NUMO is developing a generic safety case for geological disposal of high-level radioactive waste and low and intermediate level waste generated from reprocessing and MOX fabrication (named TRU waste in Japan). The safety case updates previous safety cases published in the H12 and TRU-2 reports by taking into account the progress of scientific and technical knowledge as a result of intensive R&D, led by NUMO, that focused on increasing technical reliability and confidence. While the main safety functions of the repository are intrinsic to its design and location within a deep geological system (also discussed in supporting papers submitted to this Conference), understanding the level of robustness of the proposed concept under specific geological conditions, or relevant changes of such conditions, can be evaluated only through long-term performance assessment. The assessment methodology should thus be able to evaluate the safety functions in a rigorous manner and quantify the level of robustness in a transparent and well-structured safety case.

I. INTRODUCTION

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

NUMO has been promoting a stepwise siting process based on a volunteering approach (Ref 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 the technical reliability and 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 and host rock type. Taking into account the progress in scientific and technical knowledge resulting from the R&D, NUMO is developing an updated generic safety case that builds on H12 and TRU-2 as preparation for the site selection process.

According to the internationally accepted modern safety case concept (e.g. IAEA and OECD/NEA, Refs 4, 5), the general purpose and context of the NUMO safety case which includes the overall framework for implementing the geological disposal project and its boundary conditions, safety strategy focusing on both pre- and post-closure safety, and key elements of modeling geological environments for potential candidate sites and repository concepts tailored to the geological environments are discussed in the supporting papers submitted to this Conference (Refs 6, 7, 8).

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

In this paper, the approach and methodology of post-closure safety assessment in NUMO’s safety case is presented following the discussion of the supporting papers on geological environments and repository concept for potential candidate sites.

II. FRAMEWORK OF POST-CLOSURE SAFETY ASSESSMENT

The safety assessment used for developing the NUMO safety case is not carried out on a specific site in Japan as noted above. Rather, a range of hypothetical SDMs representative of typical sites and repository concepts tailored to those siting environments have been developed. The safety assessment should be carried out for the repository system taking into account specific features of
a given SDM and corresponding repository concept. In this regard, safety assessment models and databases should be as realistic as possible.

Safety regulation for geological disposal has yet to be formulated in Japan. Safety criteria and other relevant requirements for safety assessment have therefore been assumed based on international standards and guidelines as well as recent national discussions on safety regulations.

In this section, the basic framework is defined to set up boundary conditions for the safety assessment.

II.A. SAFETY CRITERIA AND ASSESSMENT APPROACH

In general, estimates of doses and/or risks for very long time periods can be made and compared with appropriate criteria to provide an indication of ensuring post-closure safety. Referring to international standards and guidelines, it has been recommended that the likelihood of safety assessment scenarios should be identified qualitatively and/or quantitatively, and taken into the assessment according to either an aggregated or disaggregated approach (Refs. 9, 10). These recommendations have been reflected in safety regulations in some countries (e.g. Refs. 11, 12).

The Nuclear Safety Commission of Japan (NSC, now Nuclear Regulatory Authority (NRA)) discussed common important aspects for regulating post-closure safety of waste disposal (Ref 13) including application of a risk-informed approach. The NSC published then guidelines in 2010 on the regulation for disposal of low-level radioactive waste (LLW) containing comparatively high-level of beta- and gamma-emitting radionuclides (Ref 14).

The guidelines are based on a risk-informed approach in which dose and probability are treated in a disaggregated manner. Assessment scenarios related to natural events and processes have been classified based on their probability into three categories: “likely”, “less-likely” and “very unlikely”. As Japan is situated in a tectonically active region, particular concern is paid to those scenarios on potential future impacts of volcanic and fault activities depending on their probability of occurrence, even though the areas where known significant impacts from volcanism and faulting on the repository system are excluded in the siting process. Scenarios relevant to “human intrusion” are classified as an independent category and treated based on a stylized approach. A set of target doses have been defined to each scenario category taking into account ICRP 2007 recommendation (Ref.15) and required safety levels in other countries (Ref.16). The basic concept in NSC’s guidelines is similar to that applied in ICRP (Ref.17).

Although the safety guidelines for waste disposal are being reformulated by the NRA in the course of establishing a new safety regulatory system after the Great East Japan Earthquake and Fukushima-Daiichi NPP accident, the concept of a risk-informed approach defined in the previous NSC guidelines provides an appropriate basis for the safety assessment in the current NUMO safety case.

