TECHNICAL REPORT 24-21

Development of Safety Scenarios

October 2024

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Abstract

In support of post-closure safety assessment and for site comparison, this report documents the development of safety scenarios for assessing the radiological consequences of deep geological repositories for low- and intermediate-level waste and high-level radioactive waste. This process entails the identification and description of a set of safety scenarios that capture uncertainty in the initial state of the repository system and the different ways in which it could evolve over time. In doing so, the potential paths of repository evolution are conceptualised, bounded and formulated into calculation cases that facilitate the quantitative analysis of radiological consequences – the next step in the safety assessment workflow. Thus, the scenarios serve as inputs to both safety analysis in the context of site comparison and the analysis of radiological consequences in the context of post-closure safety assessment of the repository at the proposed site.

Safety scenarios are developed based on information from the assessment basis, which compiles a sound scientific understanding of the waste inventory, repository barriers and the possible long-term geological and climatic evolution of the siting region, to provide a well-developed understanding of the phenomenological evolution of the repository. This is combined with the results of performance assessment to deliver an integrated understanding of the expected initial state and evolution of the repository, its other possible lines of evolution, and the associated uncertainties. Thus, the conditions under which deviations in barrier performance could occur are identified.

Consistent with the national regulatory requirements and international guidelines, the following safety scenarios have been defined:

- a reference safety scenario, which describes the expected initial state and evolution of the repository,
- a set of alternative safety scenarios, derived from a consideration of potentially detrimental phenomena and associated uncertainties that could result in degraded performance of the repository system,
- a set of hypothetical "what-if?" cases that represent extreme or impossible situations in order to test system robustness,
- a set of future human action safety scenarios, that concern the impact of potential actions taken by human society on the performance and safety of the repository.

Each of these safety scenarios has one or more variants that share the same general description of features, events and processes occurring over time, but differ in one or more key factors that significantly affect the radiological consequences of that particular scenario. Subsequently, for each scenario or variant, one or more calculation cases have been defined that incorporate assumptions for factors specific to each case.

This report provides a detailed description of the safety scenario development methodology and documents the application of that methodology through the definition of the safety scenarios, variants and calculation cases. The justification for allocation of each safety scenario to one of the four above-mentioned categories is provided in this report. Moreover, discussion and explanation of the key factors and assumptions relevant to each safety scenario, variant and calculation case are presented, as well as a discussion of completeness and comprehensiveness.

Zusammenfassung

Im Rahmen des Rahmenbewilligungsgesuchs für ein kombiniertes geologisches Tiefenlager für schwach-, mittel- und hochradioaktive Abfälle am Standort Haberstal dokumentiert dieser Bericht die Formulierung von Sicherheitsszenarien für die Sicherheitsanalyse der Nachverschlussphase. Es werden verschiedene Sicherheitsszenarien identifiziert und beschrieben, wobei auch Unsicherheiten im Anfangszustand des Lagersystems und mögliche Entwicklungen des Lagers berücksichtigt werden.

Um eine quantitative Analyse der radiologischen Konsequenzen zu ermöglichen, werden die verschiedenen potenziellen Entwicklungspfade konzeptualisiert und gebündelt. Diese Pfade werden dann als Rechenfälle formuliert und für die Sicherheitsanalyse herangezogen. Die Sicherheitsszenarien dienen sowohl der Sicherheitsanalyse im Kontext des Standortvergleichs als auch der Analyse der radiologischen Konsequenzen im Rahmen des Sicherheitsnachweises für die Nachverschlussphase am vorgeschlagenen Standort.

Die Formulierung der Sicherheitsszenarien basiert auf Informationen aus den Grundlageberichten. Diese Berichte ermöglichen ein fundiertes technisch-wissenschaftliches Verständnis des Abfallinventars, der Barrieren und der langfristigen geologischen sowie klimatischen Entwicklung der Standortregion. In Kombination mit der Überprüfung der Barrierenwirksamkeit ergibt sich ein integriertes Verständnis für die erwartete und alternative Entwicklung des Tiefenlagers sowie der damit verbundenen Unsicherheiten. Dies erlaubt es, Bedingungen zu identifizieren, unter denen das Tiefenlagersystem von der erwarteten Wirksamkeit abweichen könnte.

Folgende Sicherheitsszenarien wurden definiert, um den regulatorischen Anforderungen der nationalen Behörden und den internationalen Richtlinien zu entsprechen:

- ein Referenzsicherheitsszenario, das den erwarteten Anfangszustand und die Entwicklung des Tiefenlagersystems beschreibt,
- eine Reihe alternativer Sicherheitsszenarien, die potenziell schädliche Phänomene und damit verbundene Unsicherheiten berücksichtigen, die zu einer verschlechterten Wirksamkeit des Tiefenlagersystems führen könnten,
- eine Reihe hypothetischer „what-if?"-Fälle, die extreme oder unwahrscheinliche Situationen darstellen, um die Robustheit des Systems zu testen,
- eine Reihe von Sicherheitsszenarien zukünftiger menschlicher Tätigkeiten, die die Auswirkungen potenzieller menschlicher Handlungen auf die Wirksamkeit und Sicherheit des Tiefenlagersystems untersuchen.

Jedes dieser Sicherheitsszenarien hat eine oder mehrere Varianten, die die gleichen allgemeinen Merkmale, Ereignisse und Prozesse im Laufe der Zeit teilen, sich jedoch in einem oder mehreren Schlüsselfaktoren unterscheiden, die die radiologischen Konsequenzen erheblich beeinflussen. Für jedes Szenario oder jede Variante wurden ein oder mehrere Berechnungsfälle definiert, die Annahmen für fall-spezifische Faktoren beinhalten.

Dieser Bericht bietet eine detaillierte Beschreibung der Methodik zur Entwicklung von Sicherheitsszenarien und dokumentiert deren Anwendung durch die Definition der Szenarien, Varianten und Rechenfälle. Die Zuordnung jedes Sicherheitsszenarios zu einer der vier genannten Kategorien wird im Bericht begründet. Darüber hinaus werden die Schlüsselfaktoren und Annahmen, die für jedes Sicherheitsszenario, jede Variante und jeden Berechnungsfall relevant sind, diskutiert und erklärt. Eine Diskussion über Vollständigkeit und Ausführlichkeit ist ebenfalls vorhanden.

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List of Acronyms

ATW	Alpha-toxic waste
BDCF	Biosphere dose conversion factor
CRZ	Containment-providing rock zone
EC	European Commission
EDZ	Excavation-damaged zone
ENSI	Swiss Federal Nuclear Safety Inspectorate (*Eidgenössisches Nuklearsicherheitsinspektorat*)
FEPs	Features, events and processes
FHA	Future human action
HLW	High-level waste (spent fuel assemblies and high-level waste from reprocessing)
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
IGSC	Integration Group for the Safety Case (main technical advisory body to the Radioactive Waste Management Committee (RWMC) of the NEA)
IRF	Instant release fraction
JO	Jura Ost (siting region)
KEG	Nuclear Energy Act (*Kernenergiegesetz*)
KEV	Nuclear Energy Ordinance (*Kernenergieverordnung*)
L/ILW	Low- and intermediate-level waste
MIRAM	Model Inventory for Radioactive Materials
MOX	Mixed oxide fuel
NAB	Nagra work report
NEA	Nuclear Energy Agency of the OECD
NL	Nördlich Lägern (siting region)
NTB	Nagra technical report
OECD	Organisation for Economic Co-operation and Development
PA	Performance assessment
QSA	Qualitative Safety Assessment (Andra)
RBG	General licence application (*Rahmenbewilligungsgesuch*)
RD&D	Research, development & demonstration
RP-HLW	Vitrified HLW from reprocessing
SA	Safety assessment

SF	Spent fuel
SGT	Sectoral Plan for Deep Geological Repositories (*Sachplan Geologische Tiefenlager*)
SSG	Specific Safety Guide (IAEA publication)
SSR	Specific Safety Requirement (IAEA publication)
THM-C	Thermo-hydro-mechanical and chemical (evolution)
ZNO	Zürich Nordost (siting region)

1 Introduction

1.1 General context

In Switzerland, legal regulations (Nuclear Energy Act (KEG 2003) and Nuclear Energy Ordinance (KEV 2004)) and guidelines are in place for the management of radioactive waste. The Nuclear Energy Ordinance (KEV) classifies Switzerland's radioactive waste into low- and intermediate-level waste (L/ILW), alpha-toxic waste[1] (ATW) and high-level waste (HLW), the latter comprising spent fuel (SF) and vitrified HLW from reprocessing (RP-HLW). The Nuclear Energy Act (KEG) requires the disposal of all these types of radioactive waste in deep geological repositories. The feasibility of this disposal solution has been demonstrated for L/ILW in Nagra (1985) and for long-lived intermediate-level waste and HLW in Nagra (2002).

The Sectoral Plan for Deep Geological Repositories (SGT) regulates the search for suitable siting regions for deep geological repositories in Switzerland. This site selection process is conducted in three stages (BFE 2008). Stages 1 and 2 have already been completed and Nagra is currently in Stage 3 (SGT-E3). Clarifications on the safety-related specifications for this stage are provided in ENSI 33/649 (ENSI 2018), while ENSI Guideline G03 and the corresponding explanatory report (ENSI 2023, ENSI 2020b) specify the protection objective, protection criteria and design principles for deep geological repositories.

In SGT-E3, three siting regions located in Northern Switzerland have been considered – Jura Ost (JO), Nördlich Lägern (NL) and Zürich Nordost (ZNO) – with the objective of selecting one siting region for an HLW repository, one for an L/ILW repository, or one for a combined repository for all waste types.

Following a comparison of these siting regions, Nagra concluded that NL is the safest and most flexible siting region. Therefore, it is applying for a general licence for a repository for both HLW and L/ILW, with surface facilities at the Haberstal site (municipality of Stadel, ZH).

The justification for this selection and the safety demonstration for a repository at the site are submitted as part of the general licence application (RBG[2]). The reports relating to post-closure safety, shown in Fig. 1-1 are structured as follows:

- The overall safety-related argumentation, including post-closure and operational safety, is summarised in an overarching safety report ("*Sicherheitsbericht"*) NTB 24-01 (Nagra 2025b) shown at the top of Fig. 1-1.
- The upper left side of Fig. 1-1 shows the reports supporting Nagra's site comparison. The available options are compared with respect to safety and technical feasibility and the results are synthesised in NTB 24-03 (Nagra 2025a) ("*Bericht zur Begründung der Standortwahl*").
- The upper right side of Fig. 1-1 shows the reports documenting the post-closure safety case for the combined repository at the site, including its synthesis in the post-closure safety report NTB 24-10 (Nagra 2024n).
- The lower part of Fig. 1-1 shows a report that presents the safety and repository concept, including the provisional design, and reports providing the assessment basis.

The present report, bordered in red in Fig. 1-1, provides input to reports supporting both the site comparison (upper left side of Fig. 1-1) and the safety assessment (upper right side of Fig. 1-1).

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[1] According to Nagra (2024a), ATW can coexist with L/ILW within the same emplacement caverns. As a result, for the sake of simplicity, the term L/ILW encompasses ATW without explicit mention.

[2] From the German *Rahmenbewilligungsgesuch.*

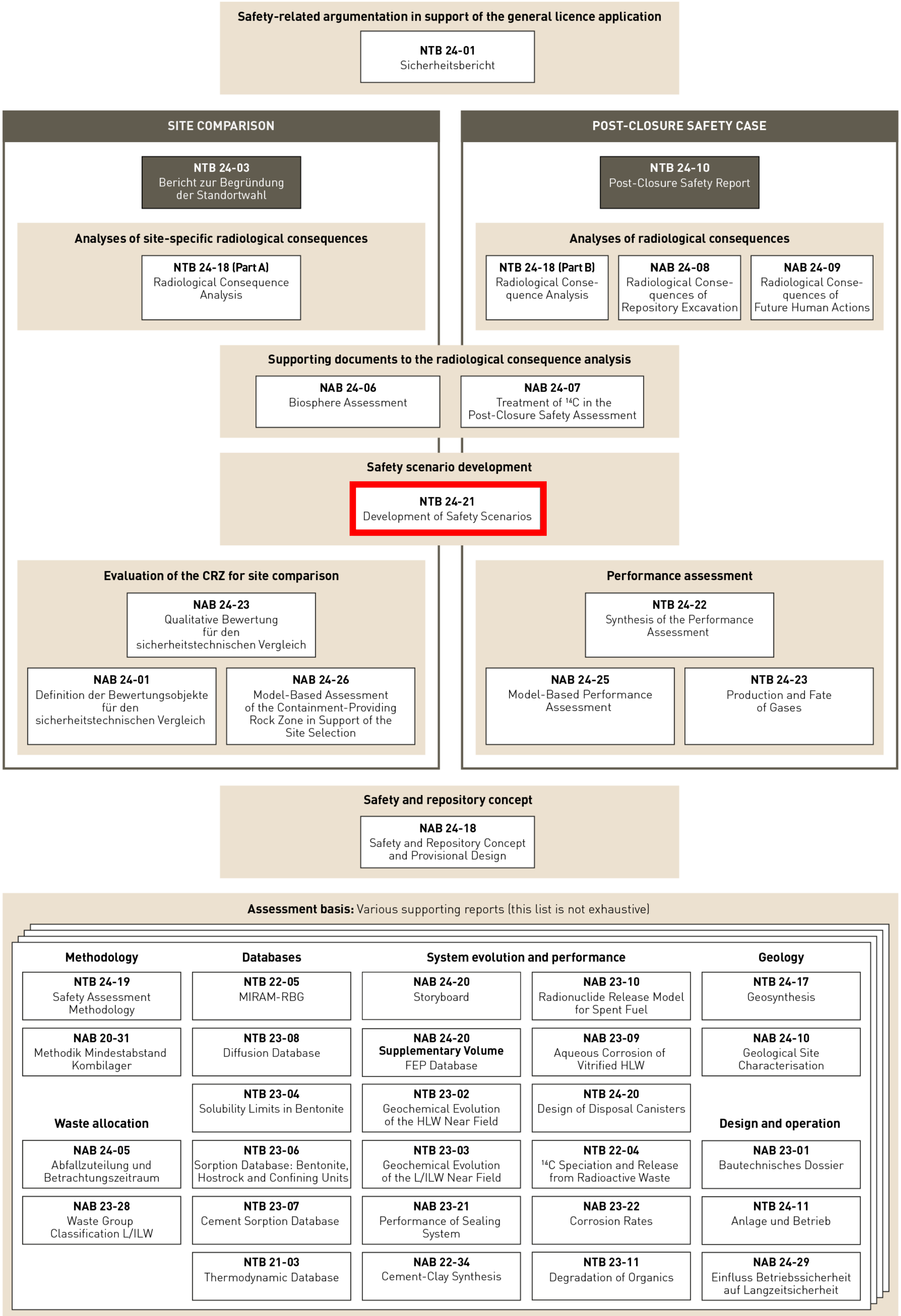

Fig. 1-1: Structure of reports covering post-closure safety aspects of the site comparison and the post-closure safety case

Site comparison workflow

The high-level workflow for the comparison of the three siting regions, ZNO, JO and NL, and for the selection of a preferred siting region is illustrated in Fig. 1-2. The figure is consistent with the methodology set out in Chapter 4 of ENSI 33/649 (ENSI 2018). The methodology is described only briefly here; for more details, see NTB 24-19 or NTB 24-03 (Nagra 2024u, Nagra 2025a) and its supporting reports (Fig. 1-1).

The methodology begins with the allocation of waste to the HLW repository and to the L/ILW repository (or to the L/ILW section of a combined repository). Thereafter, the procedure involves:

- The comparison of siting regions with regard to HLW disposal, culminating in a decision on a preferred HLW siting region. This is represented in the vertical workflow on the left-hand side of Fig. 1-2.
- The comparison of siting regions with regard to L/ILW disposal, culminating in a decision on a preferred L/ILW siting region, including the possibility of co-disposal in the preferred HLW siting region. This is represented in the vertical workflow on the right-hand side of Fig. 1-2.

In both cases, the comparison involves site-specific analyses of safety scenarios, as well as the qualitative analysis of the containment-providing rock zone (CRZ) in terms of a set of 13 siting criteria.

Post-closure safety case workflow

The post-closure protection objective for a deep geological repository is the permanent protection of humans and the environment (KEG 2003, ENSI 2023). The protection objective, design principles, protection criteria and the safety and repository concept inform the iterative design development process. This process leads to a provisional design and implementation plan for a combined repository at the Haberstal site, to serve as the basis for the post-closure safety case and underlying safety assessment (as documented in the reports shown on the upper right side of Fig. 1-1). The safety assessment consists of four main processes:

- **performance assessment**, in which the thermal, hydraulic, mechanical, and chemical (THM-C) evolution of the repository system is analysed,
- **safety scenario development**, which entails the identification and description of a set of safety scenarios that capture uncertainty in initial state and subsequent evolution of the repository system over time,
- **analysis of radiological consequences**, which consists of an evaluation of radionuclide release rates to the surface environment as a function of time, and
- **demonstration of post-closure safety**, in which evidence, arguments and results from the three previous steps are brought together in the post-closure safety report (Fig. 1-1).

This workflow is illustrated in Fig. 1-3 where the safety and repository concept leads to the iterative development of a provisional design (light blue boxes on the left) for which a safety assessment (dark blue boxes on the right) is then carried out. The full description of the post-closure safety case workflow can be found in the safety assessment methodology report, NTB 24-19 (Nagra 2024u).

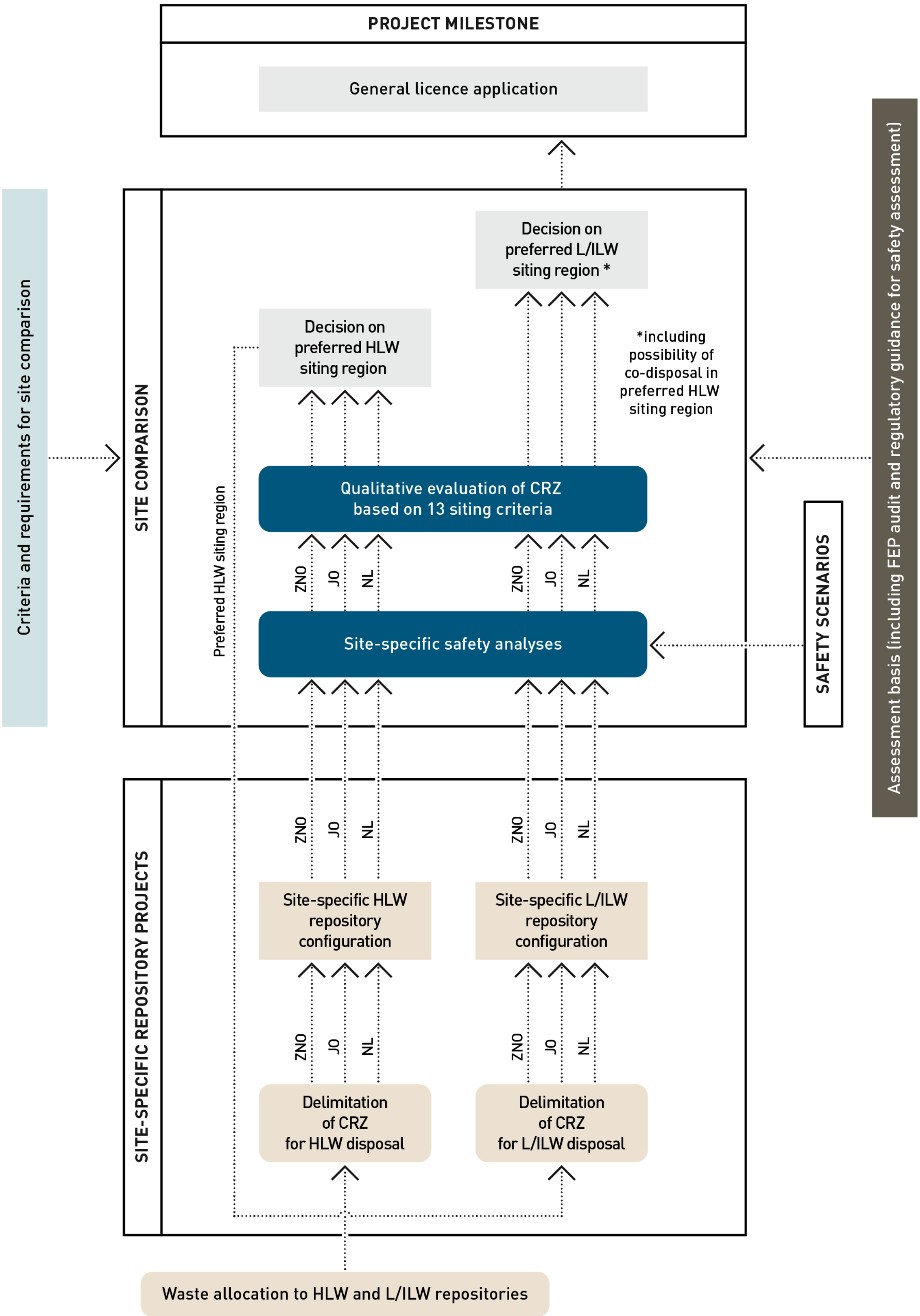

Fig. 1-2: High-level workflow for the comparison of the three siting regions, ZNO, JO and NL, and for the selection of a preferred siting region

See Chapter 6 of NTB 24-19 (Nagra 2024u) for a full description.

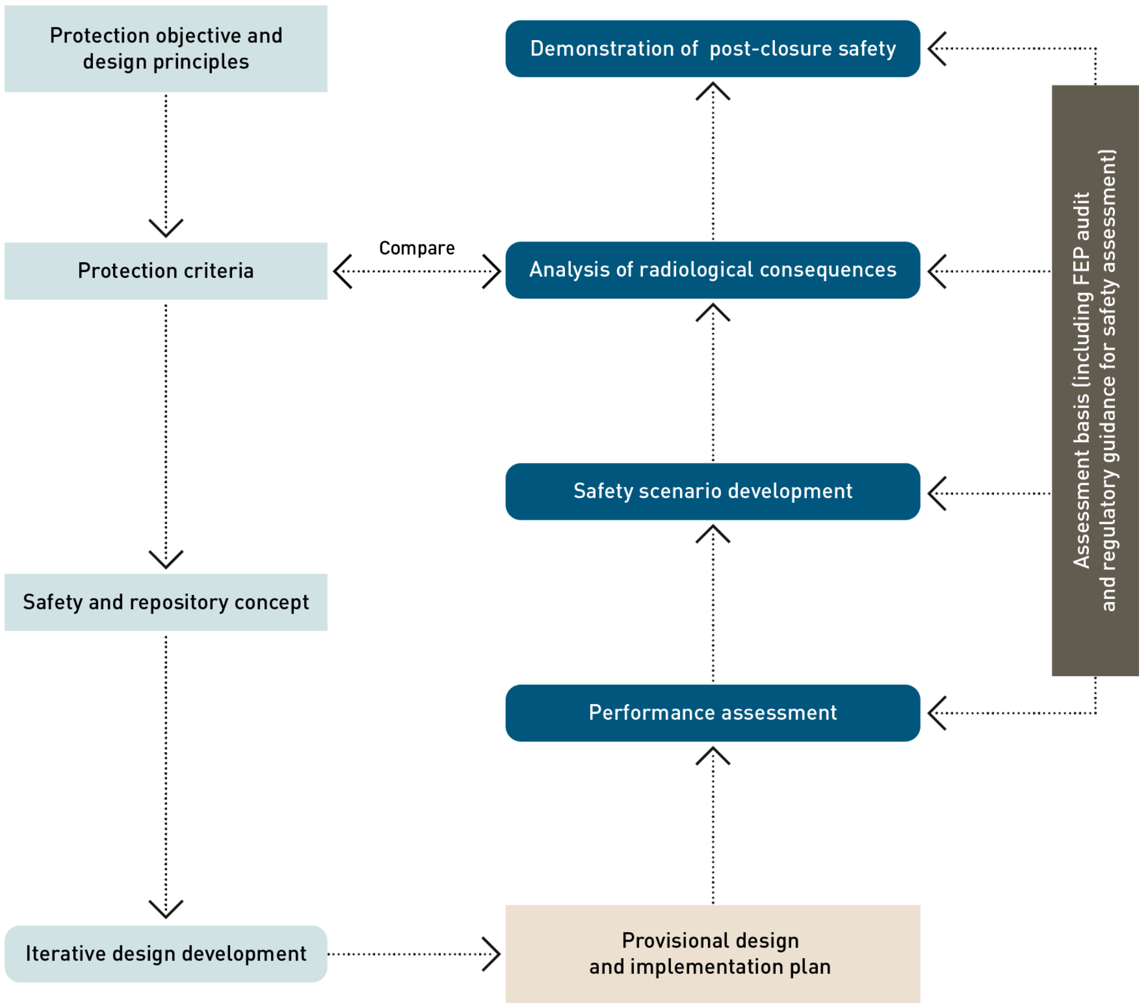

Fig. 1-3: High-level workflow for the safety assessment in support of the post-closure safety case for a combined repository in the proposed siting region

See Chapter 5 of NTB 24-19 (Nagra 2024u) for a full description.

Parallels in site comparison and safety assessment of the selected site

The development of site-specific configurations for an HLW repository and a separate L/ILW repository (Fig. 1-2) is part of the design development process. Site-specific repository projects are established for the planning of the repository facilities and are needed specifically for the site-specific safety analyses. The provisional design and implementation plan for the combined repository at the selected siting region is also an outcome of the iterative design development process (Fig. 1-3). A complete description of the site-specific repository projects as well as the combined repository project at the selected siting region can be found in the civil engineering dossier, NAB 23-01 (Nagra 2023a, Nagra 2023b).

The methodology adopted for the selection of the preferred siting region and the safety assessment methodology leading to the demonstration of post-closure safety for the repository in the proposed siting region follow parallel and consistent workflows, see NTB 24-19 (Nagra 2024u). There is a close relationship between performance assessment, one of the main elements of safety assessment for the proposed site, and the qualitative evaluation of the CRZ carried out for each siting region. There is also a close relationship between the analysis of radiological consequences in safety assessment and the site-specific safety analyses carried out for each siting region.

The development of a set of safety scenarios is one of the main processes that provides key inputs to the site-specific safety analysis (Fig. 1-2) as well as to the radiological consequence analysis process in safety assessment (Fig. 1-3). Given the similarity in the geological characteristics, expected evolution and the provisional engineering design of the repository system in all siting regions, the same safety scenarios can be used for both the site-specific safety analysis and the safety assessment of the combined repository at the selected site. Therefore, safety scenario development is mainly presented as a part of the safety assessment in this report. However, where safety scenarios are required to be propagated to site-specific safety analysis as part of site comparison, this is explicitly mentioned.

1.2 Safety scenarios, variants and calculation cases

The development of safety scenarios is based on the general scientific understanding contained in the assessment basis and the findings of the performance assessment (Fig. 1-3). Consistent with the SSG-14 guidance of the International Atomic Energy Agency (IAEA), this "*leads to a systematic focusing of the safety assessment on the important conditions and phenomena relating to performance of the disposal facility*" (IAEA 2011b). Moreover, safety scenario development enhances system understanding and supports the demonstration of system robustness. Care is taken in the selection of the set of safety scenarios to reduce scenario uncertainty by conceptualising and bounding the possible ways in which the repository might evolve. Thus, safety scenario development forms an integral part of the treatment of uncertainty in the safety assessment.

Consistent with international and national guidelines, safety scenarios are defined so that they describe both the expected evolution of the repository system over the time period for assessment, and also the less likely events and processes that may lead to deviations from expected barrier performance. Specifically, safety scenario development in the context of the general licence application involves the definition of:

- a reference safety scenario,
- a set of alternative safety scenarios,
- a set of hypothetical "what-if?" cases,
- a set of future human actions (FHA) safety scenarios.

The first two categories are also relevant for the site-specific safety analysis as part of site comparison.

Each safety scenario consists of a general description of the evolution of the repository system and its environment, starting from its initial state at the time of repository closure, and extending into the future, generally for as long as the waste presents a potential hazard.

A safety scenario may have one or more variants. Variants of a given safety scenario share the same general description of features, events and processes (FEPs) occurring over time, but differ in one or more key factors that significantly affect the radiological consequences of that particular scenario. Subsequently, for each scenario or variant, one or more "calculation cases" are defined, which incorporate more assumptions for other factors specific to the calculation case (see Chapter 4).

1.3 Objectives and scope

The objectives of this report are (1) to provide a detailed description of the safety scenario development methodology and (2) to apply the methodology in order to define safety scenarios, variants and calculation cases. These are input to both safety analysis in the context of site comparison and to the analysis of radiological consequences in the context of safety assessment. The justification for allocation of each safety scenario to one of the four above-mentioned categories is provided in this report. Moreover, discussion and explanation of the key factors relevant to each safety scenario, variant and calculation case and the corresponding assumptions are presented. It is, however, outside the scope of this report to define the background to every aspect of each scenario in detail, rather, this information can be found in the reports that comprise the assessment basis. In particular, the phenomenological evolution of the waste and the repository system is inferred from NAB 24-20 (Nagra 2024l) and the geological and climatic evolution of Northern Switzerland is deduced from the Geosynthesis, NTB 24-17 (Nagra 2024h).

This report does not provide any modelling and computational strategies to analyse the calculation cases that it defines. Detailed information regarding the models, data, computer codes used, and the assumptions made, to perform safety analysis and the analysis of radiological consequences is covered in NTB 24-18 (Nagra 2024q). The descriptions of the safety scenarios, variants and calculation cases given in the present report does, however, provide key input to the modelling and computational strategies.

The safety scenario development concerning FHAs and the excavation of the repository by erosive processes are detailed in separate dedicated reports, NAB 24-09 (Nagra 2024s) and NAB 24-08 (Nagra 2024r), respectively. For the sake of completeness, summaries of the safety scenarios, variants and calculation cases developed within the scope of these reports are provided here.

1.4 Structure of this report

Following this introduction in **Chapter 1**, the international context and regulatory framework guiding the development of the safety scenarios are summarised in **Chapter 2**. **Chapter 3** provides information on the safety and repository concept and provisional repository design, which are important inputs for safety scenario development. This chapter summarises the report NAB 24-18 (Nagra 2024t), which describes in more detail the safety requirements related to design and how different engineered and geological barriers contribute to system safety by means of the safety functions they perform. The methodology adopted for the safety scenario development is described in **Chapter 4**. It is more detailed than the summary provided in the safety assessment methodology report NTB 24-19 (Nagra 2024u). **Chapters 5 to 9** present the application of the safety scenario development methodology and the resulting safety scenarios, variants and calculation cases. The reference safety scenario is detailed in **Chapter 5**; the alternative safety scenarios are documented in **Chapter 6**; "what-if?" cases related to physical phenomena are described in **Chapter 7**; "what-if?" cases postulating a hypothetically degraded performance of the pillars of safety are defined in **Chapter 8**; and the future human actions safety scenarios are summarised in **Chapter 9**. A summary of safety scenarios developed in support of the general licence application is given in **Chapter 10,** as well as a discussion of completeness and comprehensiveness.

2 International and national context

The Swiss national regulations stipulate the requirements concerning the definition and analysis of safety scenarios for site selection and a general license application for the proposed site (ENSI 33/649 (ENSI 2018); see Section 2.2). This report documents how these requirements are fulfilled. In addition to these national regulations, a range of international standards and guidelines exist, which also contribute to the framework with which Nagra develops safety scenarios and defines their treatment in analysis. These are documented in the following sections.

2.1 International framework

The following sections provide an overview of the established international standards, guidelines and practices regarding the development of safety scenarios for the assessment of post-closure safety. This includes the work of the OECD Nuclear Energy Agency (NEA), the International Commission on Radiological Protection (ICRP) and the IAEA, including relevant IAEA Safety Standards and IAEA initiatives. Several examples of the application of these guidelines by other national waste management organisations are presented and serve to illustrate how Nagra's approach is consistent with the approaches adopted elsewhere.

2.1.1 Role of safety scenarios and general guidance on their development

A safety scenario may be defined as a "simplified description of a potential evolution of the repository system from a given initial state" (OECD/NEA 2013). Safety scenarios form the framework with which radiological consequence analysis can be formulated and discussed (OECD/NEA 2001, OECD/NEA 2021). Thus, safety scenario development supports the quantitative assessment of safety (IAEA 2012).

In addition, several other grounds for safety scenario development have been identified by the relevant international organisations. IAEA (2004) and OECD/NEA (2021) refer, among others, to the following:

- development and demonstration of system understanding,
- integration of scientific and technical knowledge, with a focus on its relevance to repository safety functions,
- influencing of model development and
- promotion of multidisciplinary communication, and the provision of a platform for communication between the developer, the regulator and other stakeholders.

OECD/NEA (2001) describes how the objectives and overall role of scenario development may change during the development of a programme. It notes how there is typically a shift "*from selection of cases sufficient for illustration of performance towards assurance of sufficiency and justification of cases as satisfying scientific coherence and regulatory requirements*". Indeed, this shift is apparent in Nagra's programme, particularly for the general licence application, and is evidenced throughout this report. Safety scenarios form part of the wider handling of uncertainty in safety assessment, addressing uncertainties in the broad evolution of the system over time, also termed "scenario uncertainties".

Safety scenario development forms a link between the understanding of the initial state and potential evolutions of the repository, including the impact of perturbing phenomena, and the analysis of radiological consequences. In performance assessment, i.e., the analysis of the THM-C evolution of the repository system (in Nagra's terminology), scenario uncertainties are identified and their effects on repository evolution and performance are analysed. Following this, safety scenarios are formulated and used to structure the analyses of radiological consequences in a way that systematically tests whether safety criteria are met for all credible potential evolutions[3] of the disposal system (OECD/NEA 2012).

Another possible route to the development of safety scenarios is the identification and evaluation of FEPs that may impact system performance or its evolution. This may include both internal phenomena, i.e., related to the repository components and their interactions, and those of external origin, e.g., climatic and geological evolution (OECD/NEA 2012, IAEA 2011b). Hence, characterisation of the site and its past evolution should help develop future evolution scenarios by aiding the identification of relevant FEPs (IAEA 2014, IAEA 2011b).

