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The Nuclear Waste Management Organization of Japan's Pre-siting Safety Case Based on the Site Descriptive Model

An International Peer Review of the NUMO Safety Case

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List of abbreviations and acronyms

AESJ	Atomic Energy Society of Japan
Andra	French National Radioactive Waste Management Agency
BASE	Federal Office for the Safety of Nuclear Waste Management (Germany)
DGR	Deep geological repository
DI	Detailed investigations
EBS	Engineered Barrier System
EDZ	Excavation Damaged Zone
FEP(s)	Features, events and processes
FEPC	Federation of Electric Power Companies of Japan
HLW	High-level radioactive waste
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
IGDTP	Implementing Geological Disposal of Radioactive Waste
ILW	Intermediate level waste
IRT	International Review Team
JAEA	Japan Atomic Energy Agency
JNC	Japan Nuclear Cycle Development Institute
JNFL	Japan Nuclear Fuel Limited
KINS	Korea Institute of Nuclear Safety
KORAD	Korea Radioactive Waste Agency
LLW	Low-level radioactive waste
LS	Literature survey
METI	Ministry of Economy, Trade and Industry in Japan
MOX	Mixed oxide fuel
NEA	Nuclear Energy Agency
NRA	Japan Nuclear Regulation Authority
NUMO	Nuclear Waste Management Organization of Japan
NWMO	Nuclear Waste Management Organization (Canada)
OECD	Organisation for Economic Co-operation and Development
ONDRAF/NIRAS	Belgian National Agency for Radioactive Waste and enriched Fissile Material

PEM	Prefabricated Engineered barrier system Module
PI	Preliminary investigations
PSI	Paul Scherrer Institute
RMS	Requirements Management System
RWMD	Division of Radioactive Waste Management and Decommissioning (NEA)
RWMO	Radioactive waste management organisation
SDM	Site Descriptive Model
SKB	Swedish Nuclear Fuel and Waste Management Company
STUK	Radiation and Nuclear Safety Authority (Finland)
THMCR	Thermal, hydraulic, mechanical, chemical and radiological
TRL	Technology readiness level
TRU	Transuranic (waste)
TSO	Technical support organisation
UIF	Underground investigation facility
UOX	Uranium oxide fuel
URL	Underground Research Laboratory
VLLW	Very low-level radioactive waste
WAC	Waste acceptance criteria
WATEC	International Radioactive Waste Technical Committee (IAEA)

Executive summary

Following a safety-oriented, stepwise procedure for geological repository siting, the Nuclear Waste Management Organization of Japan (NUMO) requested in 2021 that the Nuclear Energy Agency (NEA) facilitate an independent international review on NUMO's pre-siting Site Descriptive Model-based safety case. NUMO is responsible for the long-term management of high-level radioactive waste (HLW) and long-lived, low heat-generating radioactive waste (i.e. transuranic or "TRU" wastes) in Japan. This review was conducted to inform stakeholders in a transparent, impartial and open manner; evaluate the maturity and readiness of the generic safety case at a pre-siting stage; and confirm the technical feasibility of deep geological disposal in Japan. The review also develops a framing structure applicable to site selection based on existing national and international legislation and the best practices of other national programmes, and identifies key future challenges.

During a review workshop on 20-24 June 2022 in Tokyo, Japan, an International Review Team (IRT) assembled by the NEA finalised an independent international review on the following documentation provided by NUMO in English: "Nuclear Waste Management Organization of Japan (NUMO) Pre-siting SDM-based Safety Case Report, NUMO-TR-21-01 (2021)".

Additional supporting reports (SR), or in some cases summaries in English, were also submitted to the IRT during the exchanges with NUMO.

NUMO's SDM-based safety case report addresses its geological disposal project for HLW and TRU waste. The first objective for NUMO in this safety case is to identify potentially suitable sites and illustrate these using representative 3D Site Descriptive Models (SDMs). Beyond geological criteria, NUMO's safety case also considers the repository's design, associated technical feasibility and evaluation to show that operational and post-closure safety requirements can be satisfied.

In its efforts to identify potential areas for geological disposal, NUMO analysed Japan's geographical situation, excluding all sites that might not be stable in the long term and/or might not fulfil disposal containment requirements. NUMO has also taken into consideration recommendations from the NEA international peer review conducted in 2016 on Japan's Siting Process for the Geological Disposal of High-level Radioactive Waste.

NUMO has used a series of representative SDMs to describe in a non-site-specific way the various potential host rocks being considered in Japan. NUMO appropriately described the representativeness of the chosen SDMs vis-à-vis the spectrum of potential host rocks in Japan. The IRT notes that the SDM approach is an adequate, iterative way to describe and integrate at various scales existing geoscientific knowledge as well as geodynamic evolution. Such an approach corresponds to international good practices.

The site investigation process specified by the Designated Radioactive Waste Final Disposal Act (hereinafter "the Final Disposal Act" in short) is a three-step process. NUMO will initially focus on studying volunteer sites through literature surveys (the "volunteer sites" are the areas that applied for a literature survey and accepted a proposal for a literature survey from the Japanese government). Depending on the results of this primary phase, NUMO will progress to preliminary investigations and later to detailed investigations. The IRT considers this planned, stepwise approach reasonable as it conforms to international best practices.

In terms of design, NUMO has retained at this stage robust choices that are likely adaptable to Japan’s geological conditions. However, these will have to be studied in more detail. The IRT recommends maintaining a wide list of feasible design options open to allow for adaptability – whether in regards to specific site characteristics, changes in the waste to be disposed of and/or in requirements for disposal.

A disposal system’s safety is assessed during the operation and post-closure phases according to methods aligned with international best practice. The preliminary safety assessment is based on generic assumptions and an early conceptual design. For the post-closure phase, key elements in the methodology include identification of phenomena affecting the repository system in the long term, definition of safety functions, selection of a set of representative scenarios for the post-closure evolution, modelling of these evolutions and quantifying their radiological consequences.

An effective management system has been put in place that considers the complexity of the geological disposal programmes and their long-term duration. It is currently based on three strongly interacting pillars: characteristics of the geological site, design studies and the safety assessment. In addition, the IRT recommends consideration of waste inventory and its evolution as a fourth pillar. NUMO’s management system is recognised by the IRT as being in line with good practice, including its inherent set of iterations. It is notably aimed at ensuring adequate coupling and maintaining flexibility.

Aspects covered by NUMO through the SDM-based safety case show the ability of NUMO’s teams to carry out a safety analysis of geological disposal in Japan and to provide complete safety case documentation adapted to this stage of the project. Limits identified by the IRT are related to the generic nature of the exercise carried out and to the uncertainties surrounding its input data (in terms of geological characteristics, phenomenological understanding, repository design and safety assessment). The IRT considers that the prerequisites for demonstrating the safety and feasibility of geological disposal for HLW and TRU waste in Japan do exist. Consequently, the IRT recommends that NUMO draw lessons from the SDM-based safety case to upgrade and prioritise its R&D plan.

Given the complexities of establishing a geological disposal project, NUMO's strategy is to gather key players with the necessary skillsets to bring such a project to fruition. NUMO’s main role is to specify the needs for further developing the disposal solution and to integrate all the necessary information, allowing the key players to conduct the relevant analyses. NUMO benefits from national experience, notably in terms of radioactive waste, geosciences and studies in underground laboratories. The organisation has access to many institutions able to support its scientific developments, whether in the geological, physical or chemical fields or through assessment capabilities. It also has access to underground working technologies and nuclear technologies that could effectively contribute to developing the geological disposal project in Japan.

During the review of NUMO’s SDM-based safety case, the IRT identified the need for:

1. Greater understanding of regulatory expectations for siting and establishing the next safety case;
2. Further identifying the scope of waste characterisation and inventory;
3. Continued development of R&D programmes which support development of a deep geological repository (DGR).

Whereas it is clear that these points are not the sole responsibility of NUMO, their handling largely conditions the relevancy, appropriateness, representativeness and reliability of NUMO's future studies and safety cases. The IRT therefore strongly recommends that, taking into account the SDM-based safety case, NUMO deepen dialogue with the following key stakeholders:

- Japan's Nuclear Regulation Authority: in order to clarify regulatory expectations and steps until the formal licensing process.
- Waste producers: to develop a more realistic overview of the inventory of radioactive waste to be disposed of, and its subsequent evolution. A more accurate understanding of inventory is a key point in evaluating the adequacy of site characteristics, design and the safety assessment.
- R&D teams focused on geological disposal: so that they may more efficiently focus their research and priorities on the needs expressed by NUMO, according to the results of successive safety assessments.

Based on international experience, the national framework, including stepwise licensing and clear roles for different organisations, is a prerequisite for the successful implementation of a DGR. To further evaluate these aspects, the IRT also notes that an international peer review (such as an IAEA Artemis mission) focused on the overall DGR programme and regulatory framework would be useful and would support the successful development of the DGR.

At this stage, the long-term safety assessment is based on many conservative assumptions. Consequently, results of the different cases studied are often quite similar and do not provide more detailed information for discerning among design options and/or potential host geological formations. As a preparatory step for the next stage, NUMO could consider developing sensitivity cases with the site properties of alternative types of host rocks, covering the range of possible host rock characteristics that can reasonably be expected. Additional sensitivity studies could cover a range of inventories, different levels of requirements or a broader range of technical data, such as engineered barrier thicknesses.

Regarding the technical aspects of NUMO's strategies, the IRT makes the following recommendations:

- Safety-related functions expected for a geological repository:
  - For future phases, where possible, match the safety functions with quantitative performance indicators and, when possible, with criteria for acceptable performance.
- Capacity of the geological medium to provide an appropriate delay of radionuclide transport:
  - Take this into account more specifically during site evaluations, and may prove to be a discriminating criterion if there are several volunteer communities.
- Design options:
  - Keep open as long as possible to maintain flexibility of design as additional knowledge is acquired;
  - Flexibility of design options requires keeping track of and evaluating the effect of changes, which can be ensured using a configuration management system.

- Reversibility of disposal decisions:
  - Make proposals, in particular by proposing decision-making processes that can frame the life of the geological disposal facility, while keeping options open for next generations.
- Monitoring:
  - Integrate retrievability aspects in the objectives of monitoring.
- Additional phenomena:
  - Re-explore phenomena considered at this stage as non-dominant or non-determining in order to assess how they should or should not be taken into account in subsequent phases.
- Handling and emplacement of waste packages in disposal tunnels/vaults:
  - To be studied, with tests in an underground environment.
- Design developments:
  - To be continued, particularly with a view to adapting to the characteristics of the sites that will be considered in coming phases.
- Operational safety:
  - To be supplemented by design features allowing the reduction of operational risks, and operational safety assessment to be supplemented by taking into account possible failures of the protections envisaged by design and analysing doses to workers and to the public for such cases.
- Design and construction procedures to be adapted to the particular characteristics of the geological formations envisaged for the following stages in a way that allows contrast between formations being reflected in the design.
- Development of storyboards to be generalised:
  - Seek a more exhaustive representation of the underlying information and the data to be processed.
- Models and couplings:
  - Map the various models included in the assessment, their couplings and the associated codes. This would provide an overview of the modelling efforts, make it possible to illustrate the adaptation of the various tools at the level of analysis, and improve understanding of the simplifications of the representations involved.
- Validation of models and computer codes:
  - Increase efforts to validate models and computing tools in the near future.

1. Introduction

1.1. Objectives and expectations

This report summarises the key points of an independent international review of the English version of "The NUMO Pre-siting SDM-based Safety Case Report". The purpose of the review was to assess the sufficiency and credibility of the maturity and readiness of this generic safety case, developed at a pre-siting stage; to confirm the technical feasibility of deep geological disposal in Japan; and to develop a framing structure applicable to site selection based on national and international legislation and guidelines as well as on the best practices of other national programmes. In particular, it checked that the safety case report reflects the latest international technical knowledge and R&D achievements, built around the concept of a safety case as described in the "International Review Guidelines developed by the Nuclear Energy Agency" (NEA, 2005) and in "The Safety Case and Safety Assessment for the Disposal of Radioactive Waste, Specific Safety Guide" (IAEA, 2012).

1.2. Organisation of the international peer review

The peer review was organised by the NEA, with the support of a dedicated Scientific and Technical Secretary. To benefit from the highest standards and level of knowledge in the field of geological disposal, the NEA required the participation of Peer Reviewers with thorough experience in establishing and conducting R&D and development programmes for deep geological disposal, in siting and design of deep geological repositories, both in crystalline and sedimentary rock formations, and in conducting safety assessments of geological repositories for high-level radioactive waste (HLW) and transuranic (TRU) waste.

The list of the Peer Reviewers who compose the International Review Team (IRT) and brief biographical sketches are presented in Annex A to this report.

1.3. Terms of reference

Japan is engaging in the development of a geological repository for disposal of its HLW and TRU waste. Its Nuclear Waste Management Organization, NUMO, has developed skills and experiences for over two decades, in Japan as well as abroad. It is now moving towards a new phase of site selection. In order to study candidate sites, it has to show its capability to study these sites, design appropriate disposal facilities and demonstrate the safety of geological repositories.

Considering the boundary conditions in Japan, including the geological nature of the country as well as the socio-political context concerning radioactive waste disposal, a preliminary generic safety case was developed to test and demonstrate the capabilities of the scientific and technical teams in Japan and the relevance of their approach. The safety cases will have to be further updated at later stages of the project to continuously assess the performance that can be reached, and thus to highlight R&D needs and improve the design through an iterative process.

The goal of the international review was to assess the achievements of the pre-siting SDM-based safety case, and to check the capability of the NUMO teams to move to the next steps. The review is believed to provide a benchmark of the capabilities of the NUMO teams in an international context, and thereby also to contribute to building public confidence in Japan's waste management programme. It also aimed to identify additional needs and requirements that might influence the development of the geological repository project.

The terms of reference for this review are reproduced in Annex B.

1.4. Conduct of the review

During the initial meeting, which took place on 15 November 2021 via video conference, an initial set of presentations was made to the IRT. NUMO experts presented a detailed overview of radioactive waste management in Japan, followed by an overview of the SDM-based safety case. At the same time, the English version of the "NUMO Pre-siting SDM-based Safety Case" was delivered to the IRT (NUMO, 2021).

Following this meeting, reviewers were given four months to study the safety case and exchange written questions and answers with NUMO. A virtual meeting for clarification was held on 11 April 2022.

A review workshop, including a visit to the facilities of Japan Nuclear Fuel Limited (JNFL) in Rokkasho-mura, was then organised on 20-24 June 2022 in Tokyo, after which the report was edited and a final draft was submitted to NUMO for fact checking before it was published by the NEA.

1.5. General context for geological disposal of radioactive waste in Japan

Radioactive waste management and development of a DGR is implemented through a national framework in which organisations have different roles and responsibilities. In Japan, overall programme supervision is provided by the Ministry of Economy, Trade and Industry (METI). The Nuclear Regulation Authority (NRA) is responsible for establishing applicable radiation and nuclear safety requirements and overseeing their implementation. NUMO is the organisation in charge of the geological disposal of HLW and TRU waste. Research in support of the geological disposal of radioactive waste is carried out by a group of organisations, including the JAEA.

Radioactive waste in Japan is primarily generated by nuclear power. Spent fuel unloaded from nuclear power plants has been reprocessed in European facilities and the JAEA pilot plant at Tokai-mura. The overseas reprocessing has already been completed and once the reprocessing facility of Rokkasho-mura (Aomori Prefecture, Japan) becomes operational, reprocessing will occur there. This process yields highly radioactive waste (HLW) as well as less radioactive but long-lived waste containing transuranic elements[1]. To ensure proper management of this waste through disposal in a geological medium, NUMO was established in October 2000, pursuant to the Final Disposal Act (METI, 2000, 2015).

Regulations regarding geological disposal of radioactive waste are still being drafted by the Nuclear Regulation Authority (NRA), which leads NUMO to have to carry out its studies without a fixed regulatory framework.

Radioactive waste managed by geological disposal is generated by the reprocessing of spent nuclear fuel. The domestic organisations developing Japan's reprocessing capacities (JNFL and JAEA) and the utility companies who are contractors of the oversea

1. TRU, defined more broadly as long-lived intermediate level waste in other programmes.

reprocessing are responsible for specifying their inventories of waste that will have to be disposed of into the geological disposal.

In NUMO's DGR development programme, the first objective for NUMO is to identify potential sites likely to be able to accommodate a geological repository.

For this, a stepwise approach for the site selection process is outlined in the Final Disposal Act (METI 2000, 2015). This approach includes three successive steps, starting from volunteer candidate municipalities and aiming at progressively narrowing down the site selection:

(1) Literature survey for the volunteered candidate municipalities;
(2) Preliminary investigation stage in the areas selected in step (1);
(3) Detailed investigation stage in the areas selected in step (2).

In May 2015, the government of Japan stipulated a new introductory step in which a nationwide scientific screening using geological criteria was carried out to identify i) potentially less suitable areas; ii) potentially suitable areas; and iii) potentially more suitable areas, for hosting a geological repository of HLW. METI requested the NEA conduct an independent technical peer review to confirm the appropriateness of adding such a new step, and the applicability of these screening criteria to support future site selection. This NEA peer review on "Japan's Siting Process for the Geological Disposal of High-level Radioactive Waste" (NEA, 2016) was conducted in 2016, and concluded that i) such a stepwise site selection process is consistent with international practices; and ii) important events and processes were properly identified and categorised as to their potential impacts on the safety functions of containment and isolation.

The "nationwide map of 'scientific features' relevant for geological disposal" (METI, 2017) (see also Annex C) was published by METI in 2017. On this map, Japan is subdivided into four types of areas by applying general requirements and criteria for site suitability based on nationwide geoscientific and technical data:

(1) The areas probably unsuitable from the viewpoint of long-term stability, such as those near volcanoes or active faults;
(2) The areas with mineral resources such as oil fields and gas fields that are undesirable from the viewpoint of future potential human intrusion;
(3) The areas with a relatively high probability of being suitable due to a lack of the above-mentioned undesirable characteristics;
(4) Among the likely suitable areas, those that are preferable also in terms of transport advantages (i.e. coastal areas).

In October 2020, the town of Suttu in Hokkaido Prefecture applied for a literature survey to be undertaken. Additionally, Kamoenai (another village in Hokkaido Prefecture) accepted a proposal for a literature survey by the government of Japan. NUMO initiated literature surveys (i.e. stage 1) for both municipalities in November 2020.