While defining 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 surface and sub-surface disposal, and human related activities;
- Unexpected natural events (extreme events), which could have significant effects to the safety functions of repository system, are basically excluded by the stepwise siting process;
- The probability of occurrence extreme events is regarded as very low, even over the long-term.

The scenario categories and target doses are defined as follows in the current safety assessment:

- “likely scenario”: 10 $\mu$Sv/y
- “less-likely scenario”: 300 $\mu$Sv/y
- “very unlikely scenario”: 1 - 20 mSv/y, 20 - 100 mSv
- “human intrusion scenario”:
  - 1 - 20 mSv/y to those around the site
  - 20 - 100 mSv to intruder

For the dose values represented as a range, an appropriate value is selected depending on selection of scenarios and representative persons within the category. It should also be noted that up-lift/erosion is treated as a regional and continuous process and identified as a “likely scenario”.

II.B. THE ASSESSMENT TIMESCALES

Referring to the guideline recommended by international organizations on timescale,

- It might be considered necessary to extend the time frame to ensure that the maximum or peak dose is covered within the assessment calculations (SSG-23, IAEA/Ref.4).
- However, it is recognized that for timescales over several thousand years, calculations based on reference scenario assumptions (e.g. reference biospheres (SSG-14 IAEA/Ref.18)) are sufficient for handling the uncertainty in the evolution of future conditions of the geosphere, biosphere and natural characteristics of the disposal system.
- It is also noted that potential impacts beyond the period of quantitative assessments should be addressed in an appropriate manner in the safety case (SSG-23, IAEA).
Countries, such as Sweden, USA, Switzerland and Germany have defined around one million years after closure as a timeframe of quantitative assessment for licensing.

Taking the above into consideration, timescales for the safety assessment for the NUMO safety case at the current stage is defined as follows:

- Although “the timeframe for meaningful quantitative assessment from the scientific view” might depend on the geological condition at specific sites, dose calculation is carried out for one million years after closure following identification of scenario categories and target doses discussed in section II.A;
- Beyond the period of meaningful quantitative assessment, qualitative assessment and/or assessment applying complementary safety/ performance indicators are also conducted.

II.C. REPOSITORY SYSTEM

Repository concept options of vertical emplacement and PEM horizontal emplacement for HLW and vault emplacement for TRU waste described in the repository design and engineering study for NUMO’s safety case (Ref. 8) was first selected along with an SDM for fractured media. The repository systems based on the selected SDM and repository concepts are also considered as an example for safety assessment (see Fig. 1)

II.D. APPROACH TO DEVELOPE AN ASSESSMENT METHODOLOGY

Demonstrating a practical methodology and procedure for implementing a safety assessment that is applicable for future specific candidate site(s) is one of the purposes of the NUMO safety case at this stage. For this purpose, a methodology to conduct realistic and detailed safety assessment is required to appropriately represent specific features of repository systems and their evolution over the long-term. The scenario development methodology is especially important so that comprehensive and consistent scenario sets could be provided with their probability for each category defined in section II.A. Taking into account new findings obtained e.g. at off-site underground research laboratories at Mizunami and Horonobe in Japan, enhanced methodologies and new data for evaluating long-term behavior of materials used for the engineered barrier system, and improved mass transport and related models for analysis are under development.

The following sections describe NUMO’s safety assessment methodology presented in this paper in detail.

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III. SCENARIO DEVELOPMENT

III.A. METHODOLOGY

Scenarios for the safety assessment are being developed according to scenario categorization based on a risk-informed approach as mentioned in section II.A. The scenario development methodology has been provided applying a top-down and bottom-up hybrid approach in which definition of safety functions expected in the repository system is the starting point and then followed by the analysis of impacts of relevant events/processes on safety functions. The overall framework of the methodology is shown in Fig. 2.
Fig. 2 Overview of the methodology for scenario development (Ref.19, partly modified)

- Basic Concepts
- Safety functions
- Late time of function
- Define safety functions
- Identify attributes of each safety function
- Describe and classify scenarios
- Description of the scenarios
- Likely, Less-Likely, Other
- Formulate and application of models and data for PA
- Run safety analysis

Fig. 3 Safety functions for different timescales (NB: safety functions are defined for vertical emplacement disposal concept)

Expected safety functions are summarized in Fig. 3 for the vertical disposal concept as an example (see Fig. 1), which are derived from the two basic functions of isolation and containment. The FEPs relevant to each safety function are then selected from the project specific FEP databases for the impact analysis.