IAEA Safety Standard SSG-23 states that the choice of scenarios and the rationale for their selection are vital, as this will impact subsequent analyses, and the assessment as a whole (IAEA 2012). Fundamentally, scenarios are structured combinations of FEPs, with several key types considered, and for which the exact terms may differ between organisations (IAEA 2012):

- a "base case scenario", termed reference safety scenario by Nagra, which serves as a reference and for which the evolution is "expected",
- various "alternate evolution scenarios", termed alternative safety scenarios by Nagra, which incorporate disruptive processes and events that are less expected, though with various degrees of probability and/or disturbed performance (OECD/NEA 2016).

These scenarios focus on performance, e.g., waste and barrier degradation, and also events (e.g., earthquakes) that might impact containment and isolation (IAEA 2014). SSG-23 states that the base and alternate evolution scenarios will share most of the same FEPs, but some will differ, making each scenario distinct (para. 5.38; IAEA 2012). SSG-29 states that scenarios may be grouped to reduce the number of calculations, but the range should be sufficiently large to cover the uncertainties – thus, they should envelop the different possible system evolutions (IAEA 2014). Although SSG-29 was developed as guidance for near-surface facilities, this statement is also true for deep geological repositories. This selection of scenarios should also be accompanied by an explanation and justification of which scenarios are considered expected evolution and which have a low probability, along with an indication of how this likelihood and any uncertainty was assessed (IAEA 2012).

In addition to analysing scenarios that are judged to be broadly realistic (albeit sometimes highly unlikely), system robustness can be further demonstrated using a separate class of "what-if?" cases (IAEA 2012). These use extreme or exaggerated parameters or properties, which may be implausible or physically impossible, to bound and conceptually test robustness (OECD/NEA 2016).

There is also a need to consider FHAs, e.g., inadvertent human intrusion (IAEA 2011a), but these are generally handled as a separate class of scenarios given the inherent unpredictability and the need for significant speculation (see Section 2.1.2) (OECD/NEA 2021, OECD/NEA 2016, ICRP 1998).

Finally, several IAEA Safety Standards give general guidance on scenario development and are accounted for in the methodology applied in the present report. Key statements from these Safety Standards are presented in Tab. 2-1.

[3] For hypothetical evolutions, see the discussion on "what-if?" cases below.

Tab. 2-1: Key statements on scenarios from IAEA Safety Standards

Statement	Reference
The safety case for the period after closure should address scenarios for the more likely evolutions of the geological disposal facility and its regional setting over very long time periods (e.g., a time period comparable to that over which the waste remains hazardous) and the less likely events that might affect the performance of the facility. For geological disposal facilities, to meet the requirements, it is necessary that the safety case and the supporting assessments present evidence that the key features, events and processes that might significantly affect geological disposal system are sufficiently well understood that scenarios of possible evolutions are properly generated.	IAEA SSG-14 Para. 5.12 (IAEA 2011b)
Low probability scenarios that have a potential for major consequences should be explored to understand the robustness of the disposal system. The safety assessment should include some stylised calculations of the consequences of inadvertent human intrusion into the closed disposal facility.	IAEA SSG-14 Para. 5.15 (IAEA 2011b)
Robustness of the disposal system is evaluated through comparison of the results of analyses of the base case with a range of scenarios illustrating specific perturbations or uncertainties. Among the different types of perturbation, the most generally considered are those where one component or one of its characteristics is considered to have failed ("what if?" scenarios). Scenarios involving such strong perturbations applied to the disposal system are distinguished from scenarios describing degraded behaviour of the disposal system.	IAEA SSG-23 Para. 6.41 (IAEA 2012)
The post-closure safety case should specify a range of credible scenarios for the evolution of the disposal facility and its surroundings over the time period for which the waste represents a potentially significant hazard or as specified in national regulations, some of which prescribe the timescale for the assessment. Consideration should be given to expected scenarios (normal evolution scenarios) and to less likely scenarios.	IAEA SSG-29 Para. 5.18 (IAEA 2014)

2.1.2 Special case of future human actions

As noted above, safety scenarios that concern FHAs are considered as a separate category of safety scenarios due to their particularly unpredictable and hence speculative nature. The special character of these scenarios is recognised internationally and thus their specific treatment is explicitly mentioned in the national regulations of several countries, including Switzerland (Section 2.2). For this reason, the separate report NAB 24-09 (Nagra 2024s) is dedicated to FHA safety scenarios and includes details of the international guidelines and practices that underpin Nagra's methodology for the general licence application. Nevertheless, a brief overview is given in the present report.

The IAEA Specific Safety Requirements SSR-5 (IAEA 2011a) stipulate that only human actions that result in a direct disturbance of the repository (i.e., the waste itself, the contaminated near field or the engineered barrier materials) need to be considered and, hence, the focus is on human intrusion. However, deliberate disturbance of the repository does not need to be considered, and as such, only scenarios involving inadvertent human intrusions should be developed (IAEA 2011a). For example, this may include deep drilling or mining (IAEA 2011a, IAEA 2017). SSR-5, nevertheless, explains that the likelihood of such intrusion into the waste will be low due to the chosen depth for the geological disposal facility (IAEA 2011a).

Given the inherent uncertainties regarding FHAs (IAEA 2012), the international consensus is that any such scenarios and calculations may be stylised, i.e., use may be made of illustrative and informative, though not necessarily scientifically-derived, assumptions (IAEA 2011b, OECD/NEA 2016). Thus, these scenarios should typically assume present day technologies, procedures, and human lifestyles (IAEA 2012, IAEA 2011a).

2.1.3 Approaches to scenario development

The NEA (OECD/NEA 2021) has recently reported on the advances in methodologies for scenario development in geological disposal programmes over the past two decades. The development of scenarios has been the subject of two dedicated workshops: the first organised by the NEA Performance Assessment Advisory Group (PAAG) (a predecessor of the current Integration Group for the Safety Case, IGSC) (OECD/NEA 2001) and the second by the IGSC itself (OECD/NEA 2016). This topic has also featured prominently in several other IGSC workshops, projects, and publications, including the NEA MeSA initiative (Section 5.3 of OECD/NEA 2012). The IAEA has also documented the work of the *Improvement of Safety Assessment Methodologies* (ISAM) research project, which provides an evaluation of approaches for scenario development for near-surface facilities (IAEA 2004). The project recognises that many aspects of the methodology are similar for geological facilities. Additional guidance is provided by the IAEA safety standards (IAEA 2011b, IAEA 2012, IAEA 2014) and the European Commission (EC) PAMINA project (Galson & Richardson 2011). An overview of approaches is presented here with the intention of describing the commonalities of the international programmes.

In addition to generating scenarios that lead to calculation cases in support of quantitative safety assessment, the objectives of safety scenario development are to demonstrate complete and comprehensive accounting of perturbing phenomena; to screen them and decide how to treat them in assessment (e.g., include, exclude, perform scoping calculations); and to demonstrate traceability from data and system understanding to assessment models and calculations (OECD/NEA 2001). To achieve this, many national programmes now use specific methodologies to develop their scenarios in a systematic, structured and transparent way (OECD/NEA 2016). The IAEA sets out several reasons for this (IAEA 2004): first, a systematic process helps develop a justified and documented audit trail, which is a necessary step toward assuring comprehensiveness and permitting the scrutiny of logic and assumptions (OECD/NEA 2001). This provides assurance that all relevant phenomena have been accounted for and provides a platform for demonstrating how uncertainties in evolution have been addressed and assimilated into the safety case. The inclusion of structure and formalism in the systematic approach serves to increase traceability and thus, documentation (especially for the handling of expert judgement) using a hierarchical presentation aids transparency – an important part of confidence building (IAEA 2004, Galson & Richardson 2011, OECD/NEA 2001).

Though a formal approach to scenario development is typically adopted (para. 5.19, IAEA SSG-29 (2014)), it is acknowledged that there is no single approach and the approach chosen will be dependent on the assessment context (IAEA 2004), i.e., each waste management programme develops its own methodology adapted to specific national constraints, legislation and regulations. For example, some national regulators specify the broad types of phenomena that must be accounted for in assessment, whereas others may provide more specific FEPs lists (e.g., France) (OECD/NEA 2016). Some regulators allow for probability thresholds to aid FEP selection, though most regulations and guidelines do not explicitly require probability to be assessed (though this may be required if compliance is to be expressed in terms of risk). Additionally, some regulators stipulate a timeframe for the consideration of scenarios, which may appear as either a time cut-off or a change in the assessment criteria (OECD/NEA 2016).

In general, it is for the proponent to decide how to develop scenarios, i.e., which phenomena to include and how to represent them in models, though common objectives, features and trends can be identified. For example, there are two overarching approaches to scenario development (IAEA 2012). The "bottom-up" method first establishes a comprehensive list of FEPs that may impact performance or system evolution (IAEA 2004). These are then screened to exclude those with very low probabilities or minor consequences. Interactions between the remaining FEPs are examined and they are then combined in suitable scenarios, for which calculations can be formulated. Alternatively, a "top-down" approach focuses first on the safety functions and combines an integrated understanding of the system and its expected evolution with the identification of the relevant phenomena that may impact the system (OECD/NEA 2012). Again, scenarios are developed, and these may be audited against an appropriate FEP list (IAEA 2012). In practice, both methods may be used in combination, particularly as an internal auditing tool. Indeed, in Nagra's approach, FEPs are seen mainly as a tool to promote the completeness of the safety case as a whole, in addition to auditing the safety scenarios, and this is documented separately in NAB 24-20 (Nagra 2024k).

Regardless of whether a top-down or a bottom-up approach is employed, the first step in scenario development is an integrated description of the system, its expected initial state and potential evolutions, including the uncertainties (OECD/NEA 2012, OECD/NEA 2016). This is informed by the safety and repository concept, the safety functions, and a phenomenological description based on scientific and technological knowledge (OECD/NEA 2016). The approach adopted, however, will likely impact the degree to which FEP processing or quantitative system performance and evolution simulations (e.g., THM-C modelling) serve as the route to the analysis of disturbances and the identification of uncertainties (OECD/NEA 2012). These processes should then result in the definition of a reference/main/normal evolution scenario, and alternative scenarios, which include less probable phenomena and uncertainties that could degrade performance of the safety functions and thus impact the expected evolution (IAEA 2004, OECD/NEA 2016). There are several approaches used to do this; e.g., argumentation, safety function indicators (measurable properties that can be compared to criteria) and, for example, Qualitative Safety Assessment (QSA – Andra), which examines malfunctions with regard to safety functions (OECD/NEA 2016). The NEA MeSA initiative also highlights the importance of assessing phenomena / scenario probabilities qualitatively and/or quantitatively to structure and classify phenomena into various scenarios (OECD/NEA 2012). This may also determine their treatment in calculation cases, i.e., probabilistic or deterministic, or in qualitative discussion (IAEA 2004, OECD/NEA 2012). Likewise, stylised scenarios may also be used for phenomena with large and irreducible uncertainties, whose estimation would require undue speculation (Galson & Richardson 2011).

2.1.4 International examples

As highlighted above, the specific approaches and tools used for safety scenario development by the various national waste management programmes are varied. In order to compile the common elements and themes, the NEA coordinated a survey of the national programmes (regulators and implementers) and published the results as part of the IGSC Scenario Development Workshop Synopsis (OECD/NEA 2016). Here, the methods of SKB (Sweden), Andra (France) and NWMO (Canada) are highlighted to exemplify both the diversity and similarities between the various programmes and, thus, to further contextualise the approach selected by Nagra.

2.1.4.1 Sweden (SKB)

At the time of the NEA workshop, SKB had already completed the safety assessment in support of a general licence application for a spent nuclear fuel repository at the Forsmark site (SKB 2011) and was working toward the preliminary safety assessment report in support of a construction licence, since published in 2022 (SKB 2022). Throughout this process, safety scenario development has been used to explore all possible routes to loss of safety functions, both for the demonstration of compliance and to optimise techniques. To do this, a combination of the top-down and bottom-up approaches were used according to the following methodology: the first step involves the definition of the safety functions and analysis of the reference evolution, which includes all initial state factors, processes and predefined external conditions (provided by FEP identification). This delivers understanding of the evolution and its uncertainties and leads to the development of the "main scenario" (with two climatic variants). "Additional scenarios" are structured according to the safety functions, whereby the different failure modes of each barrier are considered. Then, the uncertainties are identified, followed by assessment of probabilities. Finally, combinations of scenarios are formulated after all individual scenarios have been defined and assessed. Here, the sequencing of scenarios within combinations are covered by relevant scenario iterations. "Residual scenarios", which are assessed independent of probability, are also formulated and are typically analogous to the "what-if?" cases of other programmes.

FEPs were identified with the aid of the NEA FEP database (OECD/NEA 2019) and formal management was facilitated by a commercially available database. A "FEP chart" derived from the database was used as a checklist and this was accompanied by "assessment model flowcharts" to link relevant processes to their modelling in safety assessment. No formal expert elicitation processes were used, but project members and internal experts reviewed the assessment report (SKB 2022) with regard to scenario comprehensiveness.

2.1.4.2 France (Andra)

Andra published the safety assessment in support of a construction licence application in 2022 (ANDRA 2022). Thus, the methods documented in the NEA synopsis (OECD/NEA 2016) represent the approach developed by Andra throughout the site selection process and since the feasibility assessment was published in 2005 (ANDRA 2005). This approach leads to the definition of two main scenarios: first, the "Normal Evolution Scenario" defines the likely evolution by incorporating probable natural events. This scenario fulfils the safety objectives of the repository and confirms that expected performance is achieved. Simulation of the expected evolution of the overall repository aids the identification of key processes. The "Altered Evolution Scenario" considers unlikely events and is based on a breakdown of safety functions. Hence, the approach is considered top-down. Additional consideration of stylised and hypothetical "what-if?" scenarios is performed separately, in addition to specific treatment of inadvertent human intrusion.

Several formalised processes outline the key steps in scenario development (ANDRA 2005). Functional Analysis (FA) is used to determine the safety functions and requirements; phenomenological analysis (PARS) develops the scientific understanding, based on site characterisation and R&D; and "Qualitative Safety Analysis" (QSA) is used to assess the effects of uncertainties in FEPs on safety functions. This leads to the definition of a series of calculation cases and thus to the derivation of scenarios and sensitivity analyses. The systematic nature of the QSA supports a component by component assessment (including safety functions) of FEP impacts and the attendant uncertainties. Then, the QSA considers whether these impacts and uncertainties can be eliminated or minimised by alternative designs, or whether they should be incorporated into calculation cases in scenarios.

In addition to the repository- and site-specific knowledge, FEP identification and guidance on implementation is obtained from a broad range of sources; including NEA's FEP database, the EC PAMINA project, and NEA and ICRP documentation. This is accompanied by the organisation of internal expert review of the processes to define FEPs, scenarios, models and parameters. The judgement of external experts is also integrated through the formal review of the QSA, scenarios and calculation cases.

2.1.4.3 Canada (NWMO)

NWMO are currently in the stage of site selection and so the level of detail and specificity in previous safety scenario assessments reflect a generic repository concept and hypothetical site (Garisto 2018). Nevertheless, the scenario development methods documented in the NEA synopsis (OECD/NEA 2016) have contributed toward "confidence in safety" documents for two potential sites in crystalline and sedimentary potential host rock formations, which will culminate in site selection (expected 2024) and a general licence application (NWMO 2023).

A systematic scenario identification approach considering FEPs and their timeframes has been developed by NWMO. This involves starting with both generic FEP databases (e.g., the NEA database) and formal exchanges between internal experts to identify external and internal FEPs (with reasoned extrapolation to a currently hypothetical site). Additionally, each iteration of the FEP catalogue reviews the previous versions and re-evaluates each FEP in turn, updating where necessary. Categorisation and screening of FEPs is performed and this leads to the development of a "normal evolution scenario" and several "disruptive event scenarios", including human intrusion and "what-if?" scenarios (Garisto 2018). The "normal evolution scenario" may include FEPs with minor consequences that, alone, are not considered scenario-generating. "Disruptive Event Scenarios" are formulated based on the potential for external and internal FEPs to compromise safety functions and features – and, in this sense, represents a top-down approach. These scenarios are audited against those of other countries.

Whilst no formal tools are employed, the treatment of FEPs and decisions on their propagation to scenarios is justified and documented (Garisto 2018). Furthermore, internal review by multi-disciplinary experts is used throughout the process to improve scenario definition and related models.

2.2 Regulatory framework

Requirements for the documentation of the general licence application and for the final stage of the site selection process in Switzerland are set out in ENSI 33/649 (ENSI 2018). Specific requirements for the safety assessment and safety case for the proposed site are set out in ENSI's Guideline ENSI-G03 (ENSI 2023), which is accompanied by an explanatory report (ENSI 2020b).

The elements to be addressed in the safety assessment, according to the ENSI-G03 guideline, include among others, a scenario analysis and definition of the calculation cases used to investigate the evolution of the deep geological repository[4]. According to the regulatory guidance, safety scenarios are possible variants of the development of waste, technical and natural barriers, the biosphere and the human way of life under the influence of assumed FEPs[5]. Each safety scenario consists of a general description of the evolution of the repository system and its environment, starting from its initial state at the time of post-closure, and extending into the future, generally

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[4] In German: *Szenarienanalyse und Festlegung der Rechenfälle, mit denen die zu betrachtenden Entwicklungen des Tiefenlagers untersucht werden.*

[5] In German: *Szenarien sind mögliche Varianten der Entwicklung der Abfälle, der technischen und natürlichen Barrieren, der Biosphäre und der menschlichen Lebensweisen unter Einwirkung von angenommenen Eigenschaften, Ereignissen und Vorgängen (features, events and processes, FEPs).*

for as long as the waste presents a potential hazard. The guideline states that the radiological effects of future developments are to be assessed using enveloping variants or estimated by using conservative assumptions[6].

ENSI-G03 further states that a period of up to one million years should be addressed by safety assessment[7], and thus implicitly also by the safety scenarios. This "time period for assessment" must take into account the evolution of the radiological hazard potential of the waste and also the predictability of long-term geological evolution[8]. ENSI-G03 also states that, at times beyond the end of the time period for assessment, the range of variation of the possible radiological impacts of a deep geological repository shall be determined, taking into account the inherent uncertainties[9]. This includes the consideration of scenarios in which the repository area is increasingly exposed to surface influences arising from geological process[10]. This implies that such scenario descriptions should extend beyond one million years, while recognising the increasing levels of uncertainty. However, the dose and risk criteria applicable up to a million years do not apply in the longer term. Rather, the effects at the surface must not be significantly higher than the average current radiation exposure of the Swiss population[11].

A site-specific reference safety scenario has been defined in ENSI 33/649 (ENSI 2018) as the expected variant of the evolution of the repository system (waste inventory, barrier system, geological situation), the biosphere and the human way of life[12]. In the context of the comparison of siting regions, this includes the requirement that the inherent bandwidths of parameters and evolution scenarios, which cannot be reduced by further investigations prior to the selection of a site, are to be considered as part of the reference scenario and taken into account accordingly in the comparison[13].

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6 In German: *Die radiologischen Auswirkungen zukünftiger Entwicklungen sind durch umhüllende Varianten einzugrenzen oder durch konservative Annahmen abzuschätzen.*

7 In German: *Für den Sicherheitsnachweis ist ein Nachweiszeitraum von bis zu einer Million Jahre festzulegen.*

8 In German: *Die zeitliche Entwicklung des radiologischen Gefährdungspotenzials der eingelagerten Abfälle und die Prognostizierbarkeit der geologischen Langzeitentwicklung sind zu berücksichtigen.*

9 In German: *Für die Zeit nach Ablauf des Nachweiszeitraums ist der Variationsbereich der möglichen radiologischen Auswirkungen eines geologischen Tiefenlagers unter Berücksichtigung der inhärent vorhandenen Unsicherheiten zu ermitteln.*

10 In German: *Szenarien, in denen der Tiefenlagerbereich aufgrund geologischer Vorgänge zunehmend Einflüssen der Erdoberfläche ausgesetzt wird, sind in diese Betrachtungen einzubeziehen.*

11 In German: *Nach Ende des Nachweiszeitraums dürfen die Auswirkungen an der Oberfläche nicht wesentlich höher sein als die durchschnittliche heutige Strahlenexposition der Schweizer Bevölkerung.*

12 In German: *Erwartete Variante der Entwicklung des Tiefenlagersystems (Abfallinventar, Barrierensystem, geologische Situation), der Biosphäre und der menschlichen Lebensweise.*

13 In German: *Die inhärenten, nicht durch weitere Untersuchungen vor der Standortwahl reduzierbaren Bandbreiten von Parametern und Entwicklungsszenarien sind als Bestandteil des Referenzszenariums zu betrachten und entsprechend beim Vergleich zu berücksichtigen.*

The specific safety scenarios to be included in safety assessment in addition to the reference safety scenario are generally deemed to be for Nagra to decide. However, ENSI-G03 requires that the safety assessment considers:

- scenarios in which the repository is increasingly exposed to influences from the Earth's surface due to geological processes[14], and
- scenarios in which the safety of the repository is influenced by human actions that are credible with regard to today's society[15].

FHAs could conceivably include inadvertent human intrusion into the repository. Regarding this possibility, ENSI-G03 states that, during the million year "time period for assessment", the radiological consequences of inadvertent human intrusion into the repository must be assessed based on the criteria stipulated by IAEA Safety Standard SSR-5 (IAEA 2011a)[16]. This means that the annual dose received by those living around the site should be less than 1 mSv, otherwise efforts to reduce the probability of intrusion or to limit its consequences are warranted.

Whilst assumptions regarding the evolution of the biosphere are part of the definition of safety scenarios, it is recognised that biosphere evolution cannot be predicted reliably over a million-year time frame. Thus, for the calculation of radiation dose, a representative individual from within the population group most affected by the potential impacts of a deep geological repository, and with realistic living habits from today's perspective, must be postulated (ENSI 2023)[17]. Nevertheless, the impact of climate development and the corresponding biosphere models must be defined and incorporated in these analyses[18].

Finally, safety scenarios are developed for both the safety assessment in support of the safety case for a combined repository in the selected siting region and also for the comparison of siting regions (Fig. 1-3). This includes the analysis of both reference and alternative safety scenarios, as specified in ENSI 33/649 (ENSI 2018). However, the analysis of "what-if?" cases is not required as part of the site-specific safety analysis for site comparison (Section 4.5 of ENSI 33/649). Indeed, the regulations stipulate that the demonstration of the effectiveness and robustness of the engineered and natural barriers, the scenario analysis and the sensitivity analyses in the safety assessment in support of the safety case are more detailed than those carried out within the safety analyses supporting site selection[19] (Section 5.2 of ENSI 33/649).

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[14] In German: *Szenarien, in denen der Tiefenlagerbereich aufgrund geologischer Vorgänge zunehmend Einflüssen der Erdoberfläche ausgesetzt wird, sind in diese Betrachtungen einzubeziehen.*

[15] In German: *Szenarien, in denen die Sicherheit des geologischen Tiefenlagers durch menschliche Handlungen beeinflusst wird, sind so anzunehmen, wie es mit Blick auf die heutige Gesellschaft glaubhaft erscheint.*

[16] In German: *Im Nachweiszeitraum sind die radiologischen Folgen eines unbeabsichtigten menschlichen Eindringens ins Tiefenlager anhand der Kriterien (c) und (e) gemäss Absatz 2.15 des IAEA Safety Standard SSR-5 zu beurteilen.*

[17] In German: *Für die Berechnung der Strahlendosis ist ein repräsentatives Individuum innerhalb der von den potenziellen Auswirkungen eines geologischen Tiefenlagers meist betroffenen Bevölkerungsgruppe mit aus heutiger Sicht realistischen Lebensgewohnheiten zu postulieren.*

[18] In German: *Mögliche Varianten der Klimaentwicklung und entsprechende Biosphärenmodelle sind festzulegen und ihre Bedeutung für die Langzeitsicherheit des geologischen Tiefenlagers ist zu untersuchen.*

[19] *Die Sicherheitsanalyse des Standortvergleichs (siehe Kap. 4.4) für den gewählten Standort wird entsprechend vertieft und mit umfassenden Szenarien- und Risikoanalysen gemäss Richtlinie ENSI-G03 ergänzt. Insbesondere wird für die in Kap. 4.4 aufgeführten Punkte b) "Wirkung und Robustheit der technischen und natürlichen Barrieren", e "Szenarienanalyse mit einer umfassenden FEP Analyse" und h "Sensitivitätsanalyse" ein höherer Detaillierungsgrad erwartet.*

Additionally, safety assessment does not need to consider intentional human intrusion, intentional damage, nor occurrences with non-radiological effects that far exceed their radiological effects (Section 9.3.4 in ENSI-G03)[20].

[20] In German: *Die Sicherheitsanalyse ist nicht zu führen für: a. absichtliches Eindringen von Menschen in ein geologisches Tiefenlager; b. gezielte Schädigung eines geologischen Tiefenlagers; c. Vorgänge, deren nicht-radiologische Auswirkungen die radiologischen um ein Vielfaches übertreffen.*

3 Safety and repository concept, provisional design, and phenomenological description of the expected evolution

Although a specific provisional design is developed for each repository type in each siting region (Fig. 3-1, for details see NTB 24-19 (Nagra 2024u)), the same general safety and repository concept applies to both the site-specific individual repositories and the combined repository at the proposed siting region. Due to the similarity of the available geological barriers in all three siting regions (Section 5.1) and the identical safety and repository concept, the provisional designs are very similar, with only some minor differences. One notable difference between the provisional designs is the access structures to the surface facilities, which can consist of either only shafts or a combination of a ramp and shafts. Moreover, for the combined repository, one central area and one set of access structures to the surface facilities are shared by both repository sections. Nevertheless, these variations in provisional design have little impact on safety scenario development, which provides only a general description of the repository evolution over time. Although all model configurations and parameter values in analyses performed in the context of the general licence application are tailored to the site and repository type under investigation, such details are out of scope of this report and are documented extensively in the performance assessment reports NAB 24-25 and NAB 24-26, and the radiological consequence analysis report NTB 24-18 (Nagra 2024j, Nagra 2024i, Nagra 2024q).

The following sections in this chapter present the safety and repository concept and the provisional design specific to the combined repository at the proposed siting region, as described in more detail in NAB 24-18 (Nagra 2024t). Since these mostly also apply to the site-specific individual repositories, repetition is avoided. The interested reader is referred to the engineering dossier NAB 23-01 for more details on site-specific individual repositories (Nagra 2023b). In addition, a phenomenological description of the expected evolution of the repository system is provided in this chapter. This forms the basis for the development of the reference safety scenario.

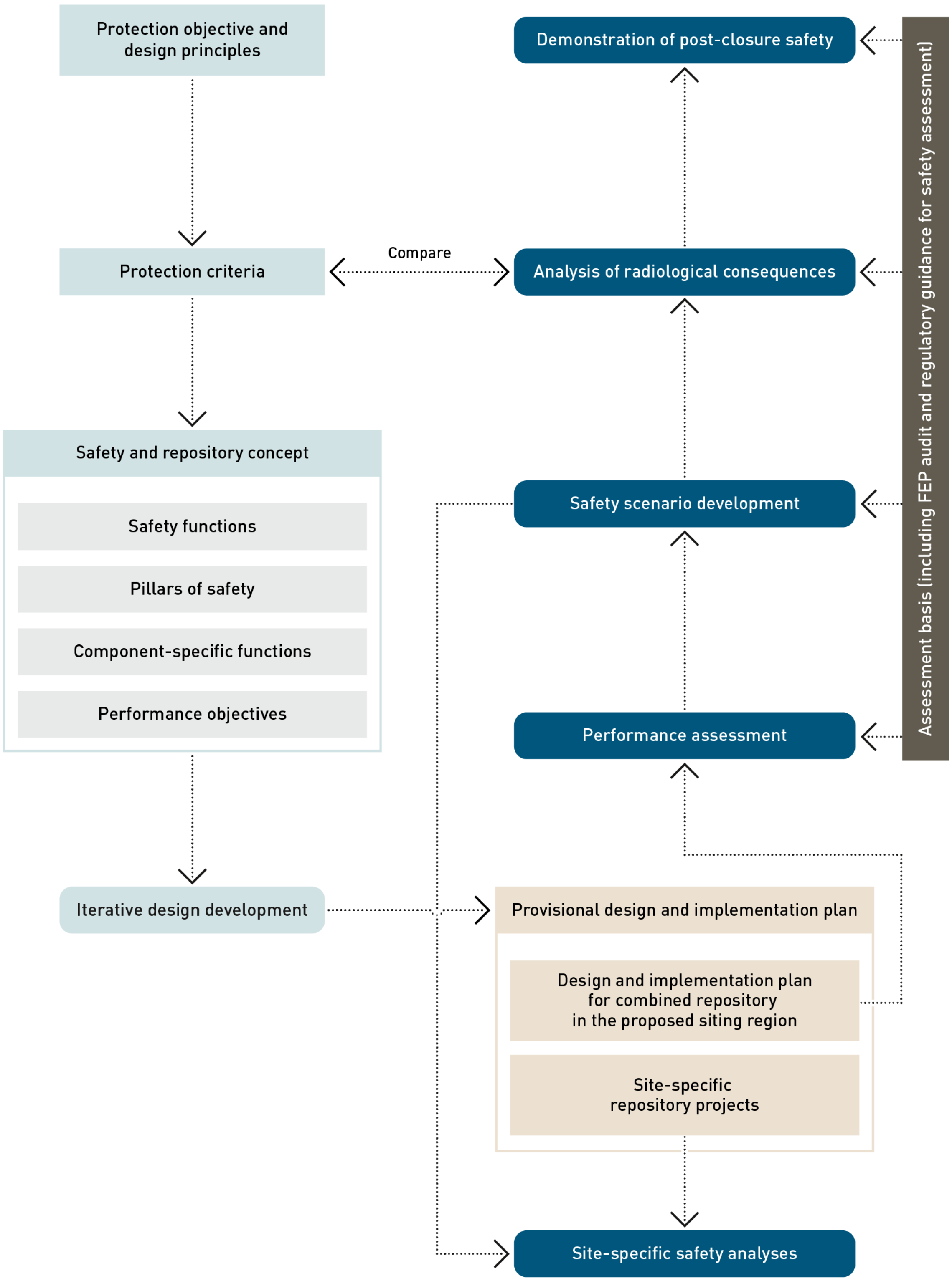

Fig. 3-1: Workflow for the post-closure safety case, highlighting the process and outcome of the development of the provisional design and implementation plan, which also provides input for the site-specific safety analyses in the framework of site comparison

3.1 Safety and repository concept

In line with the Swiss legal and regulatory framework, as well as national and international principles and practice, the repository provides safety by means of several successive engineered and geological safety barriers, i.e., the multi-barrier system. These barriers operate passively, meaning that, after closure of the repository, no further measures, such as for maintenance, control, or monitoring, are required to ensure post-closure safety. This relieves future generations of the burden of having to manage or monitor the disposed waste.

The location of the geological repositories will be such that the risk of future inadvertent human intrusion is small. Nonetheless, because the possibility of inadvertent human intrusion or disturbance of the repository in the distant future cannot be completely excluded, repository design features are incorporated that mitigate its potential impact. This also forms part of the safety concept.

The geological barrier is considered to be of primary importance in the long term, due mainly to the excellent qualities and long-term stability of the CRZ. The CRZ includes the Opalinus Clay host rock, as well as the geological units above or below the host rock that also contribute to radionuclide immobilisation and retardation of release, termed confining units. The procedure for defining the CRZ is reported in ENSI 33/649 (ENSI 2018) and is addressed in the report supporting site comparison NAB 24-23 (Nagra 2024p). The Opalinus Clay formation is characterised by:

- A fine and homogeneous pore structure with a very low hydraulic conductivity. This ensures that water movement in this clay formation is limited, and that radionuclide migration is essentially diffusion dominated.
- A high clay mineral content. This results in a high sorption capacity for many radionuclides, thereby delaying their migration through the clay.
- A high self-sealing capacity. This means that any fractures in the clay will rapidly close again.

The confining units include sections with heterogeneous distributions of clay minerals and locally lower clay contents but nonetheless contribute to the retardation of radionuclide releases.

The geological barrier is complemented by a mutually compatible set of engineered barriers. A key role of the engineered barriers is the minimisation and mitigation of disturbances to the CRZ caused by the waste and its emplacement, including, for example, the effects of heat generated by the waste and the disturbance to the rock caused by the excavation and ventilation of underground openings.

Waste is positioned in emplacement rooms, located deep underground, roughly in the middle of the Opalinus Clay host-rock layer (Fig. 3-2). The engineered barriers for HLW disposal consist of SF assemblies with fuel rods (UO_2 or mixed oxide fuel (MOX) pellets in cladding tubes) and vitrified RP-HLW that are packaged in steel canisters. The HLW canisters are emplaced in drifts, which are subsequently backfilled with a buffer and sealed. For L/ILW disposal, L/ILW packages are placed inside waste containers and voids are filled with cementitious material. The waste containers are in turn emplaced in caverns that are backfilled with cement-based mortar.