The work reported in NUMO's Pre-Siting SDM-based Generic Safety Case was conducted for sites typical of those with a relatively high probability of being suitable as indicated on the nationwide map. In the safety case, five possible rock types are reduced to three representative host rocks (Plutonic rocks, Neogene sediments and Pre-Neogene sediments) capturing all relevant key characteristics for potential suitable sites.

This NUMO pre-siting SDM-based safety case (NUMO, 2021) has the purpose of:

(1) "Illustrating the technology for surveying and evaluating sites with conditions necessary for isolating and containing designated radioactive wastes and ensuring no significant impacts on the human living environment for a variety of relevant geological environments in Japan."

(2) "Presenting site descriptive models (SDMs) that capture key characteristics of information obtained from studies of deep geological environments in Japan, illustrating repository designs and engineering safety measures tailored to these which fulfil required safety functions."

(3) "Demonstrating the safety of a potential repository site, both pre- and post-closure of the repository."

(4) "Based on integration of the above input, identifying technical issues for further improvement and the required R&D needed for geological characterisation, repository design and safety assessment."

In regard to the use of the "Pre-siting SDM-based Safety Case Report", the IRT notes at this stage that the way in which NUMO's safety case will be used for further development of the Japanese deep geological disposal programme has not yet been defined.

1.6. Structure of the review report

This chapter has provided introductory comments, terms of reference and of the conduct of the review of the NUMO Pre-siting SDM-based Safety Case, as well as a brief description of the context of geological disposal in Japan.

Chapter 2 addresses the findings according to the remit of the review, with a development of the analysis by the IRT on each of the major themes of the SDM-based safety case.

Chapter 3 presents IRT's comments on the maturity of the safety case approach in Japan, NUMO's maturity to pursue its programme, and the overall technical recommendations proposed to NUMO.

Annex D is intended for the reader more interested in the technical detail of the analysis. It includes a summary of the IRT's initial key comments to NUMO during the review of the SDM-based safety case. This Annex is mainly intended as direct feedback to NUMO teams by providing the comments of the IRT according to the document structure of the SDM-based safety case.

2. Findings according to the remit of the review

Chapter 2 is organised according to the terms of reference of the present review (detailed in Annex B). The fundamental feasibility of geological disposal in Japan is reported on in the concluding remarks in Section 3.2. The correspondence between the terms of reference and the organisation of this report is presented in Table 1.

Table 1. Organisation of the report according to the terms of reference

Item in the terms of reference	Subsection
Safety strategy at this pre-selection stage and the approach chosen to prepare to initiate site-specific work	2.1
Assessment of geological environments considered to be representative of those that would result from the siting programme and the proposed methodology for site characterisation at the beginning of the siting process, focusing on knowledge integration within SDMs	2.2
Repository design approach, tailoring layout to potential host rocks, and the assessment of the practicality of repository construction, operation and closure	2.3
Operational and post-closure safety assessments for repositories tailored to the host rocks described	2.4 and 2.5
Implementation of management tools to facilitate integration of the siting, design and safety assessment teams and to provide the iterative feedback required to assure technical quality	2.6
Critical synthesis of the safety case strengths and weaknesses as the basis for developing an R&D plan for the improvement of the credibility of the safety assessment and practicality of implementation of the geological disposal programme	2.7
Fundamental feasibility of geological disposal in Japan within geological environments similar to the type of environments assessed	3.2

2.1. Safety strategy

The safety strategy concept used within the NUMO Pre-siting SDM-based Safety Case is to isolate and contain radionuclides within the waste and disposal facility, which is generally consistent with international guidance and best international practice.

NUMO's current geological disposal strategy has been developed based on international recommendations and national assessments, and with the support of the Advisory Committee for Natural Resources and Energy in Japan. Geological disposal is the recommended solution for disposal of HLW and TRU waste, consistent with the government of Japan's 2015 "Basic Policy on Final Disposal of Designated Radioactive Wastes" (Government of Japan, 2015). This solution, shared internationally, benefits from a scientific consensus, again confirmed in the report "Management and Disposal of High-Level Radioactive Waste: Global Progress and Solutions" (NEA, 2020). Given the duration of the geological disposal project, and successive generations that will have to manage it, the concept of reversibility and retrievability is considered in the design of the disposal facility. A site-selection process is in place that aims to identify suitable sites using a stepwise approach.

NUMO's strategy for developing the safety case describes the basic approach to ensuring safety, and shows how it intends to demonstrate safe geological disposal through phases defined in the implementation programme.

The IRT notes that, overall, NUMO relies on the most up-to-date science and technology for methods implemented in developing safety assessments and safety cases. The IRT recommends that NUMO continue to establish the reliability of geological disposal based on the latest scientific knowledge and on continuous reviews.

2.1.1. Legislation, safety requirements and other preconditions for the DGR

In general, a radioactive waste disposal strategy depends on the characteristics of the radioactive waste to be disposed of and the requirements outlined in national policies and regulations.

NUMO relies on regulatory requirements published by various national authorities in other countries or guidance from international organisations involved in the development of geological disposal projects, pending the establishment of dedicated regulatory requirements in Japan.

The characteristics of the waste forms are broadly defined at this stage. However, waste inventory imposes key requirements on the waste management programme. More details on the waste types from Japan's waste producers; on their physical, chemical and radiological properties; and on the potential evolution of these inventories would facilitate NUMO's continued waste management work. The IRT recommends carrying out sensitivity analyses in order to bound the hypotheses and to have more comprehensive representations of the geological repository's safety boundaries and safety assessment. Such a sensitivity analysis could also help demonstrate the flexibility of the geological repository design approach and the robustness of the safety case, in particular with regard to future changes in the regulatory framework and the inventory and characteristics of waste to be disposed of. This is an asset that a generic safety case could provide. A clear example concerns the inventory data, not only in terms of volumes of waste but also on their nature and evolution (e.g. possibility to include MOX fuel, to consider other types of spent fuel or TRU waste), including the durations of storage before disposal. This point is important, as the characteristics of the various components of the repository must be tailored to the specific characteristics of all waste to be disposed of in the DGR.

In terms of the next siting phases, an underestimation of the volumes to be disposed of could lead to consideration of sites whose capacity would ultimately prove to be insufficient. Similar consideration can be made with the thermal power of HLW. An underestimation of the thermal power may result in an underestimation of the necessary underground footprint of the repository. Such underestimation might result from uncertainties affecting the duration of the storage phase prior to disposal or the content of heat-emitting radionuclides such as ^{241}Am, especially as a function of the type of reprocessed spent nuclear fuel (MOX vs UOX). Conversely, an overestimation of volume or thermal power could lead to the exclusion of sites whose characteristic volumes would be consistent with the characteristics of waste to be disposed of. Concerning the architecture and choice of barriers, the radioactive content of each type of waste must be taken into account in order to find the performance required to ensure safety.

2.1.2. Safety functions

The two key safety functions adopted by NUMO are isolation and containment. These encompass the requirements for operational safety as well as for post-closure safety. From these key functions, second or even lower-level functions are identified that have also been taken into account to verify or ensure the proper functioning of the disposal system over time.

"Isolation" reflects the requirement to dispose of waste in a stable geological environment devoid of exploitable resources, and at a depth that is difficult to reach by simple means, i.e. that is below the area normally accessed during engineering activities.

"Containment" refers to the capacity of the waste packages and overall barrier system to prevent releases of radioactive elements for an extended period of time and, thereafter, to limit and delay such releases. NUMO defines the term "containment" broadly and, following IAEA vocabulary (IAEA, 2022), includes also what some other organisations distinguish in a separate function: retention.

The IRT recommends that NUMO further highlight the importance of delaying and mitigating the migration of radionuclides in the geosphere. The identification and evaluation of related site characteristics could be decisive in the search for a site.

In NUMO's SDM-based safety case, safety functions are related to the various components of the repository. Such a representation constitutes an entry key for the design of the repository, as illustrated in the chapter on repository design.

To assess the efficiency of the developed system for geological disposal, the IRT recommends that NUMO define safety function indicators for the following stages of the project development or, when relevant, minimum acceptable performance targets, also as a function of time.

2.1.3. Site-selection strategy

The strategy for site selection must ensure that it is possible to identify sites which satisfy the necessary safety functions. The progressive approach developed by NUMO is coherent and seems likely to implement this approach in practice. Criteria for excluding unfavourable formations or sites, such as areas with active faults, have been defined and implemented. The ability of sites to satisfy key functions is then assessed, with particular attention to the stability of favourable characteristics over time.

A stepwise approach to further siting is defined by the Final Disposal Act in three major stages, comprising a literature survey, a preliminary investigation at the site and, lastly, detailed investigations. Each of these stages includes detailed overviews and studies through geological models, options for the design of the repository and related safety assessments. There is no question of undertaking this stepwise approach on the scale of the whole territory; this process can only be undertaken for candidate sites.

Site characteristics are subject to integration within a site descriptive model (SDM). In anticipation of the production of specific SDMs, several SDMs characteristic of different geological formations have been proposed and serve as a basis for NUMO's current safety case.

The approach illustrated by NUMO consists of analysing Japan's geological situation and identifying the possible areas for geological disposal, excluding all those presenting a risk with regard to long-term stability or a risk of not fulfilling containment requirements for radioactive waste. Doing this, NUMO took into consideration recommendations from the international peer review of the Japan's Siting Process for the Geological Disposal of High-level Radioactive Waste that was carried out in 2016 under the auspices of the NEA (NEA, 2016).

The IRT considers this site investigation approach reasonable and conforming to international best practices; it allows for staff preparation and to test applicable tools, in addition to assessing the needs for complementary methods and R&D. It is clear that several iterations are necessary. Indicators intended to assess the results obtained and to help decision-making to move from one stage to the next could also be proposed.

In addition, the IRT provides recommendations to prepare the next safety case in a way that facilitates comparison of volunteer sites, especially on the basis of sensitivity studies (see below).

2.1.4. Repository design strategy

The repository's design is adapted to the characteristics of each SDM, aiming to contain radionuclides and limit their migration. At the current stage, the design approach aims for robust solutions, offering a sufficient margin given the inherent uncertainties both in the geological data and in the concepts themselves.

Starting from an initial outline of design solutions, a representation of the disposal facility architecture and its components is proposed. As knowledge of the sites is acquired, and regulations and requirements become clearer, the choices of technological solutions are refined. The IRT suggests keeping the design options open for as long as possible in order to retain the ability to adapt to potential evolutions in the project Requirements management, including knowledge management, will be key to support future development of the geological repository project. The IRT notes that the teams in charge of the project promote a systematic search and use of the best available technology, which is highly recommendable. They can also rely on experiments and tests conducted in underground laboratories in Japan and abroad. Finally, and above all, a specific programme of technological tests is envisaged in the site selected at the end of the detailed investigation phase.

The retrievability of waste is taken into account in the facility design. The aspect of the reversibility of decisions is more a matter of management issues that will need to be investigated in due course, requiring strong interaction with stakeholders and future decision makers. Monitoring and surveillance are also well taken into account. Monitoring and surveillance are above all intended to ensure that the geological repository operates under conditions that comply with those sought by design. They are therefore also intended to detect as early as possible any anomaly that could lead to additional preventive measures in relation to long-term safety. The programme should also be explicitly linked to the issue of the reversibility of decisions, consistent with NEA definitions (NEA, 2012a), and the retrievability of waste packages. Monitoring and surveillance programmes should be developed and started at an early stage in order to produce a baseline of the sites being investigated before any major field work.

2.1.5. Safety assessment strategy

NUMO's safety assessment strategy follows the IAEA guidance (IAEA, 2012; IAEA, 2013) for developing scenarios, formulating models and conducting analyses and assessments. NUMO has also taken into consideration the relevant experience in building safety cases from foreign geological disposal programmes.

For safety during operation, regulations included in the "Act on the Regulation of Nuclear Source Material, Nuclear Fuel Material and Reactors" (METI, 2000, 2015) and regulations developed for HLW management facilities in Japan after the Fukushima Daiichi Nuclear Power Plant accident generally apply to the disposal facility. They include the assessment of conventional risks, in addition to radiation risks.

Post-closure safety assessment is a complex activity, involving the integration of a large amount of information, often associated with uncertainties that change over time. NUMO's approach to managing the post-closure safety assessment is consistent with other foreign organisations. It seeks to demonstrate that the entire disposal system will perform as planned, while meeting regulatory safety requirements. For this, it defines scenarios from which it develops its assessments. A features, events and processes (FEP) catalogue is used as a basis to define and evaluate scenarios. Numerical values for estimated doses can serve as an indicator of expected repository performance, but have to be used with care due to uncertainties in the future. Pending national regulations, NUMO has taken the recommendations of international organisations and other countries as references.

2.2. Assessment of geological environments

The purpose of assessing geological environments is to select and model representative geological environments suitable for hosting a deep geological repository.

The concept for site suitability assessment has been developed systematically for potential host rocks in Japan, starting with the exclusion of geological environments with significant effects of natural perturbing phenomena (e.g. volcanoes/igneous activity, earthquake/fault activity, and significant uplift/erosion) that could impair the safety of the repository within the next 100 000 years, and then focusing on those areas where favourable characteristics should be maintained for a sufficiently long period of time. These geoscientific criteria are appropriate for the geological setting of Japan, capturing all important events and processes of relevance, and determining how these may impact the “containment” and “isolation” safety functions.

To describe the various potential host rocks considered in Japan in a non-site-specific way, NUMO used a series of representative “Site Descriptive Models – SDMs”. The integration of the latest scientific and technological knowledge in the definition of the representative host rock SDMs has been documented in a series of supporting reports. It is worth noting that one of the objectives of the Preliminary and Detailed Investigations stages is to iteratively improve state-of-the-art knowledge for the relevant scientific disciplines and related technologies so that the site suitability will be ensured for operational and post-closure safety, based on a tailored design of the repository. It is meant to reduce the residual uncertainties through the implementation process, guaranteeing efficiency and cost-effectiveness. NUMO’s approach to integrating current geoscientific knowledge into a model of the host rock and its geological environment is traceable, well-documented and well-illustrated.

NUMO appropriately justified the representativeness of the chosen SDMs vis-à-vis the range of potential host rocks in Japan. The IRT notes that the SDM approach is an adequate, iterative way to describe and integrate at various scales existing geoscientific knowledge as well as its geodynamic evolution. Such an approach corresponds to international good practices.

At this stage, it seems reasonable to conclude that, based on the provided documentation, deep geological environments with favourable long-term characteristics from the point of view of geological disposal could be found in a range of locations in Japan.

2.2.1. Role of the geological environment in ensuring safety

The SDM-based safety case report summarises well the current knowledge of the relevant processes for geological disposal in Japan and properly references supporting reports where more details can be found. Geological criteria used in the nationwide scientific screening, which are the basis of siting criteria for the literature survey, were previously assessed by a NEA international peer review in 2016 (NEA, 2016).

The links between these geoscientific criteria – used to assess the potential stability of host rock in various geological environments in Japan – and the concept of safety are discussed in depth, and a concise statement of relevant knowledge is given. In particular, the ways in which perturbing events and processes can affect the safety functions (so-called influencing factors) are discussed in relation to the safety functions and/or repository design. NUMO also appropriately defines events/processes/characteristics that should be investigated at specific stages of implementation, based on their expected relevance/significance at a given stage of geological project development.

The exclusion of geographic areas where potential host rocks are deemed insufficiently stable to allow safety functions to be maintained for a sufficiently long period of time (i.e. of the order of 100 000 years for NUMO's safety case) is appropriate and consistent with international recommendations; similar approaches, adapted to local geological contexts, have been adopted in other countries by their radioactive waste management organisations.

With the aim of improving containment of the waste, narrowing down the siting area's location according to geological criteria by carrying out successive phases of investigation in the field (with an increasing level of detail throughout the process) is relevant and makes it possible to confirm, at each stage, the capacity of the envisaged host formation to meet the feasibility and safety requirements. It is worth mentioning that the staged methodology, as proposed by NUMO in this safety case, should allow tackling in a stepwise manner all the advisory points identified in the 2016 international peer review (e.g. exceptions for the 15 km respect distance from Quaternary volcanic centres, difficulty in estimating actual fault length).

2.2.2. Process to identify suitable environments

NUMO acknowledges that safety functions must be ensured for a long time (i.e. more than 100 000 years). The developed stepwise approach is based on the understanding of relevant geological events and processes, which allow determining the possible long-term evolution of areas to be examined.

The scale of potential siting areas and the relevant geological events and processes are narrowed down through three successive stages (i.e. literature survey [LS], preliminary investigations [PI], and detailed investigations [DI]), with an increasing level of detail. For each stage, the site-selection process is implemented in three successive steps:

1) Exclusion of unsuitable areas (e.g. Quaternary volcanoes, active faults, mineral resources with high economic value). Some areas for which no firm conclusion can be drawn because of residual uncertainties can be retained for the next stage in order to decide later, based on evidence to be acquired during field investigations.
2) Remaining suitable zones are evaluated for characteristics related to the containment of radionuclides and limitation of their migration (acknowledging that less suitable areas can be further excluded). NUMO aims at confirming that

favourable characteristics are stable enough to support sufficient barrier performance beyond 100 000 years.

3) Consideration of unlikely but high-impact geological processes that cannot be rigorously excluded.

It is to be noted that, in the PI and DI stages, in addition to an evaluation of mineral resources with high economic value, an assessment of the significance of geothermal resources, hot springs and groundwater resources will be carried out.

This stepwise approach is reasonable to ensure the acquisition of required knowledge during the overall implementation process and to ensure sufficient flexibility in the tailoring of the repository design and siting. Moreover, NUMO's approach benefits from other national programmes which successfully applied similar iterative approaches to reduce the residual uncertainties during the siting process (e.g. Finland, Sweden, Switzerland and France).

All the gathered information is interpreted in the SDM. It corresponds to a "geosynthesis" of the relevant knowledge base at a given time (including the relevant key uncertainties). Then, the SDM (knowledge base and the residual uncertainties) is passed on to the repository design and safety assessment teams. The residual uncertainties are meant to decrease as the site investigations progress in the course of this iterative approach (i.e. LS, PI, DI and associated field investigations). However, new facts and new uncertainties might arise during the successive geological investigation periods. Site investigations can be stopped when the qualitative and quantitative geological information makes it possible to meet the needs identified through the safety case as well as specified requirements, and insofar as the newly acquired information has no impact on operational and post-closure safety.

