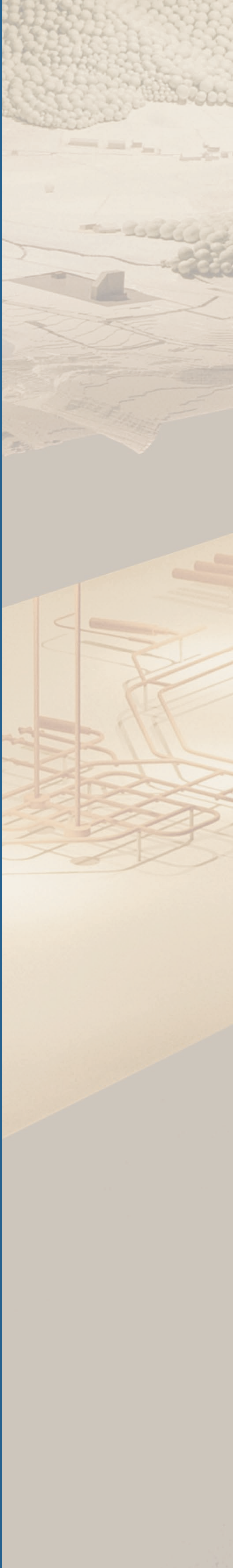

nagra

TECHNICAL REPORT 24-19

Safety Assessment Methodology

August 2024

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Abstract

This report presents a high-level description of the methodology used in the post-closure safety assessment, hereafter referred to as safety assessment, that supports the general licence application for a combined deep geological repository for low- and intermediate-level waste and high-level waste at the Haberstal site. Safety assessment is defined by Nagra as the process of gathering the evidence and arguments regarding the safety of the repository system during the post-closure phase.

The report first presents a broad perspective of the context in which the current safety assessment methodology was developed, including legal and regulatory requirements with respect to post-closure safety, as well as international developments and guidance on safety assessment and the safety case. The development of the safety and repository concept and a provisional repository design, needed to make the safety case for the general licence application, are also outlined. The key principles and features of safety assessment, including the management of uncertainties, are also presented.

Along with the post-closure safety case, the general licence application will include a justification for the siting proposal, based on a site comparison. This report provides a general overview of the "assessment basis" underlying both the safety case and the safety-related aspects of site comparison. The assessment basis, which this report is part of, includes the evidence, knowledge, assessment tools and methodologies developed or acquired in support of site selection and the safety case.

The report then describes the four main processes carried out in safety assessment, namely:

- **performance assessment,** in which the thermal, hydraulic, mechanical, and chemical 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 the initial state of the repository system and different ways in which it could evolve 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 processes are brought together in the post-closure safety report.

The focus of this report is especially on explaining how these processes are related to each other and how information flows between them.

Finally, the report highlights the similarities, parallels and general consistency between the safety assessment methodology and the methodology adopted in site comparison, including the relationship between:

- performance assessment for the post-closure safety case and the qualitative evaluation of the containment-providing rock zone carried out for each siting region in support of the site comparison, and
- the analysis of radiological consequences for the safety case and the site-specific safety analyses carried out for the different siting regions.

The present report, which is part of the assessment basis, is complemented by more detailed dedicated reports on each of the main processes of safety assessment. These describe the outcomes of the safety assessment processes, as well as methodological details not covered here.

Zusammenfassung

Der vorliegende Bericht umfasst eine übergeordnete Beschreibung der Methodik zur Beurteilung der Langzeitsicherheit. Diese Beurteilung ist integraler Bestandteil des Sicherheitsnachweises für die Nachverschlussphase (Langzeitsicherheitsnachweis) und ist Teil des Rahmenbewilligungsgesuchs für ein Kombilager für schwach- und mittelaktive Abfälle und hochaktive Abfälle für den Standort Haberstal. Die Nagra definiert die Beurteilung der Langzeitsicherheit als Prozess, worin die sicherheitsrelevanten Nachweise und Argumente für die Nachverschlussphase des Tiefenlagersystems hergeleitet und erfasst werden.