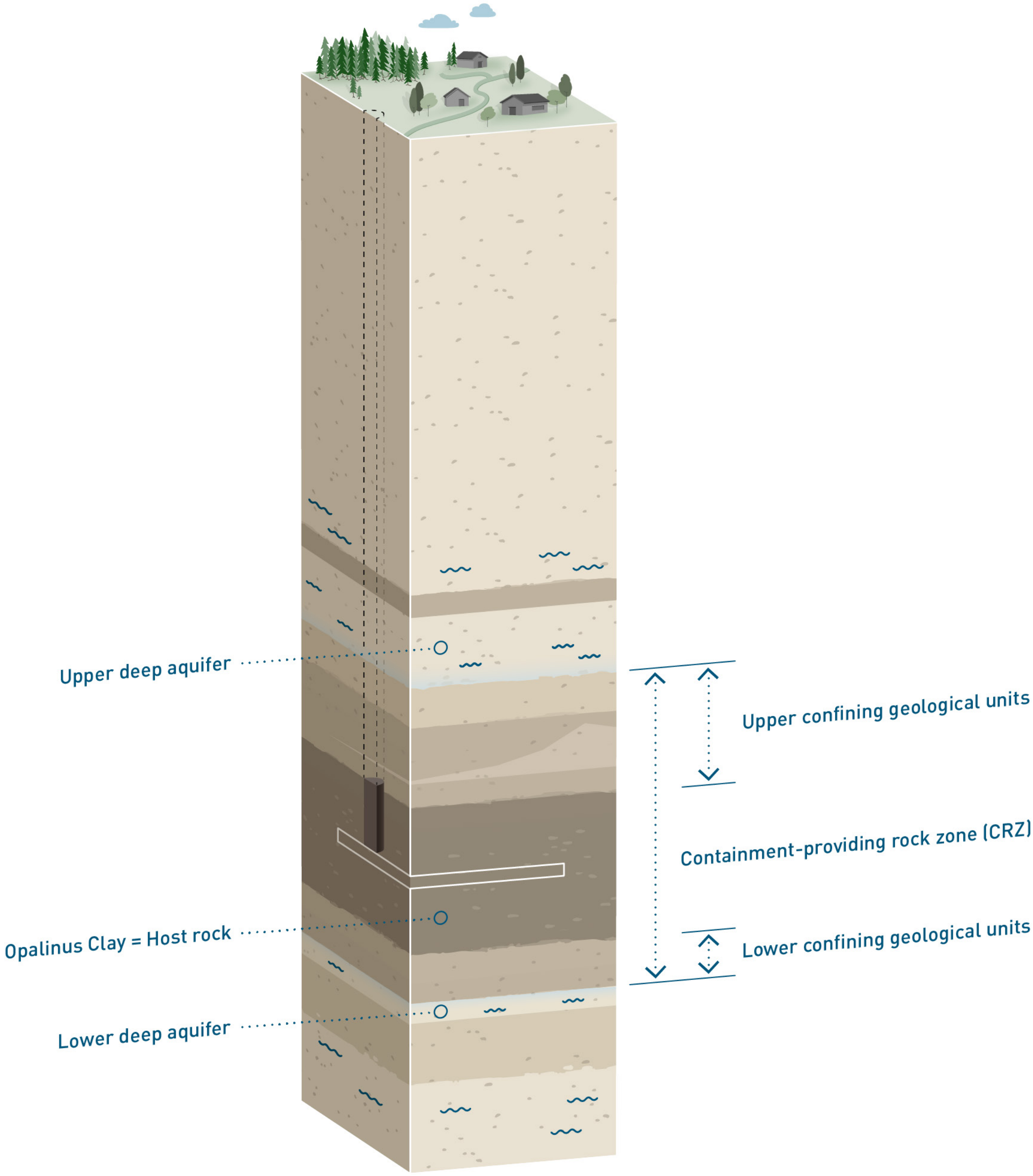

Fig. 3-2: Placement of the repository deep underground within the Opalinus Clay, between its confining units

The white rectangle depicts the location of the repository within the Opalinus Clay host rock.

3.1.1 Safety functions and related safety requirements

Collectively, the multi-barrier system provides the following safety functions:

S1: Isolation of radioactive waste from humans and the environment,

S2: Complete containment of radionuclides for a period of time,

S3: Immobilisation, retention, and slow release of radionuclides,

S4: Compatibility of the components of the repository system,

S5: Long-term stability of the multi-barrier system regarding long-term geological and climatic evolution.

These safety functions are used to derive a set of safety requirements on the system components, including the "pillars of safety" described in Section 3.1.2. The safety requirements are described and discussed at length in NAB 24-18 (Nagra 2024t).

Analysing whether the barriers meet their various requirements and thus fulfil their assigned safety functions requires an understanding of the events and processes that are likely to affect the repository design over the safety-relevant assessment timeframe; this analysis is termed performance assessment and is documented in NTB 24-22 (Nagra 2024v).

3.1.2 Pillars of safety

The repository barriers and their properties that are considered well understood and insensitive to perturbations and which are the main contributors to the safety functions are termed "pillars of safety". The pillars of safety are listed below:

- The **deep underground location of the waste emplacement rooms in a stable geological environment** that lacks underground resources specific to the region that could attract future human exploitation. It ensures that the repository is not susceptible to geological events and processes relevant to post-closure safety and that inadvertent human intrusion remains unlikely.
- The **containment providing rock zone** (**CRZ**) includes the host rock as well as upper and lower confining units. The host rock, Opalinus Clay, is characterised by a fine and homogeneous pore structure, extremely low hydraulic permeability, a homogeneous and high clay mineral content and the associated high sorption capacity for many radionuclides. The CRZ is characterised by favourable properties (especially self-sealing ability) for long-term stability, forming a very effective and stable barrier against radionuclide transport and a compatible (physical and chemical) environment for the engineered barriers.
- Both the **SF and RP-HLW matrices** are chemically stable in the expected environment.
- The **SF and RP-HLW disposal canisters** are mechanically stable and corrosion-resistant in the expected environment. They ensure complete containment of the radionuclides for at least as long as the heat generated by the waste has significant potential to affect transport processes in the surrounding barriers and satisfy the regulatory requirement of complete containment for at least 1,000 years (ENSI 2023).

- The HLW emplacement drifts will be backfilled with a **buffer**. This buffer serves as a suitable physical and chemical environment that enhances the longevity of the HLW disposal canisters. Additionally, the buffer offers mechanical support to the surrounding rock after the degradation of the tunnel support. It compartmentalises the repository by isolating the disposal canisters from one another, thereby mitigating the impact of accidental human intrusion. The buffer reduces the potential effects of heat release on the safety relevant properties of the CRZ and acts as a barrier against radionuclide transport.
- The **L/ILW cementitious near field** promotes sorption of radionuclides, decreases corrosion of metals and inhibits degradation of organic materials, which in turn reduces gas generation. The cement-based backfill can also store a significant volume of gas and provides mechanical stability to the host rock, even after the degradation of the tunnel support.
- The **closure system** provides retention of radionuclides released from the waste forms, and a transport and storage system for repository-generated gas, which retains gaseous radionuclide species within the underground structures while limiting the build-up of gas pressure. The sealing of both the individual waste emplacement rooms and the HLW and L/ILW disposal sections reduces safety-relevant interaction between the disposal sections and the radiological impact of inadvertent human intrusion. The closure system further provides mechanical stabilisation of the host rock after the rock support has degraded.

Each pillar of safety can contribute directly and/or indirectly to the safety functions. For example, the HLW disposal canisters contribute directly to the containment of radionuclides, while the surrounding buffer contributes indirectly as it helps to protect the canisters. Compatibility between the different pillars is based upon a solid technical and scientific understanding of the geological and engineered components. The contributions of these seven pillars to the five safety functions are summarised schematically in Fig. 3-3 and Fig. 3-4 and is elaborated in the discussion of component-specific functions in Section 3.4 of NAB 24-18 (Nagra 2024t).

SF and RP-HLW matrix

- contributes to the **immobilisation, retention, and slow release** of radionuclides.
- is **compatible** with the components of the repository system.

SF and RP-HLW disposal canisters

- contribute to the **complete containment** of radionuclides for a period of time.
- support the **immobilisation, retention, and slow release** of radionuclides.
- are **compatible** with the components of the repository system.

Buffer of the HLW emplacement drifts

- contributes to the **immobilisation, retention, and slow release** of radionuclides.
- is **compatible** with the components of the repository system.

Deep underground location in a stable geological environment

- contributes to the **isolation** of radioactive waste from humans and the environment.
- contributes to the **long-term stability** of the repository system with regard to long-term geological and climatic evolution.
- supports the **immobilisation, retention, and slow release** of radionuclides.

Containment-providing rock zone (CRZ)

- contributes to the **isolation** of radioactive waste from humans and the environment.
- contributes to the **immobilisation, retention, and slow release** of radionuclides.
- contributes to the **long-term stability** of the repository system with regard to long-term geological and climatic evolution.
- is **compatible** with the components of the repository system.

Closure system (backfill and seals)

- contributes to the **isolation** of radioactive waste from humans and the environment.
- contributes to the **immobilisation, retention, and slow release** of radionuclides.
- is **compatible** with the components of the repository system.

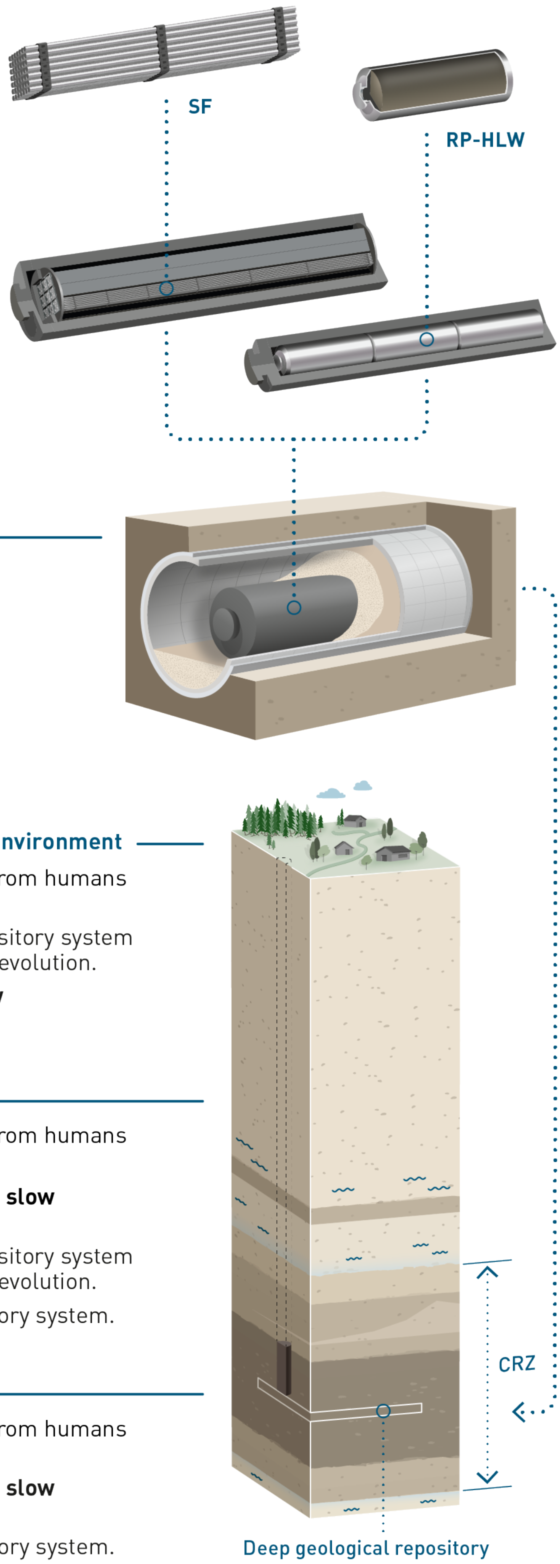

Fig. 3-3: Summary of the pillars of safety for HLW disposal and the safety functions they contribute to (in bold)

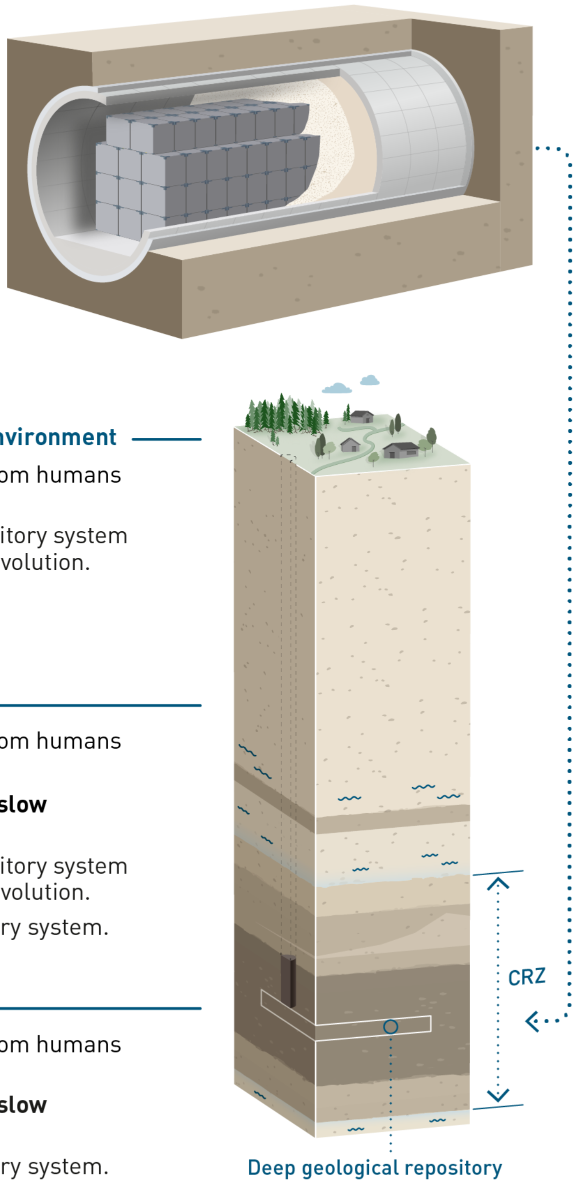

Fig. 3-4: Summary of the pillars of safety for L/ILW disposal and the safety functions they contribute to (in bold)

3.2 Provisional repository design

The provisional design for a combined deep geological repository for HLW and L/ILW at the proposed site, at a depth of ca. 900 m, is developed for the purposes of the general licence application. An overview of the provisional design is given in the following paragraphs; for more details, see Chapter 4 in NAB 24-18 (Nagra 2024t) and NTB 24-11 (Nagra 2024b). Since safety scenarios are specifically developed for the post-closure phase, this chapter does not provide details about construction phases and implementation plans.

As illustrated in Fig. 3-5, the combined repository is foreseen to consist of two separate sections: one for the disposal of L/ILW (including ATW), and the other one for HLW (including both RP-HLW and SF). It will be connected to the surface via three shafts. At the base of the shafts, a central area will be constructed, which will be connected to the emplacement rooms through multiple accessways.

Disposal takes place in parallel sets of emplacement rooms (HLW emplacement drifts and L/ILW emplacement caverns). The HLW emplacement drifts will be supported by pre-cast concrete tubing elements (i.e., ring elements). The tunnel support for the L/ILW caverns and other underground openings consists of an outer layer of shotcrete and an inner concrete liner. The engineered barriers installed within the emplacement rooms are also illustrated in Fig. 3-5.

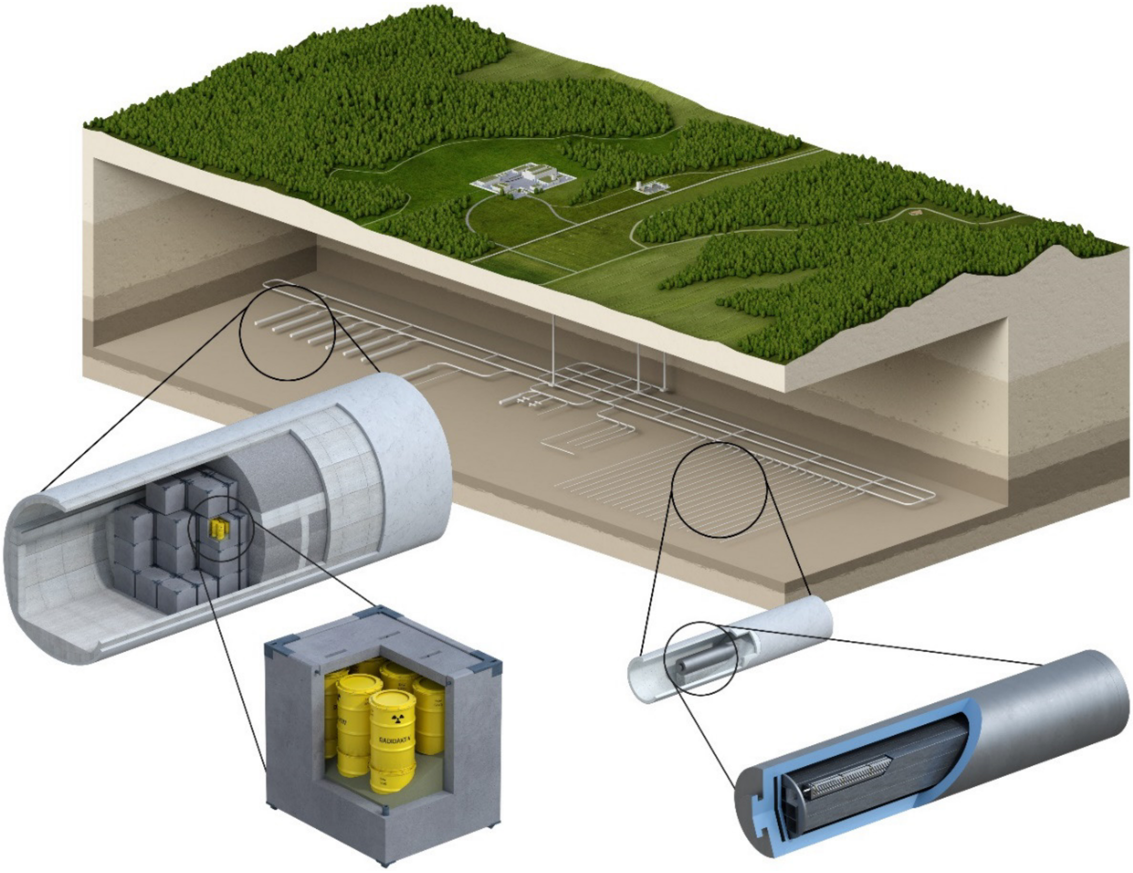

Fig. 3-5: Conceptual illustration of the two distinct repository sections in the provisional design for a combined deep geological repository

Engineered barriers foreseen for disposal of L/ILW and HLW are shown on the left and right sides, respectively.

HLW is encapsulated in carbon steel disposal canisters (pillar of safety), placed coaxially along the emplacement drifts, with the surrounding space filled with a bentonite buffer (pillar of safety), as illustrated in Fig. 3-3.

Most of the L/ILW is compacted, embedded in cementitious material and placed in standardised 200 L drums, MOSAIK-II-type casks made of cast iron, or steel casks. These waste packages are placed inside containers made of reinforced concrete and infilled with a cement-based material. In combination with the backfill mortar, the cement-based nearfield thus comprises a pillar of safety (Fig. 3-4).

Finally, the closure system (pillar of safety) consists of various clay-based seals and tunnel backfill. As illustrated in Fig. 3-6, the seals comprise:

- V1-HLW and V1-L/ILW seals (emplacement room seals) located at the entrance of the HLW emplacement drifts and L/ILW emplacement caverns, respectively. These seals are installed immediately after emplacement of the waste and the complete backfilling of the emplacement rooms.
- V2-HLW and V2-L/ILW seals (disposal area access seals) located at the entrance of the disposal area accessways (in the construction, operations and ventilation tunnels) of the HLW repository section and the L/ILW repository section (in the ventilation and operations tunnel), respectively.
- V3 seals (shaft seals) located in the shafts up to the top of the Opalinus Clay host rock. These are the outermost seals.

VF1 and VF2 backfills fill the repository structures up to the V3 seals at the top of the Opalinus Clay. In addition, shaft backfill fills the part of the shafts above the V3 seals up to the surface level.

The V1-HLW and V2-HLW seals are designed to limit water and gas flow. On the other hand, the V1-L/ILW and V2-L/ILW seals, and the backfill materials, are designed with a higher gas permeability to prevent the build-up of potentially damaging gas pressures, due to gas generated by corrosion of metals and degradation of organic materials, predominantly in the L/ILW disposal caverns. On the contrary, V3 seals are designed to be both gas- and water-tight once fully water saturated.

The provisional designs for separate deep geological repositories for HLW and L/ILW in each of the three siting regions are broadly similar to those of the HLW and L/ILW repository sections of the combined repository, although with separate access structures. The same engineered barrier layout and properties are assumed in all three siting regions, with the exception that, for the JO siting region, access to the underground is assumed to be via a ramp. A V4 seal will be placed in the lowest section of the ramp to seal the repository from the surface environment (Nagra 2023b).

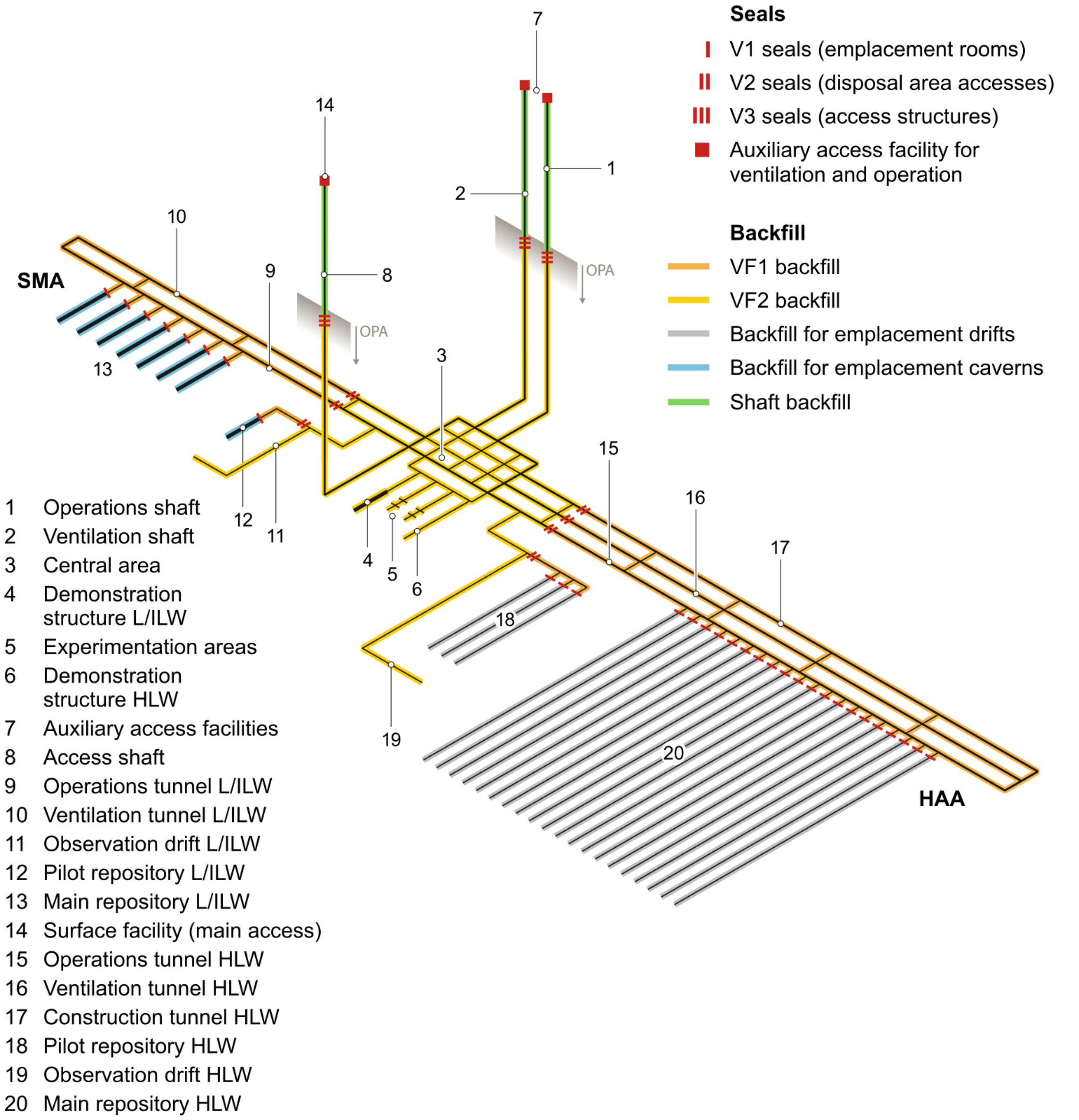

Fig. 3-6: Schematic view of the underground facilities in the provisional design, including sealing and backfill of the repository structures

From Nagra (2021b). This design may be refined and modified.

3.3 Phenomenological description of the expected evolution

A qualitative description of the expected phenomenological evolution of the repository is presented in NAB 24-20 (Nagra 2024l). Evolution in the post-closure period can be described in terms of five periods (which, to some extent, overlap):

1. The radionuclides are completely contained in the disposal packages. For the provisional design of the HLW disposal canisters, this period is expected to exceed the regulatory requirements and a containment period of at least 1,000 years is anticipated. No period of complete containment can be fully assumed for the L/ILW containers. However, the L/ILW containers, backfilled with cement mortar, contribute to the retention of radionuclides.
2. A small proportion of the radionuclides in the HLW are released shortly after canister breaching. Some releases are almost instantaneous (e.g., gaseous fission products), but most radionuclides (from activated SF assemblies or reprocessed glass) will be released very slowly, congruently with corrosion or glass dissolution, respectively.
3. The radionuclides released from the disposal packages start to migrate towards the host rock and/or the closure system. This migration is inhibited, reduced, and delayed by the physical and chemical environment created by the bentonite buffer or cementitious near-field.
4. The radionuclides reaching the host rock will continue to migrate through the CRZ away from the repository. This migration is mainly diffusion-driven and very slow in the host rock.
5. The radionuclides that penetrate the CRZ, may enter deep, regional and local groundwater aquifers, and may eventually reach the biosphere, where they will be further dispersed. This can lead to small radiological exposure to humans or the environment.

The phenomenological description highlights that the released radionuclides will migrate only slowly towards the surface environment, with substantial attenuation by radioactive decay of many radionuclides: first within the engineered barriers and then, for any that penetrate these barriers, within the surrounding geological barrier. Once reaching the biosphere, the remaining radionuclides will be diluted in different compartments (e.g., soil, atmosphere, plants, etc.). Due to the combined effect of the safety barriers, potential doses to humans or the environment are expected to be well below the protection criterion specified by the regulatory authority.

4 Methodology

Safety scenario development is one of the four main processes comprising safety assessment that is performed to demonstrate post-closure safety for the repository at the proposed siting region (Fig. 1-3). Nagra has developed a methodology for safety scenario development for the general license application that complies with the national regulatory requirements and is in line with the international guidelines (see Chapter 2). This chapter provides a thorough description of the safety scenario development methodology depicted in Fig. 4-1. It is also summarised in the overarching safety assessment methodology report, NTB 24-19 (Nagra 2024u).

Overview

Safety scenarios for the general license application are established based on the substantial system understanding within an extensive assessment basis, as well as the findings of the performance assessment. The assessment basis provides sound scientific understanding of the repository system and its evolution, as well as the associated uncertainties which are identified and, where possible, quantified. This includes key information such as the general scientific understanding of the waste inventory (Nagra 2023d), the location, layout and the engineering provisional design of the deep geological repository (Nagra 2024t, Nagra 2024b, Nagra 2023a), an integrated understanding of the host rock and its geological setting (Nagra 2024h), and the possible paths of geological and climatic evolution in the siting regions far into the future (Nagra 2024h, Nagra 2024d). The narrative of the expected evolution of the repository, inferred from the current scientific understanding documented in the assessment basis reports, is brought together within NAB 24-20 (Nagra 2024l). This report, summarised in Section 3.3, provides a high-level description of the expected evolution and behaviour of the repository system, its components, and its surrounding environment over extended periods, and is the main input for the development of the reference safety scenario.

Additionally, the results of the performance assessment, the first process performed in the safety assessment (Fig. 1-3), provide essential data and knowledge for the safety scenario development process; including the expected performance, as well as other lines of evolution of the multi-barrier system. This information is synthesised and documented in NTB 24-22 (Nagra 2024v), and is briefly described here to provide the context of how it serves as a key input to safety scenario development.

Performance assessment includes an assessment of repository barrier performance, expressed as claims at the component level for each of the pillars of safety of the multi-barrier system, and an assessment of claims related to the performance of the entire system (total system performance). A suite of arguments, backed up by evidence, was developed to substantiate each claim. To support this process, the assessment incorporates THM-C modelling of the repository system, including the interactions between the individual barrier components. Then, a set of claims related to how the repository and its components are expected to contribute to the different safety functions were defined and evaluated, and these are incorporated into the reference safety scenario. The impact of data uncertainty on modelling results was analysed and the uncertainties associated with model abstraction were identified.

The final step of the performance assessment is the "screening of performance assessment scenarios", which includes an assessment of whether the safety functions will be performed as expected (designed) and if not, examines the conditions under which *deviations in performance* could occur (Nagra 2024v). This process entails the evaluation of *performance assessment scenarios*, which address events and processes that could potentially degrade the barriers and their safety functions, including phenomena like earthquakes, gas generation and thermal stresses that could lead to faulting, for example. These scenarios permit a systematic and quantitative assessment of the impact of such deviations on the performance of the repository and determines which of these are safety relevant. Thus, this process facilitates the identification of those deviations that require an in-depth analysis of the radiological consequences.

To enable such analyses, the safety scenario development process must first use the results of the performance assessment, in addition to the knowledge contained in the assessment basis, to conceptualise a series of safety scenarios and categorise them into different classes based on their likelihood of occurrence. These safety scenarios focus on the properties of the system and their evolution as they affect radionuclide release, retention, transport and radiological consequences. For example, the description of a safety scenario detailing a fault created at some time in the future focusses on what this means in terms of radionuclide transport pathways, rather than what could lead to faulting in the first place (as addressed by the *performance assessment scenarios*). Thus, several *performance assessment scenarios* that consider the different potential causes of faulting may be captured by just one safety scenario. Hence, depending on their relevance for safety, multiple *performance assessment scenarios* may be captured by the reference safety scenario (e.g., through parameter variations) and multiple *performance assessment scenarios* may be captured by an alternative safety scenario or "what-if?" case.

The link between the performance assessment and the methodology for the definition and classification of safety scenarios is elaborated in detail in the following sections.

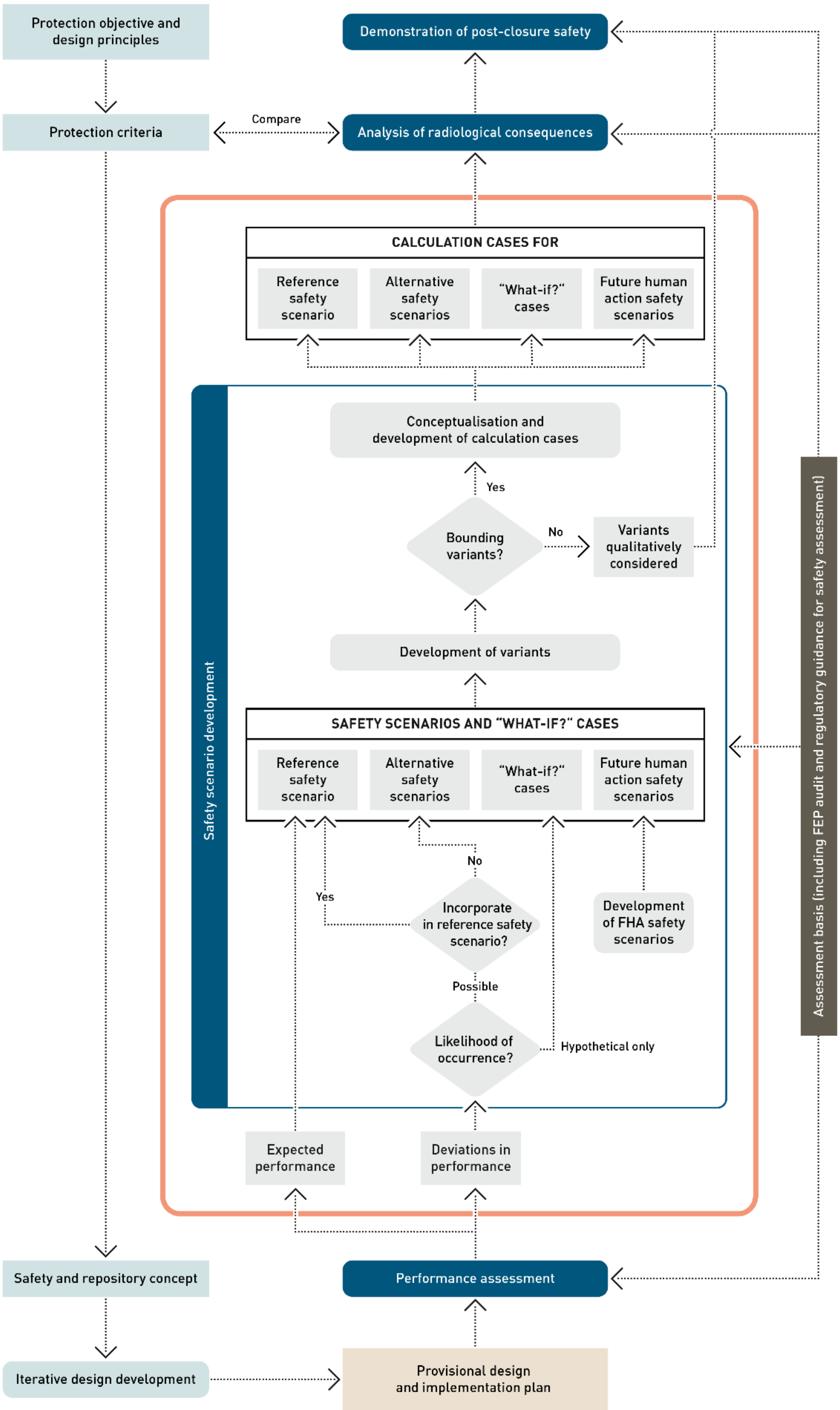

Fig. 4-1: Workflow for the post-closure safety assessment, highlighting, in the orange box, the methodology for development of safety scenarios

4.1 Expected performance and quantification of deviations

In order to assess the performance of the repository with regard to the fulfilment of the safety functions over the entire assessment period, a series of performance assessment scenarios were established that allow systematic quantitative analysis of barrier component and whole-system performance (Chapter 6 of NTB 24-22 (Nagra 2024v)). The evolution of the system under the action of the expected source terms, initial and boundary conditions corresponds to the "expected performance" performance assessment scenario, or "EXPERF" in Tab. 4-1. It encompasses all paths of repository evolution which arise from the intended fulfillment of the safety functions of all barrier components.