NUMO developed detailed workflows for the staged site investigation procedure. The evaluation of operational and post-closure safety is based on field investigations and the site suitability is confirmed at each step of the siting process (showing conformity with laws and regulations). Moreover, high impact events, even if they have a low likelihood of occurring, are considered.

These workflows are clear and present, in a synthetic way, how the different geological aspects are going to be dealt with during the successive siting stages. A preliminary investigation plan is to be issued at the end of the literature survey stage, in which the work programme to be conducted in the PI will be detailed and prioritised according to actual needs. During the PI stage, the LS results concerning site eligibility will be confirmed. The PI plan is carried out in a stepwise manner to ensure reliability and effectiveness of geological information acquisition (i.e. surface field investigations followed by borehole drillings). At the end of the PI, a detailed investigation plan is issued for selected site(s), along with a repository design, construction plan and monitoring plan. During the detailed investigation stage, the PI results concerning site eligibility are also intended to be confirmed based on new information. DI is also implemented in a stepwise manner to ensure effectiveness and cost-efficiency (i.e. surface field investigations followed by implementation of an underground investigation facility [UIF]). Based on the overall output of this process, a repository construction area can be identified.

This approach should allow reducing uncertainties progressively, conducting the investigations according to the actual needs at a given time, and setting work priorities accordingly. Proven high-quality site characterisation technologies are needed to ensure the correct information is acquired with the required level of quality. NUMO (with the relevant research institutes) will develop and validate required technologies prior to the start of each siting stage. It is to be noted that NUMO is already monitoring the development of site characterisation technologies through, on the one hand, an assessment of such technologies as used abroad in siting projects for geological repositories and, on the other hand, in situ demonstrations carried out in JAEA underground research laboratories.

2.2.3. SDM development for representative host rock settings

By presenting all relevant features and residual uncertainties, SDMs constitute the basis for repository design and safety assessment.

A conceptual SDM is developed for each type of potential host rock in NUMO's pre-siting SDM-based safety case. This includes:

(1) Geological model;
(2) Hydrogeological model;
(3) Groundwater flow analysis;
(4) Conceptual model of water-conducting microstructure (a few mm to tens of mm);
(5) Hydrogeochemical model; and
(6) Rock thermal and mechanical properties.

The SDMs are established at three different scales:

(1) Regional scale (several tens of km x several tens of km);
(2) Repository scale (a few km x a few km);
(3) Panel scale (several hundreds of m x several hundreds of m).

SDMs are developed so that the regional, repository and panel-scale representations form a nested structure.

As no sites (or volunteers) had been identified at the time of production of this safety case, "representative host rocks" are thus considered based on the current geological knowledge base for Japan. These geological formations are found in environments which may be eligible for site selection (i.e. safety functions are expected to persist for sufficiently long time periods).

Seven rock types have initially been considered, but two of these were excluded from further consideration as they are mostly unconsolidated below 300 m depth (which is the minimum repository depth required by the Final Disposal Act) and less frequent at such depths (i.e. Quaternary sediments and volcanic rocks). The five retained rock types of interest from the viewpoint of geological disposal are:

(1) Neogene sedimentary rocks
(2) Pre-Neogene sedimentary rocks
(3) Pre-Quaternary volcanic rocks
(4) Pre-Quaternary plutonic rocks
(5) Metamorphic rocks

Plutonic rocks, Neogene sedimentary rocks and Pre-Neogene sedimentary rocks are further considered as representative host rocks since these are thought to cover all key characteristics of the five possible rock types.

The approach of developing SDMs to integrate geoscientific information obtained from the stepwise site-selection process is well-illustrated, and possible arbitrary choices taken in this context are justified (e.g. location of repository within the regional domain to allow assessment of the layout disposal areas and other underground facilities and associated post-closure safety assessment). Through the SDMs, the effectiveness of NUMO's approach to use state-of-the-art scientific knowledge to search for potentially suitable geological environments has been demonstrated, providing a sound basis for the LS stage to be carried out for volunteering municipalities and also for subsequent siting stages.

Although the siting process is meant to exclude areas where events and related processes might impair the safety functions within the next 100 000 years, unlikely but highly impactful events are still considered via a risk assessment approach. The likelihood of occurrence of these processes is propagated to the quantitative analysis of their consequences. This approach is aligned with international practices.

NUMO appropriately justified the representativeness of the chosen SDMs vis-à-vis the range of potential host rocks in Japan. The IRT notes that the SDM approach is an adequate, iterative way to describe and integrate at various scales existing geoscientific knowledge as well as its geodynamic evolution. Such approach corresponds to international good practice.

2.3. Repository design approach

Development of the safety case is only in its beginning stages. Due to the safety case's generic nature, the feasibility of the disposal technology cannot be fully assessed at this stage. Many aspects require further work, followed by a detailed assessment.

Repository design follows the progressive strategy put in place by NUMO, with development gradually integrating knowledge acquired on site and evaluated through safety assessments. At this stage of NUMO's SDM-based safety case, the design bases stem from achievements of previous studies presented in reports H12 (JNC, 2000a; JNC, 2000b; AEASJ, 2019) and TRU-2 (JAEA, 2007), after having verified that requirements and functions sought are met. They are brought together in a catalogue of options, including innovative solutions developed by NUMO. The design bases are adapted to the three studied geological formations: Plutonic rocks, Neogene sedimentary rocks and Pre-Neogene sedimentary rocks.

To specify the repository design, design factors are considered. They represent all the requirements and constraints related to safety, engineering practicality, socio-economic issues and retrievability. The long-term performance of safety functions is tested using influence factors. These are thermal, hydraulic, mechanical, chemical and radiological (THMCR) processes, as well as their couplings likely to alter the desired functions. Given the time scales involved in these phenomena, influencing factors must be analysed using high-quality tests and efficient models.

The IRT recognises the considerable work that NUMO has already produced to date. NUMO's work also outlines the next steps to be addressed when more information on waste inventory and on potential sites for geological disposal becomes available. Tests and studies undertaken, as well as modelling, allow the progressive characterisation of the phenomena to be evaluated – facilitating future tasks. Major phenomena have at this stage been taken into account. Many other phenomena must still be the subject of investigations and evaluations to ensure a good representation of component evolution, and therefore functioning of the repository.

2.3.1. Knowledge of the waste inventory

A major input data for repository design is, as already indicated, the waste inventory. The IRT stresses the importance of improving the existing knowledge base and of continuing studies on increasingly reliable data. The waste management strategy before disposal is also decisive information that will need to be clarified, in particular for heat-emitting waste.

Knowledge of waste behaviour is expected to guide the development of the repository concepts so that the main functions, particularly in the post-closure phase, are satisfied. Much data is already available; their major characteristics, essentially in terms of stability, are taken into account in a satisfactory manner for the design of disposal facilities. In developing subsequent phases of the project, the IRT recommends considering more in-depth studies of certain phenomena such as radiolysis, gas generation and comprehensive couplings or interactions between barrier system materials.

2.3.2. Disposal components

The Engineered Barrier System (EBS) for both HLW and TRU waste consists of three components in shell structures, as summarised in Table 2.

Table 2. Shell structure of the EBS

	HLW	**TRU waste**
Inner shell	Glass matrix and its fabrication canister	Waste matrix and primary container
Intermediate shell	Overpack	Waste package and infill
Outer shell	Buffer material	Gap infill (mortar) and in some cases bentonite buffer

These three shells are intended to cover all required functions of the EBS. In the case of HLW, NUMO has introduced a Prefabricated Engineered barrier system Module (PEM) for direct emplacement of the three shell components simultaneously. NUMO plans to study further this innovative solution. Based on the account of the PEM and its preliminary performance in NUMO's safety case report, the IRT considers this an innovative option with adequate safety potential for the HLW EBS, and supports NUMO's plans for further studies.

Access to the underground facilities is via shaft and ramp. The IRT draws attention to the fact that the choice between ramp and shaft may be impacted by the real hydrogeologic conditions of the host site (e.g. ramp can be more challenging to implement if permeable water-bearing formations are crossed).

Long-term properties of the different components envisaged at this stage have been analysed, and their safety functions evaluated, in order to check that the required functions are fulfilled for each category of waste. This is a satisfactory approach at this stage. However, in the later phases of the project, analysis integrating the different physical couplings and the interfaces between materials will be required.

The overpack for HLW is designed to ensure its integrity for at least 1 000 years. It could maintain its functions for an order of magnitude longer than that, according to evaluations and tests. It is fabricated from carbon steel and its production has been demonstrated via prototypes. The buffer material is a bentonite-sand mixture that has been subject to numerous tests – including those which evaluate its ability to remain functional over long time periods. The production of compacted bentonite blocks as well as in situ compaction was also the subject of feasibility demonstrations.

Several technical solutions are being studied for TRU waste, but the basic concept consists of placing the primary waste packages in carbon steel containers that are subsequently filled with mortar. Full-scale demonstrations of prototype waste containers for LLW intermediate depth disposal, whose design concept is similar to that for TRU waste to be disposed of in a geological repository, were made to test their feasibility. Hence the technology required for a TRU waste case is considered to be available. Buffer material is considered for some TRU waste types, but this point is still under evaluation by NUMO's teams. In case of no buffer material, free spaces are filled with concrete. In both cases, disposal vaults are backfilled on their top.

The emplacement of waste in disposal tunnels and vaults and the construction of the EBS are still in the offsite evaluation stage, with a priority for evaluating feasibility in relevant underground environments.

2.3.3. Design of facilities

Repository design is the subject of numerous studies, the purpose of which is to analyse architectural options, procedures for constructing structures, transfer and emplacement of waste packages and engineered barriers, as well as closure of facilities. The timeline for construction and operation of a repository is an important aspect taken into account in the design, maintaining the principle of simultaneous progressive construction of the repository and emplacement of the waste packages. Another principle adopted at this stage is the disposal of HLW and TRU waste within the same disposal facility but in separate areas. It is obvious that these studies raise many questions to which NUMO systematically provides the appropriate answers. At the same time, NUMO flags further issues that will remain to be investigated as the geological disposal project progresses.

An interesting issue addressed by NUMO relates to the arrangement of disposal structures in relation to the possible characteristics of the sites to be studied. NUMO is also developing its capacity in this area, which it will be able to mobilise during the next phases of the geological disposal project.

2.3.4. Reversibility and retrievability

The technical provisions intended to ensure the retrievability of disposed waste are taken into account at the design study stage. Retrievability is a practical way to implement the reversibility of some decisions, which is a responsibility of society, including key stakeholders, local communities as well as NUMO. It is important to consider what information might be needed for future decision-making steps, and which stakeholders should be consulted. However, the needs for information and means to make decisions might change with time. This will be allowed for in the stepwise development planned for the geological disposal project.

The technical design solutions proposed by NUMO make it possible to reconcile safety requirements, which must in no way be altered, with retrievability objectives. Developments and technological tests are still planned in order to verify the conditions of retrievability, and to optimise them. NUMO has embarked on an encouraging technological programme relating to retrievability.

To inform future decisions, the IRT recommends that the observation and monitoring programme for disposal facilities explicitly take into account the question of reversibility, in addition to generating information on the performance of the geological repository. Finally, the question of the future investigation of reversibility needs to be clarified and proposed for social debate. NUMO should be proactive in proposing options in this field.

2.4. Operational safety assessment

The approach to operational safety is at a preliminary stage. The focus of the operational safety assessment at this stage is the development of concepts and methodologies of radiological safety assessment, and the evaluation of the robustness of the conceptual design. In the absence of dedicated regulations, operational safety is informed by existing international guidance (IAEA) and by national experience feedback from other industries (such as other nuclear facilities and also existing mining activities). It is expected that certain operating risks will be analysed at a later date, according to specific regulations to be established for geological disposal facilities as well as, for example, those applicable to mining works.

During normal operation, scenarios considered in the current assessment assume that the equipment and facilities perform according to the design specifications. In degraded operation, "abnormal" scenarios are considered as worst-cases in the generic safety case. Worker exposure was not calculated as no perturbation scenario considered at this preliminary stage resulted in a loss of containment of radionuclides, based on the assumption of a robust design with remote handling wherever practical and adequate protection measures. At this stage, NUMO considers that there are no potential releases of radionuclides, and only the potential direct exposure of the public to radiation outside the boundary fence is analysed. NUMO plans to extend this analysis once site-specific information becomes available, by more comprehensively considering scenarios leading to a potential release of radionuclides and their impact on the public near the repository.

The IRT notes that at the current stage of the programme, the evaluations remain hypothetical and the realism of the operational safety assessment would be greatly improved with concrete site configurations. With respect to the waste inventory, it will be important for NUMO to identify the radionuclides, determining the potential impacts during the operating phase. It will then be possible to verify whether the provisions envisaged in the conceptual design are likely to limit the impacts sufficiently, or even eliminate them. For future safety cases, the IRT also recommends considering additional design options for mitigation of operational risks (e.g. fire).

Quantitative analyses are recommended for assessing the performance of operational safety measures. The IRT also recommends that the safety assessment be supplemented by including additional scenarios, such as potential failures of the protections envisaged by the conceptual design, and by including all potential exposure pathways to workers, to the public and to the environment.

2.5. Post-closure safety assessment

2.5.1. Safety assessment methodology

The post-closure safety assessment methodology is well-designed and informed by best practices and international recommendations (NEA/IAEA).

The methodology starting point consists of selecting a set of representative scenarios based on an in-depth analysis of FEPs relevant to post-closure safety. For each of the selected scenarios, phenomena likely to occur during the lifetime of the repository are analysed using specifically derived parameters and models. The resulting behaviour of the system is described through storyboards. For each scenario, the transport of radionuclides through the system of engineered barriers, the geosphere and the biosphere is modelled to estimate potential doses to the public.

Uncertainties are taken into account in all steps of the assessment. They are related to the waste, potential sites, repository design, system evolution and the models implemented. NUMO's objective is to increase knowledge on these aspects, with the aim of reducing uncertainties over the iterations.

The methodology seeks completeness and a consistent treatment of uncertainties. Many assumptions leading to conservatism are consistently utilised. This makes the conclusions robust as regards the potential for long-term safety, but also reduces the ability to distinguish between different design and host rock options. The IRT expects that future models and datasets will be more specific once the number of candidate sites/host formations, with associated repository designs, is narrowed down. For example, the current safety case is based on a wide range of permeabilities for sedimentary rocks, but the value used in the assessment is as high as for other rock types, potentially obscuring the relative advantages of some sedimentary rocks.

The concept of complementary safety assessment indicators (multiple lines of evidence) to the dose would be useful to further develop in future iterations of the safety case. To allow NUMO to progress on a clear basis, beyond the demonstration of the applicability of the methodologies implemented, it would be necessary for the competent authorities to define the applicable regulations, in particular in terms of dose and/or risk criteria.

2.5.2. Scenarios

The analysis of the complex systems of a geological repository for radioactive waste, where a multitude of phenomena have to be taken into account on considerable spatial and temporal scales, is, in accordance with international practice, done by NUMO by defining a set of evolution scenarios. The scenarios resulting from the application of NUMO's scenario developing methodology are generally consistent and sound. Starting from a base scenario that is intended to provide a reasonable representation of the evolution of the geological repository, variant scenarios are developed, covering the uncertainties inherent in the project or based on alternative evolution hypotheses. Low-probability perturbation scenarios are also defined, in particular to take into account long time horizons, with residual uncertainties. Finally, the last series of scenarios includes the consideration of inadvertent human intrusion.

Scenario development is a combination of two methods:

1. A top-down approach where the scenarios and analysis cases (in particular the base case scenarios) are developed from the safety functions described in the safety concept of the disposal system; and
2. A bottom-up approach where the scenarios (particularly the variant scenarios) are developed from a screening of impacting features, events and processes (FEPs).

These two methods are combined appropriately to derive relevant scenarios. In the bottom-up approach, FEPs are screened from a long-term safety point of view. The starting point of analysis is the NEA International FEP list (NEA, 2019; NEA, 2020). This list is adapted on the basis of the specificities of the Japanese programme: FEPs are selected and removed from, and newly added to, the list in function of the boundary conditions for waste and system characteristics. Scenarios are derived and justified based on a comprehensive "description of system behaviour". Tools and concepts like integrated FEPs, state variables and impact analyses are useful in the derivation of scenarios from FEPs and the IRT encourages the further development of these techniques.

The FEPs list may be adapted according to the specific characteristics of the sites which will be the subject of more detailed investigations.

The method of combining a top-down and a bottom-up approach is consistent with best international practice, and in line with approaches suggested by the NEA and the IAEA.

All decisions to screen any FEPs out should be systematically supported by arguments on their irrelevance. More detailed FEP description in underlying reports should be referenced, summarising the main arguments in the safety case main report. This would increase the transparency and traceability of the screening process for the next stages.

As mentioned above, the set of scenarios appears generally to be comprehensive at this stage of NUMO's programme. A possible additional variant scenario that could be considered is one where the buffer is lost due to chemical erosion in the long term. This, as recognised by NUMO, could occur if the buffer is exposed to low salinity groundwater. The bounding lower limit salinities considered by NUMO are in fact such that erosion may occur. Future iterations of the safety case could preferably include a variant scenario where advective rather than diffusive conditions arise in the buffer.

Scenario descriptions could be further enhanced for clarity and transparency through the inclusion of input data summaries for each scenario. The illustrated application of some steps of the methodology (e.g. analysis of the impact of FEPs on state variables of the safety functions) could also be made more accessible to the external readers.

2.5.3. System evolution and storyboards

The formulation and illustration of the system behaviour through storyboards is informative and useful.

The IRT appreciates the decision to present scenarios in post-closure system behaviour in the form of storyboards, similar to several international examples (e.g. France and the United States). This approach could be extended to all scenarios and made more self-explanatory for an external reader. Segmentation of representations in space is likely to facilitate the analysis of relevant physical phenomena, supporting the development of a comprehensive assessment. A similar segmentation, refined over time to properly account for successive transients, could become more explicit as the disposal project progresses. Future safety cases would benefit from quantitative determinations of the different time periods distinguished in the assessment.