Der Bericht vermittelt zunächst einen umfassenden Überblick über den Kontext, in dem die aktuelle Methodik zur Beurteilung der Langzeitsicherheit entwickelt wurde. Dies umfasst rechtliche und behördliche Anforderungen hinsichtlich der Langzeitsicherheit sowie internationale Entwicklungen und Leitlinien bezüglich der Beurteilung der Langzeitsicherheit und des Langzeitsicherheitsnachweises. Ebenfalls dargelegt werden die Festlegungen des Sicherheits- und Lagerkonzeptes sowie einer vorläufigen Lagerauslegung, die für den Langzeitsicherheitsnachweis benötigt werden. Die wichtigsten Grundsätze und Merkmale zur Beurteilung der Langzeitsicherheit, einschliesslich des Umgangs mit Unsicherheiten, werden ebenfalls dargelegt.

Zusammen mit dem Langzeitsicherheitsnachweis enthält das Rahmenbewilligungsgesuch die Begründung der Standwortwahl. Der vorliegende Bericht liefert eine Gesamtübersicht der Grundlagen, auf welcher sowohl der Langzeitsicherheitsnachweis als auch die sicherheitsrelevanten Aspekte des Standortvergleichs beruhen. Grundlagendokumente, zu denen auch dieser Bericht gehört, enthalten zudem weitere Nachweise, Erkenntnisse, Modellierungswerkzeuge und Methoden, die zur Unterstützung der Standortwahl und des Langzeitsicherheitsnachweises entwickelt oder bereitgestellt wurden.

Der Bericht erläutert anschliessend die Prozesse, auf die sich die Beurteilung der Langzeitsicherheit stützt:

- **Prüfung der Barrierenwirksamkeit**: eine Analyse der thermischen, hydraulischen, mechanischen und chemischen Entwicklung des Tiefenlagersystems,
- **Entwicklung von Sicherheitsszenarien**: Identifizierung und Beschreibung einer Reihe von Sicherheitsszenarien, die die Unsicherheiten bezüglich des Anfangszustands des Tiefenlagersystems sowie die ganze Bandbreite dessen möglicher Entwicklung im Laufe der Zeit erfassen,
- **Analyse der radiologischen Konsequenzen**: Beurteilung der zeitabhängigen Freisetzung von Radionukliden in die Biosphäre,
- **Nachweis der Langzeitsicherheit**: Der Bericht zum Sicherheitsnachweis für die Nachverschlussphase bildet die Synthese der aus den drei vorangegangenen Prozessen erworbenen Evidenzen, Argumente und Erkenntnisse.

Der Schwerpunkt dieses Berichtes liegt insbesondere auf der Erläuterung, wie diese Prozesse zusammenhängen und wie der Informationsaustausch zwischen ihnen erfolgt.

Schliesslich werden in diesem Bericht die Ähnlichkeiten, Parallelen und die generelle Konsistenz zwischen der für die Beurteilung der Langzeitsicherheit verwendeten Methodik und der Methodik für den Standortvergleich hervorgehoben. Dies umfasst auch:

- Die Beziehung zwischen der Prüfung der Barrierenwirksamkeit und der qualitativen Beurteilung des einschlusswirksamen Gebirgsbereichs. Erstere wurde für den Langzeitsicherheitsnachweis erstellt, letztere wurde zwecks Standortvergleich für jede Standortregion durchgeführt.
- Die Beziehung zwischen den Analysen der radiologischen Konsequenzen und die standortspezifischen Sicherheitsanalysen. Erstere wurde für den Langzeitsicherheitsnachweis erstellt, letztere wurde für die verschiedenen Standortregionen durchgeführt.

Der vorliegende Bericht wird durch weitere spezifische Berichte zu den jeweiligen Prozessen zur Beurteilung der Langzeitsicherheit ergänzt. Darin werden die Ergebnisse sowie ergänzende methodische Details beschrieben, welche in diesem Bericht nicht behandelt werden.