In addition, a series of performance assessment scenarios were specified for each barrier component to evaluate the impact of a reduced performance of the single component on the safety margins of the entire multi-barrier system (Tab. 4-1, left column). This process allows deviations from expected performance to be identified. To achieve this, both conceivable (e.g., an undetected fault; FLTHLWP) and hypothetical (e.g., instant release of the entire I-129 activity; IRMAX) performance assessment scenarios were formulated, expressing a reduced performance of a barrier component as compared to its expected performance. The inclusion of hypothetical scenarios allows the maximum effect of a single barrier component on the performance of the total system to be delimited – providing an indication of its relevance to safety. Additionally, performance assessment scenarios are formulated that address the effects of conceptual uncertainties that arise during model abstraction. Typical examples of conceptual uncertainties are related to the geological and hydrogeological setting (e.g., the HARDBED and MKALK scenarios), the prevailing transport regimes (e.g., the UPFLOW and DOWNFLOW scenarios) and the source terms associated with the repository induced effects (e.g., the UBHEAT and UBGAS scenarios). A brief description of each of the performance assessment scenarios is provided in Tab. 4-1; their derivation and formulation are addressed explicitly in Chapter 6 of NTB 24-22 (Nagra 2024v).

For each performance assessment scenario, probabilistic simulations were carried out, computing the effect of parametric uncertainties on barrier performance. The evaluation procedure encompassed a comparison of eight performance indicators (e.g., temperature, pore pressures and tracer fluxes; Section 6.2.2 of NTB 24-22 (Nagra 2024v)) with the corresponding performance targets. To enable this, an evaluation matrix was established that comprises the addressed assessment aspects (i.e., FEPs), the defined performance indicator target and the calculated performance indicator value that quantifies the performance. Hence, the impact of a conceptual uncertainty or deviation in performance was quantified, providing insight into the contribution of each barrier component to the overall performance of the multi-barrier system.

4.2 Screening of performance assessment scenarios

Following quantitative evaluation, a systematic screening of the performance assessment scenarios is carried out based on the likelihood of the identified deviations occurring and their relevance to repository safety. This informs a decision on whether such phenomena should be propagated to a safety scenario, where they are conceptualised and formulated into cases for the analysis of radiological consequences.

The assessment of the likelihood of occurrence is based on qualitative arguments. This incorporates independent evidence from the assessment basis, with consideration of the design requirements, which make deviations from expected performance unlikely to occur. This step results in each performance assessment scenario being assigned one of four levels of barrier performance:

- a hypothetical deviation from expected performance,
- an unlikely deviation from expected performance,
- a likely deviation from expected performance,
- the expected performance (i.e., the EXPERF scenario only).

Whilst the likelihood of occurrence is assessed qualitatively, the relevance for safety of a given performance assessment scenario can be assessed quantitatively using indicator-based probabilistic simulations, as described above. Then, by comparison with the results of the expected performance scenario (EXPERF), the relative impact of the phenomenon on the performance margins can be quantified.

The screening process and outcome is documented in Chapter 6 of NTB 24-22 (Nagra 2024v) and is summarised below. The decision on the propagation of a phenomenon (identified by the performance assessment screening) to a specific category of safety scenario is described in the next Section (4.3), i.e., the first step of safety scenario development.

The results from the performance assessment (for details see NTB 24-22 (Nagra 2024v)) indicate that the performance assessment scenarios addressed by modelling do not, in general, affect the broad description of the evolution of the repository system in any substantive way, i.e., performance targets are met even for combinations of unfavourable parameters explored using the probabilistic workflow, generally with a large safety margin. This shows that the repository system is highly robust regarding uncertainties related to the repository system performance and that the repository is likely to evolve according to its "expected performance" as described, for example, in NAB 24-20 (Nagra 2024l).

Performance assessment scenarios associated with uncertainties in geological characterisation, i.e., the presence of an undetected, water-conducting fault, and the presence of water-conducting sedimentary features within the confining units, cannot, however, be excluded based on current geological understanding and may not be entirely excluded, even in the repository construction phase. The reason for this is the larger variability in the mineralogical composition of the confining units. Whilst the consistently high clay content in the host rock prevents the preservation of water conducting faults or layers, the confining units above and below the Opalinus Clay contain units with lower clay contents (Nagra 2024h). If such features were to occur, they could affect (at least locally) the conceptualisation of radionuclide transport in the geosphere as a diffusion-dominated process. These performance assessment scenarios therefore represent deviations in performance that are propagated to safety scenario development and to the analysis of radiological consequences (see Tab. 4-1).

The creation of new faults, or the re-activation of existing faults, in the post-closure period by repository-induced effects, i.e., by the effects of repository heat and repository-generated gas, or by geological phenomena has been shown in the performance assessment in NTB 24-22 (Nagra 2024v) and in the assessment of earthquake scenarios in NAB 24-28 (Nagra 2024d) to be either implausible or exceedingly unlikely. It has also been shown that the excavation of the repository by erosion, within a million-year time frame, by erosive processes is hypothetical (Nagra 2024h, Section 6.4.4). These effects are, nonetheless, considered in the "what-if?" cases in safety scenario development (see Tab. 4-1).

Tab. 4-1: The incorporation of performance assessment scenarios in safety scenarios and "what-if?" cases

The coloured boxes indicate the representation of the phenomenon considered by a given performance assessment scenario in a safety scenario or "what-if?" case. For an explanation of the colouring, see the supporting text. Each text code corresponds to a specific scenario, variant or calculation case, which are described throughout this report.

Performance assessment scenarios		Safety scenarios			"What-if?" cases				Incorporation in safety scenarios and "what-if?" cases	Chapter
		Reference safety scenario	Alternative safety scenarios		Related to physical phenomena			Hypothetical degraded performance of pillar of safety		
			Hydraulically active confining unit	Undetected fault	Undetected fault with hypothetically high transmissivity	Future creation or reactivation of a fault	Repository excavation			
EXPERF	Expected performance	RS							Propagated to reference safety scenario	5
MKALK	Exfiltration to Muschelkalk	RS-KEUPER_ INACTIVE							Included within reference safety scenario conceptualisation / parameterisation	5.2 & 5.3
UPFLOW	Upflow with artesian pressure in Keuper									3.3
DWNFLW	Downflow with artesian pressure in Malm									
HETOPA	Heterogeneous Opalinus Clay									
PESSGAS	Pessimistic gas generation rate (L/ILW)									5.1.4
UBGAS	Upper bound gas source term (HLW)									5.1.4
V3PERM	Highly permeable V3 seals							WI-V3	Included within reference safety scenario parameterisation. For high permeabilities, included as "what-if?" case	5.1.4 & 8
HARDBED	Hard beds as release paths		AS-HA						Incorporated in alternative safety scenario	5.1.1 & 6.1
HERWIS	«Herrenwis Unit» as release path		AS-HA/CD							

Tab. 4-1: Cont.

Performance assessment scenarios		Safety scenarios			"What-if?" cases				Incorporation in safety scenarios and "what-if?" cases	Chapter
		Reference safety scenario	Alternative safety scenarios		Related to physical phenomena			Hypothetical degraded performance of pillar of safety		
			Hydraulically active confining unit	Undetected fault	Undetected fault with hypothetically high transmissivity	Future creation or reactivation of a fault	Repository excavation			
FLTHLWP	Undetected fault parallel to HLW drifts			AS-FLT-HLW-Along	WI-FLT-HLW-Along				Incorporated in alt. safety scenario and (for hypothetically high fault transmissivities) as "what-if?" cases	6.2 & 7.1
FLTHLWN	Undetected fault normal to HLW drifts			AS-FLT-HLW-Across	WI-FLT-HLW-Across					
FLTLILW	Undetected fault affecting L/ILW caverns			AS-FLT-L/ILW	WI-FLT-L/ILW					
UBHEAT	See RIEHLW					WI-FLT/RA-HLW			Potential (though not expected and thus "what-if?") causes of faulting or fault re-activation	7.2
RIEHLW	Thermally- and gas-induced faulting (HLW)					WI-FLT/RA-HLW				
RIELILW	Gas-induced faulting (L/ILW)					WI-FLT/RA-L/ILW				
SEISHLW	Earthquake affecting HLW drifts					WI-FLT/RA-HLW				
SEISLILW	Earthquake affecting L/ILW caverns					WI-FLT/RA-L/ILW				
LOSSFLT	Fault activation due to overburden loss					WI-FLT/RA				
LOSSOB	Permeability increase due to overburden loss								Impact bounded by excavation cases	7.3
IRMAX	Instant release of entire I-129 activity							WI-SF-IRF	Considered as hypothetical "what-if?" cases	8
WPFAIL	Canister failure at time of repository closure							WI-HLW-CAN		
ZEROGAS	No gas generation								Supports the conservativity in the model assumption for the consequence analysis	See footnote

Whilst the ZEROGAS performance assessment scenario is not directly included in the reference safety scenario parameter ranges, its impact is considered implicitly through the conservative assumption of fully saturated conditions employed for the modelling of aqueous transport of radionuclides. Its representation, therefore, is dealt with in the models that support the analysis of radiological consequences (see Appendix A in NTB 24-18 (Nagra 2024q)).

4.3 Classification of safety scenarios

The development of safety scenarios involves a classification process, guided by the assessment basis and the results of performance assessment, including the expected performance and the identified deviations in performance. Thus, safety scenarios are developed that describe the different possibilities for the initial state and subsequent evolution and performance of key features of the repository system (the pillars of safety).

In practice, nearly all phenomena considered by the performance assessment scenarios are addressed by a safety scenario or "what-if?" case, either through explicit representation, or implicitly, via the parameter ranges used in the evaluation of a safety scenario (Tab. 4-1). Additionally, uncertainties that are identified and deemed to be potentially significant in the respective assessment basis reports, but are not captured by the performance assessment models, e.g., FEPs related to erosive processes or climate evolution, may also be propagated directly to the formulation of safety scenarios. Likewise, possible impacts arising from FHAs are also accounted for at this step.

Several categories of safety scenarios are defined that describe the expected, less likely and hypothetical evolutions of the repository and barrier performance. The likelihood of occurrence within the one-million-year time period for assessment is the main criterion that decides the category to which a safety scenario (other than an FHA safety scenario) belongs. This is informed by both the performance assessment scenario screening (Section 4.2) and the knowledge and evidence provided by the assessment basis. In addition, the classification is also guided by the potential impact of any deviation in performance on the safety functions, thus allowing the (qualitative) risk within the time period for assessment to be considered.

1. The reference safety scenario

The reference safety scenario is a general description of the expected initial state of the repository barriers, their expected evolution over time, including the release, retention and transport of radionuclides within the repository system, and the assumptions made regarding the biosphere for the analysis of radiological consequences. This description is primarily comprised of the phenomenological narrative contained in NAB 24-20 (Nagra 2024l), which itself is underpinned by the scientific understanding documented in the assessment basis. It is substantiated by the outcome of the performance assessment simulations, which confirm that the components and the total system perform as designed. Thus, the claims regarding the expected performance of each barrier component, or the system as a whole, are incorporated in the reference safety scenario and, hence, the performance assessment scenario "EXPERF" is propagated to the reference safety scenario (dark green box in Tab. 4-1). Note that the performance assessment scenario "MKALK", which considers a favourable scenario in which the CRZ extends to the lower Muschelkalk aquifer, is also depicted in Tab. 4-1 as being integrated with the reference safety scenario. This is explicitly addressed in Sections 5.2 and 5.3.

2. Alternative safety scenarios

Deviations in performance identified by the performance assessment, or uncertainties in the initial state or potential evolution identified by the current assessment basis, are considered for inclusion in an alternative safety scenario. Here, the general description of the initial state of the repository barriers and their evolution over time differs substantially from that of the reference scenario. Assignment to this category is based primarily on the likelihood of occurrence within the time period for assessment, whereby the likelihood is not sufficiently low that the scenario can confidently be neglected. With respect to the results of the performance assessment scenario screening, this generally includes phenomena that are deemed “likely” or “unlikely” (Section 4.2) and primarily concern the state of potential hydraulically active units or the presence of undetected faults (blue boxes in Tab. 4-1).

Not all potentially detrimental phenomena or other uncertainties identified by the performance assessment screening necessarily give rise to alternative safety scenarios. Even if the functionality of the components of the disposal system or of the disposal system-as-a-whole is negatively affected, the broad-brush description of the evolution of the disposal system provided by the reference safety scenario may still apply. In this case, the effects of the uncertain potentially detrimental phenomena and other uncertainties must be captured within the parameter ranges considered in the analysis of the radiological consequences of the reference safety scenario (light green boxes in Tab. 4-1). If, however, the degraded functionality results in a description of the evolution of the disposal system that is not captured by the reference safety scenario, then an alternative safety scenario is generated. This includes the situation when the considered phenomenon or feature would require a new model conceptualisation to enable the calculation of its radiological consequences. For example, the presence of a hydraulically active confining unit would require its explicit representation in a new model.

3. “What-if?” cases

Where the assessment basis or performance assessment scenario screening designates a scenario as being hypothetical, i.e., the evolutionary paths for the repository are judged not to be possible, at least during the million-year time period for assessment, it may nevertheless be propagated to the analysis of radiological consequences as a hypothetical “what-if?” case. This serves to bound the uncertainties and conceptually test robustness. Regarding the propagation of performance assessment scenarios, this concerns those scenarios considering the future creation or reactivation of a fault due to repository-induced effects, earthquakes or overburden loss due to erosive processes, and also increased permeability arising from overburden loss (orange boxes in Tab. 4-1). Also included are plausible phenomena but for which the scenario assumes parameter values that lie outside the range of possibilities supported by currently available evidence and knowledge, i.e., cases considering undetected faults with hypothetically high transmissivities.

Additional hypothetical “what-if?” cases are also defined that postulate a degraded performance of each of the pillars of safety, unconnected to any physical phenomena. They are intended to demonstrate the robustness of the repository system and mitigate “completeness uncertainty”, pre-empting possible criticism that some detrimental FEPs are either unknown or have been overlooked. Several performance assessment scenarios, which are not related to any conceivable physical phenomena, are propagated to this kind of case (dark pink boxes in Tab. 4-1).

4. Future human actions safety scenarios

The FHA safety scenarios concern the impact of potential actions undertaken by human society on the performance and safety of the repository. They are treated as a separate class of safety scenarios due to their particularly speculative nature and their associated use of stylistic representation. Rather than being derived from the assessment basis and the findings of performance assessment, they are developed from FHA FEPs within the Nagra FEP database (Nagra 2024k), which are first screened to identify those with the potential to perturb the pillars of safety and their safety functions. This process is depicted in Fig. 4-2. Once the FHA safety scenarios are established, the same procedure depicted in Fig. 4-1 is followed to define the variants and calculation cases. A full description of Nagra’s methodology for FHA safety scenario development for the general licence application can be found in NAB 24-09 (Nagra 2024s).

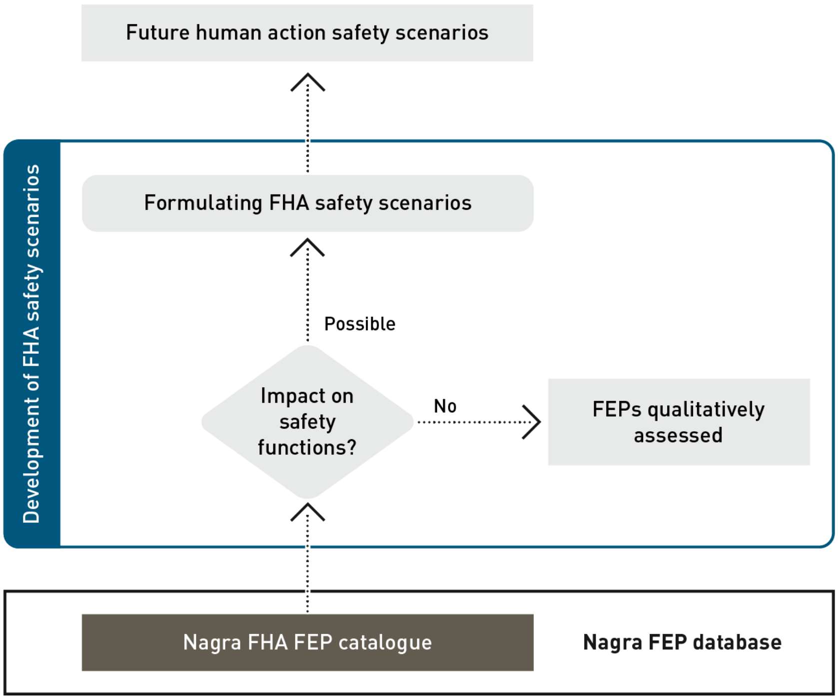

Fig. 4-2: Workflow for the development of FHA safety scenarios

4.4 Development of safety scenarios, variants and calculation cases

The systematic screening provided by the performance assessment is the primary means by which the selected set of safety scenarios are ensured to bound and represent all possible ways in which the repository might evolve, thus capturing so-called "scenario uncertainty". In order to capture conceptual uncertainty, *variants* of a given safety scenario may be defined, whilst other conceptual and parametric uncertainties are treated within *calculation cases*. Their formulation is described in the following paragraphs.

One or more variants may be defined for each safety scenario. Variants of a given safety scenario share the same general description of FEPs occurring over time, but differ, in one or more key factors that significantly affect the radiological consequences of that particular scenario. Key factors could include, for example, the extent or timing of key phenomena associated with the scenario or variant, as well as the location or properties of key features. The assumptions made regarding the identified key factor(s) are plausible and based on the current knowledge.

For the reference safety scenario, this results in the main "reference conceptualisation of the CRZ", which allows a single common scenario to be formulated for all three siting regions, and a variant considering an inactive lower aquifer (Keuper) in the NL siting region only (see Section 5.1.1).

Regarding the other types of safety scenario, only the variant that is expected to give rise to the highest radiological consequences is propagated to the analysis of radiological consequences (i.e., the "bounding variant"; Fig. 4-1). When it cannot be judged in advance, e.g., based on a qualitative assessment of the alternatives, which assumption may lead to the highest consequence analysis, more than one variant may be defined for a given safety scenario.

Subsequently, for each safety scenario or variant, one or more "calculation cases" are defined. The definitions of the calculation cases provide additional simplifications (abstraction), assumptions and parameter values to be considered when representing the key factors in the models used in the analysis of the radiological consequence. If the most conservative simplifications, assumptions and parameter values cannot be judged in advance of the calculations, more than one calculation case for a given safety scenario/variant may be propagated to the analysis of radiological consequences. Additional calculation cases, including probabilistic analyses, are also defined to quantify the effects of parameter uncertainty.

The quantity of the defined calculation cases per safety scenario or variant is minimised while they are aimed to be defined such that they confidently bound the radiological consequences resulting from this safety scenario or variant. Achieving this involves assumptions, abstractions, simplifications or setting parameter values that may be outside the realistic range reported in the assessment basis or inferred from the findings of the performance assessment. Therefore, the calculation cases should not be interpreted as realistic system representations, but as conservative representations with respect to the collective assumptions, abstractions, simplifications and parameter values.

Combinations of more than one deviation in barrier performance, or the combination of a deviation in barrier performance and an FHA FEP, are, in principle, conceivable. However, the likelihood of such combinations, though not evaluated quantitatively, is qualitatively assessed to be so low that they could, in effect, be considered as "what-if?" cases. In some instances, combined radiological consequences may be estimated by summing the consequences of individual scenarios, provided these are not correlated, or are only weakly correlated, which is sometimes the case due to the compartmentalised design of the repository. For example, the radiological consequences of an exploration borehole intersecting the HLW disposal section can be summed with the radiological consequences of another exploration borehole, possibly drilled at a different time, intersecting the L/ILW disposal section. In some other instances, the consequences of deviations in performance and FHA FEPs considered individually can be greater than if they are considered in combination. For example, the presence of an undetected fault, which is considered as an alternative safety scenario, will lead to reduced gas pressures in the repository, which would lessen the impact of gas-mediated transport of radionuclides in the event of a borehole later being drilled and penetrating the repository underground structures. In practice, the consequences of such combinations are, in any case, bounded by the extreme "what-if?" cases.

4.5 Propagation of safety scenarios to site-specific safety analysis

In line with national regulatory requirements, safety scenarios that are categorised as reference or alternative are not only analysed in the safety assessment for the proposed site but are also propagated to the safety analysis performed in the context of site comparison (Fig. 4-3).

As explained in NTB 24-19 (Nagra 2024u), given the similarity in the geological characteristics and expected evolution of all three siting regions, as well as the similarity of the provisional repository design and implementation plan developed for all siting regions, the reference safety scenario and alternative safety scenarios developed for the proposed site can also be applied to the other siting regions. All site-specific differences, e.g., in the likelihood, rates or extent of considered phenomena, are accounted for in conceptualisation and parameterisation of the models used for analysis of radiological consequences (Nagra 2024q). No FHA safety scenarios and no "what-if?" cases are analysed in the context of the site-specific safety analyses for the site comparison (Fig. 4-3).

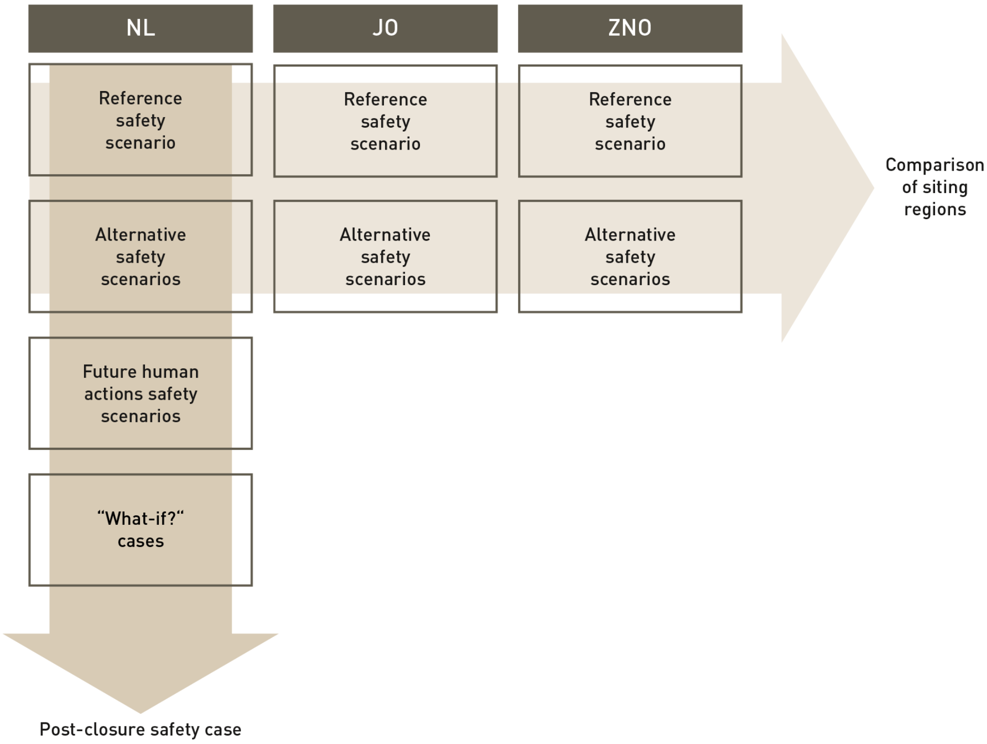

Fig. 4-3: Safety scenarios and "what-if?" cases propagated as input to the post-closure safety case and to the comparison of siting regions

5 Reference safety scenario, variants and calculation cases

5.1 General description of the safety scenario

The reference safety scenario is a general description of the initial state of the repository barriers, their expected evolution over time, and the assumptions made regarding the biosphere for the analysis of radiological consequences. This safety scenario description is formulated from both the assessment basis and the results of the performance assessment and is presented here, substantiated with details from the supporting documentation. In particular, the following sections highlight the aspects of the repository and its evolution (including external factors) that are central to the development of the safety scenario. These aspects include factors and current uncertainties that lead to both variants and calculation cases within the framework of the reference safety scenario and the additional uncertainties which lead to the development of alternative safety scenarios.

5.1.1 The geological barrier

The geological situation in Northern Switzerland is documented in the Geosynthesis (Nagra 2024h), with the focus on the potential siting regions of JO, NL and ZNO and the most important differences between them. The geological data are the result of comprehensive scientific field investigations, including 3D seismic surveys and drilling of deep boreholes as well as laboratory and underground laboratory experiments. The geological investigations yielded depth and detailed characteristics of the geological structure in the potential siting regions as well as the hydrogeological understanding of the siting regions and the regional flow systems.

The geological information inferred from the Geosynthesis (Nagra 2024h) is narrowed down to a local geological characterisation of the potential repository zones in the central areas of the three siting regions. This local geo-characterisation, as set out in NAB 24-10 (Nagra 2024g), provides a basis for the numerical modelling carried out for performance and safety assessment. The report (NAB 24-10) covers the following aspects for the three siting regions:

- abstraction of geological formations and facies into rock units with similar transport properties,
- the geometry of these units in the potential repository zones (local "layer-cake" models),
- key physical and chemical properties of the abstracted units (e.g., mineralogy, hydraulic properties), and
- an explanation of the assumptions and concepts used to constrain parameter bandwidth for the reported properties.

The conceptualisations and parameter values presented in NAB 24-10 (Nagra 2024g) are the basis for the geological assumptions made in the reference safety scenario and are not repeated in the current report. The reader is referred there for detailed information. It is worth noting that the abstracted local "layer-cake" model is further simplified for modelling purposes in the processes of performance assessment (e.g., Nagra 2024x) and radiological consequence analysis (Nagra 2024q); this is documented in NTB 23-08 (Glaus et al. 2024). The abstraction process is exemplified for the NL siting region in Fig. 5-1, including the simplifications made for performance assessment and for the analysis of radiological consequences ("SA & PA model units"). The local "layer-cake" models of the potential repository zones for each siting region are shown in Fig. 5-2, and Tab. 5-1 unifies the geological formation names with the abstracted model names.

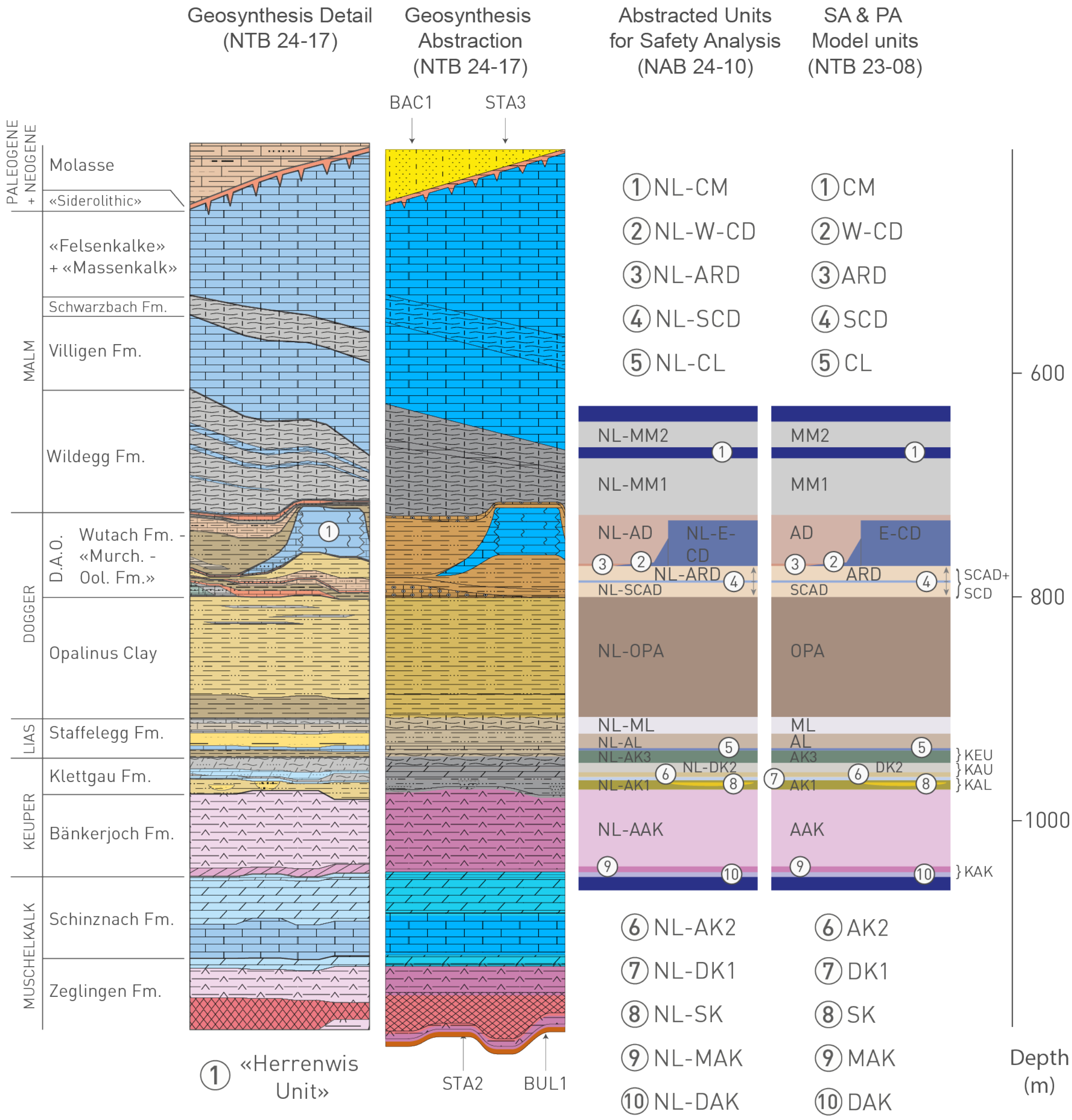

Fig. 5-1 Example of the abstraction of the sedimentary Mesozoic sequence in the NL siting region into units of comparable transport parameters

As described in NTB 24-17 (Nagra 2024h), NAB 24-10 (Nagra 2024g) and NTB 23-08 (Glaus et al. 2024), the abstraction results in the generation of the local "layer-cake" model for performance assessment and for the analysis of radiological consequences ("SA & PA Model units"). The abbreviations BAC1, STA2, STA3 and BUL1 correspond to the Bachs-1-1, Stadel-2-1, Stadel-3-1 and Bülach-1-1 boreholes, respectively, that informed the abstraction.

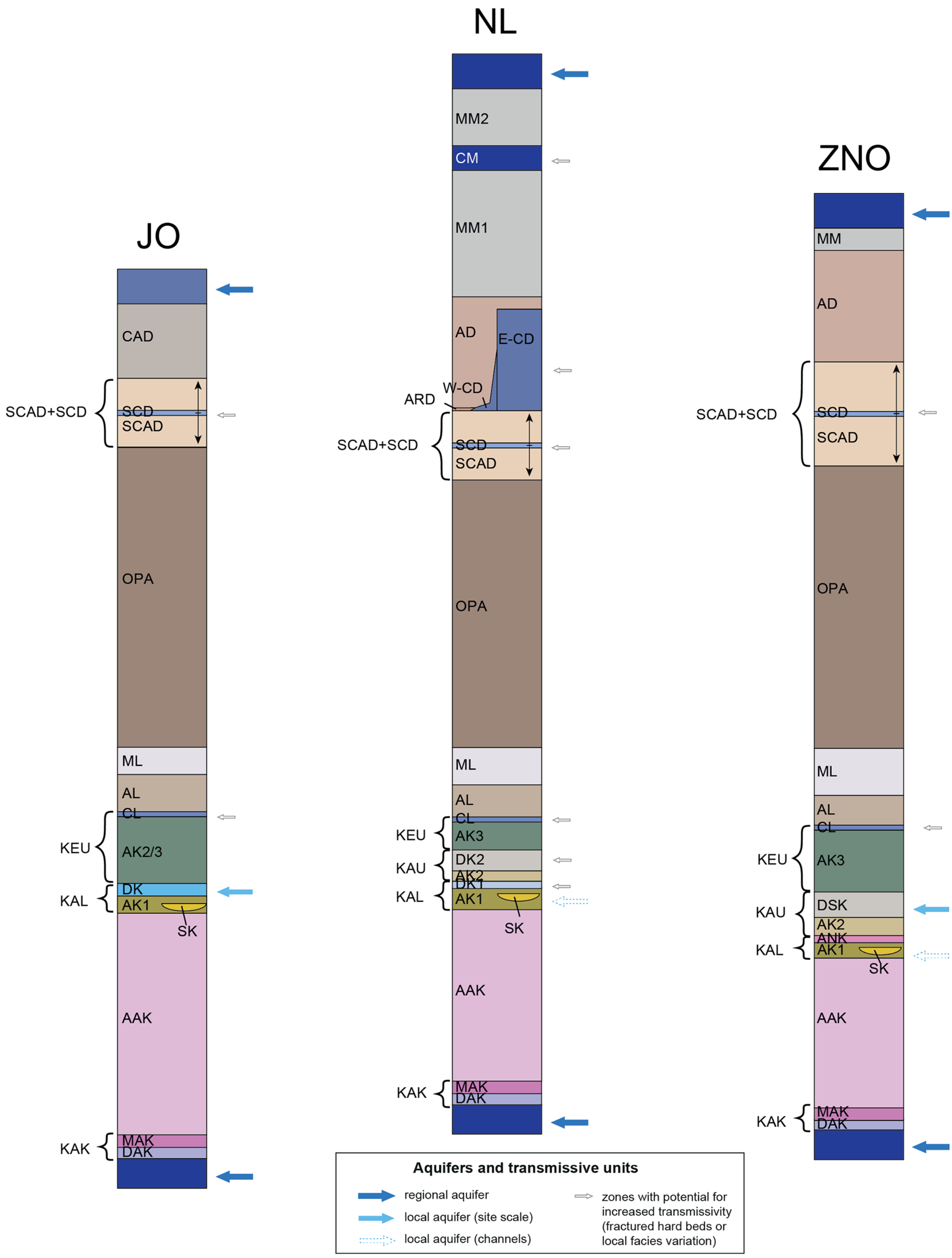

Fig. 5-2 Abstracted local "layer-cake" models of the siting regions for performance assessment and for the analysis of radiological consequences

Adapted from Glaus et al. (2024). The positioning of each stratigraphic model is normalised to the base of the OPA unit. The unit thicknesses are not to scale.