The storyboards are a valuable tool for communication across different disciplines involved in the description of the evolution of the repository on a range of spatial scales. The IRT understands that NUMO intends to further develop the storyboard technique so that it may, in future assessments, also contribute in a technical and scientific way to an improved understanding of the system, and this development is encouraged.

The IRT notes that the proper consideration of the main phenomena and processes, at different space and time scales, shows a good command of analysis in the geological repository project. During later phases of development, the importance of phenomena considered secondary at this stage must systematically be assessed in relation to the major processes and phenomena taken into account in the present assessment. Among the secondary phenomena, the IRT notes all interactions between materials of different natures, and also those on a large scale, such as, for example, the modifications of hydrodynamic regimes linked to climate change. The key to the analysis is assessing whether the functions sought at each stage of the repository's life are maintained. Also, a more comprehensive account of the gradual deterioration in the ability of the components to fulfil their functions would enhance the set of scenarios analysed.

2.5.4. Migration of radionuclides and dose assessment

The modelling of radionuclide migration is organised in nested shells, starting from the near field scale, then to the panel scale, repository scale and regional scale before reaching the biosphere. The nesting of different scale models facilitates simulation of radionuclide transport over large regional areas while accounting for smaller-scale transport features closer to and in the repository. In the IRT's view, a brief summary in the main report of the mathematical models and their limitations (assumptions, simplifications) vis-à-vis the conceptual process models would improve clarity of the safety case. A chart of the models implemented would also be useful to illustrate the link between the complexity of the physical processes analysed and simplifications essential for a macroscopic representation. Both these measures would make the safety case clearer for generalists, and also provide context for specialists involved in detailed analyses.

The set of calculations carried out for different disposal configurations and conditions illustrates the capability of NUMO to adequately represent the system for various conditions, and to carry out the required set of consequence calculations underpinning a safety case. The numerical modelling seems mature enough to simulate site-specific systems, and to consider different disposal configurations and conditions. The base scenarios are well processed, as are the variant ones and those involving inadvertent human intrusion. Thus, NUMO has demonstrated in the present generic safety case report the ability to adapt to increasingly real conditions or complex events. The high level of conservatism at this stage of the assessment is expected to tend towards more realism, based on less conservative assumptions. To facilitate the analysis of the geological disposal performance, NUMO relied on the implementation of simplified models which are suitable for the current generic phase. For future developments of the geological disposal project, even simpler models will be necessary for the purpose of communicating with the general public and stakeholders. Detailed and efficient models remain necessary for a good understanding of the evolution of disposal systems over time, and to support the justification of simplified models.

The biosphere model is in line with IAEA (BIOMASS) (IAEA, 2003) and ICRP recommendations (ICRP, 2013). The representative person is conservatively assumed to be from groups potentially exposed to the potentially highest radiation doses. In Japan, these include farmers, freshwater fishermen and marine fishermen. Exposure pathways include external irradiation, inhalation as well as ingestion of water and food (vegetables and animal products).

For radionuclide migration, as well as for the biosphere model in general, future improvements will mainly be required in the quality or representativity of data and assumptions.

Beyond the demonstration of capabilities, it will be important to clearly summarise the description of each scenario, the related set of assumptions and input data, and the discussion of results.

For future assessments, the IRT recommends taking into account the chemical toxicity aspects of the waste, as well as the chemical risks associated with non-radioactive elements. If these aspects are required by future regulations in Japan, their inclusion would of course be mandatory. It will also be appropriate to extend the analysis of transfers in the biosphere by considering the geochemical mechanisms of reconcentration of chemical forms, for example at an interface between soil horizons or along redox fronts. The potential impact on non-human organisms should also complete the analysis, in particular if an evaluation of impact is required by future legislation.

2.6. Management systems

Developing a geological disposal project requires a solid overall management system. NUMO's management system is reproduced in Figure 1 below, showing couplings between site characterisation, repository design and safety assessment. It is recognised by the IRT as being in line with good practice, including its inherent set of iterations. It is notably aimed at ensuring adequate coupling and maintaining flexibility. Flexibility is seen as a way to adapt the project to site characteristics, to developments in science and technology, and to evolving regulations and societal demands.

Figure 1. NUMO's management system

A major type of input data for this management strategy regards the characteristics and inventory of radioactive waste, for which knowledge will evolve over time. The IRT recommends that a system be considered and implemented in order to co-ordinate well with the authorities and producers of radioactive waste the fundamental assumptions on waste inventories on which the whole project is based.

In terms of the outputs of such an iterative process, the documents on knowledge of the site characteristics, on design options and on safety assessment are noted. Another major output is the identification of further needs in characterisation in order to improve the geological disposal project and to reduce remaining uncertainties to acceptable levels, in particular by developing R&D programmes and prioritising them so that the results can feed this iterative loop in a timely manner according to the progress of the disposal project.

Given the large number of cases studied within the framework of the geological disposal project, and in order to find one's way among the different versions, each with different input data and different results, the IRT recommends that in addition to the requirements management system, NUMO develop a configuration management system.

2.7. Research and development

The R&D programme for geological disposal in Japan and its funding are established under the leadership of METI.

The IRT notes the Coordination Council on R&D of Geological Disposal between METI, NUMO, JAEA and other R&D organisations. Additionally, the IRT understands that

NUMO's primary role is to identify R&D needs and integrate results in the safety case. The expression of R&D needs should be a logical result of the SDM-based safety case. In the presented documents, NUMO lists a large series of scientific and technological topics that would deserve further R&D; however, relatively little mention on key R&D programme priorities for the next development stage is made. The R&D technological development plan is available in Japanese (NUMO, 2020), and its summary has been produced in English by NUMO to enable the IRT to assess its content.

Given the current priority for Japan to identify sites suitable to host a geological repository, a major effort by NUMO is required on understanding the behaviour of the geological environment. It includes a scientific component for the assessment of natural phenomena likely to influence the repository and a modelling component relating to long-term changes in the geological environment. The methods for acquiring knowledge about the repository's host geological environment are also the subject of research programmes, in particular during the siting phase. In situ demonstrations carried out in JAEA underground research laboratories are relevant to that effect.

The installation of a repository in a geological environment also calls for innovative technologies. NUMO has so far focused on concepts similar to those considered abroad, adapting them to the context in question, but also considering original solutions such as the PEM. Indeed, some host rocks characteristics will require changes or adaptations in the design/EBS materials (e.g. gas-tight sedimentary rocks may require a limitation of corrosion-induced gases in the repository). The R&D programme calls appropriately for the study of alternative materials for engineered barriers, in particular for the reduction of corrosion-induced gas build-up or for cost reasons. The IRT is again of the opinion that sensitivity analyses could help NUMO focus its R&D programme. The IRT also suggests that the research explore alternative materials better suited to safe disposal in the geological medium to be studied. An interesting point of the programme concerns the packaging of TRU waste, particularly with regard to gas generation. This aspect, which had also been raised by the IRT, must be the subject of attention for long-term safety. On the technological level, the IRT notes the demand for the development of the PEM and, above all, of the means of automation for the handling and emplacement of the waste packages. Repository design approaches must also be developed further.

From the facility design point of view, the IRT recommends integrating the geological and hydrogeological characteristics of the site into the general architecture of the repository and the design of its various components. Retrievability is also considered; on this issue, the IRT recommends integrating disposal monitoring and following up with relevant parameters in terms of retrievability. The information generated will be able to feed into decision-making in terms of reversibility, an issue that remains to be investigated.

Safety assessments are also the subject of the research effort relating to improved consideration of the phenomenological evolution of the disposal system and its modelling, in line with the opinions of the IRT. It also calls for the improvement of information management tools for the migration of radionuclides and FEPs, in particular through storyboards. The examples presented in the SDM-based safety case illustrate that this work is underway, and the IRT strongly encourages its continuation. One of the important aspects of the programme concerns the migration of radionuclides through the geosphere and further into the biosphere. The aim is to achieve increasingly realistic representations, a need also identified by the IRT.

The IRT recommends a sustained effort be made to validate models and codes intended to evaluate disposal behaviour and performance. This is all the more important since the spatial and temporal scales in question are outside the usual scope, and it is therefore essential to strengthen the confidence of all stakeholders.

The five-year R&D plan will terminate shortly. The recommendations resulting from this review could preferably be integrated in a new forthcoming R&D programme. Moving from a generic safety case to site- and waste-specific safety case(s) would require strong steering by NUMO on R&D priorities and their adequacy. To advise METI on the R&D programme and associated budget, the IRT recommends that NUMO develop an R&D proposal based on the current safety case. Such a proposal should clearly define and substantiate key R&D priorities to inform the next phase of siting and the next safety case. A direct and structured exchange of research needs and research outcomes between NUMO and the involved research entities could further improve the abstraction of R&D results to the safety case and the systematic reduction of uncertainties and conservatism.

According to international experience, an implementer (in this case, NUMO) should have a major responsibility in defining and steering R&D for geological disposal.

3. Conclusion and recommendations

Summary of key observations and recommendations

Recommendations to NUMO

- ***To continue efforts to further increase its understanding of the systems in order to be able to analyse them.***
- ***To reinforce its role as specifier of R&D studies and integrator of the results obtained with the support of specialised research institutions in Japan. To rely on the lessons of the SDM-based safety case to specify R&D needs, prioritise them and submit them to the institutions in charge of conducting studies and research.***
- ***To continue its investments in international activities, both with the international bodies, the NEA, IAEA and the EC, and with the organisations abroad working on geological disposal projects.***

General observations

- ***To use the NUMO pre-siting SDM-based safety case to guide dialogue with the NRA. The pre-license dialogue's objective is to clarify expectations and steps until formal licensing phases.***
- ***To organise the exchange between waste producers and NUMO in order to refine the data on the characteristics and inventory of radioactive waste to be disposed of in the geological repository. Requested data should also ideally cover potential evolutions of waste inventories and characteristics.***
- ***To consider, for the next phase of site selection, an international peer review (such as an IAEA Artemis mission) focused on the overall program and regulatory framework of the DGR, which is useful to support the successful development of the DGR.***

3.1. General

NUMO has conducted significant work to produce the SDM-based safety case. This is based on the experience developed over the years from previous safety cases, adequate consideration of foreign practices, extensive R&D, experiments in URLs and NUMO's sustained activities within international bodies. The implementation of geological disposal of high-level and TRU waste (termed long-lived ILW in some countries) is a complex discipline with only limited international operational experience (i.e. limited to the US WIPP disposal site for defence-related TRU waste in bedded salt [US-DOE]). However, many countries are developing their disposal solutions and NUMO has also taken advantage of the progressive learning of other organisations and gradually developed methods to meet the challenges of geological disposal.

Disposal projects are complex in that they require multidisciplinary knowledge and integration, with physical representations on unusual scales of space and, above all, of time. They also use technologies that must integrate geological or mining aspects as well as aspects related to radiological protection. As for the question of the safety demonstration, it involves the development of new approaches that must embrace the complexity of the systems and the issues they raise.

In such a context, NUMO's role is to bring together and organise the necessary skills around the geological disposal project. Its major role is to be able to specify the needs for further developments, and to integrate all the scientific and technological information needed to conduct relevant analyses. NUMO benefits from national experience, notably in terms of radioactive waste and studies in underground laboratories. It also has access to many institutions able to support it in its scientific and technological developments, whether geological, physical, chemical or digital. NUMO also has access to underground working technologies and nuclear technologies that could effectively contribute to the development of the geological disposal project in Japan.

The IRT recognises that NUMO has compiled a sufficiently comprehensive safety case for the current programme stage. Given the large uncertainties associated with the basis for NUMO's SDM-based safety case, including fundamental programme uncertainties related to the waste inventory and regulatory requirements, the IRT also considers that NUMO's programme development could benefit from extending its safety case with additional sensitivity studies. Such studies could, for example, cover a range of inventories, different levels of requirements, data ranges of site properties such as rock permeability, or variation of technical specification like engineered barrier thicknesses. Such an approach, used in other countries in the framework of pre-licensing studies, would be an effective way to illustrate the flexibility and the robustness of the proposed geological disposal concepts and of the methodology used in the safety case. This would be an asset, not only from a scientific and technological point of view (e.g. for steering of R&D), but also for communication purposes with the interested local communities.

The IRT recognises that the SDM-based safety case is an adequate iterative way to describe and integrate existing knowledge at various time and space scales. The IRT notes the "more realistic" nature of the SDMs vis-à-vis the previous safety cases for geological disposal in Japan (JNC, 2000a; JAEA, 2007). NUMO has demonstrated its capability and maturity in developing a safety case, including the methodologies and tools that will be used for the assessment at specific sites, which is consistent with international practice. The IRT's recommendation to NUMO is to continue its efforts and further increase its understanding of the systems in order to be able to analyse repository performance to an adequate level for future decision-making. To do this, NUMO should have access to key capabilities nationally and continue to draw on the potential of international collaboration. The IRT encourages NUMO to continue its investments in international activities, both with the reference bodies represented by the NEA and the IAEA and with organisations abroad working with geological disposal projects.

The approach for reversibility (NEA, 2012a) and stepwise decision-making regarding DGR is not reported. It could benefit from a comprehensive description of the process leading to reverse decisions. This aspect, relating mainly to the reversibility of disposal decisions, should also be the subject of specific development. The IRT notes that NUMO, from its own role, could consider proposing a reversible decision-making process. Whereas this would imply constraints on NUMO's programme, it could also help the dialogue with possible DGR host municipalities, decision makers and other stakeholders, as well as providing guidance to future generations at major disposal decision points.

NUMO's activities and the successful development of a DGR also require exchanges and interactions with many institutional stakeholders, some of whom should provide decisive information and guidance for the design and safety assessment of the geological repository, as recommended in the IAEA Safety Standards on the Safety Case and Safety Assessment for the disposal of Radioactive Waste (IAEA, 2012):

> *"Involvement of interested parties 4.91. Early involvement of interested parties should be ensured as part of the process of building confidence in the safety of the disposal facility. A range of different models for interested party involvement has been applied in different States, and extensive research has been conducted on the methods of engaging interested parties in both national and international research programmes. A key consideration is that interested party involvement should take place within an open and transparent framework for consultation, with clearly defined rules of procedure. The process for involvement of interested parties should be set out in the safety case."*

A key consideration is that such exchanges and interactions with institutional stakeholders should take place within an open and transparent framework, with clearly defined procedures. The IRT considers that, on the one hand, the current SDM-based safety case constitutes an adequate foundation for such dialogue and that, on the other hand, such dialogue must inform the next steps in siting and in safety assessment. The process of involving interested parties should therefore be tailored to the various needs for future safety cases and associated decisions

In the following subsections, the IRT suggests key points to be investigated, together with the regulators, nuclear industry and R&D organisations, and makes recommendations specific to NUMO's activity.

3.2. Fundamental feasibility of geological disposal in Japan

NUMO's SDM-based safety case shows the ability of NUMO's teams to carry out a safety analysis of geological disposal in Japan and to provide a complete safety case adapted to the current stage of the project. Limits identified by the IRT are related both to the generic nature of the exercise carried out, and to the uncertainties surrounding its programme boundary conditions:

- Geologically, areas offering the stability necessary for geological disposal have been identified despite the complex structures forming the Japanese archipelago. Three groups of a priori suitable geological formations have been the subject of more detailed, non-site-specific representations through site descriptive models (SDMs). Though appropriate at this stage of DGR development, the SDMs remain generic in nature; the introduced conservativeness and arbitrary choices may therefore obscure specific rock characteristics. Future challenges include ensuring the capacity of sites located in the territory of voluntary municipalities to provide the key safety functions: namely, according to NUMO terminology, isolation and containment. With the knowledge already available, NUMO is able to mobilise teams capable of pursuing increasingly detailed site investigations and assessments. It is also able to specify the needs for additional knowledge on the sites, in particular through performance and safety assessments of individual sites. The IRT considers that, at this stage, the tools and technologies for field data acquisition and for their processing are available.
- Disposal design, while again generic by nature, also appears to be at an advanced stage of maturity. It builds on international experience, but is also based on targeted developments, as illustrated by the concept of PEM. The studies carried out and the tests and models show that the needed technologies are available, and, above all, that the teams are able to develop them to meet the specific needs that could arise during subsequent phases of the geological disposal project. One of the major challenges, when real sites are studied, will consist in adapting the concepts to the real characteristics of the geological environment in order to ensure post-closure safety over a very long time frame.
- NUMO has demonstrated its ability to conduct safety studies. NUMO conducts its safety assessments and draws up its safety cases consistent with international recommendations and practices, in particular those proposed by the NEA (NEA, 2005) and the IAEA (IAEA, 2012) as well as with other international practices. Numerous studies in support of the safety demonstration, and the resulting models, illustrate NUMO's ability to represent geological disposal and to describe and analyse its possible evolutions. Here again, the limitations of the exercise are due to its generic nature. This results in high levels of uncertainty: however, many of

these will be gradually reduced over the successive phases of investigation. Phenomena considered non-determining at this stage can be analysed during the later phases of the development of the geological disposal project. In addition, certain aspects need to be clarified independent of site data. These are related specifically to the regulatory requirements and the inventory data of the waste that will have to be disposed of. As the implementer and considering its experience, NUMO has an important role in analysing and specifying these needs and informing the authorities and waste generators, which will have to establish requirements and specify waste inventories.

- As previously underlined, the study of geological disposal is complex. It calls upon many scientific disciplines, technologies and methodologies that are both complex and evolving. The development of geological disposal should take into consideration a framework of requirements and, especially, should comply with a dedicated regulatory framework. The political and social context of the development of geological disposal projects also has its own requirements and dynamics that must be taken into account. Management systems have been put in place to adequately integrate all the information available at any one time and to reproduce the studies and their results. NUMO has set up these systems to allow it to ensure good control of its projects. It will be able to continue its studies in later phases, ensuring adequate quality management.

Having reviewed the various points necessary for the realisation of geological disposal of radioactive waste, and taking into account the geological context of Japan, the IRT considers that elements of its feasibility have been demonstrated. The fact remains that many studies are still necessary for the next steps, in particular according to the characteristics of the sites that will be considered. NUMO has demonstrated its ability to fulfil such a mission. The observations made in Annex D are intended to support NUMO for future developments of the geological disposal project in Japan.