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List of Acronyms

ATW	Alpha-toxic waste
BDCF	Biosphere dose conversion factor
CRZ	Containment-providing rock zone
ENSI	Swiss Federal Nuclear Safety Inspectorate (*Eidgenössisches Nuklearsicherheitsinspektorat*)
FEP	Features, events and processes
FHA	Future human actions
GDMS	General Data Management System
HLW	High-level waste (spent fuel assemblies and high-level waste from reprocessing)
IGSC	Integration Group for the Safety Case (main technical advisory body to the Radioactive Waste Management Committee (RWMC) of the NEA)
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 Organisation for Economic Co-operation and Development (OECD)
NL	Nördlich Lägern (siting region)
NTB	Nagra technical report
PDF	Probability density function
QA	Quality assurance
QC	Quality control
RBG	General licence application (*Rahmenbewilligungsgesuch*)
RD&D	Research, development & demonstration
RP-HLW	Vitrified HLW from reprocessing
SF	Spent fuel
SGT	Sectoral Plan for Deep Geological Repositories (*Sachplan Geologische Tiefenlager*)
THM-C	Thermo-hydro-mechanical and chemical (evolution)
ZNO	Zürich Nordost (siting region)

1 Introduction

1.1 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 2018b), while ENSI Guideline G03 and the corresponding explanatory report (ENSI 2023a, 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 and is therefore applying for a general licence for a combined repository for both HLW and L/ILW at the Haberstal site.

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 2024l).
- 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.

[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.*

The present report (bordered in red in Fig. 1-1) describes the methodology for the post-closure safety assessment for the combined repository at the Haberstal site. It is considered to be part of the assessment basis, which refers to the evidence, knowledge, assessment tools, and methodologies developed or acquired by Nagra in support of site comparison and safety assessment (Fig. 1-1).