Tab. 5-1 Stratigraphic units, geological abstracted units and abstracted safety assessment and performance assessment model units ("SA & PA units") for the three siting regions of JO, NL, and ZNO

Jura Ost (JO)

Stratigraphic unit	Abstracted unit and full name		SA & PA model unit
Passwang Fm	CAD	Calcareous-Argillaceous Dogger	CAD
Dogger Group above Opalinus Clay	SCD	Sandy-Calcareous Dogger	SCAD +SCD
	SCAD	Sandy-Calcareous Argillaceous Dogger	
Opalinus Clay	OPA	Opalinus Clay	OPA
Staffelegg Fm	ML	Marly Lias	ML
	AL	Argillaceous Lias	AL
	CL	Calcareous Lias	KEU
Klettgau Fm	AK2/3	Argillaceous Keuper	
	DK	Dolomitic Keuper	KAL
	AK1/SK	Argillaceous Keuper / Sandy Keuper	
Bänkerjoch Fm	AAK	Anhydritic-Argillaceous Keuper	AAK
	MAK	Massive Anhydritic Keuper	KAK
	DAK	Dolomitic-Anhydritic Keuper	

Nördlich Lägern (NL)

Stratigraphic unit	Abstracted unit and full name		SA & PA model unit
Wildegg Fm	MM2	Marly Malm	MM2
	CM	Calcareous Malm	CM
	MM1	Marly Malm	MM1
Dogger Group above Opalinus Clay	AD	Argillaceous Dogger	AD
	E-CD / W-CD*	Calcareous Dogger («Herrenwis Unit»)	E-CD / W-CD
	SCD	Sandy-Calcareous Dogger	SCAD +SCD
	SCAD	Sandy-Calcareous Argillaceous Dogger	
Opalinus Clay	OPA	Opalinus Clay	OPA
Staffelegg Fm	ML	Marly Lias	ML
	AL	Argillaceous Lias	AL
	CL	Calcareous Lias	KEU
Klettgau Fm	AK3	Argillaceous Keuper	
	DK2	Dolomitic Keuper	KAU
	AK2	Argillaceous Keuper	
	DK1	Dolomitic Keuper	KAL
	AK1/SK	Argillaceous Keuper / Sandy Keuper	
Bänkerjoch Fm	AAK	Anhydritic-Argillaceous Keuper	AAK
	MAK	Massive Anhydritic Keuper	KAK
	DAK	Dolomitic-Anhydritic Keuper	

Zürich Nordost (ZNO)

Stratigraphic unit	Abstracted unit and full name		SA & PA model unit
Wildegg Fm	MM	Marly Malm	MM
Dogger Group above Opalinus Clay	AD	Argillaceous Dogger	AD
	SCD	Sandy-Calcareous Dogger	SCAD +SCD
	SCAD	Sandy-Calcareous Argillaceous Dogger	
Opalinus Clay	OPA	Opalinus Clay	OPA
Staffelegg Fm	ML	Marly Lias	ML
	AL	Argillaceous Lias	AL
	CL	Calcareous Lias	KEU
Klettgau Fm	AK3	Argillaceous Keuper	
	DSK	Dolomitic-Sandy Keuper	KAU
	AK2	Argillaceous Keuper	
	ANK	Anhydritic Keuper	KAL
	AK1/SK	Argillaceous Keuper / Sandy Keuper	
Bänkerjoch Fm	AAK	Anhydritic-Argillaceous Keuper	AAK
	MAK	Massive Anhydritic Keuper	KAK
	DAK	Dolomitic-Anhydritic Keuper	

* ARD is not considered separately.

The geological characterisation focuses on the clay-rich rock units bounded by aquifers that exist above and below the CRZ in each siting region. The aquifers are hosted by the Malm and Keuper units above and below the CRZ in the NL and ZNO siting regions, and the Hauptrogenstein (Calcareous Dogger) and Keuper aquifers above and below the CRZ in the JO siting region. Most of the rock units between these deep aquifers, including the host rock itself, are hydraulically impermeable and hence transport of solutes, including any radionuclides released from the repository, is expected to be diffusion-dominated (Nagra 2024h, Section 4.5). In fact, one of the requirements for the CRZ around the repository is that diffusion is the main transport mechanism (ENSI 2018).

Criteria laid out by ENSI imply that the CRZ should be bounded vertically by the first water-conducting features encountered above and below the repository horizon. Some zones of likely groundwater flow, most notably the Keuper aquifer below the host rock, were detected in some boreholes between the upper Malm / Hauptrogenstein and the lower Muschelkalk deep aquifers (Nagra 2024h, Section 4.5.3.10). The Keuper aquifer appears to have different characteristics in the three siting regions. Hydraulic tests and the profiles of natural tracers in adjacent porewater indicate that the Keuper aquifer is hydraulically active in ZNO, and probably also in JO. By contrast, in NL, permeable layers are limited to locally occurring sandstone channels that were only observed below the provisional location of the L/ILW repository (or the L/ILW section of a combined repository) (Nagra 2024h). Therefore, in NL, units down to the Muschelkalk aquifer could contribute to the barrier function. However, for the sake of consistency between the safety scenarios developed for all siting regions, it is nonetheless assumed in the reference conceptualisation of the reference safety scenario that the CRZ is bounded below the repository horizon by the Keuper aquifer in all siting regions and for all repository types (Nagra 2024x).

5.1.1.1 Hydraulic activity of "hard beds" and the «Herrenwis Unit»

Units within the CRZ above and below the host rock include intercalated sandy, calcareous, or dolomitic interlayers and a laterally confined biohermal limestone unit. Overall, they are also characterised by high to intermediate clay-mineral content, but show higher variability compared with the host rock and include sections with low clay-mineral contents, typically with thicknesses of up to a few metres ("hard beds"). Compared with the homogeneous host rock, conceptual and parametric uncertainties are larger in the confining units.

The units directly above and below the Opalinus Clay include so-called "hard beds" with intermediate-to-low clay-mineral contents and with thicknesses of up to a few metres. These thin competent (i.e., hard and brittle) horizonal limestone features are embedded between layers of more plastic clay. Despite intensive testing, only low hydraulic conductivities were derived from packer tests (Nagra 2024h, Section 4.5.3) and no relevant excursions in the profiles of natural tracers were observed (Nagra 2024h, Section 4.6). In addition, considering their low porosities and their restricted thicknesses, the presence of hydraulically active fracture networks or a permeable matrix is excluded (Nagra 2024h, Section 5.6). Therefore, hard beds are not considered to act as a lateral flow path in the reference safety scenario.

A 40-m-thick biohermal limestone unit (the «Herrenwis Unit») with low clay content occurs in the upper confining units of eastern NL (Fig. 5-1 and Nagra 2024h, Section 4.5.3.7). The available geological and hydrogeological data, such as the low hydraulic conductivities observed within this unit, the existence of hydraulic under-pressures and the fact that the unit is embedded in other clay-mineral-rich units, indicate that it is also hydraulically isolated from the regional flow systems and is thus regarded as part of the low-conductivity upper confining units (Nagra 2024h, Sections 4.2.7, 4.5.3.7 and 4.6). Thus, the reference safety scenario also describes the «Herrenwis Unit» as hydraulically inactive, in line with the current scientific evidence.

5.1.1.2 Detected faults

The main factors affecting tectonic settings and the fault inventory in Northern Switzerland are well described (Nagra 2024h, Section 4.3). Regional fault zones are avoided during placement of the repository, along with other seismically mappable faults (Nagra 2024h). Furthermore, future deformation is prone to preferentially localise along existing faults, i.e., fault reactivation is more likely than new fault formation (Nagra 2024h, Sections 4.3.4 and 4.3.6).

Existing faults within the siting regions are small in scale, i.e., centimetre to metre scale (Nagra 2024h, Section 4.3.4). Therefore, given that hydraulic packer test intervals cover a larger scale (several metres to decametres), the transmissivities incorporated by the reference scenario already include the contribution of any faults and joints (Nagra 2024g, Section 5.3.1).

Fault transmissivities are strongly correlated with clay content (Nagra 2024g, Section 5.3.3). Hence, for the Opalinus Clay, this does not lead to elevated hydraulic conductivities, largely due to its capacity for self-sealing and the stronger segmentation of faulting that precludes strong enhancement of fault transmissivity (Nagra 2024g and Nagra 2024h, Sections 5.5 and 5.7). Given the high clay contents of the confining units, these also exhibit very low hydraulic conductivities, albeit with a lower self-sealing potential than the Opalinus Clay (Nagra 2024h, Section 5.10).

Regarding the confining units (Nagra 2024h, Section 5.6.3.2), intervals with clay mineral contents above 35 – 40 wt.% have consistently low hydraulic conductivities similar to the Opalinus Clay, demonstrating that the variable tectonic overprint is not associated with elevated transmissivities. Intervals with clay mineral contents of ~20 – 40 wt.% are characterised by slightly higher hydraulic conductivities, even for tests with tectonic overprint, indicating a reduced but relevant self-sealing potential. Even the presence of thin hard beds in some test intervals have no visible impact on the measured transmissivities, reflecting their small fracture inventory. Intervals with clay mineral contents below 20 wt.% show a broader range of hydraulic conductivities, correlated with the thickness of the clay-poor sections. Thus, test intervals with thinner clay-poor layers display hydraulic conductivities approaching those of medium clay mineral contents, even in the presence of small-scale faults.

With particular reference to the Staffelegg Formation in the lower confining units, only slightly elevated hydraulic conductivities are observed in tectonically fractured intervals, and there is no evidence of connected fracture networks (Nagra 2024h, Section 4.5.3.9)

In summary, existing smaller faults do not show elevated hydraulic activities beyond the bulk matrix, therefore, in the reference safety scenario, the CRZ is conceptualised without any existing faults.

5.1.1.3 Long-term geological evolution

Future neotectonic movements, changing climate and morphological changes due to erosion can change the hydrogeological and hydrogeochemical conditions (states, properties) and ultimately affect barrier performance (Nagra 2024h). Although the repository is planned to be constructed deep underground, in a location where it is not susceptible to geological events and processes of long-term safety relevance, the potential consequences of such processes and their treatment in the reference safety scenario are discussed here.

Future deformation will result in reactivation of existing faults, with movement mainly concentrated on the regional fault zones, which are avoided during placement of the repository along with other seismically mappable faults (Nagra 2024h, Sections 4.3 and 6.2). If new faults were to develop in the CRZ, their fault architecture is prone to segmentation (i.e., they are discontinuous), and they are expected to be small in length and small in offset (Nagra 2024h, Sections 4.3 and 6.2). They will also readily re-seal if they undergo secondary shear movements in the event of an earthquake centred on a larger-scale fault at a distance from the repository. Such secondary shear movements are not expected to be large enough to damage the engineered repository barriers (Nagra 2024h, Nagra 2024v, Nagra 2024d). Hence, the impact of faults on radionuclide transport would be limited and fault creation is therefore excluded from the reference safety scenario.

If the host-rock overburden decreases drastically due to erosion from the surface, decompaction effects may lead to less efficient self-sealing, increased porosity and permeability, and a change in the host-rock mineralogy and porewater chemistry. Studies of the erosion processes that will affect the siting regions over the one million year time period for assessment indicate that, considering the 5 – 95% probability range, between approximately[21] 125 and 410 m of residual overburden might be expected in JO, between approximately 350 and 670 m in NL and between approximately 220 and 560 m in ZNO (Nagra 2024h, Section 6.4.4).

The efficient self-sealing of reactivated faults in Opalinus Clay is expected to be maintained as long as the overburden remains >200 m (Nagra 2024h, Section 5.7.4). Furthermore, in the absence of faulting, the favourable hydrogeological and hydrogeochemical properties of the host rock (matrix permeability, diffusion, porosity, etc.) are expected to be maintained, provided as little as a few decametres of overburden remains (Nagra 2024f and Nagra 2024h, Sections 5.6.3.1 and 6.5.3). The most likely erosion scenarios at the provisional repository locations in all siting regions result in at least ~400 m of overburden remaining above the repository after one million years (Nagra 2024f and Nagra 2024h, Section 6.4.4). Therefore, for these most likely erosion scenarios, key host-rock properties are maintained. The JO siting region shows a more significant loss of overburden for certain less likely scenarios than the other siting regions. Enough overburden is nonetheless expected to be maintained in the immediate surrounding of the provisional repository location (Nagra 2024f) to ensure that the barrier functions of the CRZ are provided throughout the time period under consideration (Nagra 2024h).

Since a critical reduction of the host rock overburden leading to a significant change of the key CRZ barrier properties (hydraulic conductivity, diffusion, self-sealing capacity) is unlikely at all sites, this process is excluded from the reference scenario. Rather, the likely, but small, impact of erosion on the properties of the host rock is included in the bandwidths of the parameter values reported in Nagra (2024g).

Dissolution of soluble evaporite minerals or carbonates (i.e., karst development) is also unlikely to affect the properties and long-term stability of the CRZ (Nagra 2024h, Sections 6.5.2.3 and 6.5.5). The Muschelkalk will not be affected by major decompaction and will thus remain saturated with calcite and be near or at saturation with dolomite. In addition, the small and limited water fluxes at these depths mean the water flow will likely not result in the evolution of larger cavities. Where there is evidence of deeper groundwater mixing and cross-formation flow, any dissolution of evaporite minerals is a local phenomenon and represents a slow process. Therefore, these processes are not considered in the reference safety scenario.

5.1.2 Long-term evolution of the surface environment

The surface environment will change on timescales ranging from tens of thousands of years to hundreds of thousands of years due to processes driven by climate, erosion, sedimentation, hydrology / hydrogeology and human behaviour. The current landscape of Northern Switzerland, with valleys and hillsides, has in the past been shaped by endogenic and exogenic processes, including tectonic uplift, erosion, and sedimentation under glacial and non-glacial conditions, and will continue to be affected by these processes. Hence, there is an indirect link to climate conditions.

[21] Rounded to the nearest 5 m

As evidenced by palaeoclimatology, on timescales of hundreds of thousands to millions of years, the Earth's climate will continue to go through cycles of colder (glacial) and warmer (interglacial) conditions (Nagra 2024e). Over the past one million years, the Earth's climate has been subject to cycles of glacial and interglacial conditions, with an overall periodicity of about 100 ka during the last 800 ka, and with interglacial conditions typically lasting some several thousands of years (Nagra 2024e). The last glacial maximum occurred around 24 ka before present. Anthropogenic emissions of greenhouse gases mean that the Earth's climate is expected to experience a prolonged period of interglacial conditions. The next glacial inception, under the influence of the most optimistic emission scenarios, is considered very unlikely to occur before 50 ka after present and, considering the current atmospheric greenhouse gas concentrations, is not expected to reach full glacial conditions for 200 ka after present or even longer, depending on the continuation of greenhouse gas emissions and any mitigation scenarios (Nagra 2024e). Glacial conditions are accompanied by ice sheet development over the Alps and Northern Switzerland, with the extent dependent upon the intensity of glacial conditions. After a glacial state has passed, the climate gradually warms, and climatic conditions change from a polar climate (Switzerland largely covered by ice and/or permafrost conditions) towards a continental, temperate or potentially even a dry climate. Climate simulations assuming high anthropogenic emissions of greenhouse gases predict warm-temperate or even humid-subtropical climates for Switzerland (Nagra 2024e).

Changes in the aquifer flow system due to climatic and geological processes will alter the hydraulic gradient and thus the rate and pattern of porewater flow in the low-permeability sequence hosting the repository. In particular, ice loading and unloading will induce overpressures and under-pressures in the host rock, respectively. It is expected, however, that a dominant diffusive transport regime will continue to prevail (Nagra 2024h, Section 6.5). As mentioned above, glacial and fluviatile erosion processes, driven by uplift and changes in climate, will gradually result in a partial reduction in the thickness of the overburden, over a period of hundreds of thousands of years. Nonetheless, no excavation of any part of the repository (excluding the access shafts) is expected over the next million years (Nagra 2024h, Section 6.4.4). The effects of erosion in the longer term, beyond a million years, are addressed by the "what-if?" cases documented in Section 7.3.

Overall, long-term geological and climatic evolution is not expected to negatively impact the safety-relevant properties of the repository barrier system over a million-year period and the CRZ provides a stable mechanical and geochemical environment which efficiently protects the engineered barriers over the entire lifetime of the repository.

Nevertheless, to evaluate the impact of these changes in climate, as well as the impact of other changes to surface conditions driven by erosion, sedimentation, hydrology/hydrogeology, and human behaviour on potential radiological consequences, it is necessary to model radionuclide behaviour within the biosphere. As described in Section 5.1.5, Nagra's biosphere modelling (Nagra 2024m) calculates potential dose rates (Sv/a) at equilibrium for a constant unit release of radionuclides (Bq/a) in groundwater to the biosphere – termed biosphere dose conversion factors (BDCF). A reference case is established, based on the present-day climate with groundwater from deep aquifers discharging to a porous shallow aquifer in a valley bottom, with the local area being used for agriculture. In order to capture the aforementioned variation in the climate, alternative biospheres are defined to explore potential consequence of releases occurring during warmer-drier and cold climate conditions. Another alternative case explores potential consequences of discharges to regions where groundwater is naturally closer to the surface and the landscape has been drained for agriculture, reflecting one possible evolution of the morphology.

These biosphere cases aim to bound potential dose consequences. For each biosphere, a separate set of BDCFs is calculated and for each calculation case in the context of the reference safety scenario, persistent presence of one biosphere case is assumed.

5.1.3 Initial state and the long-term evolution of the waste and engineered barriers

Waste inventory. In the reference scenario all waste is assumed to conform to acceptance criteria. The effective waste inventory is the same as that of the modelled reference assumptions in the MIRAM-RBG database (Nagra 2023d).

Initial state of the repository. The repository is assumed to be constructed, operated and closed according to the provisional repository design, described in Section 3.2 (for detail, see NAB 24-18 (Nagra 2024t)). All the engineering repository components are assumed to be manufactured, handled, and emplaced with state-of-the-art technologies and best engineering practices in compliance with all relevant design requirements and specifications (Nagra 2024b). If necessary, measures will be taken to ensure that any deviations from the planned implementation occurring in the pre-closure period have no impact on long-term safety (e.g., in the case of accidental flooding of the repository during the operational phase (Nagra 2022)). The construction of all underground structures is also assumed to be carried out using proven and reliable technologies and engineering practices and in compliance with all relevant requirements and specifications (Nagra 2024b). A respect distance to exploration boreholes is observed. The CRZ, including the Opalinus Clay host rock, is as described in Section 5.1.1. Repository construction and operation are assumed to have no impact on the structural integrity of the host rock, other than the creation of excavation-damaged zones (EDZs) around the underground openings (Nagra 2024l, Section 3.2.2). The EDZs will, however, re-seal early in the post-closure period as they re-saturate over time (Nagra 2024l, Section 6.1.4). Consequently, the EDZs have a very small impact on the radionuclide retention and transport properties of the CRZ. The mechanical integrity of the host rock is also supported by the drift and cavern liners, and, after these degrade, by the bentonite buffer and the cavern backfill, as well as by the VF1 and VF2 backfill used in the sealing system (Nagra 2024v, Martin et al. 2023).

After closure, the waste and engineered barriers are assumed to evolve according to the phenomenological description of their expected evolution given in NAB 24-20 (Nagra 2024l), which is supported by the results of the performance assessment (Nagra 2024v) and is also in accordance with the safety and repository concept presented in Chapter 3 of NAB 24-18 (Nagra 2024t). Details are presented in the following sections.

Evolution of the access structures. During closure, the V3 seals placed in the access shafts to isolate the repository from the surface environment, will saturate relatively rapidly, within a few thousand years of installation, due to the high capillary pressure (suction) of their compacted bentonite sealing elements and the flow of water from more permeable rock formations above the repository down the shafts and into the seals (Nagra 2024o, Section 5.3.1, and Nagra 2024v, Section 3.5.4). Once saturated, the V3 sealing elements will have a low permeability to both water and gas. This will largely prevent further water flow down the shafts into the unsaturated underground structures of the repository. It will also largely prevent the migration of repository-generated gas from the underground structures of the repository towards the surface environment. This is relevant to radiological safety, as repository-generated gas may convey gaseous and volatile radioactive species, such as C-14 in the form of methane (Nagra 2024y, Section 4.1). The build-up of excessive gas pressures that could otherwise damage the rock is limited, in part, by the available gas storage volume of the backfill mortar and the high gas permeability of the L/ILW part of the sealing system and by the high gas storage of the VF1 and VF2 backfill (Nagra 2024o, Section 5.3.1; Martin et al. 2023, Section 2.2.4, and Nagra 2024j, Chapter 9).

Evolution of the L/ILW disposal section and connected underground structures after backfilling. The major components within the L/ILW near field are cement-based and compatible with each other, thus limiting the rate and extent of THM-C processes (Nagra 2024v, Section 3.4). Nonetheless, the cementitious near field will also evolve over time due to various degradation processes, which are dependent on the availability of water and CO_2 generated by the degradation of organics in the waste (Guillemot et al. 2023 and Kosakowski et al. 2023, Section 3.5).

After the emplacement of L/ILW and ATW and the backfilling and sealing of the emplacement caverns, the partially saturated EDZ and rock support around the caverns will begin to resaturate with water, although some gas-filled pores will remain because of repository-generated gas (see below) (Nagra 2024o, and Chapter 2 of Kosakowski et al. 2023). Some water may also enter the caverns and accumulate under gravity above the cavern floor (Nagra 2024o, Section 5.3.1, and Kosakowski et al. 2023, Section 3.2.1). Anaerobic and reducing conditions develop due to the consumption of O_2 and hyperalkaline conditions develop due to the interaction of porewaters with cementitious materials (Leupin et al. 2016 and Kosakowski et al. 2023, Section 3.3.1).

Gas generation in the L/ILW disposal section of the repository will take place due mainly to the corrosion of metals and the degradation of organic materials in the caverns. Some of this gas will dissolve in porewater within and around the caverns, with the remainder accumulating within the caverns themselves, increasing the gas pressure and limiting further inflow of water (Nagra 2024o, Section 5.4, and Nagra 2024j, Chapter 9).

The V1 seals that close the L/ILW caverns and the V2 seals located at the entrance of the access-ways to the L/ILW disposal section will also start to resaturate. However, full saturation will be prevented by gas from the caverns, which will migrate through these seals and accumulate in the backfill of the adjoining underground structures, which provides a storage volume for the gas in addition to that provided by the caverns themselves (Nagra 2024o, Section 5.3.1, and Nagra 2024v, Section 3.4.5). Desaturated conditions will persist in the upper parts of the L/ILW caverns and in the backfill of the connected underground structures for several tens of thousands to hundreds of thousands of years (Nagra 2024o, Section 5.3.1). Some gas may enter the rock but will migrate through it mostly by diffusion in the dissolved state (Nagra 2024o, Section 5.3.1, and Nagra 2024j, Chapter 9). The resulting elevated pore pressures, however, have no long-term impact on the performance of the barriers (Nagra 2024v, Chapter 4).

Pore-clogging due to cement-clay interactions within the V1-L/ILW and V2-L/ILW seals, which may impact overall seal permeability, is not expected due to the transition layer that comprises inert material and which separates the cement and clay sections. This is further supported by the fact that the sand-bentonite seals are expected to remain only partially saturated (Martin et al. 2023, Chapter 6, and Nagra 2024o, Section 5.3.1).

Any heat generated from cement hydration is expected to be limited to an increase of 12 – 15 °C and will cease within a period of days to weeks (Martin et al. 2024). Temperature increases from radioactive decay in L/ILW and ATW will be lower, although persisting over a longer period, and any effect on chemical or physical processes will be negligible (Leupin et al. 2016, Section 4.2). Furthermore, the heat emitted from the HLW canisters will not reach the L/ILW repository (Nagra 2024v, Section 4.2.2; Nagra 2024o, Section 5.3.1; Nagra 2024j, Chapter 6).

The disposal containers may provide an initial resistance to water ingress, though they degrade over time and, eventually, water will begin to contact the waste matrices (Nagra 2024l).

The liner around the emplacement caverns will degrade and lose its mechanical strength over time, but the resulting stress redistribution will have no impact on the safety-relevant properties of the barriers. In particular, the presence of backfill material, where the grain-to-grain contact of the aggregate is assumed to take up the stresses (Martin et al. 2024 and Section 3.4.5 of Nagra 2024l), will limit cavern convergence.

The cementitious near-field evolves over time due to the mineralogical evolution of cement phases (Kosakowski et al. 2023). In view of the limited supply of porewater from the rock to the L/ILW emplacement caverns (Nagra 2024o, Section 5.4, and Section 7.2.4 of Martin et al. 2023), the degradation of the cementitious material will be heterogeneous, dependent on the composition of the cementitious material, availability of water and the degradation of the organic materials (Kosakowski et al. 2023, Section 3.5). A high pH is expected to be maintained for a very long period of time, in particular in the partially saturated part of the repository (Kosakowski et al. 2023, Section 2.4), but changes in the radionuclide retention properties of the cement-based near field are expected and are included in the reference safety scenario (Tits & Wieland 2023, Appendix D). Interactions between the cementitious near field and the surrounding rock will be limited in their spatial extent and will not affect the safety-relevant properties of either barrier (Prasianakis et al. 2022). Any pore clogging that occurs due to precipitation will have a limited effect on gas release into the host rock (Martin et al. 2023, Chapters 4 and 5).

Evolution of the HLW disposal section after backfilling. After sealing of the HLW emplacement drifts, the liner and partially saturated EDZ will resaturate with water, followed by saturation of the buffer and seals (Nagra 2024o, Section 5.3.1, and Nagra 2024j). The (geomechanical and chemical) evolution of the liner does not significantly impair the technical and/or natural barriers (Nagra 2024v, Section 3.3.3 and Curti et al. 2023, Section 6.7).

Buffer saturation will occur relatively quickly due to the high capillary pressure of the compacted bentonite used as buffer material and in the sealing elements, though the rate of saturation will be limited by the low permeability of the rock and by decay heat generated by the waste (Nagra 2024o, Section 5.3.1). Full saturation is expected to occur some hundreds of years after emplacement (Nagra 2024o, Section 5.3.1) and will be sufficiently uniform such that no potentially damaging stresses will be exerted on the canisters (Nagra 2024v, Section 3.3.1). Any initial inhomogeneities in the buffer density are diminished over time. The bentonite buffer, once saturated, will provide favourable environmental conditions, contributing to the longevity of the canister and the retention and slow release of radionuclides (Nagra 2024v, Section 3.3). Furthermore, the buffer density around the canister will be sufficiently high, when saturated, to prevent microbial activity (Jenni et al. 2019, Section 5.6) that might otherwise increase the rate of canister corrosion (Nagra 2024c, Section 2.2.4). Radiation shielding provided by the disposal containers will be sufficient to protect the barriers from radiation-induced effects.

Anaerobic conditions will quickly develop due to the consumption of O_2 by various processes, e.g., canister corrosion. H_2 generation will occur due to the gradual anaerobic corrosion of the disposal canisters, leading to reducing conditions (Nagra 2024c, Section 2.2.2). Much of this gas will dissolve in the porewater of the saturated bentonite buffer surrounding the canisters and diffuse through the liner into the Opalinus Clay porewater (Nagra 2024o, Section 5.3.1). However, some gas may also migrate in the gas phase through the buffer and into the rock, where it will dissolve (Nagra 2024o; Nagra 2024j, Chapter 9; Leupin et al. 2021). Gas migration will cause no irreversible changes to either the buffer or rock (Nagra 2024o).

In the first few thousands of years post-closure, repository-generated heat, primarily decay heat from the waste forms, will lead to a transient increase in temperature and pore pressure within and around the HLW disposal section, including within the CRZ (Nagra 2024o, Section 5.3.1). These elevated temperatures and pore pressures, however, will have no long-term impact on the performance of the barriers (Nagra 2024v, Chapter 4). The concrete liner around the emplacement drifts will degrade and lose its mechanical strength, but the resulting stress redistribution will have no impact on the safety-relevant properties of the barriers (any reactivation of EDZ fractures will be temporary, as the fractures will re-seal) (Nagra 2024v, Section 3.3).

The porewater composition of the buffer will gradually equilibrate with that in the rock (Curti 2023 and Curti et al. 2023, Chapter 7). Chemical interactions, including interaction of canister corrosion products with the clay barriers and between the cementitious liner and the surrounding rock, will be of limited spatial extent and will not affect the safety-relevant properties of the repository barriers (Curti et al. 2023, Nagra 2024v).

As assessment basis, a canister lifetime of at least 10,000 years is anticipated (Nagra 2024c), after this, increasing numbers of disposal canisters will become locally breached due to mechanical failure following weakening by corrosion (Nagra 2024v, Nagra 2024c, Nagra 2024l). The exposure of internal metal surfaces to water will result in corrosion of these surfaces and local increased gas production rates (Nagra 2024o, Section 5.3.1). The products of canister degradation (corrosion) are not detrimental to other technical and/or natural barriers (Nagra 2024v, Section 3.2).

The SF and RP-HLW matrices, as well as the SF cladding and HLW stainless steel flasks, hardly interact and do not impair the chemical integrity of the canister or (after canister breaching) the bentonite buffer (Nagra 2024v, Section 3.1).

5.1.4 Repository-induced effects on the barrier system

Based on the performance assessment, repository-induced effects associated with heat, gas, the formation of EDZs, and chemical interactions are expected to have minimal effects on the performance of the barrier system (Nagra 2024v, Sections 3.3, 3.4, 4.3 and 4.4). Performance related claims regarding these effects are summarised in the following paragraphs, supported by arguments and evidence, which justifies the incorporation of the expected performance claims in the reference safety scenario.

Heat from radioactive decay does not impact the contributions of the bentonite buffer (Nagra 2024v, Sections 3.3 and 6.3.2), the host rock or the V1-HLW seal to the safety functions (Nagra 2024v, Sections 4.3, 6.2.3, 6.3.2; Nagra 2024j). Additionally, thermal impacts do not enhance radionuclide release along the backfilled and sealed HLW structures (Nagra 2024v, Section 4.3.1). This is supported by model-based assessments that show the loss of radionuclide retention capacity of the bentonite buffer associated with thermal disequilibrium is insignificant, and that thermally-induced displacement of porewater along the backfilled structures is negligible (Nagra 2024v, Nagra 2024o, Nagra 2024j). Pore pressure changes due to HLW heat evaluated in probabilistic simulations do not exceed the shear failure criterion in the EXPERF performance assessment scenario (Nagra 2024v, Section 6.2.3). This indicates that thermally-induced faulting due to heat induced over-pressures is very unlikely to occur under the expected geomechanical conditions.

Likewise, gas-related impacts do not impair the stable geochemical and geomechanical environment of the repository, nor do they enhance radionuclide release along the backfilled and sealed HLW structures (Nagra 2024v, Section 4.4; Nagra 2024o, Nagra 2024j). The gas production rate in the HLW and L/ILW repository sections is limited compared to the gas transport capacity of the rock and repository structures, such that excessive pressure build-up in the repository, which could otherwise affect the properties of the host rock, is avoided (Nagra 2024o, Nagra 2024j). Gas generated by HLW canister corrosion is transported through the buffer without significant reduction of its function as a hydraulic barrier (Nagra 2024v, Section 3.2) and the porosity and permeability of the L/ILW cavern backfill mortar provides a gas storage volume and a pathway for the release of gas through the closure system, preventing excessive gas overpressures (Nagra 2024v, Section 3.4; Nagra 2024o, Nagra 2024j). Pore pressure changes due to gas generation in the HLW and L/ILW repository sections evaluated in probabilistic simulations do not exceed the shear failure criterion in the EXPERF, UBGAS (HLW upper bound gas source term) and

PESSGAS (pessimistic gas generation rates in the L/ILW) performance assessment scenarios (Nagra 2024v, Sections 6.2.3, 6.3.2 and 6.3.5). Collectively, these analyses indicate that gas-induced faulting is very unlikely to occur under the expected geomechanical conditions.

The EDZ around the HLW tunnels does not represent a significant transport path for dissolved radionuclides (Nagra 2024v, Section 3.3). The EDZ is self-sealing once the near-field saturates, and repository design prevents significant axial porewater flow along the EDZ and liner (Nagra 2024j). Likewise, the EDZ around the HLW drifts does not impair the chemical and mechanical integrity of the other components of the barrier system (Nagra 2023c, Geomechanica Inc., Toronto 2018). Regarding the other repository structures, the EDZ is expected to be sufficiently limited, such that the barrier function of the host rock is not impaired (Geomechanica Inc., Toronto 2018, Alcolea 2018).

Regarding the potential effects of chemical interactions, the following claims are elaborated in Section 3.1 of Nagra (2024v). The SF assemblies are chemically highly inert and do not impair the chemical integrity of the canister or the bentonite buffer. The SF matrix mainly comprises UO_2, which dissolves at a very slow rate, such that any chemical interactions with the canister and bentonite are very limited in extent. Likewise, the stainless steel flask containing the RP-HLW is compatible with the glass and canister, due to their low degradation rates. Indeed, corrosion rates of stainless steel and other metals are very low within a bentonite porewater environment (Diomidis et al. 2023). Furthermore, any interaction between canister corrosion products and the bentonite buffer does not significantly reduce the buffer's function as a hydraulic barrier. This is evidenced by models that show the extent of any interactions are limited compared with the total bentonite thickness (Nagra 2024w). Regarding the L/ILW near field, the cement-based components are compatible with each other and result in a highly alkaline environment, which acts to limit the corrosion of steel and degradation of organic materials (Nagra 2024v, Section 3.4).

Although the repository-induced effects described above are not expected to cause any significant deviations from anticipated performance, the following phenomena associated with these effects are still included in the definition of the reference safety scenario:

- Repository-generated heat could lead to a narrow zone of altered bentonite around the HLW canisters (Chapter 5 of Curti et al. 2023 and Section 6.1 of Nagra 2024l).
- Repository-generated gas will permeate much of the sealing system but will be largely retained underground by the V3 seals and will slowly dissolve and diffuse into the host rock (Nagra 2024o, Section 5.3.1; Nagra 2024j, Chapter 9). Whilst no impact of gas generation on the mechanical integrity of the multi-barrier system is expected (Nagra 2024v, Section 4.4), the effect is considered due to its impact on flow and transport processes.
- Stress changes during the construction of the underground openings will result in the formation of EDZs, which will largely re-seal over time (Nagra 2024l, Chapter 4). However, their constant presence is conservatively accounted for in the description of the reference safety scenario.
- Ventilation during the operational phase leads to depressurisation and partial desaturation of the EDZ (Nagra 2024l, Section 4.2.3). This process will be reversed during the early post-closure phase.

5.1.5 Release and transport of radionuclides

The release, retention and transport of radionuclides from the repository during its expected evolution in the reference safety scenario conforms with the safety and repository concept, as described in Chapter 3 of NAB 24-18 (Nagra 2024t). The following paragraphs describe these key steps.