3.3. Key points related to the safety case framework

It is useful to recall here the supervisory role of METI, the independent role of Japan's Nuclear Regulation Authority (NRA) in charge of establishing requirements and regulating compliance, and NUMO's role as the implementer of the geological disposal project.

As a DGR project has numerous external interfaces, i.e. regulatory, industrial, political and social, the project will also have to be bounded and supported according to these different dimensions. For those dimensions, the IRT has limited its observations to the technical aspects directly related to the SDM-based safety case, namely the regulations and the industry producing the radioactive waste to be disposed of, and to R&D.

Through the SDM-based safety case, three essential points caught the attention of the IRT. These are the regulatory expectations for siting and establishing the next safety case, the scope of waste characterisation and inventory, and R&D programmes supporting DGR development. Whereas it is clear that these are not the sole responsibility of NUMO, their handling largely conditions the relevancy, appropriateness, representativeness and reliability of NUMO's future studies and safety cases.

The IRT understands that the NRA is in the process of developing dedicated DGR regulations and would like to emphasise the importance of having a first set of such regulations as early as possible. International experience shows that regulatory requirements can and should evolve as knowledge of disposal increases. With this approach, the first set of regulatory requirements would not need to cover all detailed level requirements related to the DGR safety.

International experience shows that a pre-licensing dialogue between the implementer and the nuclear regulatory authority (without compromising the independency of the regulatory authorities) provides the implementer with an understanding of regulatory expectations, and is an important element for successful DGR development. The IRT recommends that NUMO proactively engage with the necessary organisations for the establishment of a pre-licensing dialogue with the regulator based on the current safety case. Such exchanges prior to the development of the successive safety cases would reduce the risk of NUMO's future work deviating from the regulator's expectations.

Regarding waste inventory and characterisation, the IRT recognises that NUMO works within the boundaries of Japan's Final Disposal Act (METI, 2000 and 2015) and Final Disposal Plan. The IRT notes that the utilised inventory in the safety case dates back to 2008 and is generic in nature. The IRT recommends that this be updated, taking into consideration the full spectrum of current waste inventory and possible future waste from different streams. The IRT also recommends that NUMO carry out sensitivity studies regarding the consequences of potential evolutions in the inventory in terms of e.g. design, safety and disposability. This will make it possible to identify the areas where uncertainty needs to be reduced most and to test the robustness and the flexibility of the safety case methodology, design options and repository capacity. Such sensitivity studies would also foster a dialogue with the waste producers (i.e. the JNFL, JAEA and utility companies in NUMO's case) regarding the optimisation and disposability of potential waste types to be disposed of by NUMO. Such exploratory analyses would also be useful in specifying the limits of inventories to be retained for future geological disposal studies.

Moving from a generic safety case to site- and waste-specific safety case(s) would require strong steering from NUMO on R&D priorities. The IRT recommends that NUMO develop an R&D proposal based on the current safety case in order to advise METI on the nationwide R&D programme for DGRs. Such a proposal should clearly define and substantiate key R&D priorities to inform the next phase of siting and the next safety case. According to international experience, an implementer (in this case, NUMO) should indeed have a major responsibility in defining and steering the R&D for geological disposal.

Based on international experience, a national framework including stepwise licensing and clear roles for different organisations is a prerequisite for the successful implementation of a DGR. The IRT focused its peer review work on NUMO's generic safety case, but observed the above-mentioned elements of the national framework that might need enhancement. To further evaluate these aspects, the IRT also notes that an international peer review (such as an IAEA Artemis mission) focused on the overall DGR programme and regulatory framework would be useful and would support the successful development of the DGR.

3.4. Technical recommendations to NUMO

Summary of specific recommendations to NUMO

- **Safety-related functions expected for a geological repository: for future phases, where possible, to match the safety functions with quantitative performance indicators and, when possible, with criteria for acceptable performance.**
- **Capacity of the geological medium to provide an appropriate delay of radionuclide transport: to be taken into account more specifically during site evaluations. This may prove to be a discriminating criterion in the event several volunteer communities arise.**
- **Design options: to be kept open as long as possible in order to keep flexibility in design as additional knowledge is acquired.**
- **Flexibility of design options requires monitoring of changes, which can be ensured using a configuration management system.**
- **Reversibility of disposal decisions: to make proposals, in particular by proposing decision-making processes that can mark out the life of the geological disposal, and keeping options open for future generations.**
- **Monitoring: to integrate retrievability into the objectives of monitoring,**
- **Additional phenomena: to explore the phenomena considered at this stage as non-dominant or non-determining in order to assess how they should or should not be taken into account in subsequent phases.**
- **Handling and emplacement of waste packages in disposal tunnels/vaults: to be studied, with tests in an underground environment.**
- **Design developments: to be continued, particularly with a view to adapting to the characteristics of the sites that will be considered for future studies.**
- **Operational safety: to be supplemented by design features allowing the reduction of operational risks, and operational safety assessment to be supplemented by taking into account possible failures of the protections envisaged by design and by analysing resultant doses to workers and to the public.**
- **Design and construction procedures to be adapted to the particular characteristics of the geological formations envisaged for the following stages in a way that allows contrast between formations being reflected in the design.**
- **Development of storyboards to be generalised, by seeking a more exhaustive representation of the underlying information and the data to be processed.**
- **Models and couplings: to establish a mapping of the various models included in the assessment, their couplings, and the associated codes. This would provide an overview of modelling efforts, make it possible to illustrate the adaptation of the various tools at the level of analysis, as well as to better understand the simplifications of representations proposed.**
- **Validation of the models and the computer codes: to increase efforts to validate models and computing tools in the near future.**

NUMO has carried out an in-depth analysis of the safety-related functions expected for a geological repository. For future phases, the IRT recommends, where possible, matching the safety functions with quantitative performance indicators and criteria for acceptable performance.

The IRT encourages NUMO to continue using the SDM approach to iteratively integrate geoscientific knowledge as it is acquired during the different stages of the site-selection process. Such an approach will ensure a coherent and multidisciplinary description of the different volunteer sites.

NUMO's overall strategy is based on the sound insight that geological disposal can only be evaluated as a system, the components of which contribute to fulfilling the various functions needed. In this perspective, and especially for the research and site evaluation phase, the role of the geosphere is important. The capacity of the geological medium to provide an appropriate delay of radionuclide transport will have to be taken into account in more detail during site-specific evaluations, and this may prove to be a discriminating criterion.

In terms of repository design, and given the uncertainties inherent in the system, the IRT encourages NUMO's plans to keep the various options open as long as possible in order to keep flexibility of design evolution as additional knowledge is acquired. Such flexibility also requires monitoring of changes, which can be ensured using a configuration management system, also covering the various interdependencies between knowledge of the waste and the geological environment, design of the disposal facilities, relevant phenomena, and the integration of these aspects through safety studies.

NUMO addresses well the retrievability of waste in disposal and takes this into consideration in the repository design approach. The IRT recommends integration of monitoring aspects into the reversibility and retrievability objectives.

An integrated management system is in place to support the efficient implementation of activities. In order to properly trace the numerous case studies and calculations, each with their own sets of data and hypotheses, the IRT recommends, as mentioned above, the implementation of a configuration management as part of the overall management system. The configuration management should be coupled with requirement management and enable recording of the various technical options studied as well as the sets of calculations associated with each of them. The scope of configuration management should be adequately adjusted, considering the nature of the DGR and the phase of implementation.

The design of the repository is, at this early stage, accompanied by numerous uncertainties. NUMO has considered major phenomena likely to affect the evolution of the repository and therefore its safety. For subsequent phases, the IRT sees a need to evaluate also phenomena that have at the present stage been disregarded with the justification that they are of secondary importance for the system evolution.

Studies on disposal packaging should continue, in particular with handling and emplacement tests in an underground environment. The IRT encourages NUMO to continue its design developments, particularly with a view to adapting to the characteristics of the sites that will be considered for future studies.

The approach to operational safety is also at a preliminary stage. The IRT acknowledges NUMO's development of a preliminary assessment at the current stage of the programme, based on generic assumptions and an early conceptual design. For future safety cases, the IRT recommends considering additional design options for mitigation of operational risks (e.g. fire). The IRT also recommends that the safety assessment be supplemented by including additional scenarios, such as potential failures of the protections envisaged by design and by including all potential exposure pathways to workers, to the public and to the environment.

The long-term safety assessment is based on many assumptions that are considered very conservative at this stage. Consequently, the results of the different cases studied are often quite similar, and do not provide more detailed information for discriminating among design options and/or potential host geological formations. It is reasonable to imagine that the means of design and construction will be adapted to the particular characteristics of the geological formations envisaged for the following stages, and hence that contrasts between formations should be reflected in the design.

NUMO's safety assessment methodology seeks completeness and a consistent treatment of uncertainties. Many assumptions leading to conservatism are consistently utilised. This provides robustness to the conclusions as regards the potential for long-term safety, but also reduces the ability to distinguish between different design and host rock options.

As a preparatory step for the next stage, NUMO could consider developing sensitivity cases with alternative site properties, those of the range of host rock types that can reasonably be expected. This could inform the development of a methodology to make better use of the host rock characteristics in view of optimising the design. The presentation of cases using storyboards is relevant. It makes it possible to better understand the different phenomena that must be taken into account at each disposal location, but also as a function of time. Their development could be generalised by seeking a more exhaustive representation of the underlying information and the data to be processed.

Finally, a mapping of the various models included in the assessment, their couplings and the associated codes would be beneficial. It would provide an overview of modelling efforts, make it possible to illustrate the adaptation of the various tools at the level of analysis, as well as to better understand the simplifications of the proposed representations. In this framework, the IRT recommends taking up arguments from underlying reports to substantiate decisions for screening processes to be considered at the different levels of modelling. To provide further confidence in the results of modelling, there is also a need to further validate the models and the computer codes used in the safety case. The IRT recommends NUMO increase its efforts on this work in the near future.

Annex A. Members of the International Review Team

JeHeon Bang

JeHeon Bang is a researcher at KINS, a Korean nuclear safety organisation (TSO). He is a nuclear engineer and physicist with over 10 years of professional experience in the field of radioactive waste disposal. He graduated from Kyungpook National University (Korea) with a Bachelor of Science in physics in 2009 and received his Master of Science in nuclear engineering from Pohang University of Science and Technology (Korea) in 2013.

From 2012 to 2014, he was a staff member of KORAD, Korea's radioactive waste management agency, where he was responsible for operational accident analysis for cavern disposal facilities and post-closure safety assessments for surface disposal facilities.

JeHeon Bang has been in his current position as Senior Researcher at KINS since 2015. As part of the Radioactive Waste Disposal Regulatory Department, he is responsible for the review of licence applications, on-site inspections and rulemaking for radioactive waste disposal. In particular, he has been contributing to the development of regulatory requirements and guidelines for HLW disposal through a national regulatory research project, planned for 2021-2029.

Allan Hedin

Allan Hedin is a Senior Company Specialist on safety assessments at the Swedish Nuclear Fuel and Waste Management Company (SKB). His responsibilities include the management of SKB's safety assessment projects for deep repositories for spent nuclear fuel.

Allan Hedin received a M.S. in engineering physics from the University of Uppsala in 1983 and a Ph.D. in ion physics from the same university in 1987. His thesis concerned theoretical and experimental work on interactions between fast heavy ions and solids with applications in mass spectrometric techniques. After four years of further academic research in the fields of laser-induced desorption and scanning tunnelling microscopy, he was employed by the Swedish National Chemicals Inspectorate in 1991 to work with risk assessments of chemical substances and products.

Allan Hedin has been working with SKB since 1994. He was originally employed to work with probabilistic radionuclide transport calculations and has gradually obtained more general responsibilities for safety assessment methodology issues. He has a particular interest in developing simplified mathematical models that capture the essential properties of more complex representations in the field of safety assessment. He led the work on the safety assessment in support of SKB's licence application for a spent nuclear fuel repository at Forsmark, Sweden.

Allan Hedin is a member of the NEA's Integration Group for the Safety Case (IGSC) and has taken active part in several international projects organised within the IGSC. He was responsible for reviewing the safety assessment methodology in the NEA international peer reviews of Andra's Dossier 2001 and Dossier 2005 reports. Through SKB's international consultation services he has worked in advisory groups to several national programmes. He is also a member of the international advisory group for the Finnish safety assessment in support of an operational licence application for a spent fuel repository at the Olkiluoto site in Finland.

Jussi Heinonen – Chair of the IRT

Since December 2020, Jussi Heinonen leads strategic regulatory oversight development for Finland’s Radiation and Nuclear Safety Authority (STUK), involving risk-informed regulation and oversight, customer orientation and digital transformation as key drivers. Jussi Heinonen holds a Master’s degree from the Helsinki University of Technology in material sciences with a specialisation in corrosion and electrochemistry.

Before his current position, Jussi Heinonen worked as Director of Nuclear Waste Regulation and Safeguards, and has almost 20 years of experience in regulating spent fuel and radioactive waste management. He has been working as Section Head for Nuclear Waste Facilities Regulation, which is responsible for the regulatory oversight of nuclear waste facilities design, construction and operation in Finland. Jussi Heinonen has been involved with regulatory oversight of spent nuclear fuel disposal, focusing on disposal canister long-term performance, and engineered barrier development, design and construction of the underground disposal facility. Jussi Heinonen was also co-ordinating oversight of spent nuclear fuel interim storage design and construction, spent nuclear fuel encapsulation plant design and preparation for the licensing process of Posiva’s spent fuel encapsulation and disposal facility.

Jussi Heinonen has been a member in several international committees and groups in the NEA, IAEA and Nordic countries supporting regulatory organisations. He has participated in several IAEA Artemis peer review missions as team leader and review team member. He has also participated in an IAEA peer review in France evaluating Cigéo’s safety options dossier for disposal, and in Russia regarding deep well injection practices for liquid radioactive waste.

Jean-Michel Hoorelbeke

Currently Senior Advisor for Strategy and Foresight with French RWMO Andra, Jean-Michel Hoorelbeke has thirty-nine years of experience in the design and safety of radioactive waste management facilities in France and abroad. His expertise includes storage, disposal (geological, shallow depth) and holistic and graded approaches to waste management from VLLW to HLW. He successively acted as scientist and department head with the French Atomic Energy Commission from 1982 to 1993, Andra’s project manager for the now-called Cigéo geological disposal project from 1993 to 2007, Andra’s projects and programmes deputy director from 2007 to 2015 and Andra’s safety, environment and waste management strategy deputy director from 2015 to 2020.

He chaired or contributed to numerous consultancies and technical meetings with the IAEA and the NEA to develop international guidance. He also provided expert support to develop radioactive waste management programmes in various countries (especially Hungary, Ukraine and the United Kingdom).

He holds a Master's degree in science and executive engineering (MINES ParisTech PSL University in France, 1982). He was awarded in 2008 the French National Engineering Grand Prix for the Meuse/Haute-Marne (Bure) Underground Research Laboratory. He is Chevalier in the National Order of Merit of France.

Mihaela Ion

Mihaela Ion is Manager, Safety Assessment at the Nuclear Waste Management Organization (NWMO) of Canada, overseeing activities related to the fuel waste inventory, operational safety and the long-term safety assessment supporting a deep geologic repository for used fuel in Canada. Mihaela Ion has over 25 years of experience in the nuclear safety and licensing of nuclear facilities, including over 13 years in the field of radioactive waste disposal. She has been responsible for the development, technical review and management of safety analyses and for ensuring compliance with regulatory requirements in nuclear safety and environmental protection in Canada, Romania, the United Kingdom and the United States.

In 2018, Mihaela Ion contributed to the development of waste disposal and storage considerations for small modular reactor applications in Canada, as a member of the waste management expert working group.

Mihaela Ion participated as IAEA Joint Convention Officer at the Sixth IAEA Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management Review Meeting in 2018, and as member of Canada's team at the Fifth IAEA Joint Convention Review Meeting in 2015.

Mihaela Ion represented the NWMO at the Nuclear Energy Agency (NEA) contributing to the last phase of the NEA's Preservation of Records, Knowledge and Memory initiative. She is currently an active member, as a representative of the NWMO, of the NEA's Integration Group for the Safety Case and NEA's Expert Group on Operational Safety.

Philippe Lalieux

Philippe Lalieux is Director for Long Term Waste Management within ONDRAF/NIRAS, the Belgian Agency for Radioactive Waste and Enriched Fissile Material. His responsibilities encompass the definition of strategies and policies for the long-term management of waste and spent fuel, the RD&D programme regarding geological disposal, the establishment of waste acceptance criteria, the qualification of waste production and measurement equipment as well as the confirmation of the disposability of waste. He is also in charge of the international relationships and obligations of the Agency (in particular related to the 2011/70/Euratom Directive).

Since 2016, he has also been a member of the Board of the EIG Euridice, which oversees the Belgian underground research laboratory.

Philippe Lalieux has more than 30 years of professional experience in the field of radioactive waste and spent fuel management, both at national and international levels.

From 1995 to 2000, he worked for the Radiation Protection and Waste Management Division of the Nuclear Energy Agency in Paris.

Philippe Lalieux is the current Chair of the IAEA's International Radioactive Waste Technical Committee (WATEC) and the Vice-chair of the "*Groupe Permanent Déchets*" that provides advice to the French Nuclear Safety Authorities for all aspects pertaining to the safety of radioactive waste management. He is also member of the External Advisory Board of the European Joint Programme on Radioactive Waste Management (EURAD). He is the past Chair of the Implementing Geological Disposal of Radioactive Waste (IGDTP) technological platform that co-ordinates a large range of organisations active in R&D for geological disposal.

He actively participates as an expert in various international peer reviews (e.g. safety case, licence application).

He holds a Master’s in geological sciences and a Master’s in geophysical sciences as well as a degree in radiation protection.

Jens Mibus

Jens Mibus is Head of Division at the Federal Office for the Safety of Nuclear Waste Management (BASE), the German nuclear supervisory authority. He is a geochemist with over 25 years of experience in the field of radioactive waste management with a special focus on geological disposal.

Jens Mibus holds a PhD in geochemistry and a diploma in mineralogy/geochemistry from the Freiberg University of Mining and Technology (Germany). After working as an environmental consulting engineer on the legacies of uranium mining (1996-2000), he was Research Assistant at the Dresden-Rossendorf Research Centre (2001-2006), where he investigated solute transport and speciation in porous media. Following that, he was awarded the Marie-Curie Fellowship (2006-2008) to study the pore structure of compacted claystones (Opalinus Clay) at the Laboratory for Waste Management, Paul Scherrer Institute (PSI, Switzerland).