NUMO has been developing a project specific FEP database for a given repository system referencing generic FEP lists provided by OECD/NEA (Ref.20) and Japan Atomic Energy Agency (JAEA, Refs.21,22). The relationship between project specific FEPs are also identified and included in the databases.

The impact analysis is carried out taking the repository system evolution in terms of thermal (T), hydrological (H), mechanical (M) and chemical (C) conditions into account. For the analysis, quantitative models have been developed (see sections IIIb and IV).

Based on the arguments in the impact analysis, system evolution focusing on safety functions are described using a scenario story board method (Refs. 23,24,25) to construct scenarios for the safety assessment. Fig. 4 shows an example of a story board. The uncertainty and probability of scenarios are also discussed in the analysis to classify scenarios into defined categories.

The story board methodology is a useful tool for not only guiding scenario development so that it captures state-of-the-art scientific and technical knowledge from a range of technical disciplines, but also for providing a communication interface to various stakeholder groups of experts in different disciplines.

Fig. 4 An example of scenario story board (Ref.26, partly modified)
III.B. NEAR FIELD SCENARIOS

The evolution of the near field of the repository system is derived by modelling THMC coupled processes in order to define scenario categories as illustrated in Fig.5.

Fig.5 The process for scenario development and classification of the near-field is based on quantitative T-C coupled models (Ref. 24, partly modified)

III.C. EVOLUTION OF THE GEOLOGICAL ENVIRONMENTS

When discussing geological disposal in Japan, it is necessary to consider the specific geological conditions of the archipelago, which is located in a tectonically active zone. As a result, Japan has a high frequency of earthquakes, fault movement and volcanic activity. Showing that such natural phenomena will not affect the safety of the geological disposal system is an essential element in demonstrating the technical reliability of disposal (e.g. Ref.1). Placing focus on such geological perturbations is indispensable to develop a robust safety case for geological disposal in Japan.

Regarding the evolution of geological environment, the likelihood of occurrence of relevant natural processes and events are in principle qualitatively argued based on expert opinion and classified into defined categories. Table I shows an example of the qualitative judgmental process of natural events.

These processes and events are further evaluated clearly to identify their effects on the safety functions taking the evolution of the repository system into account. At the same time, the probability of occurrence of the processes and events are discussed depending on the time when they occur to provide a basis for scenario classification.

Table I Classification of natural processes and events into scenario categories

<table>
<thead>
<tr>
<th>Category and type of Natural event</th>
<th>Natural event example in the FEP list</th>
<th>Scenario category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous natural events and processes cannot be avoided by site selection.</td>
<td>· Uplift and erosion, · Subsidence and sedimentation, · Sea level change, · Diagenesis · Metamorphism, and others</td>
<td>Likely scenario or Less-likely scenario</td>
</tr>
<tr>
<td>High frequency natural events and processes cannot be avoided by site selection.</td>
<td>· Seismic activity, and others</td>
<td>Likely scenario or Less-likely scenario</td>
</tr>
<tr>
<td>Events and processes that are unexpected over the assessment period; possible to avoid such events and processes.</td>
<td>· Volcanic activity, · Fault movement, and others</td>
<td>Less-likely scenario or Very unlikely scenario</td>
</tr>
</tbody>
</table>

The ITM (International Tectonics Meetings: Ref.27) methodology has been developed to support the judgmental process by using probabilistic based techniques to evaluate the likelihood and scale of future tectonic processes and events, shown as a function of their type and geographical distribution. Information on these potential likelihoods and impacts will be fed into NUMO’s performance assessment team so that feedback can be provided on repository performance under the given tectonic setting (Ref. 26).

The ITM methodology has been extended to different time scales for up to one million years for site scale (~ a few square km area) and termed the TOPAZ (Tectonics of Preliminary Assessment Zones) methodology (Ref. 26). The procedure of TOPAZ methodology is illustrated in Fig.6.