Radionuclide release following breaching of HLW canisters. The provisional design of the HLW canisters affords at least 1,000 years of complete containment (Nagra 2024c). They will, however, eventually breach, most likely at weld flaws, allowing buffer porewater to enter.

In the case of SF, water will first contact the Zircaloy SF cladding. The cladding has a low corrosion rate (Diomidis et al. 2023) and is likely to prevent the contact of water with the SF pellets until it has substantially corroded. Nevertheless, the cladding of a small fraction of the fuel rods may have suffered from embrittlement, either in the reactor or during interim storage, or could have been damaged during handling. For this reason, in the reference safety scenario, no credit is taken for the Zircaloy cladding in delaying contact between the buffer porewater and the SF pellets. Activation products within the Zircaloy will mainly be released congruently as it corrodes, although a small fraction of the C-14 will be released instantaneously (Nagra 2024y, Section 3.3.1.2).

As water contacts the SF pellets, a small fraction of the inventory of some radionuclides will also be released instantaneously; the so-called instant release fraction (IRF) (Johnson et al. 2023). These gaseous or volatile species (I-129, C-14, Cl-36, Cs-135) are segregated from the fuel matrix and accumulate in the gap between the pellet and the cladding, and at grain boundaries. However, the majority of the radionuclide inventory resides in the uranium dioxide and MOX pellets and is released slowly and congruently with their dissolution rate. Dissolution of SF pellets is expected to be slow in the prevailing reducing conditions provided by the partially dissolved H_2 generated by metal corrosion. Furthermore, once the concentration of uranium in the porewater approaches the solubility limit of $UO_2(s)$, the dissolution rate is expected to be close to zero (Johnson et al. 2023).

The RP-HLW is protected by the outer disposal canister and the inner stainless steel flask that is several millimetres in thickness. When the canister has breached, the stainless steel flask may prevent contact of porewater with the RP-HLW until it has largely corroded. Despite this, no credit is taken for the stainless steel flasks in delaying contact between the buffer porewater and the RP-HLW matrix in the reference scenario. Once water contacts the waste, radionuclides in the waste matrix will be released congruently during the slow dissolution of the matrix (Curti 2022).

Radionuclides that enter solution will migrate through the saturated bentonite buffer, the degraded liner and into the host rock (Hummel et al. 2023). Some, however, will be temporarily immobilised by precipitation and coprecipitation within and around the waste forms for as long as the respective solubility limits are exceeded. Any colloids formed within and around the waste forms will not migrate into the bentonite buffer, due to its fine and homogeneous pore structure. Some radionuclides, notably C-14, may also be transported in the gas phase into the rock by gas generated by canister corrosion (Nagra 2024y).

Radionuclide release from the L/ILW containers. L/ILW containers provide containment for the radionuclides for a limited period, though no credit is taken for any L/ILW containment in the reference safety scenario. Soluble radionuclides released from the waste barrels into the container infill mortar and, if not retained, out from the containers will dissolve in the porewater that accumulates initially at the bottom of the emplacement caverns. They will then diffuse through the partly saturated emplacement cavern backfill mortar and liner, and into the host rock. Some dissolved radionuclides may be immobilised by precipitation and retained by sorption and adsorption within the cement paste of the cement-based near-field (Tits & Wieland 2023). Any colloids formed within and around the waste forms will not migrate into the host rock or through the disposal section seals, due to the fine and homogeneous pore structure of the rock and sealing elements (Kosakowski et al. 2023, Section 3.3.6).

Gaseous radionuclides, or those forming volatile species, will be conveyed with other repository-generated gas through the backfill mortar and into the gas-permeable sealing system of the L/ILW disposal section (Nagra 2024o, Martin et al. 2023) and further into the host rock or along the access structures up to the low-permeability (V3) shaft seals (Nagra 2024y, Section 4.1).

Radionuclide retention and transport processes in the repository barriers. Dissolved radionuclides in the porewater of the emplacement drifts and caverns will migrate through the near-field porewater and into the CRZ (Nagra 2024l, Section 9.2). The migration of many radionuclides will be strongly retarded by sorption on solid phases in both the near field and geosphere (Marques Fernandes et al. 2024). Retardation by sorption in the cement-based L/ILW near field will be affected by the evolving cement mineralogy as cement phases, as is accounted for by the cement sorption database (Tits & Wieland 2023).

Transport of radionuclides in the CRZ occurs by advection and diffusion, with diffusion being the dominant transport mode for dissolved radionuclides (Nagra 2024h, Section 5.9). Any discontinuities within the CRZ are assumed not to affect porewater flow and radionuclide transport significantly because of their limited transmissivity and connectivity and because of the self-sealing properties of the clay rich formations (Nagra 2024h, Section 5.7). Diffusion is also the dominant transport mode for radionuclides in the repository near field, due mainly to the low hydraulic conductivity of the sealing system, the bentonite buffer and the surrounding CRZ and also due to the dead-end architecture of the emplacement drifts and caverns. The EDZ around the HLW tunnels does not represent a significant lateral transport path for dissolved radionuclides (Nagra 2024v, Section 3.3.2). Advection of dissolved radionuclides due to the displacement of near-field porewater by gas will be negligible (Nagra 2024v, Section 4.4).

Radionuclides that form volatile species are transported along with repository-generated gases through the engineered barriers and enter the CRZ. These too eventually dissolve in porewater within the repository barrier system, including the confining units, or within groundwater flowing through the deep aquifers (Nagra 2024y, Section 4.2 and 4.3).

Transport of radionuclides to the biosphere and their radiological consequences. Eventually, non-sorbing and poorly sorbing radionuclides that have not decayed within their residence time in the barrier system will reach the overlying and underlying aquifers (Nagra 2024v, Section 6.2.3). Here, they will be diluted substantially and be transported by advection to the biosphere, hundreds of thousands of years in the future. During this time, most of the radioactivity will have further decayed, and any releases that do occur will be distributed over hundreds of thousands of years or more. The resulting dose rates to hypothetical humans inhabiting the biosphere are evaluated in NAB 24-06 (Nagra 2024m).

A key feature of radionuclide release rates to the biosphere is that, in the reference scenario and for most radionuclides, they vary over timescales that are much longer than the timescales that characterise the most relevant transfer and accumulation processes in the biosphere. This allows radionuclide concentration equilibrium to be assumed within individual biosphere model compartments and for dose rates to be calculated using steady-state BDCFs. The BDCFs are based on a biosphere model that stylistically assumes constant climatic conditions and a fixed human way of life throughout the time period for assessment (Nagra 2024m).

There are no performance assessment claims that specifically address the distribution of radionuclides in the biosphere and their radiological consequences. These are addressed in other reports, notably NTB 24-18 and NAB 24-06 (Nagra 2024q, Nagra 2024m).

5.1.6 Future human actions

Human intrusion and other FHAs, either deliberate or inadvertent, that could impair the functionality of the repository during the time period for assessment are assumed not to occur in the reference safety scenario. This is justified by the placement of the repository in a deep underground location where human intrusion is unlikely and which is isolated from human activities occurring at or near the surface.

5.1.7 Criticality

Safety regarding criticality is also assumed; criticality safety will be a design requirement of the repository, specifically, for the HLW final disposal canister and for the HLW canister loading plans. Criticality safety will be ensured through the implementation of technical and administrative measures.

5.2 Scenario specific factors affecting radiological consequences

The most important factors affecting the radiological consequences in the framework of the reference safety scenario for all siting regions are the parameter value bandwidths reported in the assessment basis and the state assumed for the future biosphere.

Specifically in the case of the proposed siting region, geological evidence suggests that the Keuper aquifer below the provisional location of the HLW repository, or the HLW section of a combined repository is hydraulically inactive (Section 5.1.1). This is contrary to the assumptions of the reference conceptualisation of the reference safety scenario and is a factor that could have a non-negligible impact on radiological consequences. An alternative assumption is thus considered in the form of a variant of the reference safety scenario specifically for the proposed siting region. These variants and their associated calculation cases are described below.

5.3 Variants and calculation cases propagated to the analysis of the radiological consequences

For each siting region a reference calculation case is defined, which forms the basis for further safety scenario development and for the interpretation of the results of other calculation cases in the analysis of radiological consequences (Nagra 2024q). The reference case (RS-RC)[22] is a single, deterministic calculation case. A key assumption is that the Keuper aquifer below the repository is hydraulically active, which is conservative in the case of the HLW repository, or the HLW repository section of a combined repository in the proposed siting region. A steady state reference biosphere based on present-day climatic conditions is also assumed for the entire time period for assessment. Otherwise, where there is quantified uncertainty in the properties of repository features, the rates of processes and other model parameters, realistic values are assumed (other uncertainties are generally handled using conservative assumptions).

The reference case and other calculation cases defined for each siting region are listed in Tab. 5-2, some of which are shown schematically in Fig. 5-3. These calculation cases are propagated to the analysis of radiological consequences for separate HLW and L/ILW repositories in all three siting regions in the framework of safety analysis, and, for a combined repository in the NL siting region, in the framework of post-closure safety assessment.

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[22] To facilitate the presentation and discussion of calculation results in the analysis of radiological consequences (Nagra 2024q) short keys are associated with the calculation cases; e.g., for the reference case RS-RC (**R**eference Safety **S**cenario – **R**eference **C**onceptualisation).

Tab. 5-2: Variants and calculation cases for the reference safety scenario

Variant	Case	Description
Reference conceptualisation of CRZ; hydraulically active Keuper aquifer.	RS-RC	Reference case (reference biosphere).
	RS-BIOS/WARM_DRY	Warmer and drier biosphere.
	RS-BIOS/COLD	Colder biosphere.
	RS-BIOS/ DRAINED_FARMLAND	Biosphere with drained farmland.
	RS-PROB	Probabilistic simulation by considering the parameter uncertainty.
	RS-PROB-*param*	Multiple cases in each of which a single sensitive parameter (*param*) is set to its conservative, bounding value.
	RS-CMB	All sensitive parameters are set to their conservative, bounding values.
Specific to the proposed siting region: hydraulically inactive Keuper aquifer.	RS-KEUPER_INACTIVE	Hydraulically inactive Keuper aquifer below HLW repository in NL siting region, or below HLW disposal section of a combined repository in NL.

For the reference conceptualisation of the CRZ with a hydraulically active Keuper aquifer, three additional calculation cases are defined that assume different, though still steady-state, climatic and surface conditions:

- a warmer and drier climate (RS-BIOS/WARM_DRY),
- a colder climate (RS-BIOS/COLD), and
- a drained farmland (RS-BIOS/DRAINED_FARMLAND).

Further details of the reference and alternative biospheres, and of biosphere modelling in general, are provided in NAB 24-06 (Nagra 2024m).

Additional calculation cases, again based on the reference conceptualisation, are defined that aim to identify, illustrate and quantify the impact of uncertainty in the parameters that control radionuclide retention and transport in the repository barriers:

- A probabilistic calculation case (RS-PROB):

  This case entails multiple realisations in which uncertain parameters are sampled at random from probability distributions, derived from an assessment of parameter uncertainty. The aim is to illustrate the range of uncertainty in calculated consequences and to provide the data for a global probabilistic sensitivity analysis to identify those parameters to which the calculated consequences are most sensitive.

- A set of pessimistic deterministic calculation cases (RS-PROB-*param*):

  In these cases, each individual parameter (*param*) to which the radiological consequences are sensitive, as identified in RS-PROB, is set to its most unfavourable value within its probability distribution.

- A single deterministic calculation case (RS-CMB):

  In this case, all parameters to which the radiological consequences are most sensitive, as identified in RS-PROB, are simultaneously set to their most unfavourable value within their respective probability distributions.

A single deterministic calculation case, RS-KEUPER_INACTIVE, is defined for the variant conceptualisation specific to NL, in which the Keuper aquifer below the HLW repository, or the HLW section of a combined repository, is assumed to be hydraulically inactive. Here, all radionuclides reaching the Keuper aquifer are assumed to diffuse across it, without being diverted along it by groundwater flow, and continue to diffuse towards the underlying Muschelkalk aquifer.

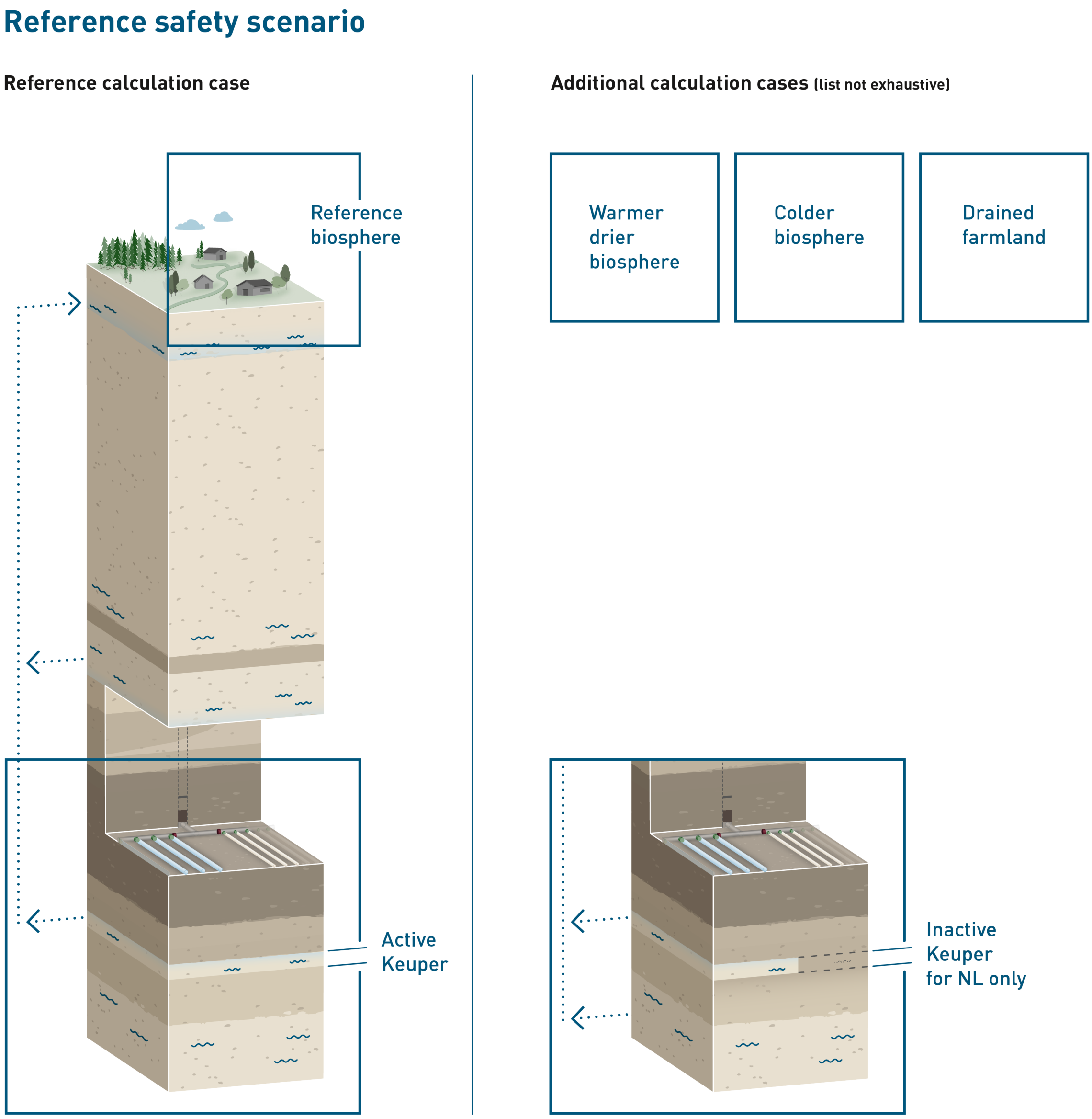

Fig. 5-3 Illustration of variants and calculation cases for the reference safety scenario

The figure shows, in the bottom left box, the reference conceptualisation with a hydraulically active Keuper aquifer and, in the bottom right box, the variant for the proposed siting region only, in which the Keuper aquifer below the HLW repository, or HLW section of a combined repository, is hydraulically inactive (calculation case RS-KEUPER_INACTIVE, Tab. 5-2). The figure also illustrates the reference and alternative biosphere assumptions, each of which is applied in one calculation case for the reference safety scenario.

6 Alternative safety scenarios, variants and calculation cases

The results from the performance assessment (for details, see NTB 24-22 (Nagra 2024v)) indicate that the potentially detrimental phenomena addressed by performance assessment modelling do not, in general, affect the broad descriptions of the evolution of the repository safety functions in any substantive way, i.e., performance targets are met even for combinations of unfavourable parameters explored using probabilistic analyses, generally with a large safety margin. This shows that the repository is highly robust regarding uncertainties related to system performance and that it is likely to evolve according to its "expected performance" and, hence, according to the reference safety scenario.

Some uncertainties nonetheless remain, specifically those concerning the geological characterisation. For instance, the «Herrenwis Unit» and the so-called "hard beds" within the confining units above and below the host rock were considered as hydraulically inactive in the reference safety scenario (Section 5.1.1.1). However, the presence of a hydraulically active confining unit cannot currently be excluded entirely. In addition, the CRZ is conceptualised in the reference safety scenario without any existing faults (Section 5.1.1.2). Nonetheless, an undetected fault in the vicinity of the repository cannot be entirely excluded, and this would provide a limited preferential pathway for porewater flow and radionuclide transport. An assessment of the radiological consequences of such features also requires a new model conceptualisation of the CRZ. Thus, these uncertainties in geological characterisation of the siting regions give rise to the following two alternative safety scenarios:

- a hydraulically active confining unit within the CRZ above or below the Opalinus Clay host rock, and
- an undetected fault in the vicinity of the repository.

It is expected that further site investigations for future licensing milestones will reduce the uncertainty concerning these features, and it may then be possible to exclude these alternative safety scenarios or only include them as "what-if?" cases in future iterations of the safety case.

6.1 Hydraulically active confining unit

6.1.1 General description of the safety scenario

In this alternative safety scenario, it is assumed that one of the features in the confining units above or below the Opalinus Clay is hydraulically active (i.e., hard beds, see Section 5.1.1.1). Although no evidence is so far established, it is speculated that this might be due to fractures within a lower-clay-content unit being denser and having a higher degree of connectivity than currently understood based on the site characterisation data summarised in Chapter 5. Zones with potential for elevated local transmissivity in each siting region are marked in Fig. 5-2 with grey arrows. These were identified and classified according to their hydrogeological or mineralogical properties as part of the geological site characterisation documented in NTB 24-10 (Nagra 2024g). The number and identities of units that could be hydraulically active varies between the three siting regions. In summary, there is one such unit in the upper confining units (SCD) and one in the lower confining units (KEU) in the case of JO and ZNO. In NL, there are three in the upper confining units (CM, CD and SCD, where CD corresponds to the above-mentioned «Herrenwis Unit») and two in the lower confining units (KEU and KAU).

6.1.2 Scenario-specific factors affecting radiological consequences

The most important factors affecting the radiological consequences of this scenario are the location of the hydraulically active rock unit, the fluid flow parameter values and the connectivity of the unit that is assumed to be hydraulically active.

6.1.3 Variants and calculation cases propagated to the analysis of radiological consequences

The variants and calculation cases propagated to the analysis of radiological consequences are summarised in Tab. 6-1. Two variants are defined for this safety scenario based on the location of the hydraulically active units with respect to the Opalinus Clay. These two variants are distinguished due to the considerable difference between the horizontal hydraulic gradients of the upper and lower aquifers bounding the CRZ (Nagra 2024g), which is perceived to cause similar gradients in case of the other potentially transmissive units.

Each calculation case is propagated to the analysis of radiological consequences for separate HLW and L/ILW repositories in all three siting regions in the framework of safety analysis, and for a combined repository in the NL siting region in the framework of post-closure safety assessment.

Tab. 6-1: Variants and calculation cases for the alternative safety scenario that assumes an additional hydraulically active unit within the CRZ above or below the Opalinus Clay

Variant	Case	Description
Additional hydraulically active unit within the CRZ above the Opalinus Clay.	AS-HA/SCD	Hydraulically active SCD unit
	AS-HA/CD	Hydraulically active CD unit (NL only)
	AS-HA/CM	Hydraulically active CM unit (NL only)
Additional hydraulically active unit within the CRZ below the Opalinus Clay.	AS-HA/KEU	Hydraulically active KEU unit
	AS-HA/KAU	Hydraulically active KAU unit (NL only)

For the definition of the calculation cases, each potentially hydraulically active unit present in each siting region is considered, in turn, to be hydraulically active, while the remaining units are considered hydraulically inactive (identical to the assumption of the reference safety scenario). In each of these calculation cases, it is assumed that radionuclides reaching the hydraulically active unit may either be transported vertically across it by diffusion or be diverted into the unit. It is conservatively assumed that the hydraulically active unit is connected to the biosphere and, similar to the deep aquifers, thus provides a pathway for the advective transport of radionuclides to the biosphere (see Fig. 6-1). This assumption is made even though no lateral flow paths from these units have been observed despite extensive investigations (Nagra 2024h). The occurrence of more than one hydraulically active unit in a single case is excluded on the grounds that the available evidence indicates that the likelihood of even one such features is already very low. The hydraulic conductivity of the hydraulically active unit is set to the upper bound (conservative) value reported in NAB 24-10 (Section 5.3.1 in Nagra 2024g).

For the radiological consequence analysis concerning transport of volatile radionuclides in potentially hydraulically active units, only a single pessimistic bounding case is considered. Here, the closest upper unit is chosen (SCD) since it has the shortest transport path and hence, the highest radiological consequences.

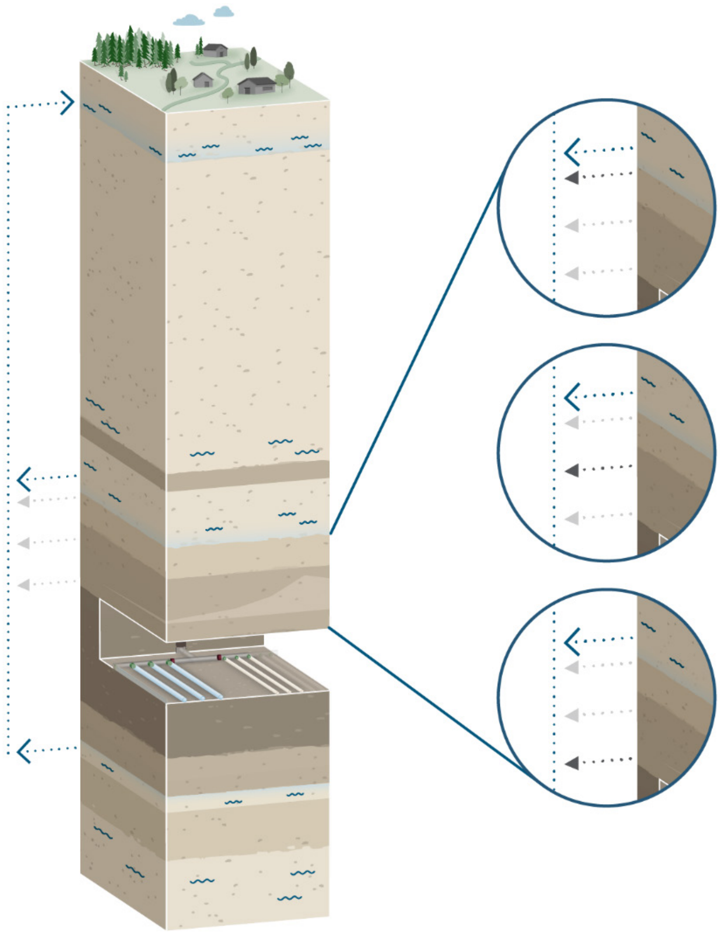

Fig. 6-1: Illustration of the alternative safety scenario in which it is assumed that one of the confining units above or below the Opalinus Clay is hydraulically active and provides an additional pathway for the advective transport of radionuclides to the biosphere

6.2 Undetected fault

6.2.1 General description of the safety scenario

All three siting regions show large areas devoid of seismically mappable faults. Therefore, the provisional location of the repositories at all three siting regions are planned away from large-scale tectonic zones, which are very well characterised (Nagra 2024h). If hydraulically active faults that are currently undetected are identified during repository construction, design measures would then be implemented to avoid waste emplacement in their vicinity. However, such measures are disregarded in the development of this current alternative safety scenario. Here, it is assumed that a fault is present in the location of the repository and the repository is built as though the fault did not exist.

6.2.2 Scenario-specific factors affecting radiological consequences

The most important factors affecting the radiological consequences of this scenario can be categorised as:

- locational, i.e., the location of the fault with respect to the underground repository structures,
- geometrical, e.g., the fault structure (i.e., whether it is a single feature, a braided structure, or combination of the two), as well as its dip, strike and spatial extent,
- hydrogeological, i.e., transmissivity and hydraulic gradient.

Due to the low permeability of the Opalinus Clay, any fault that does not intersect the underground repository structures can be assumed to have a very limited impact on the performance of the geological barrier (Nagra 2024d). Therefore, variants of this scenario involving a fault that intersects the underground repository structures are conservative in this regard. All other variants are discarded on the grounds that they will evidently have lower consequences. The variants that are retained and propagated to the analysis of radiological consequences are described further in the following section. The geometrical factors as well as hydrogeological factors are then considered in the definition of calculation cases.

6.2.3 Variants and calculation cases propagated to the analysis of radiological consequences

An existing fault under the conditions that allow liquid flow could provide a pathway for the advective transport of radionuclides present in solution in addition to the radionuclides present in the repository generated gas. The fault could intersect either the HLW emplacement drifts or L/ILW disposal caverns[23]. Alternatively, it may intersect one of the horizontal tunnels connecting the emplacement drifts or caverns to the repository central area and shafts. However, both radionuclide concentrations and gas pressures will be higher in the emplacement drifts and caverns compared to other repository structures. Thus, this scenario focusses on a fault that intersects the HLW emplacement drifts in one variant, and the L/ILW emplacement caverns in another, these being the most penalising situations.

Regarding geometry, a fault that intersects only part of the CRZ, and is not connected to other faults, is unlikely to potentially provide a significant pathway for groundwater flow and for the advective transport of any dissolved radionuclides released from the repository. This is because of the low permeability of the Opalinus Clay and most layers within its confining units, which

[23] The possibility that the fault intersects both disposal sections is not considered, given the large distance between the two disposal sections.

means they have a very low capacity to supply water to the fault (Nagra 2024h). Only if the fault (or connected set of faults) extends from the deep aquifers below the repository to the deep aquifer above is there a potential for the part of the fault within the CRZ to provide a conduit for fluid flow and for the advective transport of radionuclides. To achieve bounding radiological consequences, the fault is conceptualised as a vertical planar feature, which is a conservative simplification that minimises the transport distance via the fault to the deep aquifers. For gas migration, this assumption is the most pessimistic as well. Thus, the fault connecting the aquifers is assumed also for the radiological consequence analysis of volatile radionuclides.

For each variant, two calculation cases are defined (see Tab. 6-2) which differ in their strikes. When the fault strike is parallel to the emplacement rooms (cases AS-FLT-HLW-Along and AS-FLT-L/ILW-Along), the fault is assumed to pass through the whole length of one, single emplacement room. When the fault strike is perpendicular to the emplacement rooms (cases AS-FLT-HLW-Across and AS-FLT-L/ILW-Across), the fault is assumed to pass through all emplacement rooms in the respective disposal section (but not the emplacement rooms of the pilot facilities). These different fault configurations are illustrated in Fig. 6-2.

The fault transmissivity is conservatively assumed to be 10^{-10} m^2/s. This is one order of magnitude higher than the highest observed fault transmissivity in Opalinus Clay measured at relevant depths in Northern Switzerland, which occurs in a prominent thrust zone observed in the Schafisheim borehole, well away from the proposed siting region (Nagra 2024h, Section 5.6). No such faults are expected in the siting regions (Nagra 2024h). It is also conservatively assumed that the fault provides constant groundwater flow over the entire time period for assessment. Consistent with the characterisation of hydraulic heads (Nagra 2024g) and with the assumptions made in the performance assessment (Nagra 2024h), flow of water through the fault is assumed to occur vertically upwards from the aquifer underlying the repository to the aquifer above. However, for the modelling concerning gas migration, the two-phase flow in the fault is mainly caused by the pressure difference between the aquifer and the nearfield, where the assumption of constant groundwater flow is not relevant.

Tab. 6-2: Variants and calculation cases for the undetected fault alternative safety scenario

These calculation cases are propagated to the analysis of radiological consequences for separate HLW and L/ILW repositories in all three siting regions, and for a combined repository in the NL siting region.

Variant	Case	Description
Fault intersects the HLW emplacement drifts.	AS-FLT-HLW-Along	Fault, with a transmissivity of 10^{-10} m^2/s, with strike running along the axis of a single emplacement drift
	AS-FLT-HLW-Across	Fault, with a transmissivity of 10^{-10} m^2/s, with strike running perpendicular to drifts, cutting each drift at its centre
Fault intersects L/ILW emplacement caverns.	AS-FLT-L/ILW-Along	Fault, with a transmissivity of 10^{-10} m^2/s, with strike running along the axis of a single emplacement cavern
	AS-FLT-L/ILW-Across	Fault, with a transmissivity of 10^{-10} m^2/s, with strike running perpendicular to caverns, cutting each cavern at its centre

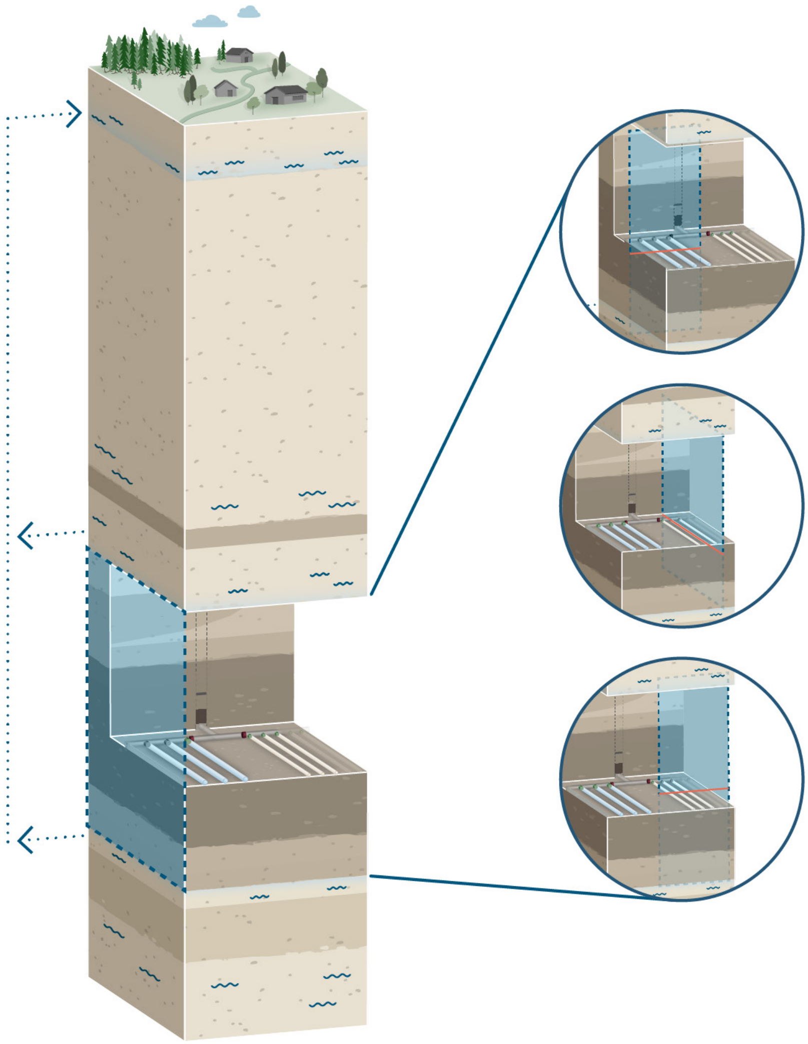

Fig. 6-2: Illustration of the alternative safety scenario in which it is assumed that there is an undetected fault that intersects one or more L/ILW emplacement caverns or HLW emplacement drifts

The small inset figures show different ways in which the fault is conceived to intersect these repository features.

7 "What-if?" cases related to physical phenomena

The "what-if?" cases described in this chapter concern the occurrence of features and processes either with characteristics that lie outside the range of possibilities supported by currently available evidence and knowledge, or whose occurrence during the million-year time period for assessment is judged to be exceedingly unlikely. They are nonetheless defined and analysed to demonstrate the robustness of the repository system. Three such groups of "what-if?" cases are identified, which consider:

- the occurrence of an undetected fault with a transmissivity that is hypothetically assumed to be much higher than could realistically be expected (i.e., much higher than in the alternative safety scenario for an undetected fault described in Section 6.2),
- the future creation or re-activation of a fault either by geological processes or by repository-induced effects at a time when the fluid pressure in the repository due to repository-generated gas is above hydrostatic pressure, and
- excavation of the repository, within a million-year time frame, by erosive processes.

Like the safety scenarios described in the previous chapters, each of these three groups can have one or more variants, each of which may give rise to one or more calculation cases that are propagated to the analysis of radiological consequences.

7.1 Undetected fault with elevated transmissivity

7.1.1 General description

As argued in Section 6.2, the initial presence of undetected faults in the vicinity of the repository that carry any significant water flow can be confidently excluded. Even if any such structures were to exist, they would likely be detected and avoided during repository construction. Nevertheless, "what-if?" cases are defined that assume a fault with a transmissivity that is much higher than could reasonably be expected, i.e., much higher than that of the fault described in Section 6.2, exists in the vicinity of the repository.

7.1.2 Factors affecting radiological consequences

As in the case an undetected fault described in Section 6.2, the most important factors affecting the radiological consequences of this scenario can be categorised as locational, geometrical and hydrogeological. Locational properties of the fault are considered in the development of variants. Both geometrical and hydrogeological factors are then considered in the definition of calculation cases.

7.1.3 Variants and calculation cases propagated to the analysis of radiological consequences

For the same reasons as given in Section 6.2, only variants involving a fault that intersects the waste emplacement drifts or caverns are propagated to the analysis of radiological consequences. All other variants are discarded on the grounds that they will evidently have lower consequences. As in the case of the undetected fault described in Section 6.2, and for the same reasons, two variants are considered, where the fault intersects either the HLW or the L/ILW emplacement rooms.