Jens Mibus joined the National Cooperative for the Disposal of Radioactive Waste (NAGRA, Switzerland) in 2008 as Project Manager in Safety Analysis. In this role he was in charge of conducting safety analyses, developing assessment scenarios, managing FEPs, conceptualising radionuclide transport, and managing national and international research projects, among others.

Since 2018, Jens Mibus has served as Head of Division “Overarching and International Questions of Site Selection” at the BASE. His main responsibilities in this role include: regulatory review of the safety case, management system and safety culture, and representation in international bodies and committees, such as the IAEA and NEA. He is a member of the Integration Group for the Safety Case (IGSC) and contributes to working groups of the NEA (EGSSC), IAEA (WASSC) and WENRA-WGWD.

Annex B. Terms of reference

INTERNATIONAL PEER REVIEW OF THE

"NUMO Pre-siting, SDM-based Safety Case Report"

Following a safety-oriented, stepwise procedure for geological repository siting, it is important for NUMO to increase its activities in communicating with stakeholders in a transparent, impartial and open manner. It must also keep its knowledge and skills in relevant fields up to date through the promotion of relevant R&D activities in co-operation with experts in Japan and abroad.

In November 2020, NUMO started a literature survey (LS), the first stage of the site investigation process, at two volunteer municipalities in Hokkaido. The LS was conducted via desk-studies based on site-specific information and data in the open literature, such as geological and natural resources maps. The Japanese government and NUMO are continuing to promote dialogue throughout Japan to deepen public understanding of geological disposal and to encourage more municipalities to accept such literature surveys.

It is important to demonstrate to a broad range of stakeholders the capability to implement the programme. Key boundary conditions include:

- NUMO is responsible for disposing of large inventories of HLW and ILW generated from the reprocessing of spent nuclear fuel and mixed-oxide fuel fabrication (termed TRU waste in Japan);
- Japan is an archipelago characterised by active tectonics and geological complexity;
- Siting will proceed on the basis of volunteer communities, either responding to an open call or to government solicitation of more technically favourable areas based on the METI Nationwide Map www.enecho.meti.go.jp/en/category/electricity_and_gas/nuclear/rwm/pdf/map_en.pdf (METI, 2017);
- It is hoped to encourage more volunteer municipalities to accept the LS;
- For the two current volunteer sites, a decision to go forward to the next investigation stage will only be made after the LS is complete and will be dependent on the results of the LS and agreement of both the mayors of each municipality and the governor of Hokkaido;
- The associated regulatory framework is not yet fully established;
- Socio-political challenges in gaining public acceptance following the Fukushima Daiichi accident have resulted in a requirement for increased operational resilience.

Therefore, NUMO cannot decisively focus on the likely geological environment of sites that may come forward to initiate the first phase of characterisation. However, NUMO is required to develop and demonstrate, in a general manner, that it possesses the experience and technology to assess these and identify pros and cons to support the decisions involved in the stepwise siting process. As a starting point, NUMO will build on the knowledge base developed to show the fundamental feasibility of disposal of HLW and TRU waste in Japan provided by the H12 (JNC, 2000a) and TRU-2 (JAEA and FEPC, 2007; JAEA, 2007) studies. These studies summarised work carried out by R&D organisations to support management of such waste before NUMO took responsibility for their geological disposal.

A major advance since the earlier work is the move towards site-specific assessment via the definition of site descriptive models (SDMs), which represent typical features of geological settings in Japan. The SDMs are then used to illustrate how repository designs – and in particular the layout of underground facilities – are tailored to the conditions found at the site examined. These designs are then assessed in terms of both operational and post-closure safety, in the latter case with consideration of the need to evaluate performance as realistically as possible so that pros and cons of particular sites / design options are highlighted. However, as is also pointed out in several places throughout the report, only limited efforts have been made to assess the importance of uncertainties. Instead, uncertainties are usually handled by simplifying descriptions, making conservative assumptions and introducing stylisations. This approach is justified, since data from specific sites are not yet available and since detailed designs remain to be developed. However, this also means that at this stage, only limited conclusions can be drawn on key issues, for example the differences between types of environments and how to optimise waste packages or repository layouts

In addition, to confirm the fundamental feasibility of safe disposal in Japan, this work aims to identify key future challenges and R&D priorities. However, it is important not to consider it as a rigorous safety case, which would be premature at the current stage of our programme. It is more utilisation of the safety case approach to provide a check on NUMO's preparation for future phases of work and development of a template for future, more complete and rigorous, safety cases for specific sites. Because of this important role in providing a focus for our future programme, the safety case should be extensively reviewed by both national and international experts to ensure that it is fit for purpose.

A Review Committee consisting of Japanese experts established by the Atomic Energy Society of Japan (AESJ) reviewed the Japanese version of the NUMO Safety Case Report and issued the review result in December 2019 (AESJ, 2019; AESJ, 2019). Taking into account the comments and suggestions from the AESJ Review Committee, the safety case report was revised and published as the "NUMO Pre-siting, SDM-based Safety Case Report" (in Japanese) in February 2021. An English version of this publication has now been produced for an international audience.

Objective

The objective of the peer review is to provide an independent review of the English version of the "NUMO Pre-siting, SDM-based Safety Case Report". The review will assess the maturity and readiness of this generic safety case, developed at a pre-siting stage, to confirm the technical feasibility of deep geological disposal in Japan and to develop a framing structure applicable to site selection. In particular, it will check that the report reflects the latest international technical knowledge and R&D achievements, built around the concept of a safety case, as established by the NEA and IAEA.

Taking into account the NEA international review (NEA, 2016) requested by METI on the siting process in the Japanese programme, which is relevant to the boundary conditions for the NUMO Safety Case Report, NUMO requested that NEA also review this report. The review should determine sufficiency and credibility of the following components of the report:

- the safety strategy at this pre-selection stage and the approach chosen to prepare to initiate site-specific work;
- the assessment of geological environments considered to be representative of those that would result from the siting programme and the proposed methodology for site characterisation at the beginning of the siting process, focusing on knowledge integration within SDMs;
- the repository design approach, tailoring layout to potential host rocks, and the assessment of the practicality of repository construction, operation and closure.
- the operational and post-closure safety assessments for repositories tailored to the host rocks described;
- the implementation of management tools to facilitate integration of the siting, design and safety assessment teams and provide the iterative feedback required to assure technical quality;
- the fundamental feasibility of geological disposal in Japan within geological environments similar to the type of environments assessed;
- the critical synthesis of the safety case strengths and weaknesses as the basis for developing an R&D plan for the improvement of the credibility of the safety assessment and practicality of implementation of the geological disposal programme.

Basis for the review

The review is focused on the following material, which was made available in November 2021, at the kick-off meeting:

- 'Main report' of the NUMO Pre-siting, SDM-based Safety Case (~ 600 pages)

The main report forms the basis of the safety case. The Japanese report is complemented by 'supporting reports' (171 documents, ~ 4 000 pages) which are hyperlinked to and provide background technical detail for the main report. Although such supporting reports are referenced in the English translation of the main report, these have not been translated into suitably high-quality English and hence are not hyperlinked. We have tried to ensure that the English report provides sufficient detail for the NEA review but, if required, translated summaries of specific supporting reports can be provided.

These materials will be delivered via email.

The International Review Team

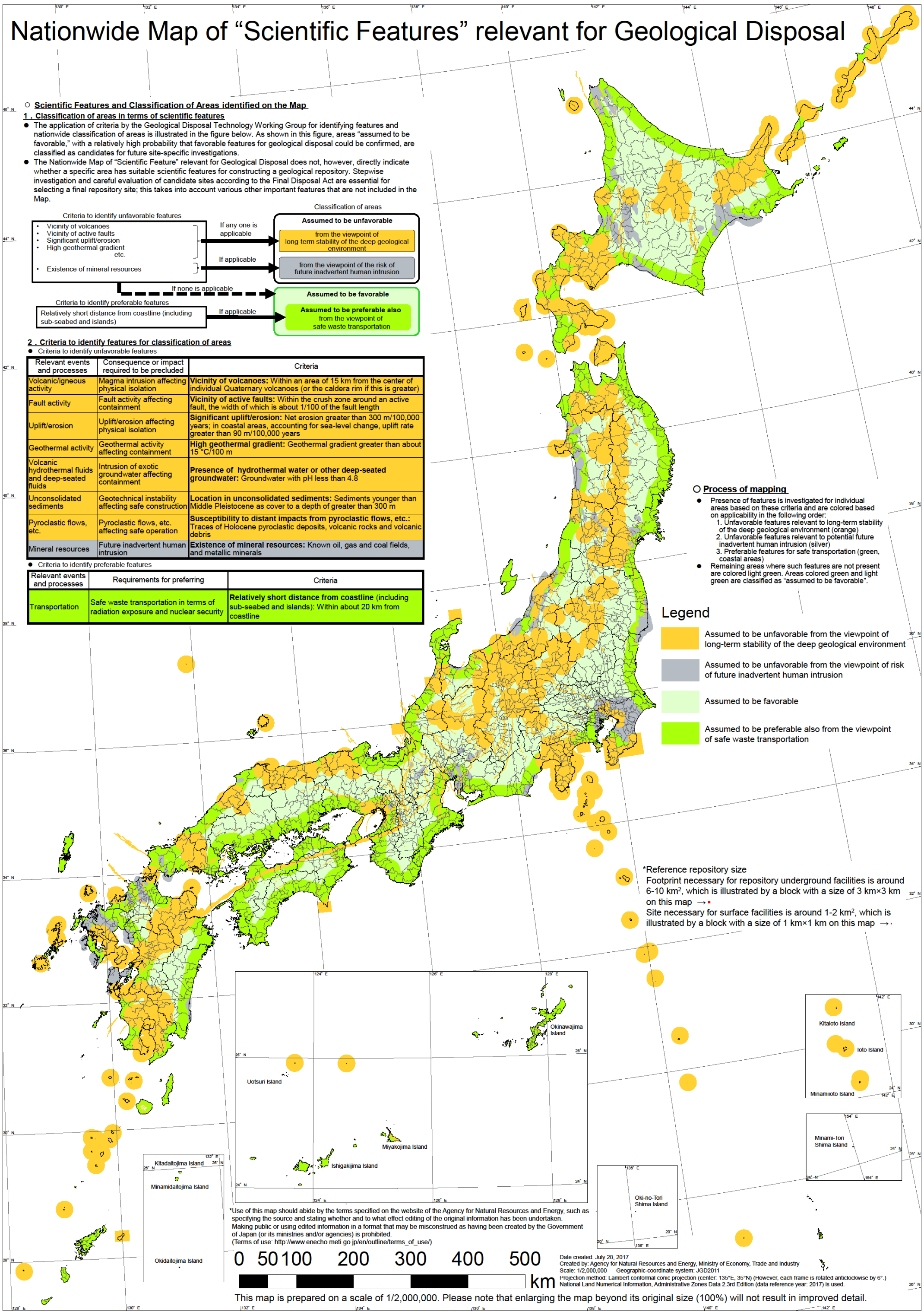
An International Review Team (IRT) with broad international experience should be assembled independently by the NEA. It is assumed to consist of seven external experts, a hired technical writer and two NEA staff, covering the following areas of competence:

- Expert knowledge in siting and design of deep geological repositories in crystalline and sedimentary rock formations;
- Expert knowledge for conducting safety assessment of geological repositories for HLW and TRU waste.

Impartiality requirements

To assure high standards of integrity and to avoid conflicts of interest, the selected review team experts must not have been involved with the Japanese radioactive waste management programme, including the Japanese government or any of its subsidiaries / affiliated bodies, in the last five years. A statement of impartiality will be included in the review report.

Annex C. - Nationwide map of "scientific features" relevant for geological disposal



Annex D. Summary of IRT's comments, findings, recommendations for each of the sections of NUMO's pre-siting safety case

For the convenience of NUMO authors, this Annex presents a summary of the IRT's key comments submitted to NUMO during the review of the Pre-siting SDM-based Safety Case. Presentation of the comments follows the outline of the safety case report. These comments refer to selected topics applicable to each section of the report.

D1. Background and basic concept of geological disposal in Japan

D1.1. Basic concept of geological disposal

Geological disposal is discussed in light of the fact that the radioactivity of the disposed waste decreases over time. This is illustrated with a diagram showing the radioactive decay of high-level activity vitrified waste, in comparison with the radioactivity of uranium ore. This regularly used representation is, however, incomplete in the sense that it only compares the radioactivity and not the respective compositions of the uranium ore, and that of the waste, which is much more complex, containing not only radioelements with very long half-lives (^{129}I, ^{36}Cl, ^{79}Se), but that are also more mobile than many other fission products or actinides.

An additional justification is provided, indicating that one of the objectives is to place the waste in depth, protected from natural hazards or human activity. Without questioning these foundations, it would be useful to recall the principle of isolation sought, in an environment that is not conducive to the transfer of radioelements to the biosphere and the surface. The provided illustration may also be somewhat difficult to grasp for non-specialists.

D1.2. Background to deep geological disposal in Japan

The brief historical review provides an appropriate account of the options considered in Japan for the geological disposal of high-level activity waste and TRU waste, in particular reviewed following the Fukushima Daiichi accident. It also illustrates the experience already accumulated by the Japanese teams in terms of studies for geological disposal.

D1.3. Revised strategy for geological disposal

The relevance of geological disposal for high-level waste and for TRU waste has been confirmed, despite the rather restrictive geological conditions in Japan. The updated approach is characterised by its progressiveness and flexibility. This is reflected in particular in the establishment of a reversibility mechanism.

The involvement of the various authorities for the implementation of the geological disposal project has been specified by the government. Consultation and dialogue are recognised as key to the continuation of the project.

Given the complexity of geological disposal projects, many organisations are involved. For a good understanding, the respective roles and responsibilities should be presented (for example in Table 1.4.2).

D1.4. Overview of the NUMO safety case

The purpose of the report "The NUMO Pre-siting SDM-based Safety Case" is clearly displayed. It covers the description of technologies for site assessment, the presentation of repository design options and possible engineering choices to ensure safety, the demonstration that this can be achieved by the means envisaged, and finally the identification of additional R&D needs.

D2. Safety concept

Chapter 2 presents the safety concepts and the strategy for safety demonstration. The IRT shares the view that there is a need for an iterative approach, throughout the phases of the project, but also during the study of the various options. On the other hand, the iteration points are not identified at this stage. It would be useful for NUMO to identify additional indicators, making it possible to specify the points of foreseeable iterations.

D2.1. Inventory of waste

The volume of HLW and TRU waste to be disposed of in the repository is based on the guidance in the Final Disposal Plan provided by the government according to the Final Disposal Act. The inventory is important input data. The generic safety assessment can at this stage be carried out on the basis of present data, and updates will be necessary as soon as more targeted assessments become necessary. It is therefore important to have detailed knowledge of the types of waste and their respective volumes. There is also a clear need for defining waste acceptance criteria (WAC) as early as possible. NUMO already has an important basis to develop generic acceptability criteria as a starting point (NEA, 2012b). Such a definition must also be progressive and linked to iterations for the safety assessment. Continued activity in this area should be considered for all types of radioactive waste to be disposed of in the geological repository, HLW and TRU waste.

It will also be necessary to fully understand the upstream phases, those of production and storage of waste, particularly that of very high activity. Indeed, the management strategy, and therefore the disposal concepts, could be sensitive to the cooling time of vitrified waste. Beyond the earlier indication of a cooling period of 30 to 50 years, it would also be advantageous for NUMO to develop its own analysis based on possible site characteristics.

The question of the reprocessing of MOX fuels has not been dealt with, as this is a matter for future political decisions. However, a preliminary analysis of the possibilities or conditions of their disposal could enlighten the political decision to come.

D2.2. Required safety functions

The basic concept for ensuring the long-term safety of geological disposal is expressed in terms of two key functions, namely isolation and containment. The latter covers the notion of containment as well as retardation, this being clearly indicated in the report. However, in order to avoid any risk of confusion, and also to clearly distinguish the physical phenomena and the processes involved in order to be able to analyse them distinctly, it is recommended to adopt the terminology that clearly distinguishes between containment and retardation.

Care must also be given to the term "complete containment", since this type of function may answer to requirements for specific contexts such as in Finland or Sweden, but its relevance in other cases needs to be justified.

The main functions identified during operation are containment and radiation shielding. It is also suggested to clearly analyse the risks of criticality as well as the risks linked to the gases which could be generated by radiolysis.

The 50 years' operation duration is based on unavoidable assumptions. However, this duration should be possible to specify in more detail, in particular from the experiences of other projects now available.

The main post-closure safety functions are defined as isolation and containment, with the reservation expressed previously on the meaning given to the latter term. The duration granted to "complete containment" must include all of the transitional phases after closure, with justification based on the physical processes identified and their detailed analysis.

D2.3. Requirements of laws and regulations

The legal framework for geological disposal may be supplemented by safety requirements, which will allow NUMO to develop its project on clear bases. A stepwise approach to site selection has been described through the Final Disposal Act, with clearly identified requirements for each step. Most of the presented requirements are qualitative, but NUMO has developed its own vision on the use of siting factors, in a report which was not submitted to this review. One of the future challenges will be to properly reconcile the respective requirements for the site characteristics and the design of the repository, the system requiring an assessment of its safety.

The reversibility and retrievability approach is based on the corresponding NEA publications, integrating technical, safety and above all decision-making processes or social constraints. In this perspective, the inventories of waste to be disposed of will have to be gradually more realistic. The regulatory expectations should be informed and safety regulations drawn up as quickly as possible in order to allow the NUMO teams to move forward and to decrease risks that NUMO is performing site survey in a manner not sufficient for the regulator. The needs for any new environmental impact assessment should also be identified as soon as possible, so that they can be properly addressed by the teams.

D2.4. Geological environment and site-selection strategy

The requirements management system needs to be further developed and be used as a dashboard to ensure the completeness of the identification and classification of safety functions, the setting of performance requirements and performance periods for each component from the identified safety functions.

As noted earlier, site-selection criteria should be presented explicitly, even in quantitative form, where appropriate. One of the first criteria would be the availability and quality of information during the literature survey phase.