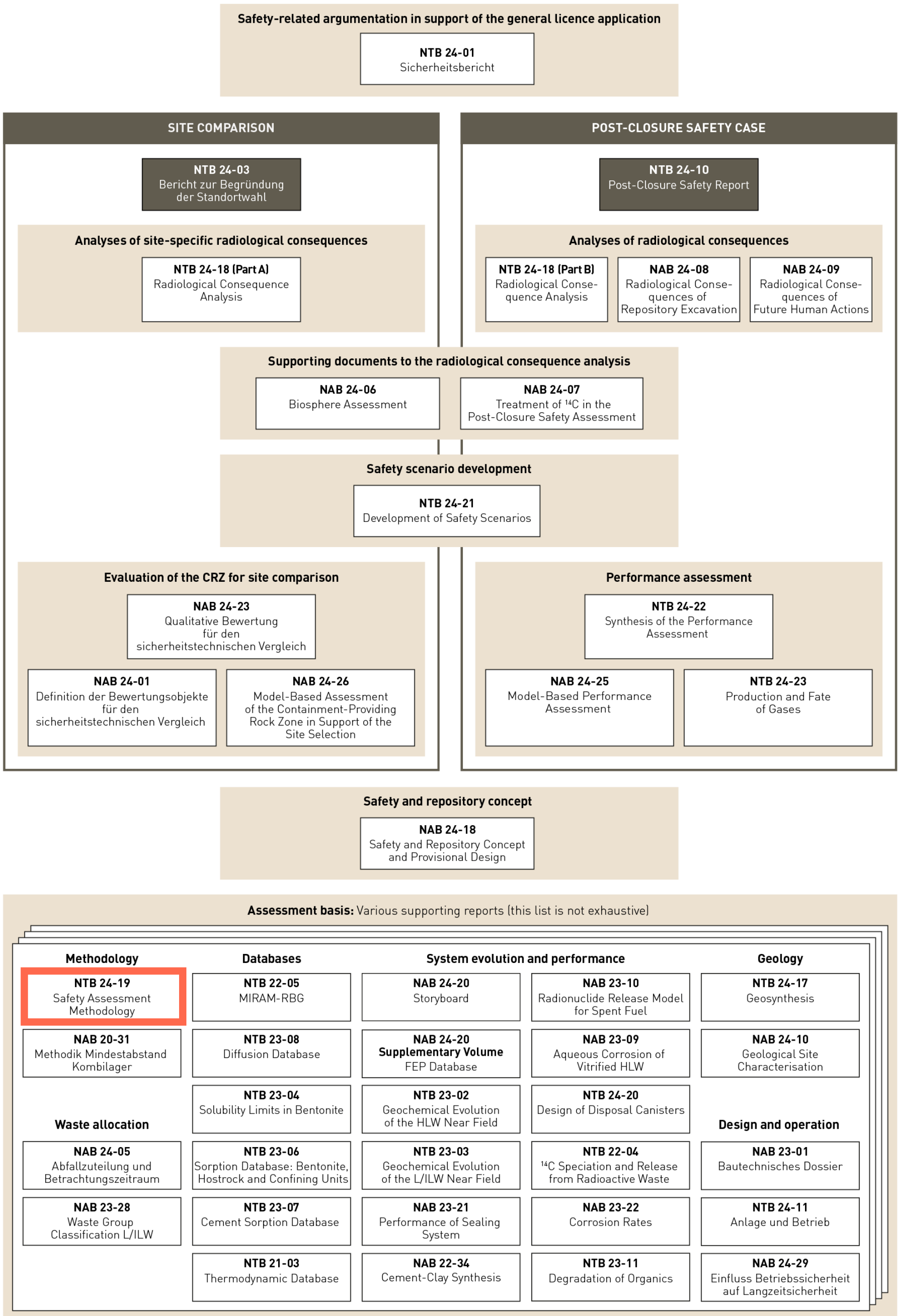

Fig. 1-1: Structure of reports covering post-closure safety aspects of the site comparison and the post-closure safety case

1.2 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 2023a). 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 (cf. Fig. 1-1).

This workflow is illustrated in Fig. 1-2, 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.

1.3 Scope of the present report

The present report describes the processes listed above and explains how they will be implemented to provide the safety case for a combined repository at the Haberstal site as part of the general licence application. The report focuses especially on explaining how the elements are related to each other and how information flows between them.

To achieve this aim, the following additional objectives are addressed:

1. To present a broad perspective of the context in which the current safety assessment methodology was developed.
2. To provide a general overview of the common assessment basis underlying both the safety assessment and the safety-related aspects of the site comparison.
3. To highlight the similarities, parallels and general consistency between the safety assessment methodology and the methodology adopted for the selection of NL as the proposed siting region. This is also to be documented as part of the general licence application (Fig. 1-1).

This report provides only a high-level description of the safety assessment processes. Further details of these processes and their outcomes are provided in numerous other reports and are referenced in the following chapters.