The fault is conservatively conceptualised as a vertical planar feature that extends across the entire thickness of the CRZ and carries a constant water flow in space and time. It should be noted that Opalinus Clay and other rock units in the CRZ with high clay content show high self-sealing potential and fractures, if formed, do not remain transmissive and thus do not jeopardise the barrier integrity over relevant timescales (Nagra 2024h).

Again, for each variant, two calculation cases are defined (see Tab. 7-1). When the fault strike is parallel to the emplacement rooms (cases WI-FLT-HLW-Along and W-FLT-L/ILW-Along), the fault is assumed to pass through the whole length of one, single emplacement room. When the fault strike is perpendicular to the emplacement rooms (cases WI-FLT-HLW-Across and WI-FLT-L/ILW-Across), the fault is assumed to pass through all emplacement rooms in the respective disposal section, but not the emplacement rooms of the pilot facilities. These various fault configurations are the same as those illustrated in Fig. 6-2. The possibility that the fault intersects both disposal sections is again not considered, given the large distance between the two sections.

Tab. 7-1: “What-if?” cases for an undetected fault with elevated transmissivity

These calculation cases are propagated to the analysis of radiological consequences for a combined repository in the NL siting region in the framework of post-closure safety assessment.

Variant	Case	Description
Fault with elevated transmissivity intersects the HLW emplacement drifts.	WI-FLT-HLW-Along	Fault, with a transmissivity of 10^{-7} m^2/s, with strike running along the axis of a single emplacement drift
	WI-FLT-HLW-Across	Fault, with a transmissivity of 10^{-7} m^2/s, with strike running perpendicular to drifts, cutting each drift at its centre
Fault with elevated transmissivity intersects L/ILW emplacement caverns.	WI-FLT-L/ILW-Along	Fault, with a transmissivity of 10^{-7} m^2/s, with strike running along the axis of a single emplacement cavern
	WI-FLT-L/ILW-Across	Fault, with a transmissivity of 10^{-7} m^2/s, with strike running perpendicular to caverns, cutting each cavern at its centre

The fault transmissivity is assumed to be 10^{-7} m^2/s. This is similar to observed fault transmissivities in the thin competent, horizonal limestone features, i.e., the “hard beds”, embedded between layers of more plastic clay of the CRZ (Nagra 2024g). It is four orders of magnitude above the highest fault transmissivity measured for Opalinus Clay at relevant depths in Northern Switzerland, which occurs in a prominent thrust zone observed in the Schafisheim borehole, well away from the proposed siting region (Nagra 2024h).

7.2 Fault re-activation by geological processes or repository-induced effects

7.2.1 General description

This group of "what-if?" cases concerns either the generation of a new fault, or the re-activation of an existing, non-transmissive fault, during the post-closure period at a time when the fluid pressure in the repository due to repository-generated gas is above hydrostatic pressure, thus potentially leading to enhanced gas-mediated radionuclide transport.

Many of the processes that could lead to faulting or fault re-activation, i.e., stress changes induced either by geological processes, such as seismic activity, or repository induced effects such as the impact of heat or gas generated within the repository, are excluded, or judged to be highly unlikely, on the basis of geological understanding (Nagra 2024h) and calculations presented in the performance assessment (Nagra 2024v).

Performance assessment demonstrates that gas generated within the repository does not give rise to stress changes sufficient to be a cause of this scenario, even with the most pessimistic combination of uncertain parameters (Nagra 2024o). Heat generated in the HLW disposal section, which causes differential expansion of rock minerals and pore fluids, could conceivably lead to fault creation or reactivation, although performance assessment shows that it requires several parameters, including the heat source term[24], to be simultaneously set to pessimistic values (Nagra 2024j). Additionally, the fault would be created or reactivated during the thermal phase of the HLW repository section, during which the HLW canisters will provide full containment of the radionuclides. By the time that canisters may breach, and the transport of radionuclides starts, the newly created or reactivated fault would be sealed.

In the longer term, the most likely cause for faulting or fault reactivation is the occurrence of an earthquake. Seismic activity in all three siting regions has historically been low, and seismic waves from a large earthquake sufficiently far from the repository would have no influence on repository performance (Nagra 2024d). In addition to earthquakes, phenomena such as glacial loading and unloading, dissolution below the CRZ, regional tectonic stress regime change, and glacial and fluviatile erosion could also lead to faulting or fault reactivation on a timescale of tens to hundreds of thousands of years. Observations made on different scales (seismic, macroscopic and microscopic core description) provide evidence that fault reactivation is more likely than formation of new faults (Nagra 2024h). All three siting regions show large areas devoid of seismically mappable faults, providing flexibility for repository placement and design. Along the exploration boreholes, long intervals devoid of any natural fractures were observed across the Opalinus Clay. As explained in Sections 6.2 and 7.1, currently undetected faults in the vicinity of the repository, if any, are expected to be detected as the programme advances and design measures will be implemented to avoid them. Thus, re-activation of such features by a future earthquake or by other geological processes is highly unlikely to affect the repository over a million-year time frame, and is certainly outside the time frame when repository-generated gas is above hydrostatic pressure, which could extend to a few hundreds of thousands of years at most (Nagra 2024o).

This evidence was considered in the definition of the reference safety scenario. Nevertheless, a group of "what-if?" cases considering fault re-activation due to some unspecified cause is developed, regardless of the available evidence, in order to test the robustness of the system.

[24] Nagra does not currently estimate the heat source term from individual canisters. Such data will only be generated in later stages of the programme. The pessimistic heat source term corresponds to the average heat source term in a scenario where all the most heat generating canisters are placed next to each other.

7.2.2 Factors affecting radiological consequences

The most important factors affecting the radiological consequences of this scenario can be categorised as locational, geometrical, hydrogeological and temporal. Locational, geometrical and hydrogeological factors are the same as those discussed in the context of the undetected transmissive fault in Section 7.1.2. The temporal factor of concern in this scenario is the timing of fault creation / reactivation which is assumed such that these variants confidently lead to bounding radiological consequences.

7.2.3 Variants and calculation cases propagated to the analysis of radiological consequences

Two variants are considered, where the fault intersects either the HLW or the L/ILW emplacement rooms at a time that leads to bounding radiological consequences.

For the fault intersecting the HLW disposal section, it is assumed that the fault creation or activation occurs at 10,000 years. Although repository-generated heat or seismic activity could, in principle, lead to the creation or re-activation of a fault intersecting the HLW disposal section earlier than this, full containment of the radionuclides for at least 10,000 years is anticipated to be provided by the provisional design of the canister. Thus, the radiological consequences of faulting/fault re-activation earlier than 10,000 years would be less than or identical to that of faulting/fault re-activation at 10,000 years. Additionally, it is expected that the creation or re-activation of a fault intersecting the HLW disposal section later than 10,000 years would lead to lower radiological consequences, at least for liquid-mediated transport, due to the decay of radioactivity within and around the repository.

Regarding gas-mediated transport, 10,000 years is also the earliest time when, according to performance assessment, a gas overpressure could occur in the HLW emplacement drifts (Nagra 2024o), allowing the possibility of rapid gas-mediated transport along the fault. The radiological consequences of gas-mediated radionuclide transport in this variant will be different to those assuming a pre-existing undetected transmissive fault. For the fault intersecting the HLW disposal section, it is assumed that damage to the bentonite buffer could occur as a result of faulting/fault re-activation, i.e., resulting in a degraded performance of this barrier. Thus, the consequences of this variant both for the liquid- and gas-mediated transport of radionuclides are potentially higher than those of an initially present, undetected transmissive fault intersecting the HLW disposal section, as described in Section 7.1.3. Therefore, faulting/fault re-activation at 10,000 years is a pessimistic bounding assumption for the fault intersecting the HLW disposal section.

The creation or re-activation of a fault intersecting the L/ILW repository section could also, in principle, occur at any time. For radionuclides that migrate in solution, the most pessimistic possibility would be early faulting/re-activation, as covered as a bounding case by the initially present, undetected transmissive fault considered in Section 7.1. For gas-mediated transport of radionuclides, the more pessimistic situation would, however, be later faulting/re-activation, occurring at a time when a gas overpressure has developed in the L/ILW caverns, and so would be expelled along the fault, but not so late that substantial radioactive decay of those radionuclides that may be transported in the gaseous phase (Nagra 2024u) has occurred. To address this, 20,000 years is selected as it is the expected time when, according to performance assessment, a gas overpressure begins to develop in the L/ILW emplacement caverns (Nagra 2024o). There could be damage to the L/ILW near field as a result of faulting/fault re-activation, but this would be unlikely to affect radiological consequences, given that substantial mechanical degradation of the L/ILW cavern backfill cannot, in any case, be excluded by this time.

For each variant, two calculation cases are defined (see Tab. 7-2). When the fault strike is parallel to the emplacement rooms (cases WI-FLT/RA-HLW-Along and W-FLT/RA-L/ILW-Along), the fault is assumed to pass through a single emplacement room. When the fault strike is perpendicular to the emplacement rooms (cases WI-FLT/RA-HLW-Across and WI-FLT/RA-L/ILW-Across), the fault is assumed to pass through all emplacement rooms in the respective disposal area (but not the emplacement rooms of the pilot facilities). These different fault configurations are again the same as those illustrated in Fig. 6-2.

The transmissivity of the fault is assumed to be 10^{-7} m^2/s, for the same reasons as given for the "what-if?" cases concerning an undetected fault with elevated transmissivity in Section 7.1.3.

Even if faulting or fault re-activation were to occur, the faults would close due to the self-sealing capacity of the host rock and the clay-rich layers within the CRZ (Nagra 2024h). The persistent presence of transmissive structures in the vicinity of the repository can thus be confidently excluded. Nevertheless, this group of "what-if?" cases is defined with the assumption that a transmissive fault is created in the vicinity of the repository in the post-closure period and persists over the entire time period for assessment.

Tab. 7-2: "What-if?" cases for fault re-activation by geological processes or repository-induced effects

These calculation cases are propagated to the analysis of radiological consequences for a combined repository in the NL siting region in the framework of post-closure safety assessment.

Variant	**Calculation case**	**Description**
Newly created or re-activated fault intersects the HLW emplacement drifts.	WI-FLT/RA-HLW-Along	Fault, with a transmissivity of 10^{-7} m^2/s created at 10,000 years, with strike running along the axis of a single emplacement drift
	WI-FLT/RA-HLW-Across	Fault, with a transmissivity of 10^{-7} m^2/s created at 10,000 years, with strike running perpendicular to drifts, cutting each drift at its centre
Newly created or re-activated fault intersects L/ILW emplacement caverns.	WI-FLT/RA-L/ILW-Along	Fault, with a transmissivity of 10^{-7} m^2/s created at 20,000 years, with strike running along the axis of a single emplacement cavern
	WI-FLT/RA-L/ILW-Across	Fault, with a transmissivity of 10^{-7} m^2/s created at 20,000 years, with strike running perpendicular to caverns, cutting each cavern at its centre

7.3 Excavation of the repository by erosive processes

In the very long term, uplift and erosive processes will bring the repository closer to the surface. Erosion may be caused by glacial and also non-glacial processes, including fluvial incision due to the uplift and the evolution of the local topography (e.g., due to hillslope processes); see Fig. 7-1.

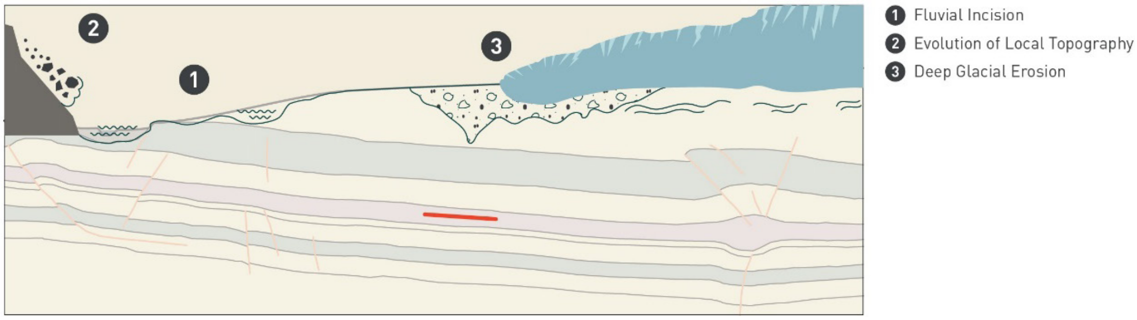

Fig. 7-1: Illustration of erosive processes affecting the rock overlying the repository (red bar)
From Nagra (2024h)

During the first million years, the effects on the performance of the repository system are expected to be negligible (Nagra 2024v). Uplift and erosion are thus included in the reference safety scenario, but they are assumed to have no significant impact on performance and safety of the repository (Section 5.1.2). In the more distant future, there is, however, the potential for repository material to be excavated by glacial and non-glacial erosion processes (Nagra 2024h).

Even though excavation of the repository by erosive processes is predicted to be possible only after the million-year time period for assessment, Nagra is, nonetheless, required by ENSI's guideline ENSI 33-649 (ENSI 2018) to analyse such events as part of the safety assessment. "Excavation of the repository by erosive processes" is thus categorised as a "what-if?" case and analysed in the safety assessment.

The conceptualisation of variants and the corresponding calculation cases for the analysis of radiological consequences are described in detail in NAB 24-08 (Nagra 2024r). The variants and calculation cases are grouped by the two main erosive processes, glacial erosion and non-glacial erosion, and are as follows:

- Three variants for glacial erosion, reflecting three distinct post-glacial configurations: river, lake, and spring. The river variant is developed into two calculation cases, whereas lake and spring variants have one calculation case each.
- Two variants are defined for the non-glacial erosion: erosion of the repository on the hillside and erosion of the repository at the valley floor. The former has four calculation cases (reflecting different hillslope angles), whereas the latter has one calculation case.

The variants and calculation cases for this group of "what-if?" cases are shown in Tab. 7-3 and Tab. 7-4. The derivation of the variants and calculation cases, as well as the radiological consequences of excavation of repository material by erosion are comprehensively discussed and analysed in NAB 24-08 (Nagra 2024r). Uncertainties in key parameters, such as the assumed erosion rates, as well as the nature of the erosion (glacial and non-glacial), are taken into account and lead to the consideration of times of excavation between 700,000 and four million years. This timescale spans hypothetical scenarios at earlier times and plausible scenarios at later times, and is informed by both erosion modelling (Nagra 2024f) and climate modelling (Nagra 2024e).

For excavation by deep glacial erosion, the calculation cases consider excavation and subsequent deposition of 10% of the HLW repository inventory, though this is varied in sensitivity analyses. For excavation by non-glacial erosive processes, the whole HLW repository inventory is assumed to be excavated over time, with the release rates dependent on the various erosion rates considered by each of the calculation cases. In all cases complete loss of containment is assumed, including waste matrices, such that the radionuclides are distributed throughout the Opalinus clay or within the deposited glacial sediments in the case of glacial processes.

Tab. 7-3: Variants and calculation cases for the assessment of repository excavation by deep glacial erosion

All calculation cases are calculated for excavation times 700,000 and 1, 2, and 4 million years after repository closure.

Variant	**Calculation case**	**Description**
River	River base case	• River variant with excavated material initially deposited in the shallow permeable sediments • Groundwater connected to the river • Water for drinking, animals and irrigation drawn from the shallow aquifer
	Alternative river case	• River variant with excavated material initially deposited in the impermeable layer below the shallow permeable sediments • Groundwater connected to the river • Water for drinking, animals and irrigation drawn from the shallow aquifer
Lake	Lake case	• Lake variant with excavated material initially deposited in the impermeable sediments below the lake • Water for drinking, animals and irrigation drawn from the lake
Spring	Spring case	• Spring variant with excavated material initially deposited in the permeable sediments on the hillside • Water for drinking, animals and irrigation drawn from the spring

Tab. 7-4: Variants and calculation cases for the assessment of repository excavation by non-glacial erosion

All calculation cases are calculated for excavation times 700,000 and 1, 2, and 4 million years after repository closure.

Variant	Calculation case	Description
Hillside	Case A	• Shallow valley with 50 m high hillslope • Low erosion rate: 0.08 mm a^{-1} • Considering long-term exposures and discrete landslide events
	Case B	• Average valley with 250 m high hillslope • Average erosion rate: 0.2 mm a^{-1} • Considering long-term exposures and discrete landslide events
	Case C	• Steep valley with 500 m high hillslope • High erosion rate: 25 mm a^{-1} • Considering long-term exposures and discrete landslide events
	Case D	• Average valley with high permeability limestone layer creating springs on the hillside below the repository
Valley floor		• Release from weathered repository below the local aquifer in a valley floor setting

8 "What-if?" cases postulating a hypothetically degraded performance of pillars of safety

Additional "what-if? cases are defined in this chapter with the primary aim of demonstrating the robustness of the repository system by illustrating the effects of a hypothetical degraded performance of each of the system components that are the main contributors to the repository safety functions, i.e., the pillars of safety, as defined in Section 3.1.2. Unlike the reference and alternative safety scenarios and "what-if?" cases described in the previous chapters, these additional "what-if?" cases are not linked to any causal physical phenomena and are thus purely hypothetical.

The cases are developed by systematically going through the pillars of safety and either removing them or assuming a degradation of the safety function they serve, as illustrated schematically in Fig. 8-1. The only pillar of safety not considered here is the deep underground location of the waste emplacement rooms in a stable geological environment. The "what-if?" cases related to physical phenomena described in Chapter 7 can, however, be seen as examples of the degradation of this pillar of safety. Specifically, if fault re-activation is caused by a large earthquake, this could imply a geological environment that is less stable than expected. Excavation of the repository by erosive processes implies that the deep underground location no longer exists. These "what-if?" cases also imply a degraded performance of the CRZ, another pillar of safety.

In addition to testing system robustness, the "what-if?" cases described in this chapter can also be helpful in elucidating the roles or contributions of specific barriers and processes to the overall performance and safety of the repository. For example, if sorption coefficients are set to zero for a particular barrier in the analysis of radiological consequences, a comparison with the results of a calculation case where realistic sorption coefficient values are applied, e.g., the reference case, can elucidate the contribution of sorption by this barrier to the limiting of radionuclide releases to the surface environment.

Each pillar of safety addressed can be considered a variant and, depending on the characteristic of each pillar, several calculation cases are defined and propagated to radiological consequence analysis.

For the **CRZ** these are:

- two calculation cases with no sorption (WI-CRZ-NOSORB) or hypothetically high diffusion coefficients (WI-CRZ-DIFF),
- two cases with hypothetically high downwardly- or upwardly-directed hydraulic gradients (WI-CRZ-GRADdown and WI-CRZ-GRADup),
- one case without upper and lower confining units (WI-CRZ-NOCONFINING), and
- a case with hypothetically high radial dimension of the EDZ around emplacement rooms (WI-CRZ-EDZ)

For the **HLW matrices**, the calculation cases assume a hypothetically high IRF for radionuclides in SF (WI-SF-IRF), hypothetically high matrix dissolution rates for SF and the glass matrix of RP-HLW (WI-HLW-DISS) and hypothetically high corrosion rates of SF cladding and other structural parts (WI-SF-CORR).

For the **HLW disposal canisters**, a calculation case (WI-HLW-CAN) assumes the hypothetical early failure of all canisters at 1,000 years.

For the **buffer in the HLW emplacement drifts**, no solubility limits (WI-HLW-NOSOL) or no sorption (WI-HLW-NOSORB) in the near-field and hypothetically high diffusion coefficients (WI-HLW-DIFF) or a hypothetically high permeability of the bentonite buffer (WI-HLW-BUF) lead to four calculation cases.

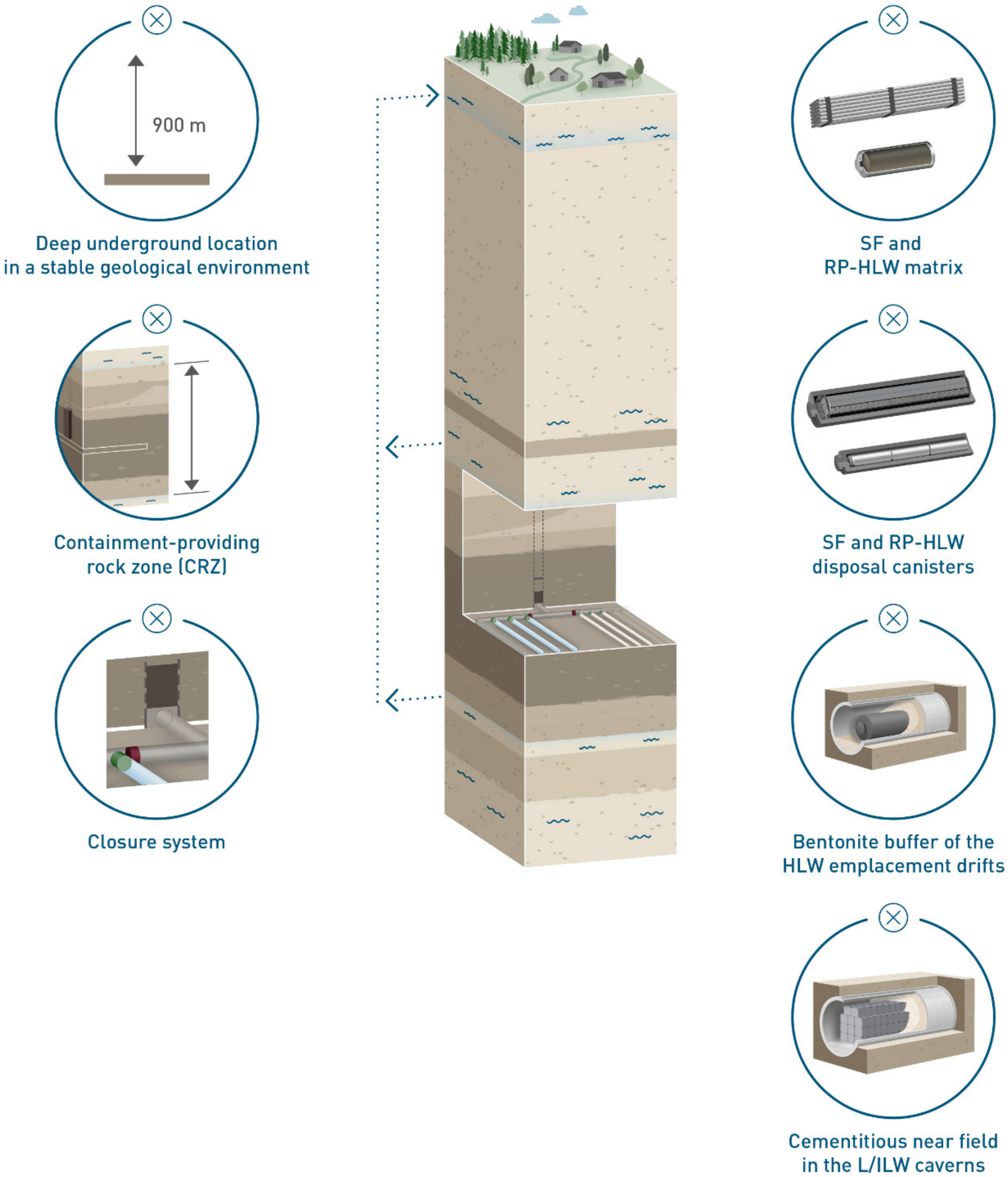

Fig. 8-1: Schematic illustration of the approach to developing "what-if?" cases postulating a hypothetically degraded performance of the pillars of safety

For the **L/ILW cementitious near field**, no sorption (WI-L/ILW-NOSORB) and an IRF of volatile radionuclides present (WI-L/ILW-C14) are considered.

Finally, the failure of the **closure system** leads to five calculation cases with hypothetically high permeabilities for the different types and locations of seals: WI-V1-HLW, WI-V1-L/ILW, WI-V2-HLW, WI-V2-L/ILW, WI-V3. In these cases, each seal is conceptually removed, such that the material assumes the same properties as that of the adjacent back-fill.

These additional, hypothetical "what-if?" cases are summarised in Tab. 8-1. Given that they are hypothetical, the radiological consequences calculated for these cases do not need to comply with regulatory dose and risk criteria; in effect, the risk is zero since they are considered to have no possibility of occurrence. Although these additional "what-if?" cases are not linked to any causal physical phenomena, some may be considered to bound the effects of poorly manufactured or emplaced engineered barriers, notably the cases related to the HLW disposal canister, the bentonite buffer, the L/ILW cementitious near field and the sealing system.

Where calculation cases involve the assumption of degraded performance (e.g., hypothetically high diffusion coefficients in the CRZ), as opposed to complete removal of a barrier, the assignment of hypothetical parameter values is performed as part of model abstraction for the analysis of radiological consequences. The justification of selected values is also documented in NTB 24-18 (Nagra 2024q) and is informed by the assessment basis and the results of performance assessment.

Tab. 8-1: "What-if?" cases postulating a hypothetically degraded performance of pillars of safety

These calculation cases are propagated to the analysis of radiological consequences for a repository in the proposed siting region in the framework of post-closure safety assessment. Where the description indicates the magnitude of a given assumption with respect to an upper bound value, this relates to the parameter value range reported in the assessment basis.

Pillar of safety	Case	Description
CRZ	WI-CRZ-NOSORB	No geosphere sorption
	WI-CRZ-EDZ	Hypothetically enlarged radius of the EDZ surrounding emplacement rooms (increased by a factor of two)
	WI-CRZ-DIFF	Hypothetically high diffusion coefficients in the geosphere (an order of magnitude higher than the upper bound values)
	WI-CRZ-GRADdown	Hypothetically high downwardly-directed hydraulic gradient (1 m/m, versus zero in RS-RC)
	WI-CRZ-GRADup	Hypothetically high upwardly-directed hydraulic gradient (1 m/m, versus zero in RS-RC)
	WI-CRZ-NOCONFINING	Upper and lower confining units disregarded
HLW	WI-SF-IRF	Hypothetically high instant release fractions (IRFs) for radionuclides in SF (all radionuclides in SF are released in IRF)
	WI-HLW-DISS	Hypothetically high matrix dissolution rates for SF and RP-HLW (an order of magnitude higher than the upper bound values)

Tab. 8-1: Cont.

Pillar of safety	Case	Description
HLW	WI-SF-CORR	Hypothetically high corrosion rates of SF cladding and other structural parts (an order of magnitude higher than the upper bound values)
HLW disposal canister	WI-HLW-CAN	Hypothetical early failure of all HLW canisters at 1,000 years
Buffer (HLW)	WI-HLW-NOSOL	No near-field solubility limits in HLW disposal section
	WI-HLW-NOSORB	No near-field sorption in HLW disposal section
	WI-HLW-DIFF	Hypothetically high diffusion coefficients in bentonite buffer (an order of magnitude higher than the upper bound values)
	WI-HLW-BUF	Hypothetically high permeability of bentonite buffer in HLW drifts (set to the same value as the VF2 backfill material, more than five orders of magnitude higher)
L/ILW cementitious near field	WI-L/ILW-C14	All volatile radionuclides present in L/ILW released instantaneously
	WI-L/ILW-NOSORB	No near-field sorption in L/ILW disposal section
Closure system	WI-V1-HLW	Hypothetically high permeability of V1-HLW seals (the same as the VF2 backfill material)
	WI-V1-L/ILW	Hypothetically high permeability of V1-L/ILW seals (the same as the VF2 backfill material)
	WI-V2-HLW	Hypothetically high permeability of V2-HLW seals (the same as the VF2 backfill material)
	WI-V2-L/ILW	Hypothetically high permeability of V2-L/ILW seals (the same as the VF2 backfill material)
	WI-V3	Hypothetically high permeability of V3 seals (the same as the VF2 backfill material)

9 Future human action safety scenarios, variants and calculation cases

The derivation and analysis of FHA safety scenarios is described in detail in NAB 24-09 (Nagra 2024s). Two stylised FHA safety scenarios, a deep borehole scenario (FHA-1) and a repository abandonment scenario (FHA-2), are propagated to the analysis of radiological consequences.

An inadvertent borehole affecting the repository would likely have a limited impact on dose consequences for humans and the environment and minimal impact on the overall waste isolation and retention provided by the repository system, as it would affect the fate of only a limited part of the repository. Nonetheless, some radionuclides may be released to the environment due to gas, core recovery and/or fluid circulation. Even after fluid circulation ceases, the boreholes could provide release pathways for repository-generated gas and radionuclides, both in solution and in the form of gaseous species. Thus, a scenario is developed to allow such impacts to be assessed.

There are numerous possible motivations for the construction of such a borehole, covering many of the FHA FEPs in Nagra's FEP database. Regardless of the grounds, a single scenario (FHA-1), with several variants and calculation cases, has been defined to bound the radiological consequences. Here, the construction of a borehole through the repository that connects an overlying aquifer with a deep aquifer below the CRZ is assumed, which provides a conduit for groundwater flow and advective radionuclide transport (of the penetrated waste). The scenario implies that knowledge of the repository and its content has been lost, so no specific precautions are taken to avoid the repository or barrier system during drilling.

Of all the possible variants of FHA-1, the ones propagated to the analysis of radiological consequences are; (i) borehole penetration of an HLW emplacement drift (FHA-1a), and (ii) borehole penetration of an L/ILW cavern (FHA-1b), specifically penetrating geological barriers, engineered barriers, and radioactive waste (see Fig. 9-1).

FHA-1a considers the breaching of an SF disposal canister by the borehole (direct hit), which is pessimistic given that RP-HLW disposal canisters have a lower radiotoxicity compared to SF and do not release volatile C-14. Calculation cases assume transport of a portion of the SF assemblies to the surface, as cuttings or core, together with the SF canister's IRF. Additionally, the open borehole is assumed to serve as a long-term release pathway to the biosphere. FHA-1a assumes that the borehole is drilled, at the earliest, 500 years after repository closure, which represents the earliest time after knowledge of the repository and its contents is assumed to be lost. Multiple later penetration times (up to 50,000 years) are considered in several calculation cases to account for the impact of the evolving repository conditions (e.g., due to gas generation) on the radiological consequences.

FHA-1b considers two cases, one involving the breaching of a single waste container with the highest L/ILW activity available and a second considering the whole radionuclide inventory of an L/ILW cavern affected by the borehole. The former assumes that the entire waste package inventory is transported to the surface, where it immediately enters the biosphere aquifer. Here, borehole penetration times of 500 to 5,000 years are considered. The latter case assumes that the borehole serves as a preferential flow path to the biosphere aquifer for both gaseous and dissolved radionuclides. Here, borehole penetration times of 500 to 5,000 years post-closure are considered for the modelling of dissolved radionuclides, and up to 50,000 years for volatile radionuclides. Again, multiple intermediate times are considered, which allows the impact of the evolving repository conditions on radionuclide release to be evaluated.

In the case of abandonment of the repository (FHA-2), it is assumed that all waste is emplaced underground but backfilling and sealing are incomplete. Subsequently, water inflow to the repository structures may follow, and the release of both dissolved and gaseous radionuclides via non-backfilled tunnels and shafts could result in radiological consequences. These releases are modelled in two separate calculation cases.

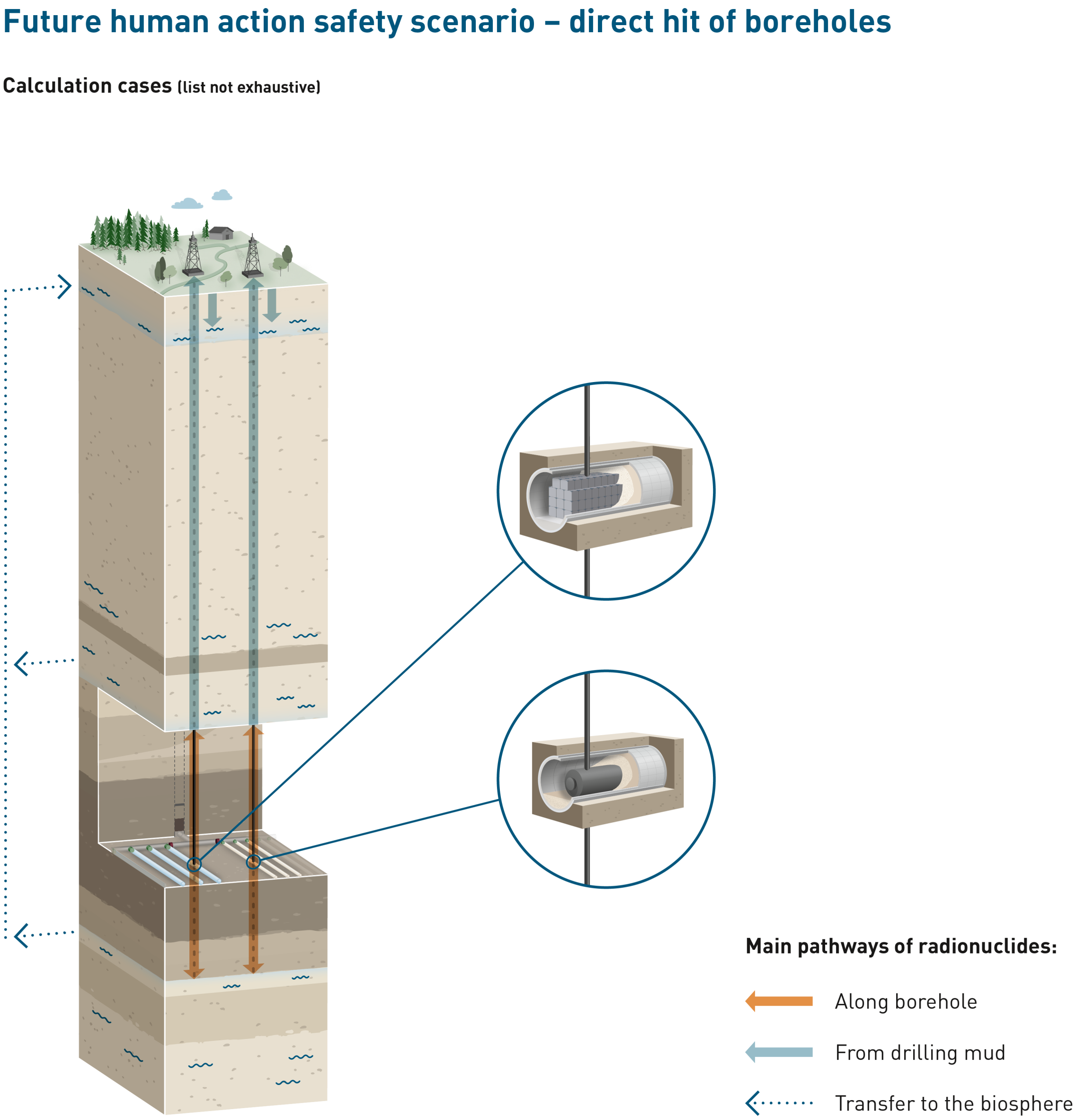

Fig. 9-1: Illustration of FHA safety scenario FHA-1, which considers the drilling of a borehole through the repository that connects an overlying aquifer with a deep aquifer below the CRZ, providing a conduit for groundwater flow and advective radionuclide transport

10 Summary and final discussion

This report has provided a description of the safety scenario development methodology, and applied the methodology in order to define:

- the reference safety scenario,
- a set of alternative safety scenarios,
- a set of hypothetical "what-if?" cases, and
- a set of future human actions (FHA) safety scenarios,

together with scenario variants and their associated calculation cases. These scenarios, variants and cases provide input to both safety analysis in the context of site comparison (reference and alternative safety scenarios only) and to the analysis of radiological consequences in the context of post-closure safety assessment of the repository at the proposed site.