The main steps of the TOPAZ methodology involve the development of alternative conceptual models characterizing how the tectonic setting of a region might develop in future and attaching expert’s degrees of belief to these alternative ‘Regional Evolution Scenarios’ (RES), using a formal expert elicitation methodology. These, in turn, are used to develop ‘Site Evolution Scenarios’ (SES), which describe how an RES might ‘play out’ at a specific location within the region being evaluated. SESs have been identified for each of three time periods which has been set as time frames in the scenario story board as shown in Fig. 4. Each RES might generate one or more SESs.

Impact Scenarios (ISs) are then defined for each SES, identifying how specific impacts of relevance to the safety case might evolve or occur in response to each SES. This is facilitated if the safety assessment analysts are able to specify events and processes that may be of concern or interest for them to analyze (i.e. omitting those of little significance to the performance of the repository). For instance, an IS might be formation of a new volcano at the
site, leading to occurrence of a volcanic event greater than a certain magnitude, or evolution of a fracture system to an active fault generating displacement greater than a certain magnitude. The expert elicitation (EE) approach is used to assign quantitative degrees of belief (weights) to each SES and IS. This process is integrated in a logic tree as presented in Fig. 6.

Case studies have been carried out for Kyusyu and Tohoku regions by applying the TOPAZ methodology to provide a hazard map.

It is considered that probabilistic approaches are fundamental to any evaluation of tectonic hazards to long-term repository safety in Japan. The Fukushima disaster has highlighted graphically how, even on a much shorter-term basis, the use of multiple geoscientific data sets and probabilistic techniques is necessary to characterize hazards to facilities for quantitative risk assessments.

Although the regulatory approach to geological disposal is still under consideration in Japan, it would be vital to be able to present estimates of event likelihood when discussing hazards and potential health impacts of a repository. These may be in the form of actual risk estimates (as used in the regulatory guidelines and requirements for geological disposal in several countries), or in the form of disaggregated estimates of radiation doses and their likelihoods. Whichever direction regulatory development takes, it will be necessary to present hazard potential and uncertainty estimates clearly to various audiences in a probabilistic as well as a deterministic sense. The ITM-TOPAZ methodology will be an effective tool for doing this.

II.D. SETTING SAFETY ASSESSMENT EVALUATION CASES

Cases for the assessment calculation are then defined for each scenario category by setting assumptions that can cover all impacts of relevant processes and events. Depending on intensity of the impact on safety functions and possibility of occurrence, some processes and events might be excluded from the calculation cases.

The calculation cases have been defined along with the three different timeframes in which the evolution of repository system can be well characterized.

For the time frame for 0 – 1,000 years after closure, physical containment of the overpack is basically ensured and the evolution of engineered barriers, in terms of thermal and chemical conditions expected at a repository near field is of particular concern for carrying out a quantitative evaluation. Less likely or very unlikely scenarios of early loss of containment by the overpack followed by radionuclide release would be calculation case for this period. The likelihood of large earthquake could also be taken into consideration for this period.

After this time frame, the likelihood of extreme natural events would increase. The TOPAZ project has identified nine impact scenarios for which calculation cases are to be defined as shown in Table II (Ref.28).

Fig. 6 Main steps of the TOPAZ methodology and an example of a hazard map on volcanic activity and uplift (Tohoku region case) (Refs.28, 29 partly modified)

Table II Possible aggregation of impact scenarios, with associated issues regarding performance assessment analyses. (Ref.28)

<table>
<thead>
<tr>
<th>Impact Scenario</th>
<th>No future volcanic event</th>
<th>Volcanic event no interaction into repository</th>
<th>Volcanic event interaction into repository</th>
</tr>
</thead>
<tbody>
<tr>
<td>No new feeding</td>
<td>No uplift to near-surface</td>
<td>IS-1 Reference Case</td>
<td>IS-5</td>
</tr>
<tr>
<td>Uplift to near-surface</td>
<td>IS-2 Combined IS-3 and IS-6 analyses</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Partnership</td>
<td>IS-4 Combined IS-3 and IS-6 analyses</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Impacts scenarios are defined for different timeframes and classified into three scenario categories, taking into account the likelihood and associated uncertainties for disruptive events, e.g. faulting, and parameter values with associated uncertainties of continuous processes like uplift/erosion rates.
For human intrusion scenarios, a stylized approach has been applied to define calculation cases in order to evaluate the robustness of repository system by assuming direct drilling into the repository, populations living at repository site, etc.