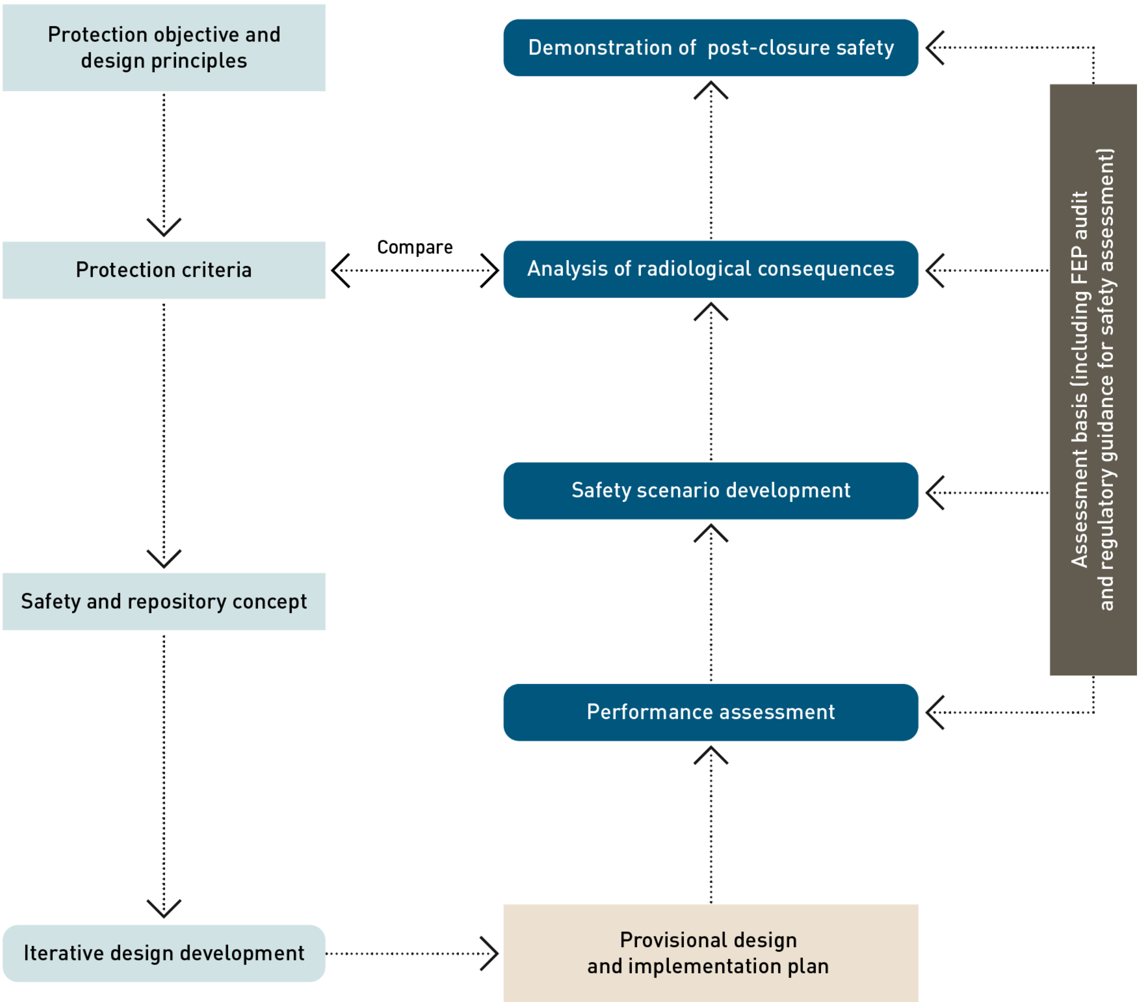

Fig. 1-2: Workflow for the post-closure safety case

Overview of the top-down procedure (left) for the development of a design and implementation plan for the current project milestone (bottom right) and the safety assessment of the repository system to demonstrate safety (right). Processes are illustrated with boxes with rounded corners and products / knowledge with boxes with square corners.

As part of the documentation of the assessment basis, the present report directly underpins reports on the main processes of safety assessment, i.e., performance assessment (Nagra 2024s), safety scenario development (Nagra 2024e), analysis of radiological consequences (Nagra 2024o) and the post-closure safety report (Nagra 2024l). These higher-level reports describe the outcomes of these safety assessment elements, as well as methodological details not covered by the present report (right side of Fig. 1-2). The methodology for site comparison and for the selection of NL as Nagra's proposed siting region, which is only briefly summarised in this report, is described in detail in Nagra (2025a) and its supporting reports (Fig. 1-1).

As noted above, the scope of safety assessment for this report is safety during the post-closure phase. Engineering feasibility and operational safety are dealt with in separate reports (Nagra 2023a, Nagra 2024c). The influence of the operational phase on post-closure safety is also described in a separate report (Nagra 2024b), although possible deviations from the planned initial state of the repository at the time of closure are also accounted for in the performance assessment and in the safety scenario development.

1.4 Structure of the present report

The remaining chapters of this report are structured as follows:

- Chapter 2 describes the context and the boundary conditions according to which the current safety assessment methodology is developed. This chapter covers legal and regulatory requirements for the general licence application, international guidance on safety assessment and the safety case and an overview of the iterative design development process for the system to be assessed.
- Chapter 3 describes the principles, foundations and key features of safety assessment, including the management of uncertainty.
- Chapter 4 provides an overview of the evidence, knowledge and assessment tools used in site comparison and in safety assessment, which, together with the methodologies described in the present report, constitute the assessment basis.
- Chapter 5 describes the methodology used in the safety assessment in support of the general licence application.
- Chapter 6 gives an overview of the methodology used in the analyses that support site comparison, highlighting the similarities, parallels and general consistency between this and the safety assessment methodology.
- Chapter 7 concludes the report by summarising how the report has fulfilled its stated objectives.

2 Context and boundary conditions

We refer to NAB 24-18 (Nagra 2024r) for an extensive discussion of the legal and regulatory requirements with respect to safety, international standards and guidance, as well as institutional decisions and strategic choices made in Switzerland. NAB 24-18 also describes the Nagra safety concept and safety-related design requirements in detail. For a comprehensive discussion of aspects specific to the final stage in the site selection process, we refer to NTB 24-03 (Nagra 2025a). In the following sections, we summarise aspects of specific relevance to the safety assessment methodology and its link to the safety argumentation for the site comparison.