The reference safety scenario is a general description of the initial state of the repository barriers, their expected evolution over time, and the assumptions made regarding the biosphere for the analysis of radiological consequences. The general description of the initial state and evolution of the repository is inferred from the assessment basis and results of the performance assessment.

The results from the performance assessment indicate that the potentially detrimental phenomena addressed by performance assessment modelling do not, in general, affect the broad description of the evolution of the repository system in any substantive way, i.e., performance targets are met even for combinations of unfavourable parameters explored using probabilistic analyses, generally with a large safety margin. This shows that the repository system is highly robust regarding uncertainties related to the repository system performance, and that the repository is expected to evolve according to the reference safety scenario. Some uncertainties nonetheless remain, such that, based on the current geological understanding, the potential for the presence of the following features cannot be completely excluded in any of the siting regions:

- a hydraulically active confining unit within the CRZ above or below the Opalinus Clay host rock, and
- an undetected hydraulically relevant fault in the vicinity of the repository.

These uncertainties give rise to alternative safety scenarios that are propagated to radiological consequence analysis.

Three sets of "what-if?" cases are defined that concern the occurrence of features and processes either with characteristics that lie outside the range of possibilities supported by currently available evidence and knowledge, or whose occurrence during the million-year period for assessment is judged to be exceedingly unlikely, namely:

- the occurrence of an undetected fault with a transmissivity that is hypothetically assumed to be much higher than could realistically be expected (i.e., much higher than in the alternative safety scenario for an undetected fault described in Section 6.2),
- the future creation or re-activation of a fault either by geological processes or by repository-induced effects at a time when the fluid pressure in the repository due to repository-generated gas is above hydrostatic pressure, and
- excavation of the repository, within a million-year time frame, by erosive processes.

These cases are defined and analysed primarily to demonstrate the robustness of the repository system. Further "what-if? cases are also defined, again with the primary aim of demonstrating the robustness of the repository system, by illustrating the effects of a hypothetical degraded performance of each of the system components that are the main contributors to the repository safety functions. These additional "what-if?" cases are not linked to any causal physical phenomena and are thus purely hypothetical.

Finally, two stylised FHA safety scenarios, a deep borehole scenario and a repository abandonment scenario, are defined and propagated to the analysis of radiological consequences.

Discussion on completeness

A key issue in safety scenario development, and in safety assessment in general, is that of completeness. Although it is impossible to prove beyond all possible doubt the completeness of a safety assessment, i.e., "completeness uncertainty" can never be eliminated, measures can be taken to ensure the inclusion of a comprehensive set of potentially relevant phenomena within safety scenarios. Equally importantly, such measures ensure that the safety-relevant phenomena have been represented appropriately in the safety scenarios and analyses carried out within a safety assessment.

This issue of phenomenological "completeness" in safety assessment is discussed in general terms in Section 3.3 of NTB 24-19 (Nagra 2024u). The safety assessment methodology has been developed such that it ensures full consideration of all the phenomena and processes within the extensive assessment basis described in Chapter 4 of NTB 24-19 (Nagra 2024u). Understanding of the initial state and post-closure evolution of the repository, on which safety scenario development and other parts of the safety assessment are all based on, is synthesised in NAB 24-20 (Nagra 2024l), together with the more detailed account of the characteristics and evolution of the site provided by the geosynthesis (Nagra 2024h). The description of the phenomenological evolution of the repository provided in Nagra (2024l) has been developed iteratively over many years, with each version having been peer reviewed, drawing on Nagra's extensive RD&D programme (Nagra 2021a). The comprehensiveness of this description is further assured by effective information exchange between safety assessors and technical experts within Nagra and between these experts and the wider scientific community.

The reference safety scenario is based directly on the expected phenomenological evolution of the repository described in Nagra (2024l). This report also identifies key features of the initial state and key phenomena relevant to repository evolution. The impact of uncertainties in these features and phenomena, e.g., uncertainty in the timing and magnitude of events, the rates of processes and in the occurrence and conceptualisation of geological features, are analysed in the performance assessment, which provides essential information to the process of safety scenario development.

A FEP audit has been carried out to further confirm that all FEPs are either included in the safety scenarios or that their omission is well justified. A catalogue of FEPs relevant to the current safety concept has been developed iteratively over many years (see Section 4.5.3 of NTB 24-19 (Nagra 2024u)), largely independently of the main safety assessment process, with each version having been reviewed by experts internally within Nagra and externally, and comparison made with other relevant national and international FEP databases. The FEP audit then considers whether all the FEPs in the FEP catalogue have been adequately treated in the safety assessment. FEPs may be included in different ways, e.g.,

- in the description of the safety scenarios, and/or
- in the models used in performance assessment and in the analysis of radiological consequences, either explicitly, or implicitly, through the selection of parameter values for those models.

Where FEPs are excluded, it is shown that these are either outside the scope of, or irrelevant to, the safety assessment in support of the general licence application. This then helps to ensure that no relevant FEPs have been overlooked, and that there is a sound justification for the exclusion of any FEPs. The audit is reported in an annex to NAB 24-20 (Nagra 2024k).

Thus, confidence in the comprehensiveness of the safety scenarios presented in the present report rests on:

- The comprehensiveness of the assessment basis and, in particular, the understanding that is available regarding the initial state and post-closure evolution of the repository, which is ensured by its iterative development, peer review and an extensive RD&D programme.
- The comprehensive identification, as part of performance assessment, of uncertainties in key features of the initial state of the repository and in key phenomena affecting its subsequent evolution, and a sound evaluation of their consequences for repository evolution and performance.
- The comprehensiveness of the FEP database, ensured by its iterative development, peer review and comparison with other relevant FEP databases.

A final point on the topic of completeness concerns the "what-if?" cases, in which extreme and hypothetical assumptions are made. As noted above, the aim is primarily to illustrate the robustness of the system, but such analyses may also pre-empt possible criticism that the selected ranges are too narrow or that some detrimental FEPs are either unknown or have been overlooked.

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12 Glossary

Term	Definition
Alternative safety scenarios	Alternative safety scenarios arise from the potential for deviations in the expected evolution and performance of the repository system that have been identified in the performance assessment. They postulate a degraded functionality of one or more of the main components of the repository system compared with that assumed in the reference safety scenario. They include unlikely, or highly unlikely, but scientifically non-excludable evolutions of the repository system and its environment in which the assumptions made in the reference scenario are significantly changed.
Analysis of radiological consequences	The use of quantitative models to analyse radionuclide release, retention and transport to the surface environment which results in an evaluation of radionuclide release rates to the surface environment as a function of time, based on the assumed transport properties of the nearfield and geosphere. The release rates are then converted into annual individual effective doses, annual individual risks and complementary safety indicators. The outcomes are then compared with regulatory protection criteria (and other suitable measures) and the safety margin for each calculation case is evaluated.
Assessment basis	The methodologies, assessment tools, databases and all other evidence and knowledge developed or acquired in support of the safety assessment. Key elements of the assessment basis include the general scientific understanding of the waste inventory and engineered barriers, an integrated understanding of the containment-providing rock zone and its geological setting, and an understanding of the phenomenological evolution of the repository. The assessment basis also includes the assessment methodologies and the models, codes and data used in the analyses.
Calculation cases	Calculation cases define specific calculations that are carried out to analyse the radiological consequences of a particular safety scenario or "what-if?" case, for which a conceptual model is formulated. A calculation case consists of a mathematical model and a set of input parameter values, solved using one or more computer codes or analytical solutions. Each safety scenario or "what-if?" case will typically have one or more calculation cases associated with it.
Combined repository	A repository comprising disposal areas for both HLW and L/ILW in the same siting region.
Compartmentalisation	Partitioning of waste, e.g., in different sections of the repository, through a designated layout of the repository and the installation of seals and backfill.

Term	Definition
Complementary lines of argument	Argumentation that supports the safety assessment, in addition to those arguments developed in performance assessment, safety scenario development and the analysis of radiological consequence. This includes arguments based on natural and archaeological analogues, performance and safety indicators complementary to dose and risk, and conservatism in the calculations of radiological consequence analysis, including the existence of reserve FEPs.
Conservative / conservatism	Simplifications, assumptions, parameter values, etc., that are confidently expected to lead to consequences that are less favourable than those anticipated under real conditions, taking uncertainty into account. Conservative choices can lie outside the range of what is physically possible (e.g., hypothetical assumptions). Conservatisms include the deliberate omission from quantitative analysis of some phenomena that are considered likely and beneficial to safety because suitable models, codes or databases are unavailable.
Containment-providing rock zone (CRZ)	The volume of rock that, together with the engineered barriers, ensures the containment and retention of radioactive substances contained in the waste during the assessment period considering the expected evolution of the deep geological repository. It comprises the host rock as well as the upper and lower barrier-effective confining geological units.
Demonstration of post-closure safety	The demonstration of safety brings together the evidence, arguments and analyses of the three main processes of safety assessment (performance assessment, safety scenario development, and analysis of radiological consequences), together with *complementary lines of argument*, to form the overall post-closure safety case. The demonstration comprises: • the safety-driven repository siting, design and implementation process, • the favourable qualities of the siting region, the containment-providing rock zone and the engineered barrier system, • the quality and comprehensiveness of the safety assessment, • the favourable results of the safety assessment, • *complementary lines of arguments*.
Design requirements	Requirements placed on the design of system components such that they are expected to fulfil their respective performance objectives and component-specific functions. These design requirements are developed in association with the repository design and system analysis as part of an iterative design development process. For the safety assessment in support of the general licence application milestone, this process leads to the provisional design and implementation plan, for which safety is assessed.
Design specifications	Solutions to the design requirements, concerning technical, quality and organisational aspects of individual components or the whole repository system.

Term	Definition
Deviation from expected performance	Occurs when an individual barrier component, or the repository as a whole, does not provide its intended safety functions or component-specific function. This may be quantitatively assessed using performance indicators evaluated against performance targets. The importance of such a deviation may depend on its relevance to safety and on the likelihood of occurrence.
Disposal area	Underground body of rock that encloses a group of adjacent emplacement rooms, including a minimum distance around these emplacement rooms. In addition to the emplacement rooms, a disposal area also has branch tunnels, unloading areas and sealing structures.
Disposal packages	Generic term for SF/RP-HLW disposal canisters and L/ILW disposal containers.
Emplacement rooms	Generic term for HLW emplacement drifts (HLW repository or combined repository section) and L/ILW emplacement caverns (L/ILW repository or combined repository section) for the long-term emplacement of radioactive waste.
Envelope scenarios	Scenarios that cover possible lines of evolution.
Expected performance (of the multi-barrier system)	The situation when the multi-barrier system of the repository provides its intended safety functions and component-specific functions, both at the component level and at the total system level, and for which all performance assessment claims are expected to be met. The repository is designed such that, for the expected evolution (see *reference safety scenario*), it performs as required.
FEPs	*Features, events and processes.* Internal or external phenomena (or factors) that can either define the repository system or might influence its evolution or radiological consequences.
Component-specific functions	A specific set of properties of, or actions to be performed by, one or more system features that contribute directly (or indirectly) to the *safety functions*.
Future human actions (FHA)	Potential actions, activities, behaviours and lifestyles undertaken by human society in the long term which may impact repository safety, particularly regarding human intrusion into the repository (e.g., by deep borehole drilling). Future human actions safety scenarios consider actions which appear credible from the viewpoint of today's society, i.e., considering current human activities in the regional vicinity of the site combined with state-of-the-art technology (e.g., drilling equipment and techniques, etc.).
Matrix (waste)	In the case of L/ILW and RP-HLW, this comprises the solidified waste and the material in which it is embedded. In the case of spent fuel, this comprises the crystalline phases which make up the UO_2 or mixed oxide fuel pellets.

Term	Definition
Multi-barrier system	A system of staged, passive engineered and geological barriers that fulfil the overarching safety functions. In the context of the present safety case, the multi-barrier system includes engineered barriers consisting of the waste matrix, disposal canisters, backfill, and seals, as well as the containment-providing rock zone as a geological barrier.
Performance assessment	An analysis of the thermal, hydraulic, mechanical, and chemical evolution of the repository system. Performance assessment verifies whether the expected evolution of the repository system, as provided by the assessment basis, is indeed the expected evolution based on the arguments and evidence available. Performance assessment also identifies deviations in performance that could degrade the functionality of the components of the repository system or of the repository system as a whole, as inputs to safety scenario development.
Performance assessment scenarios	Performance assessment scenarios address features, events and processes that could potentially degrade the repository barriers and their safety functions. They permit a quantitative assessment of the impact of deviations in performance on the performance of the repository system as a whole and enable the consideration of uncertainties related to the evolutionary path. This provides information on their relevance to safety, which facilitates the identification of those deviations that require an in-depth analysis of the radiological consequences.
Performance indicators	Quantitative metrics of the performance of individual or multiple system components that permit evaluation against a given performance target.
Performance objectives	Performance objectives describe how the system components, including both engineered and geological barriers, perform their individual, component-specific functions and thus, collectively, the safety functions. They are a part of the safety and repository concepts relating to the pillars of safety, safety functions and component specific functions, that guide the design development process to achieve the provisional design and implementation plan.
Performance targets	Specified requirements for the performance of individual or multiple system components, or of the total system. A target value is set for a relevant performance indicator to allow quantitative evaluation of whether expected performance is met, including the assessment of uncertainties.
Pessimism / pessimistic	The use of an assumption or parameter value that is possible but leads to consequences that are less favourable than the most likely consequences. The use of such a value means that not every single parameter variation needs to be carried forward into a calculation case to demonstrate safety. Whilst both pessimism and conservatism lead to calculated consequences less favourable than the most likely, conservatism includes the use of hypothetical assumptions or parameter values and results in consequences that are less favourable than the most likely, including the uncertainty.

Term	Definition
Pillars of safety	The main features or characteristics of the repository concept that contribute to the *safety functions* of the multi-barrier system which, together, ensure long-term safety. These are: • deep underground location of the waste emplacement rooms in a stable geological environment, • containment-providing rock zone, • closure system (backfill and seals), • SF and RP-HLW matrix, • SF and RP-HLW canisters, • buffer of the HLW emplacement drifts, • cementitious L/ILW near field. Each of the pillars of safety makes a direct and significant contribution to at least one of the *safety functions*, but may also make indirect or more minor contributions to other *safety functions*.
Provisional design and implementation plan	The provisional layout, material choices and dimensions of all components of the repository, and the sequence of operations for repository construction, operation and closure. It results from the iterative design development process that is informed by the safety and repository concepts, system analyses and other design considerations, such as engineering practicality and operational safety.
Reference safety scenario	A general description of the initial state of the repository barriers, their expected evolution over time (including the release, retention and transport of radionuclides within the repository system), and the assumptions made regarding the biosphere for the analysis of radiological consequences. Essentially, in the reference safety scenario, the repository system will perform as expected and the pillars of safety are assumed to provide their assigned functions, in accordance with the safety and repository concept.
Repository section	In the combined repository, in addition to the main HLW and L/ILW disposal areas, the HLW and L/ILW repository sections each include a pilot facility, in which the behaviour of the wastes, the backfill, the seals and the host rock is monitored until the end of a monitoring period.
Repository system	The repository system comprises the underground structures, the emplaced waste, the installed engineered barriers, and the containment-providing rock zone.
Requirements	Conditions that must be fulfilled or attributes that must be possessed by the repository system or its components to achieve certain objectives. Requirements are organised hierarchically. At the highest level, these are overarching objectives and principles, including those specified in Swiss legislation and regulations. Low-level requirements are more detailed and specific and support the fulfilment of the overarching requirements.

Term	Definition
Reserve FEPs	*Features, events and processes* considered likely to occur and beneficial to safety that are deliberately excluded from quantitative analysis because the level of scientific understanding is insufficient to support quantitative modelling, or because suitable models, codes or databases are unavailable. Reserve FEPs may be mobilised at a later stage of repository planning if the level of scientific understanding is sufficiently enhanced, and the necessary models, codes and databases are developed. The existence of reserve FEPs constitutes an additional, qualitative argument for reserves of safety beyond those indicated by the quantitative analysis.
Robustness principle	The principle of siting and designing the repository system such that it is insensitive to detrimental processes and events and so that post-closure safety can be demonstrated irrespective of the remaining uncertainty.
Safety analysis (site-specific)	A synonym for *analysis of radiological consequences* in the context of site-specific analyses performed within the framework of site comparison. As for the more detailed safety assessment in support of the general licence application, this analysis also comprises a systematic and quantitative analysis approach, including a reference and alternative safety scenarios, but does not include future human action safety scenarios or "what-if?" cases.
Safety assessment	The process of gathering the claims, arguments, evidence, and performing associated analyses, regarding the safety of the repository system and its environment during the post-closure phase. It is the means by which the safety case is developed. Safety assessment includes performance assessment, safety scenario development, analysis of radiological consequences and the demonstration of post-closure safety.
Safety assessment methodology	A description of how the four processes of safety assessment (performance assessment, safety scenario development, analysis of radiological consequences and demonstration of post-closure safety) are implemented to provide the safety case. Thus, it explains how the four processes of safety assessment are related to each other and how information flows between them. The safety assessment methodology is considered part of the assessment basis.
Safety case (post-closure)	The synthesis of claims, arguments and supporting evidence gathered, and analyses carried out, in the course of the safety assessment to make the case for the post-closure safety of a repository system.

Term	Definition
Safety and repository concept	The safety and repository concept explains how, through the safety barriers and the safety functions they perform, the deep geological repository ensures the protection of humans and the environment. It provides information about the basic principles of how the deep geological repository is designed. This includes, for example, the concept of the multi-barrier system or the concept of storing final storage containers in long, layer-parallel storage chambers in a suitable host rock. Additionally, it includes the performance objectives, which describe how the system components, including both engineered and geological barriers, are envisioned to perform their individual, component-specific functions and thus, collectively, the *safety functions*.
Safety functions	Safety functions are the roles of the multi-barrier system that together ensure long-term safety. Engineered and natural barriers and other system components contribute to one or more of these functions. They consist of: S1: Isolation of radioactive waste from the surface environment S2: Complete containment of radionuclides for a period of time S3: Immobilisation, retention, and slow release of radionuclides S4: Compatibility of the multi-barrier system elements and the radioactive waste types among each other and with other materials. S5: Long-term stability of the multi-barrier system with respect to long-term geological and climatic processes
Safety indicators	Quantitative metrics of post-closure safety used for the analysis of radiological consequences. These include the annual individual effective dose and annual individual risk as the primary safety indicators, and radioactivity fluxes and radiotoxicity as complementary safety indicators.
Safety scenarios	The different possibilities for the initial state of key features, conditions and processes of the repository system and the ways in which they may evolve and perform their safety functions over time. They capture uncertainty in the broad ways the system may evolve, considering all relevant sources of uncertainty, and include: 1. a reference safety scenario, corresponding broadly to the expected evolution, 2. a set of alternative safety scenarios, arising from conceivable deviations in expected performance/evolution, 3. a set of future human actions safety scenarios. Note that "what-if?" cases are not defined as safety scenarios, although they are an output of safety scenario development.

Term	Definition
Safety scenario development	The identification and description of a set of safety scenarios that capture uncertainty in the initial state of the repository system and the different ways in which it may evolve over time. Based on the knowledge provided by the assessment basis and the findings of the performance assessment, safety scenario development enables a systematic assessment of how key features, events and processes may impact post-closure safety. Safety scenario development also leads to a set of additional "what-if?" cases that are used to demonstrate robustness of the repository system.
Safety scenario variants	Variants of a given safety scenario (reference, alternative or future human action) that share largely the same general description of features, events and processes occurring over time, but may differ, for example, in the extent or timing of key phenomena associated with that safety scenario as well as positioning or properties of a feature. Contrast with *alternative safety scenario*.
Scenario analysis	With respect to the regulatory guidance, this refers to a combination of (in Nagra's terminology) *safety scenario development* and *radiological consequence analysis* for the defined *calculation cases.*
Sensitivity analysis	Technique to investigate the how the variance in modelling results is impacted by the variance in input parameters. Thus, it identifies the parameters to which the computational model outcomes are most sensitive.
Stylised approach	An approach that involves imposed, rather than scientifically derived, assumptions for handling poorly quantifiable or unquantifiable uncertainties in scenario development. This approach aims to limit arbitrary speculation on matters that are inherently unpredictable. Thus, no attempt is made to cover the full range of possible scenarios or to assign probabilities to them, rather, a limited set of illustrative cases are analysed. In agreement with the regulations and international standards (e.g., SSG-23 (IAEA 2012), see also ENSI-G03 (ENSI 2020a)), stylisation is used by Nagra for aspects of biosphere evolution, future human actions and lifestyles and for developing human intrusion scenarios.
Time period for assessment	The timeframe over which assessment of post-closure safety is performed. For site comparison in SGT Stage 3, this is defined as extending up to 10^5 years for an L/ILW repository and up to 10^6 years for a HLW repository. For a combined HLW and L/ILW repository in the NL siting region, a 10^6-year assessment period is considered. Consistent with the regulatory requirement that dose and risk calculations up to the time of maximum radiological impact of the repository have to be carried out as part of the safety assessment, dose calculations are generally performed through to 10^7 years for HLW and 10^6 years for L/ILW. Analyses for volatile radionuclides that focus on C-14, with a 5,730-year half-life, are carried out for a 10^5-year period.
Uncertainty analysis	Quantification of the influence of uncertainties in data, processes and model assumptions on calculation results.

Term	Definition
"What-if?" cases	"What-if?" cases are calculations of hypothetical cases that use a particular set of assumptions and/or parameter values that lie outside the range of possibilities supported by currently available evidence and knowledge. Such cases are primarily aimed at demonstrating the robustness of the repository system or to improve understanding of the system performance (e.g., by hypothetically removing a barrier or favourable process). Additionally, phenomena that could realistically occur, but whose occurrence is implausible during the million-year *time period for assessment,* may also be considered as a "what-if?" case.

App. A Compiled safety scenarios, variants and calculation cases

Tab. A-1: Variants and calculation cases for the reference safety scenario

These calculation cases are propagated to the analysis of radiological consequences for separate HLW and L/ILW repositories in all three siting regions in the framework of safety analysis, and, for a combined repository in the NL siting region, in the framework of post-closure safety assessment.

Safety scenario	Variant	Calculation case	Description
Reference safety scenario	Reference conceptualisation of CRZ; hydraulically active Keuper aquifer	RS-RC	Reference case (reference biosphere)
		RS-BIOS/WARM_DRY	Warmer and drier biosphere
		RS-BIOS/COLD	Colder biosphere
		RS-BIOS/DRAINED_FARMLAND	Biosphere with drained farmland
		RS-PROB	Probabilistic simulation by considering the parameter uncertainty
		RS-PROB-*param*	Multiple cases in each of which a single sensitive parameter (*param*) is set to its conservative, bounding value
		RS-CMB	All sensitive parameters are set to their conservative, bounding values
	Specific to the proposed siting region: hydraulically inactive Keuper aquifer	RS-KEUPER_INACTIVE	Hydraulically inactive Keuper aquifer below HLW repository in NL siting region, or below HLW disposal section of a combined repository in NL

Tab. A-2: Variants and calculation cases for the alternative safety scenarios

These calculation cases are each propagated to the analysis of radiological consequences for separate HLW and L/ILW repositories in all three siting regions in the framework of safety analysis, and for a combined repository in the NL siting region in the framework of post-closure safety assessment.

Safety scenario	**Variant**	**Calculation case**	**Description**
Alternative safety scenario: Hydraulically active confining unit	Additional hydraulically active unit within the CRZ above the Opalinus Clay	AS-HA/SCD	Hydraulically active SCD unit
		AS-HA/CD	Hydraulically active CD unit (NL only)
		AS-HA/CM	Hydraulically active CM unit (NL only)
	Additional hydraulically active unit within the CRZ below the Opalinus Clay	AS-HA/KEU	Hydraulically active KEU unit
		AS-HA/KAU	Hydraulically active KAU unit (NL only)
Alternative safety scenario: Undetected fault	Fault intersects the HLW emplacement drifts	AS-FLT-HLW-Along	Fault, with a transmissivity of 10^{-10} m^2/s, with strike running along the axis of a single emplacement drift
		AS-FLT-HLW-Across	Fault, with a transmissivity of 10^{-10} m^2/s, with strike running perpendicular to drifts, cutting each drift at its centre
	Fault intersects L/ILW emplacement caverns	AS-FLT-L/ILW-Along	Fault, with a transmissivity of 10^{-10} m^2/s, with strike running along the axis of a single emplacement cavern
		AS-FLT-L/ILW-Across	Fault, with a transmissivity of 10^{-10} m^2/s, with strike running perpendicular to caverns, cutting each cavern at its centre

Tab. A-3: "What-if?" cases related to physical phenomena

"What-if?" case	Variant	Calculation case	Description
"What-if?" cases related to physical phenomena: Undetected fault with elevated transmissivity	Fault with elevated transmissivity intersects the HLW emplacement drifts	WI-FLT-HLW-Along	Fault, with a transmissivity of 10^{-7} m^2/s, with strike running along the axis of a single emplacement drift
		WI-FLT-HLW-Across	Fault, with a transmissivity of 10^{-7} m^2/s, with strike running perpendicular to drifts, cutting each drift at its centre
	Fault with elevated transmissivity intersects L/ILW emplacement caverns	WI-FLT-L/ILW-Along	Fault, with a transmissivity of 10^{-7} m^2/s, with strike running along the axis of a single emplacement cavern
		WI-FLT-L/ILW-Across	Fault, with a transmissivity of 10^{-7} m^2/s, with strike running perpendicular to caverns, cutting each cavern at its centre
"What-if?" cases related to physical phenomena: Fault generation or re-activation by geo-logical processes or repository-induced effects	Newly created or re-activated fault intersects the HLW emplacement drifts	WI-FLT/RA-HLW-Along	Fault, with a transmissivity of 10^{-7} m^2/s created at 10,000 years, with strike running along the axis of a single emplacement drift
		WI-FLT/RA-HLW-Across	Fault, with a transmissivity of 10^{-7} m^2/s created at 10,000 years, with strike running perpendicular to drifts, cutting each drift at its centre
	Newly created or re-activated fault intersects L/ILW emplacement caverns	WI-FLT/RA-L/ILW-Along	Fault, with a transmissivity of 10^{-7} m^2/s created at 20,000 years, with strike running along the axis of a single emplacement cavern
		WI-FLT/RA-L/ILW-Across	Fault, with a transmissivity of 10^{-7} m^2/s created at 20,000 years, with strike running perpendicular to caverns, cutting each cavern at its centre

Tab. A-4: "What-if?" cases considering repository excavation by erosive process

Compiled from NAB 24-08 (Nagra 2024r). All calculation cases are performed for excavation times of 700 ka, 1 Ma, 2 Ma and 4 Ma after repository closure.

"What-if?" case	**Variant**	**Calculation case**	**Description**
"What-if?" cases related to physical phenomena: Repository excavation by deep glacial erosion	River	River base case	• River variant with excavated material initially deposited in the shallow permeable sediments; groundwater connected to the river • Water for drinking, animals and irrigation drawn from the shallow aquifer
		Alternative river case	• River variant with excavated material initially deposited in the impermeable layer below the shallow permeable sediments; groundwater connected to the river • Water for drinking, animals and irrigation drawn from the shallow aquifer
	Lake	Lake case	• Lake variant with excavated material initially deposited in the impermeable sediments below the lake • Water for drinking, animals and irrigation drawn from the lake
	Spring	Spring case	• Spring variant with excavated material initially deposited in the permeable sediments on the hillside • Water for drinking, animals and irrigation drawn from the spring
"What-if?" cases related to physical phenomena: Repository excavation by non-glacial erosion	Hillside	Case A	• Shallow valley with 50 m high hillslope • Low erosion rate: 0.08 mm a^{-1} • Considering long-term exposures and discrete landslide events.
		Case B	• Average valley with 250 m high hillslope • Average erosion rate: 0.2 mm a^{-1} • Considering long-term exposures and discrete landslide events
		Case C	• Steep valley with 500 m high hillslope • High erosion rate: 25 mm a^{-1} • Considering long-term exposures and discrete landslide events
		Case D	Average valley with high permeability limestone layer creating springs on the hillside below the repository
	Valley floor		Release from weathered repository below the local aquifer in a valley floor setting

Tab. A-5: "What-if?" cases postulating a hypothetically degraded performance of pillars of safety

"What-if?" case	**Variant (pillar of safety)**	**Calculation case**	**Description**
"What-if?" cases postulating a hypothetically degraded performance of pillars of safety	CRZ	WI-CRZ-NOSORB	No geosphere sorption
		WI-CRZ-EDZ	Hypothetically enlarged radius of the EDZ surrounding emplacement rooms (increased by a factor of two)
		WI-CRZ-DIFF	Hypothetically high diffusion coefficients in the geosphere (an order of magnitude higher than the upper bound values)
		WI-CRZ-GRADdown	Hypothetically high downwardly-directed hydraulic gradient (1 m/m, versus zero in RS-RC)
		WI-CRZ-GRADup	Hypothetically high upwardly-directed hydraulic gradient (1 m/m, versus zero in RS-RC)
		WI-CRZ-NOCONFINING	Upper and lower confining units disregarded
	HLW matrices	WI-SF-IRF	Hypothetically high instant release fractions (IRFs) for radio-nuclides in SF (all radionuclides in SF are released in IRF)
		WI-HLW-DISS	Hypothetically high matrix dissolution rates for SF and RP-HLW (an order of magnitude higher than the upper bound values)
		WI-SF-CORR	Hypothetically high corrosion rates of SF cladding and other structural parts (an order of magnitude higher than the upper bound values)
	HLW disposal canister	WI-HLW-CAN	Hypothetical early failure of all HLW canisters at 1,000 years

Tab. A-5: cont.

"What-if?" case	**Variant (pillar of safety)**	**Calculation case**	**Description**
"What-if?" cases postulating a hypothetically degraded performance of pillars of safety	Bentonite buffer (HLW)	WI-HLW-NOSOL	No near-field solubility limits in HLW disposal section
		WI-HLW-NOSORB	No near-field sorption in HLW disposal section
		WI-HLW-DIFF	Hypothetically high diffusion coefficients in bentonite buffer (an order of magnitude higher than the upper bound values)
		WI-HLW-BUF	Hypothetically high permeability of bentonite buffer in HLW drifts (set to the same value as the VF2 backfill material, more than five orders of magnitude higher)
	L/ILW cementitious near field	WI-L/ILW-C14	All volatile radionuclides present in L/ILW released instanta-neously
		WI-L/ILW-NOSORB	No near-field sorption in L/ILW disposal section
	Closure system	WI-V1-HLW	Hypothetically high permeability of V1-HLW seals (the same as the VF2 backfill material)
		WI-V1-L/ILW	Hypothetically high permeability of V1-L/ILW seals (the same as the VF2 backfill material)
		WI-V2-HLW	Hypothetically high permeability of V2-HLW seals (the same as the VF2 backfill material)
		WI-V2-L/ILW	Hypothetically high permeability of V2-L/ILW seals (the same as the VF2 backfill material)
		WI-V3	Hypothetically high permeability of V3 seals (the same as the VF2 backfill material)

Tab. A-6: Future human action safety scenarios

Compiled from Nagra (2024s)

<table>
<tr><th>Safety scenario</th><th>Variant</th><th>Calculation case</th><th>Description</th></tr>
<tr><td rowspan="5">Future human action:

Deep borehole
(FHA-1)</td><td rowspan="2">FHA-1a: borehole penetration of an HLW emplacement drift</td><td>FHA-1a-DH-Diss</td><td>• Direct hit: the borehole penetrates a SF canister
• IRF and 20% of the canister's SF is transported to the surface and the borehole provides a long-term preferential transport pathway to the biosphere aquifer</td></tr>
<tr><td>FHA-1a-DH-Vol</td><td>The borehole provides a preferential transport pathway to the biosphere aquifer for (volatile) C-14 methane</td></tr>
<tr><td rowspan="3">FHA-1b: borehole penetration of an L/ILW cavern</td><td>FHA-1b-WP-Diss</td><td>Borehole through a single L/ILW waste package with the highest available activity</td></tr>
<tr><td>FHA-1b-PFP-Diss</td><td>Borehole through an L/ILW cavern and considering the whole radionuclide inventory of the cavern</td></tr>
<tr><td>FHA-1b-PFP-Vol</td><td>Borehole through an L/ILW cavern and considering the C-14 methane inventory of the whole cavern</td></tr>
<tr><td colspan="2" rowspan="2">Future human action
Repository abandonment (FHA-2)</td><td>FHA-2-Diss</td><td>Abandonment of combined repository after backfilling of emplacement drifts and caverns, but before sealing and backfilling of remaining access ways and shafts
The radiological consequences of soluble radionuclides are considered</td></tr>
<tr><td>FHA-2-Vol</td><td>As for FHA-2-Diss, but considering volatile C-14 methane.</td></tr>
</table>