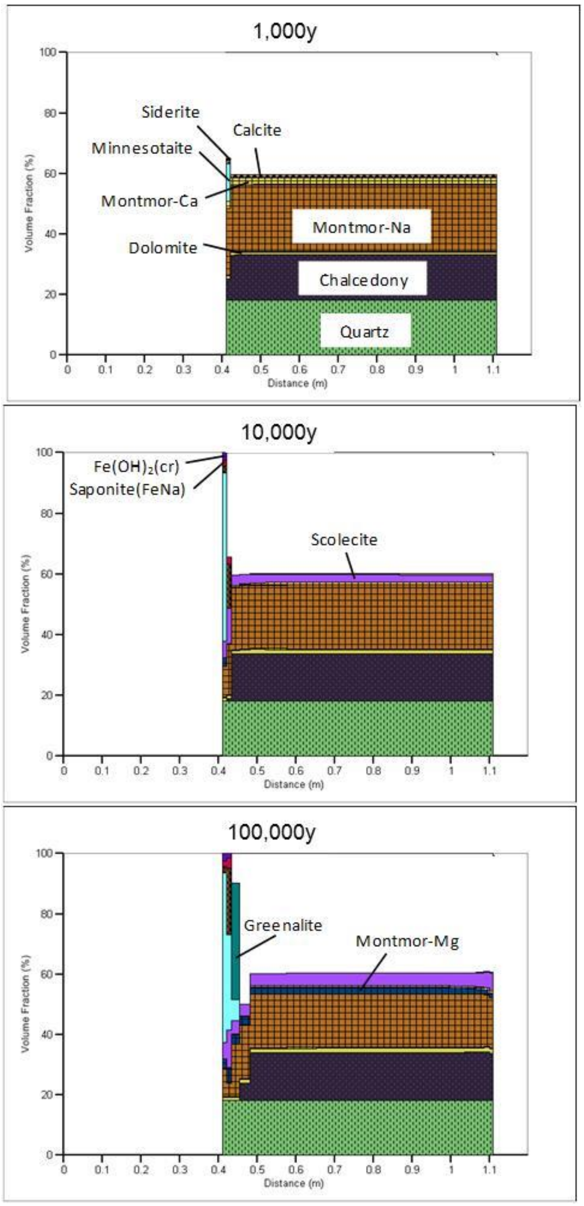

Figure 5 Bentonite alteration due to iron-bentonite interaction.

Assuming thermodynamic equilibrium and solubility established by pure solid phases, the solubility of relevant elements can be calculated. Important uncertainties associated with such solubilities include lack of empirical data of thermal effects and kinetics. For thermal effects, solublities using data-set at 25°C are adopted at thermal conditions (30°C or 45°C) at each repository depth because almost thermodynamic data have empirically been obtained at the room temperature (25°C) and the difference between 25°C and 45°C can be assumed not to be significant[19]. For kinetics, solubilities are conservatively assessed assuming control by amorphous phases for many elements in the likely scenario; in real life these would gradually age to more crystalline forms with associated reduction in solubility.

"K_ds" for bentonite are defined by approximation of results from diffusion experiment using of compacted bentonite by the modified Fickian approach because batch experiments can't realistically describe the radionuclide sorption behavior in the compacted bentonite. While "K_ds" for host rocks are logarithmic mean values of data around the groundwater conditions in JAEA-SDB(Sorption Database)[20]. Uncertainty relevant to thermal condition is expected to be significant because of reasons similar to "solubilities".

"D_es" of nuclides measured in the buffer vary depend on their electric charge and the bentonite density. The charge of each element is set based on the dominant chemical species obtained as a result of thermodynamic equilibrium calculation with the pore water. Neutral ion, cationic ion and anionic ion have been reported to be dependent on the ionic strength and montmorillonite density[21]."D_e" for host rock has also been reported to depend on electric charged states of elements and porosity of host rock. "D_es" for specified conditions are derived from empirical equations based on measured data in the JAEA-DDB (Diffusion Database)[22]. Since "D_e" is well known to have temperature dependency, correction is made according to the expected temperature at each repository depth (30°C or 45°C).

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