To ensure post-closure safety, the iterative approach to improving the performance of the containment function is recognised by the IRT as good practice. The stepwise characterisation of the geological environment, the repository design and the safety assessment are appreciated. They could benefit from regular assessment and review loops to ensure compliance of the project with all requirements and foreign experiences.

The natural resources considered deserve to be clarified, in particular with regard to water and heat.

D2.5. Basic concepts and design

The design strategy should also be developed gradually, based on regular evaluations. However, it should also be noted that all boundary conditions are subject to change. Thus, requirements management and configuration management are essential in the study of a geological repository that lasts several decades.

The accumulated experience of the Japanese teams, acquired in laboratories in Japan as well as operations abroad, constitutes a capital of knowledge that should be used for the geological disposal project in Japan. However, since the experiences are rather dispersed among several organisations, a structured and co-ordinated approach to transfers would be beneficial for NUMO.

Reversibility and retrievability are well taken into account. However, it will be necessary to take this phase into account in the monitoring operations. The monitoring will also have to be sized realistically, in periods that are probably much shorter than the lifetime of the repository.

D2.6. Safety assessment strategy

The safety case strategy consists of assessing operational and post-closure safety based on information on the selected sites and the associated repository designs and available scientific and technological knowledge, in the light of the relevant regulatory standards and the requirements of the stakeholders. In the NUMO Pre-siting SDM-based Safety Case, generic cases are taken into account in order to demonstrate the ability to develop such a safety case on a real site in the near future.

D2.6.1. Operational safety

Safety in operation is studied according to the typical rules applicable to nuclear facilities, supplemented by specific rules for mining works, and even for other types of projects. It will be necessary to reconcile sometimes contradictory rules in order to propose an acceptable approach in all its dimensions. Security measures will also have to be considered, including cyber security, in particular if remote-controlled or possibly automated systems are to be used in the facility in the future.

D2.6.2. Post-closure safety

The safety assessment strategy follows international guidance, including those issued by IAEA and NEA, for developing scenarios, formulating and justifying models and running analyses and assessment. A FEP catalogue is used as a basis to define and evaluate scenarios.

The numerical values of the calculated doses can be used as an indicator of the expected performance of the repository, but must be used with caution due to uncertainties, in particular regarding the future biosphere and human lifestyle. To determine the safety assessment period, in the absence of national regulations, those of other countries were at this stage taken into account. The main indicator used for post-closure safety assessment is the human radiological dose. Doses to non-human organisms and impacts of non-radioactive hazardous substances are not included. It is recommended for future developments to consider doses to non-human organisms in relation to the food chain and non-radioactive hazardous substances for their chemical hazard.

It is also recommended to justify or to properly document some of the assertions, such as for example that the uplift or the erosion could be negligible from a judicious site selection. Since the criteria are not reported, the evaluation of this type of assertion is challenging.

D2.7. Comments on the completeness of the project and its overall feasibility

D2.7.1. Comments on the management systems

The proposed management systems aim in particular to ensure adequate coupling between the investigation and site assessment approaches, the engineering measures and the safety assessment. The management systems are also intended to maintain flexibility, seen as a means of adapting the project to the characteristics of the site, developments in science and technology, changes in regulations and societal demands. The flexible approach should also take account of changes in the inventory of waste to be disposed of. The interactions between the approaches could be further improved by introducing the iterative nature of the development of the project, according to its successive phases.

The way in which NUMO will guide future R&D activities to be carried out by the various scientific actors in Japan and abroad on the basis of this SDM-based Safety Case also deserves development, at least in the same way as the other management systems. This should ideally be part of the management system. This is all the more important since it is one of the stated ambitions of this report. The management system could cover the definition of R&D priorities, the assurance of the relevance of the R&D undertaken, the integration of the results into the next iteration of the safety assessment, and of course the methods of their management.

D2.7.2. Uncertainty management

Given the complexity of the repository system (various processes [THMCR] with couplings, multiple spatial scales and characteristic time scales), it is necessary to identify uncertainties in a systematic way to ensure traceability and completeness of uncertainty management. NUMO presents the concept of management and the treatment for each type of uncertainty, but the description of the method of identification of uncertainty deserves to be enriched. Because of its importance, it might be useful to consider devoting a separate chapter to dealing with high-level uncertainties. Chapters 3, 4, 5 and 6 could benefit from the inclusion of subsections to discuss how uncertainty is managed for site selection, repository design as well as operational safety assessment and post-closure.

It might be useful to discuss in more detail the extent of "acceptable" conservatism, for example that models should not include an excessive amount of conservatism. As an illustration, when selecting a site, this could lead to evaluation bias. An important aspect is also how conservatism is explained to the reader, especially the non-technical reader who might be guided on how to understand and interpret the results.

For the clarity of the approach, it is also suggested to identify separately what comes under variability from what comes under uncertainty, although the processing may involve identical methods.

D2.7.3. Quality management

The IRT recognises that a quality management system based on the ISO 9001 standard is appropriate. The system ensures the quality of the processes. That of production and information requires the definition of adequate indicators which deserve to be presented. (For example, how is it possible to ensure the completeness of the information of the geological information management support system?)

D2.7.4. Requirements management

The Requirements Management System (RMS) is one of the important parts for the geological disposal project, given its complexity and its duration. The IRT measures the work accomplished and the outstanding questions, in particular with regard to the follow-up of the evolution of the requirements, but also of their treatment. It could advantageously be envisaged to couple it with configuration management, also specifying the links between RMS, design and safety functions. Any couplings between requirements and the processing of contradictory requests or inconsistencies should also be able to be dealt with there. Finally, the question of the extent of completeness needs to be clarified.

D2.7.5. Knowledge management

The work undertaken by the Japanese teams in terms of knowledge management is already substantial. The IRT supports the idea of integrating the various components within a single knowledge base, open to all project partners.

D2.7.6. Data and models management

The management of data and models is not explicitly listed among the management systems. Special treatment of this point would be necessary, again given the size and duration of a geological disposal project.

D2.7.7. Management of scientific and technological development (RD&D)

The IRT noted NUMO's commitment to basing its studies on the best available technologies. However, it would seem judicious to NUMO to also consider the scheme adopted in many large-scale projects with the technology readiness level (TRL) Scale to assess the evolution and maturity of the geological disposal project.

D2.7.8. Management of human resources

The management of human resources on a project as long as that of geological disposal aims to ensure the availability of human resources for the specific needs of geological disposal. The transfer of knowledge and experience between generations is well taken into account and should over time be the subject of continuous attention.

D2.7.9. Communication with stakeholders

The sensitivity of the various stakeholders and populations to nuclear issues, and therefore in this case to the disposal of radioactive waste, means that the information, communication and dialogue should be proposed and presented. The societal approach is also part of the safety case, as indicated in numerous publications under the aegis of the NEA, and also taken up by the NUMO teams during the Global 2015 Conference. The IRT recommends that NUMO consider this issue as soon as possible and devote the necessary development to it in the next phases of the safety case.

D3. Selection and modelling of geological environments suitable for geological disposal

The site descriptive model (SDM) approach developed by NUMO seems suitable. Models make it possible to provide design and safety assessment with fully integrated comprehensive data rather than field data. Models will be refined along with the progress in siting and field survey. The generic safety case developed in the SDM-based Safety Case is based on three typical models covering various types of potential geological formations encountered in Japan. Chapter 3 justifies in detail the elaboration of these models. This approach is relevant at this stage.

For Neogene/Pre-Neogene volcanic and metamorphic rocks, the decision was made at this stage to not elaborate specific SDMs as three representative SDMs are considered to cover the characteristics of these rocks. It is however recommended that, as soon as field data become available, the characteristics of these formations be differentiated from those of volcanic and igneous rocks.

Throughout Chapter 3, site selection seems primarily based on “natural disturbances”, i.e. internal and external geodynamics, and on the existence of natural resources with regard to isolation safety function. Parameters that are more or less related to containment, such as host rock geometry, permeability, strength, thermal conductivity, are well characterised and included in the SDM. Nevertheless, these containment-related parameters do not seem to be taken into account to exclude a candidate site, to compare sites or to optimise the siting of the repository in a candidate zone, with the exception of the distribution and hydraulic characteristics of water-conducting features. Quantitative or qualitative criteria would be suited for site selection with regard to containment-related parameters, representing the main functions of the geological disposal. If there are several sites in competition, these types of criteria will also be suited to further compare the sites on the basis of their respective performances.

D3.1. The role of the geological environment in ensuring repository safety

The main function of the geological environment of the radioactive waste repository is to isolate and contain the radioactivity for as long as it poses a risk to humans. Among its derived functions, the geological environment must be stable and also ensure the protection of the engineered barriers, and therefore of the packages. It is not reasonable to consider suppressing the inevitable effects of phenomena of external origin, such as uplift and erosion, which must also be able to be apprehended based on the knowledge available. On the other hand, it is reasonable to seek to limit the effects linked to these disturbances.

The effects of climate change are also cited and will merit specific development during a future safety assessment, in particular relating to the hydrogeological and hydrogeochemical regimes. The suitability criteria of the geological environment for geological disposal still need to be developed, in particular with more quantitative criteria. One of the challenges will be to assess a site's ability to become suitable by compensating for certain weaknesses with appropriate design and construction measures. This amounts to considering not a site as such but as part of a “disposal system” comprising the site, the waste packages to be disposed of and all the engineered systems (engineered barriers and overall architecture).

Among the physical characteristics of the geological medium, several are also to be considered within the framework of the disposal system, and not only from the point of view of the geological parameters. All being the results of coupled processes, it becomes essential to consider them in this way. By way of example, the thermal issue may also concern the geological environment, the mechanical strength of the packages (including for TRU waste), or even geochemical disturbances in connection with ventilation or with backfill material.

D3.2. Process for identifying environments suitable for geological disposal

A gradual approach to identifying environments suitable for geological disposal is presented, starting with the exclusion of areas largely disturbed by natural phenomena, then identifying those whose characteristics could be most conducive to containment. The information from the literature review can then be confirmed or not during preliminary investigations, which can lead to refocusing searches on other suitable sites.

All relevant processes and couplings are considered. The role of microbial activity may also be further investigated in subsequent phases.

The design of repository components as well as decisions on disposal depths are guided by compliance with the safety functions, and primarily with regard to isolation and containment. A key parameter, in particular for HLW, would be the cooling time during storage. The maximum admissible temperature in disposal also depends on the environmental conditions and the optimum will have to be sought according to the characteristics of the site. The hypothesis of 30 or 50 years of storage can at this stage only cover an exercise value.

Concerning HLW, two points would benefit from being underlined as boundary conditions: firstly, the very low solubility of the vitrified matrix, which can be considered as a safety function, but which above all constitutes physical data of the system; and secondly, the need to take into account the radiolytic corrosion of the overpacks, as indicated later in this document.

Bentonite is selected as the reference option for buffer material, mainly because already chosen in most other geological disposal projects. Nevertheless, a specific analysis would be needed for the Japanese case, especially taking account of the geological environment and of the overall design of the repository. Interactions between materials should also be further explored, such as the interaction between cement and bentonite, which could alter the functions of the latter.

The overall architecture presented in the SDM-based Safety Case is still generic. The orientation of the disposal galleries is based on the hydraulic gradients of the plutonic rock. The same should apply to the other components of the installation, such as the shafts, the ramps or the disposal panels. Furthermore, the option between shafts or ramps must also be analysed, particularly with regard to any superficial aquifers.

The transport of waste to the site as well as its transfer underground still requires studies, for example concerning the location of the repository, close to coastal areas, or even on the size of the loads to be taken underground for the Prefabricated Engineered barrier system Modules (PEM).

At this stage, it is planned to backfill and plug the tunnels and vaults once the waste has been emplaced. However, given the reversibility requirement, there is a need for further studies to assess how these operations could be staggered over time, without altering the safety performance. Concerning the different repository components, the use of safety indicators, when possible quantitative, for each of them may prove necessary during future developments of the geological repository project. It will also be necessary to have a phased approach, because the relationship between the component and the safety function can change over time. For example, in case of interaction between corrosion products and bentonite, some of the functions of the engineered barrier may be affected. A focus is put on isolation and containment, which are defined as the major safety function; however, protection from the significant effects of natural perturbing phenomena would as well be relevant to consider.

Zoning of underground facilities would be considered, as already planned by NUMO, to properly separate radiologically protected areas from mining areas and thus allow parallel waste emplacement and excavation operations.

One of the main risks in mining conditions is that of fire. Fire detection and firefighting provisions are provided. A particular effort on prevention could also contribute to reducing this risk, in particular by the use of fire division and fire door systems, but also by the choice of transportation technologies, as well as materials such as this is already envisaged.

Neogene sedimentary rock type is defined by very low strength, a relatively high thermal conductivity and a high hydraulic conductivity. These are very dimensioning parameters which can significantly differ from one site to the next. Thus, the design to such changes will need to be adapted to the real cases, probably more than for other rock types.

D3.3. Development of SDMs for representative host rock settings

For the development of SDMs for representative host rock settings, several characteristics are compiled and then selected to provide as much representative cases as possible. Conceptual models are proposed, but they would gain in justification with a finer description of the methodology of their development. In particular, it will be necessary to describe how the field data will be used to arrive at the conceptual model.

For Neogene/Pre-Neogene volcanic and metamorphic rocks, no specific SDM is elaborated. Three representative SDMs are considered to cover the characteristics of these rocks and used for design and safety assessment for the safety case. For the specific sites, respective SDMs are developed based on the literature and characterisation. Depending on site-specific SDMs, design and safety assessment approaches will need to be well co-ordinated, especially during inevitable iterations for optimisation. Hydraulic conductivity is a key parameter for the different geological formations and could be very discriminating in terms of post-closure containment performance. It is thus recommended to use the most possible representative values rather than having almost the same value for all. This question may also need to take account of the scale effect, especially in the case of fractured rocks such as granites.

D4. Repository design and engineering technology

D4.1. Approach to development of repository concepts

The starting points for the designs are the H12 (JNC, 2000a) and TRU-2 (JAEA, 2007) reports. The concepts presented therein are subject to adaptations to the specificities of geological formations and sites, and progressively refined as the programme progresses, including from underground investigation installation projects. The experience of foreign programmes shows that it can be difficult to evolve the concepts because the development teams as well as the stakeholders are accustomed to the very first versions studied. However, a number of remarks throughout the report aim to keep alternatives open, which is a good point at this stage.

The methodology for defining and using "design factors" would benefit from further development. It would also be interesting to be able to assess their use, particularly in terms of prioritisation or orientation of design decisions. Among the design factors, retrievability could be a factor in reducing safety margins. It is, in fact, a requirement, thus implying the search for solutions capable of reconciling the respective requirements of reversibility and safety. Other types of trade-offs are also part of the design process, especially in economics.

Design factors are related to requirements; a presentation of the requirements elicitation process could further enhance the quality of the approach. It could contain the documentation on the requirements as well as the tree of requirements and the links between high-level requirements and derived requirements. Finally, the requirements could more finely be related to the different components of the disposal system.

D4.2. Repository design procedures and boundary conditions

The design of repository components as well as decisions on disposal depths are guided by compliance with the safety functions, and primarily with regard to isolation and containment.

A key parameter, in particular for HLW, would be the cooling time during storage. The maximum admissible temperature in disposal also depends on the environmental conditions and the optimum will have to be sought according to the characteristics of the site. The hypothesis of 30 or 50 years of storage can at this stage only cover an exercise value.

Concerning HLW, two points would benefit from being underlined as boundary conditions: firstly, the very low solubility of the vitrified matrix, which can be considered as a safety function, but which above all constitutes a physical data of the system; secondly, taking into account the radiolytic corrosion of the overpacks, as indicated later in this document.

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Neogene sedimentary rock type is defined by a very low strength, a relatively high thermal conductivity and a high hydraulic conductivity. These are very dimensioning parameters which can significantly differ from one site to the next. Thus, the design to such changes will need to be adapted to the real cases, probably more than for other rock types.

D4.3. Setting of repository depth

The selection of the repository depth is the result of an approach that needs to be explained, responding to particular constraints or functions. Therefore, the depth depends not only on the geological nature of the formation, but also and above all on the site considered. The IRT shares the vision of a specific analysis on this point, in connection with all the other criteria (i.e. construction practicality, costs, thermal dimensioning and risk of human intrusion) when candidate sites are known.

D4.4. EBS design

Although the components of the EBS are the subject of specific developments and evaluations, their behaviour and the phenomena likely to affect them are analysed more globally, as performance and maintenance of system performance.

Specific issues still need to be addressed in future studies. They relate in particular to the interfaces between components and therefore between materials. The overpack for the HLW will be made of carbon steel of sufficient thickness to ensure the confinement of the radionuclides during the thermal and hydraulic transient phases. This material is considered as the reference in the framework of the systemic approach to the geological repository. The thickness envisaged also makes it possible to ensure the mechanical strength during the operation phase of the repository. As regards the requirements of the overpack, it will also be useful to consider its ability not to alter the functions of the bentonite.

Since most interactions take place through water, the characteristics of the latter are essential. Therefore, it would be good to present the models of acquisition and regulation of water chemistry to explain the compositions taken into account.

The different forms of corrosion must be evaluated before any final choice of material, without forgetting those linked to galvanic couplings or the forms of corrosion under stress or even those of microbial origin.

As indicated above, the choice of bentonite as a buffer material must be the result of an approach intended to identify the material most capable of fulfilling the functions sought, in the short as well as in the long term. Depending on the characteristics of the geological formation retained, such a choice could be revisited, not only for its containment qualities but also for its ability to maintain its functions during the thermal transient and resaturation phase.

The idea of the PEM is appealing. It is still very generic and requires numerous studies, both of a fundamental nature and on its implementation. Its behaviour during the thermal transient and the resaturation phase must be described. Functional clearances, or remaining free spaces, must be dealt with appropriately. Long-term stability of the buffer material, and especially of its safety-related functions, is key. A good illustration of the investigations done is the distribution of stress ratio severity of buffer around the overpack; the methodology implemented deserves to be presented.

The basic concept for the disposal of TRU waste includes the grouping of packages in containers, then filled with mortar, which chemical functions need to be detailed. The issues of buffer materials and backfill quality are still open, and it is clear that their treatment will depend on the characteristics of the site that will be considered. The cross section of vaults for TRU waste is very large compared to the volume of emplaced waste packages. Optimisation possibilities remain wide, especially in the perspective of sedimentary rocks.