2.1 Legal and regulatory requirements with respect to safety for the general licence application

Requirements on the documentation for the general licence application, for the final stage of the site comparison process and for the safety assessment for the site proposed by Nagra are detailed in ENSI 33/649 (ENSI 2018b). Specific requirements for the safety assessment and safety case for the proposed site are set out in ENSI Guideline G03 (ENSI 2023a) and further elaborated in the explanatory report (ENSI 2020b). These requirements are described further in the following sections.

2.1.1 Comparison of siting regions

The comparison of the siting regions is conducted within the framework of a safety-based optimisation in line with the safety criteria defined in the Sectoral Plan (BFE 2011) and the ENSI requirements specified and supplemented for Stage 3 of the Sectoral Plan in ENSI 33/649 (ENSI 2018b). Chapter 4 of the latter includes safety-related requirements for the site comparison and describes the procedure to be followed for the comparative overall evaluation of the potential siting regions leading to the siting proposal, as shown in Fig. 2-1.

The procedure begins with the waste allocation to the two repository types; since the requirements for a repository site also depend on the inventory to be disposed of, the waste allocation must be used consistently for both the site comparison and the safety assessment for the proposed siting region. Thereafter, the next step is to select the location for a potential HLW repository. Finally, a location for the L/ILW repository is selected, which can include the possibility of co-disposal of L/ILW with HLW at the same site.

As also set out in Chapter 4 of ENSI 33/649 (ENSI 2018b), the proposed site or sites for the potential HLW repository, L/ILW repository or combined repository are chosen using an approach consisting of the following sub-steps:

1. Delimitation of the containment-providing rock zone (CRZ):

   The CRZ is defined by ENSI 33/649 (ENSI 2018b) as the spatial area in the geological subsurface that, in conjunction with engineered barriers, ensures the containment and retention of the radioactive substances contained in the waste during the expected evolution of the deep geological repository for the period under consideration. The CRZ includes the host rock as well as over- and underlying confining geological units that support barrier performance[3] (Fig. 2-2). Nagra must propose at least one CRZ for the site comparison per siting region and per repository type and justify how spatially effective elements have been included in its delimitation.