IV. MODELS AND DATABASES

IV.A. REALISTIC MODELLING

A conservative quantitative analysis to assess repository safety is required to demonstrate compliance with regulatory guidelines. A problem with such an approach is that the simplification required is often so great that the analysis is completely insensitive to even rather major variations in site and repository concept properties.

Along with the challenge to improve the scenario development process aiming at better representation of gradual evolution/degradation of the repository barriers for different concepts and sites as discussed in the previous sections, an aim was also to further develop the models and databases established in H12 report. Specific aims include:

• More realistically representing the geometry of all components of the engineered barriers (essential for distinguishing between different repository design options);
• Including explicit representation of all materials present in the repository engineered structures and considering any significant interactions between them;
• Realistically representing the 3D geometry of the geosphere, with particular emphasis on the solute transport characteristics of all relevant formations;
• Developing a model of a Japan-specific biosphere which contains appropriate diet and lifestyle information and improved representation of the geosphere / biosphere interface for inland and coastal conditions;
• Incorporation of time dependency into the model chain in order to evaluate scenarios which evolve gradually with time;
• Improved assessment of uncertainties and their development in time and space;
• Increased efforts to test (verify and validate) models and databases;
• Improvement of presentation formats to make results understandable to a wider audience.

These developments are being coordinated in parallel with efforts in the international safety assessment community to ensure qualification and taking into account state-of-the-art knowledge.

Fig. 7 illustrates an example of the systematic application of models developed for performance assessment. A fracture network model has been directly applied to represent a typical SDM and incorporated into a 3-dimensional mass transport code PARTRIGE (Particle tracking in deep geological environment) (Ref.30) which can represent a repository concept. In Fig. 7, simulation using the particle tracking method to identify dominant flow paths are presented for HLW repository concepts shown in Fig. 1 as an example. This will provide a basis for radionuclide migration analysis. For the whole repository system, careful simplification with a reasonable amount conservatism is carried out using a system model such as GoldSim (Ref. 31).

Fig. 7 An example of systematic model application for safety performance assessment

A THMC coupled process model has been developed to evaluate the long-term evolution of the near-field, which is taken into consideration for scenario development (see Fig. 5) and setting parameter values for mass transport. For example, a TC coupled process model has been developed and applied for the PEM horizontal emplacement repository concept to evaluate alteration of bentonite buffer by interactions with iron corrosion and cement degradation (Ref.32).

IV.B. DATABASE DEVELOPMENT

Since the H12 report, R&Ds have been carried out by relevant organizations to update and extend existing
databases so that safety assessment parameters are more reliable. These include:

- Thermodynamic database (JAEA-TDB) (Ref. 33);
- Sorption database (JAEA-SDB) (Ref. 34);
- Diffusion database (JAEA-DDB) (Ref. 34);
- Glass dissolution database (GlassDB) (Ref. 35);
- Database for parameters relevant to biosphere TF (transfer factors) (Ref 36).

For setting parameters from the modified databases, a clear and traceable approach to data screening has been applied. As an example, Fig. 8 illustrates the procedure to set reliable Kd values of Cs for granitic rock in safety assessment by screening the appropriateness of the boundary conditions and methods of experiments used to obtain the Kd values (e.g. Ref. 37).

![Screening criteria](image)

**Screening criteria**
- Sufficient description of the contents of the experimental conditions
- Reliability of the experimental method
- Reliability of the experimental conditions

![Fig.8 An example of extraction process of reliable Cs Kd-values from JAEA-SDB (Ref 34)](image)

### V. CONCLUSIONS

An approach and methodology for safety assessment has been developed for the NUMO safety case which updates that provided in the H12 report on geological disposal of HLW and TRU waste in Japan. The safety case is still generic but the assessment approach and methodology can be applied to future candidate sites.

In the assessment approach and methodology, emphasis has been placed on methods and tools for scenario development according to a set of scenario categories based on a risk-informed approach and on realistic models and databases to represent a repository system which consists of an SDM representing a given siting environment and repository concept tailored to the siting environment.

A rigorous quality assurance system is key for the assessment methods and tools and has been also developed to provide a comprehensive FEP database, and reliable models and databases.

### VI. ACKNOWLEDGEMENTS

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