D4.5. Design of underground facilities

The IRT recognises the quality of the design approach. The repository design flow is clear; it can be completed by indicating the partially iterative nature of the design. Thermal effects are taken into account. Couplings must also be considered as for example HM for TRU waste disposal vaults or THM for HLW disposal tunnels.

The design of the backfill and plugs is still preliminary. The respective functions over time still need to be clarified, and therefore, the selection of materials, geometries and locations will require studies adapted to the context of the site. The orientation and slopes envisaged for the different types of galleries are the subject of detailed consideration, which must also be adapted to the site conditions, for hydraulic reasons and also to avoid long-term transfers of radionuclides through the EDZ. The conditions for placing plugs and backfilling are also taken into account, with the aim of avoiding any alteration of the desired functions. Adaptation to formation and site conditions is more generally true for the overall architecture. A particular point will concern the optimisation according to the hydraulic regimes and trajectories, also to maintain the properties of the host formation. It is also essential for the footprint required for TRU waste disposal, which should be quite different depending on the nature of the geological formations.

The PEM option is attractive for the advantages it presents. It is the subject of specific studies which deserve to be supported.

An exhaustive review of the phenomena liable to affect the operation of the repository could be envisaged. It should be possible to take into account in the design phenomena such as radiolysis, and the production of gas of radiolytic origin, or even corrosion in an anaerobic environment. If they cannot be taken into account, that needs to be explained. The evaluation of these phenomena is of particular importance for the question of retrievability. The latter is taken into account, but the aspect of reversibility takes second place. Other provisions in the design may contribute to the reversibility of decisions as well such as a stepwise approach (NEA, 2012a) in the implementation, construction, operation and closure of the repository, and associated monitoring.

D5. Operational safety assessment

The approach used for the operational safety assessment appropriately reflects this generic phase. At this phase NUMO has been focused on the evaluation of design robustness. The radiological impact on workers has not been the subject of specific treatment in normal situations, since it is taken into account in the nominal design of the facilities.

D5.1. Strategy for operational safety assessment

Procedures for developing scenarios are presented. However, the consideration of abnormal operation scenarios, particularly in the event of an accident, remains to be clarified, particularly with regard to future regulations. On the other hand, an analysis in anticipation on the part of NUMO could also be considered in order to shed light on future developments in the regulations.

The conservatism is always challenging to deal with. It deserves an explanation allowing its extent to be assessed. To this end, the production of the complete list of abnormal situations identified would be useful, by setting out the approach to reduce the number of those taken into account.

D5.2. Premises for the assessment

The only risk taken into account is that relating to waste forms. Note in particular the robustness of the overpacks, which are supposed to avoid any release of radionuclides. However, despite the confidence that can be placed in this robustness, the operating conditions could subsequently be optimised to reduce any risk of a fall.

Although by design no release of radionuclides is envisaged, it will nevertheless be useful to identify those which could contribute the most to a radiological impact, in particular for further analyses of accidental situations.

D5.3. Assessment of normal operational scenarios

At this still very generic stage of the project, the analysis of the operating conditions is preliminary. A detailed analysis will only be made possible when a precise description of the facilities and their operating conditions will be available. However, the details of principles and tools for assessing the exposure to radiation, even without any release of radionuclides, at the boundary fence of the facility will need to be presented.

The assumption regarding the conservatism of the shielding, and therefore of the safety margins taken into account, deserve to be clarified. With the presentation of the methodology and assessment tools, it would, among other things, provide a better understanding of compliance with the limit dose at the fence.

D5.4. Assessment of abnormal operation scenarios

As pointed out before, the absence of a release of radionuclides assumed to be achieved through a robust design does not exclude potential exposure to radiation. The corresponding analysis approach could be further developed, with output on the potential impact on the public.

The list of events or failures (such as for the ventilation system, shielding) can be completed during future developments, while taking into account common failure modes.

One of the major risks underground is that of fire. The most critical case is that of Gr.3 waste. Dedicated disposal vaults as well as specific operating conditions could probably reduce this risk. The risk of explosion is limited by separating waste emplacement operations from excavation. However, this point may be supplemented by an analysis of the risk associated with the gases likely to be produced either by the geological formation (CH_4) or by the waste (H_2).

At this stage, the fire scenarios are only taken into account underground. Vehicle scenarios deserve great attention for the future. They could also, as indicated above, be envisaged with largely preventive provisions such as for example the avoidance of flammable equipment or materials. The experience of fire in surface conditions will make it possible to envisage solutions and studies within an already well-controlled technical framework.

D5.5. Summary and future perspective

As this is a chapter devoted to safety in operation, it should present quantified results on the radiological impacts in normal situations as well as in abnormal situations, for all potential exposure pathways.

D6. Post-closure safety assessment

The numerical modelling considers multiscale levels and seems well mastered and mature enough to simulate site-specific systems. At this generic stage, NUMO relied on simplified numerical models which seem well suited to the present phase of the programme. These simplified models are supported by sophisticated tools in the different fields of studies. A summary table would be helpful in which all scenarios (calculation cases) studied are summarised with references to subsections for additional clarifications and data. Besides safety assessment calculations, international recommendations on demonstrating repository safety, as shown in the introduction of the SDM-based safety case, emphasise the role of additional evidence and arguments (e.g. multiple lines of arguments), including for example natural analogues and any other qualitative knowledge about the site and repository design. In the safety case report, such aspects are covered in Chapter 7, which could be presented in more detail and with more prominence in a separate section in future iterations of the safety case.

Finally, a reminder of the application of the management procedures described in Chapter 2 could be proposed here, in particular with regard to quality assurance for post-closure safety, as well as for the qualification of the data and models implemented.

D6.1. Basic framework of safety assessment

NUMO's safety assessment is clear. The analysis is based on an appropriate partitioning in space at different scales. The analysis could additionally be improved by a more systematic partitioning in time.

The description of the repository remains brief at this level. However, it raises the question of the distribution of TRU wastes in the disposal position, in particular concerning the distinction between A and B packages, with the question previously raised of type Gr.3 waste.

The selection of relevant radionuclides for HLW should be the result of a systematic approach. It should in particular result from an analysis of the radiological and chemical properties of the waste, and be representative of the waste packages already produced. The presentation of a rigorous methodology would also make it possible to justify the consideration of the mobile radionuclides ^{14}C, ^{36}Cl and ^{129}I. The distinction between long-lived and short-lived species should also be further substantiated. Typical inventories provided for HLWs would best be expressed in standard units of mass or volume and then calculated for glass blocks.

Similarly, the selection of radionuclides for the reference TRU waste inventory should be representative of the existing TRU waste characteristics, for all categories and sub-categories. Again, the approach and methodology for selecting relevant radionuclides need to be explained.

The treatment of the spatial scales in the models is relevant. The nesting of different scale models facilitates the simulation of radionuclide transport over large regional areas while accounting for smaller-scale transport features closer to (and in) the repository. Assumption for the near field, panel, repository and regional scales for each of the rock types would need to be presented. The Partridge analytical code that is cited for the near field scale would benefit from a brief description, including information on its verification and validation to support the confidence in the results of the near field modelling.

Concerning the scenarios, a summary description for each of them in the different rock types would be helpful for the reader. It would also be useful to distinguish for each type of rock what relates to uncertainty and what relates to variability, and to have a differentiated treatment. Dose constraints are presented for the different scenario classes. The use of complementary safety evaluation criteria as they have been developed in recent years (e.g. NEA, 2012: Indicators in the safety case) could be used in future versions of the safety case. Target values for dose are proposed; these values are not linked to any regulatory requirement pending the establishment of such criteria in Japanese legislation. It should be recalled here that these target values are indicative, defined in order to identify R&D needs, but also to identify safety margins or design optimisation options.

D6.2. Methodology of safety assessment

NUMO identifies a set of FEPs driving the evolution of the system (the NUMO FEP list). Scenario development is a combination of two methods supported by the NEA and IAEA. In a top-down approach, the scenarios and analysis cases (in particular the base scenario and base cases) are developed from the safety functions described in the safety concept of the disposal system. In a bottom-up approach, the scenarios (particularly the variant ones) are developed from a screening of impacting features, events and processes (FEPs). These two methods are combined appropriately by NUMO in order to derive relevant scenarios. In the bottom-up approach, the FEPs are screened from a long-term safety point of view. The starting point of the analysis is the NEA International FEP list (NEA, 2019; NEA, 2020). This list is adapted on the basis of the specificities of the Japanese programme: FEPs are selected, some are removed and new ones are added to the list as determined by the boundary conditions and waste and system characteristics. The scenarios are derived and justified based on a comprehensive so-called "description of system behaviour".

The role of the integrated FEPs is to group the FEPs in blocks to structure the impact analysis. As they are general in nature, e.g. "water chemistry", they do not seem to be used as such in the impact analysis. The role of the integrated FEPs vs the individual FEPs in the impact analysis should be developed. An example of a list of FEPs that are grouped into one integrated FEP would help illustrating the approach.

Lastly, each FEP will need to be thoroughly described and documented so that it can be appropriately handled in the assessment.

Uncertainties are usually grouped into three main classes: conceptual, model and parametric, in agreement with international practice. The discussion on uncertainty could be more clearly differentiated, for example by discussing in more detail how these uncertainty types are handled in the SDM-based Safety Case. As an illustration, the description/discussion of the effect of uncertainties in the initial state of the system (including both site and technological uncertainties) on the calculated doses can be considered as one particular group; uncertainties from external causes (e.g. climate change) can be processed as another.

D6.3. Developing scenarios and establishing analysis cases

Storyboards are mostly used to describe the behaviour of the system after the disposal facility is closed. This is a relevant way of illustrating the successive periods of disposal evolution. Differentiating the lifetime of the repository in time could also be complemented by further differentiation in space, as previously illustrated, since the typical time constants are different for different locations and scales of the repository. Concurrent processes for each time period could also be described in order to illustrate the evolution of the repository. Storyboards will also differ with geological setting, as well as for the different types of waste. A full set of storyboards would be useful for illustrating the variety of situations, also with typical values for each of the time periods in each case. The provided illustration corresponds to the normal evolution scenario. From this, other scenarios can also be developed, especially in order to further analyse all the THMC and radiological processes, including the possible microbial activity and its consequences.

One of the potential benefits of storyboards is also to identify the major processes likely to occur at each segment of time or space, and thus to have a less complicated modelling than that of the global repository. Thus, the characteristics or safety functions would be better distinguished from one situation to another. A chart of the various models implemented as well as their couplings could complement the information on the analysis of the physical phenomena studied. Moreover, a brief summary of the mathematical models and their limitations (assumptions, simplifications), as well as their validation vis-à-vis the conceptual process models, is needed to better understand the methodology used.

Such storyboards would also be a good basis for analysing the effects of uncertainties. The IRT strongly recommends developing the work already well underway from the storyboards for the next stages of the geological repository project in Japan. These can also be a good way to communicate with stakeholders and the public, making it clear that storyboards help to understand all of the underlying processes and assumptions that need to be considered.

The detailed description of each of the phases in time is appreciated. It deserves a much longer development than a report on the SDM-based safety case can contain. However, some information requires quantification, or at least order of magnitude estimation (e.g. corrosion rates or H_2 generation rates). Other potential improvements include an account of the way in which the operating phase is taken into account more in detail for the analysis of the post-closure phase, justification of the estimated lifetime of HLW overpacks, and taking into account the effects of climate change and their consequences on hydrogeological and geochemical regimes. It is recognised that this only makes sense for identified sites, but boundary conditions could be proposed to properly frame the consideration of such subjects.

The NUMO FEP list used in the SDM-based safety case would be useful; it may be updated next on the basis of more recent publications by the NEA. NUMO applies a structured approach to the development of scenarios, using safety functions, state variables, factor analysis diagrams and impact analyses, and the IRT encourages the further development of these tools. It is planned in the future to develop what-if approaches to assess the robustness of scenarios. It will also be useful to present in the safety case main report how evaluations and decisions on the cases and on the assumptions are recorded and documented, even though summarised in supporting reports in Japanese.

A point which also deserves to be revisited is that of the timeframes taken into account in the safety assessment. Moreover, for the assessment of the long-term stability of the functions of the engineered barriers, it will be necessary to consider their possible alterations, both chemical and physical.

D6.4. Radionuclide migration analysis and dose assessment

With regard to the release and migration of radionuclides, the consideration of certain interactions must be specified, such as those between cement and bentonite, or those linked to the presence of bitumen or nitrates. In relation with the design of the repository, migration can be modelled either with migration average rates, or by considering individual disposal panels. The processing of data and models will depend in part on the types of geological formations, their level of fracturing and characteristics of any preferential flow paths, and therefore the modelling approaches will be different. At this preliminary stage of the safety assessment, NUMO's focus was to understand and describe the evolution of the repository in a broad sense, and the emphasis was therefore placed on deterministic approaches rather than probabilistic approaches, which could be considered in future work.

A point that also deserves clarification is that of the lack of interaction between the HLW disposal area and that of the TRU wastes. In other words, whether it can be verified over the long term, including in the event of climate change.

For the presentation of the analysis of the radionuclide migration and dose assessment, taking into account the complexity of the systems, a summary of the basic assumptions would be useful for each of the cases treated. Since the geochemistry of water plays a major role for these phenomena, the consideration of possible ligands will be necessary. The hypotheses underlying the modelling may also be explained, in particular with regard to non-equilibrium processes.

Transport of radionuclides needs to be consistent with the results from migration through the geosphere. Models, data and assumptions for assessment of transfers in the biosphere, although consistent with the IAEA BIOMASS project, could benefit from additional information.

The maximum doses presented for the various cases are below the specified limits, but not by a large margin. It is understood that this reflects the high level of conservatism and non-discriminating underlying assumptions between different rock types. However, it also suggests the need to revise some of these assumptions in order to replace them with more realistic ones in the future, hereby reducing the level of pessimism. In order to better appreciate the results of the various cases vis-à-vis the Base scenario, it would be useful to present doses as a function of time, and not only the peak dose in the safety case main report.

D6.5. Evaluation of inadvertent human intrusion scenarios

For inadvertent human intrusion assessments, to avoid a large number of calculations, envelope scenarios should be identified. In all cases, the assumptions and associated quantifications should be justified.

D6.6. Summary and future perspective

Based on the experience of the present safety case, future development needs can be ranked in terms of their perceived importance, and also according to the overall agenda of geological disposal in Japan. The most sensitive phenomena and processes will be a first key for ranking, but other criteria will also be defined. In any case, the development programme will be built so that major milestones are met.

In addition to the development needs identified by NUMO, the IRT emphasises the need to improve the understanding of microbial processes. The impact of microbial processes on the performance of the overpack (especially corrosion), buffer and backfill and on radionuclide transport in the geosphere will have to be evaluated. In addition, in the event that deep groundwaters with high ionic strength are expected, an important aspect will be to develop approaches to quantify their impact on various safety related aspects, such as solubility, sorption and radionuclides transport.

Finally, fast transport zones between the geosphere and the biosphere are modelled in the NUMO report. However, the IRT believes that the strategy should primarily be to avoid such areas at first by site selection, then by design studies.

D7. Safety case synthesis

D7.1. Integration of arguments in a safety case

Chapter 7 would ideally be a standalone part of the SDM-based safety case. Thus, additional figures showing the surface/underground layouts and EBS design would be useful. In the spirit of a standalone note, it will be necessary to explain how the EBS satisfies the requirements for the different geological formations, with sufficient margins.

General work safety, security measures and security management practices are planned by NUMO to be based on their equivalent in similar industries; some examples would increase the confidence in this plan. The scope of the current operational safety assessment for normal operation is at present limited to evaluation of public doses due to external radiation exposure. The scope of the assessment will need to be expanded in the future to include the more comprehensive and rigorous assessment of the possibility of internal exposure of the public assumed in the vicinity of the facility to radiation, the radiological effects of underground facilities during normal operation, as well as doses to workers exposed to radiation. For post-closure safety, radiation doses to exposed individuals in the vicinity of the site are calculated to be significantly lower than the dose target value (10 µSv/y for base scenario and 300 µSv/y for variant scenarios). A table with the key data and assumptions and a high-level summary of the variant scenarios should also be included and described in this section in order to support the conclusions.

Despite different rock types, two groundwater types and assuming different depths of the repository, the outcomes of the various cases differ very little. This can be understood because the project is designed to meet requirements. Nevertheless, one would expect more different results between cases.

As an alternative dose indicator, NUMO considers transfer of radionuclides to the biosphere in a stylised release to a river, demonstrating that dilution reduces concentrations to insignificant levels. The IRT encourages NUMO to further develop such cases, e.g. the possibility of accumulation of radionuclides into specific compartments of the biosphere.

A key point in the long-term safety assessment is the stability of vitrified waste forms. Although it is well demonstrated under many conditions, it could also be modified under others, such as in the presence of stainless steel, or possibly other components. The interactions between several types of materials must be analysed and, if necessary, design measures will be necessary to avoid them. In using natural analogues to support certain results, the constrains and limits of analogies are worth describing.

On organisational aspects, the multitude of cases, the evolutions of requirements, those of knowledge, and therefore of designs and then safety assessments imply a need for a rigorous management of configurations. It will be one of the challenges for NUMO to ensure this management for future developments.

D7.2. Assuring the safety case is "fit for purpose" (confidence building)

A considerable range of models is necessary for the study of geological disposal. As already mentioned, a mapping of the models implemented would be useful, illustrating the links between models. Of course, each of them should benefit from a detailed description and the conditions for their verification and validation.

For future versions of the safety case, dose to workers will need to be considered for the operational safety assessment. For long-term safety, depending on future legal requirements, chemical impacts could be assessed.

NUMO has introduced the concept of state variables and factor analysis diagrams as tools for evaluating safety functions in the development of scenarios, and, as mentioned, the IRT encourages the further development of these tools.

In addition to the configuration management system, additional management systems will need to be updated or improved as the geological disposal project evolves.

D7.3. Outlook for future safety cases

NUMO has gathered and tested all the ingredients necessary for the safety assessment. The inherent complexity of a subject involving the natural environment still raises many questions, which NUMO will have to address. Among other things, it will be necessary to make choices, and to discriminate between sites with overall suitable properties, but with relative advantages in different areas, for which NUMO needs to be prepared.

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