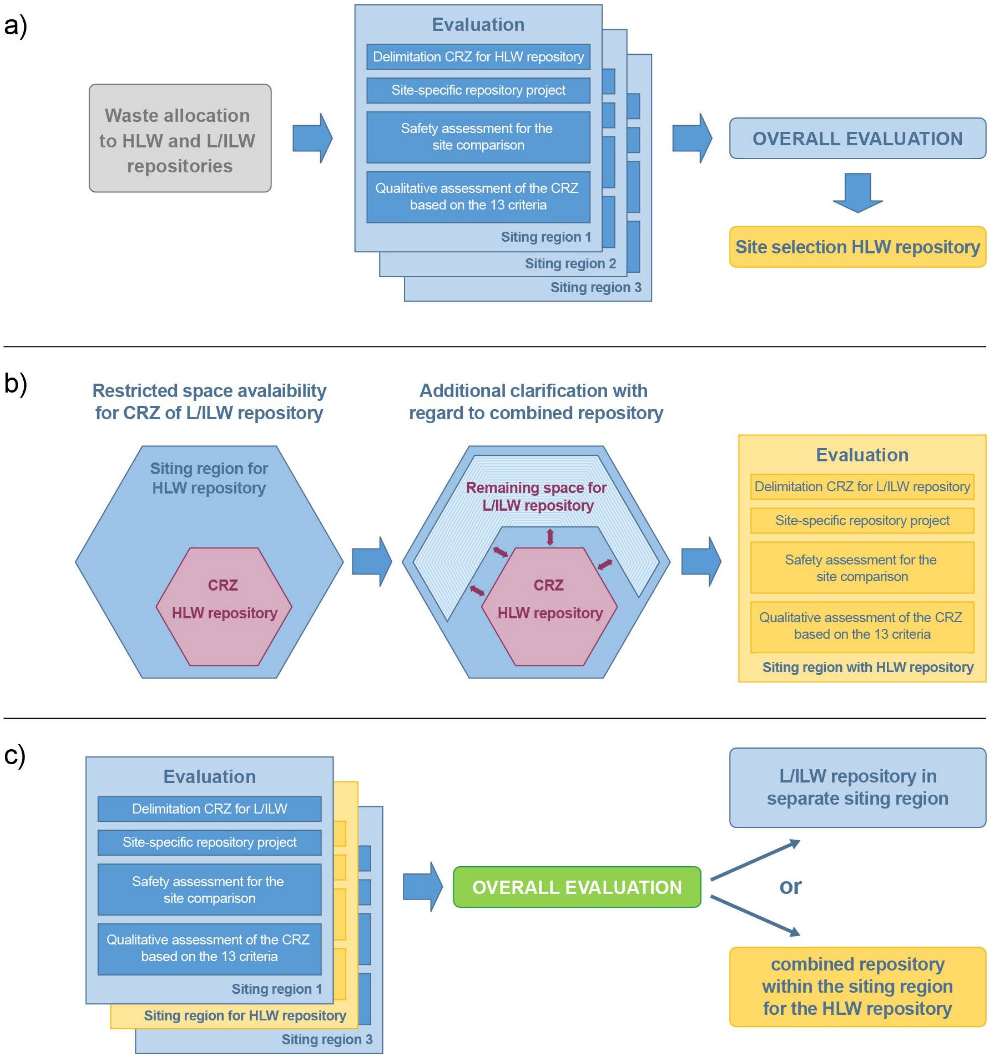

Fig. 2-1: Schematic illustration of the methodology for the site comparison in Stage 3 of the Sectoral Plan

Figure translated from ENSI 33/649 (ENSI 2018b).

[3] *Räumlicher Körper im geologischen Untergrund, der bei zu erwartender Entwicklung des geologischen Tiefenlagers für den Betrachtungszeitraum, im Zusammenwirken mit technischen Barrieren, den Einschluss und die Rückhaltung der im Abfall enthaltenen radioaktiven Stoffe sicherstellt. Zum EG gehören das Wirtgestein sowie obere und untere barrierenwirksame Rahmengesteine.*

2. Concept, design and planning of the deep geological repositories (i.e., establishment of site-specific repository projects):

   For the CRZs used in the site comparison, site-specific facility designs must be developed that adequately address the aspects of construction, operation, retrieval without undue effort, closure, and post-closure safety.

3. Site-specific, quantitative safety analyses for the site comparison:

   Safety analysis is understood here as a systematic quantitative investigation with the aim of showing compliance with the protection criteria and the fulfilment of the specified safety requirements.

4. Qualitative evaluation of the CRZ:

   The qualitative evaluation of the CRZ is based on 13 criteria for safety and engineering feasibility included in the Sectoral Plan (Annex I of BFE (2008)); see Tab. 2-1 and Section 6.2.5. The criteria are divided into four groups and, for each of the criteria, the Sectoral Plan also specifies the various *"aspect(s) to be evaluated"* and their corresponding *"relevance for safety"*.

5. Overall comparative safety evaluation:

   Finally, an overall comparative safety evaluation and selection of proposed siting region or regions are carried out, based on the geological situation in each siting region, the delineated CRZs of the siting regions, the site-specific repository projects, the safety analyses for the site comparison, and the qualitative assessment of the CRZs with respect to the 13 criteria.

Tab. 2-1: Criteria for the qualitative evaluation of the CRZ to be assessed from the viewpoint of safety and engineering feasibility according to SGT

BFE (2008)

Criteria group	Criteria
1. Properties of the host rock and the effective containment zone	1.1 Spatial extent 1.2 Hydraulic barrier effect 1.3 Geochemical conditions 1.4 Release pathways
2. Long-term stability	2.1 Stability of the site and rock properties 2.2 Erosion 2.3 Repository-induced influences 2.4 Conflicts of use
3. Reliability of geological findings	3.1 Ease of characterisation of the rock 3.2 Explorability of spatial conditions 3.3 Predictability of long-term changes
4. Engineering suitability	4.1 Rock mechanical properties and conditions 4.2 Underground access and drainage

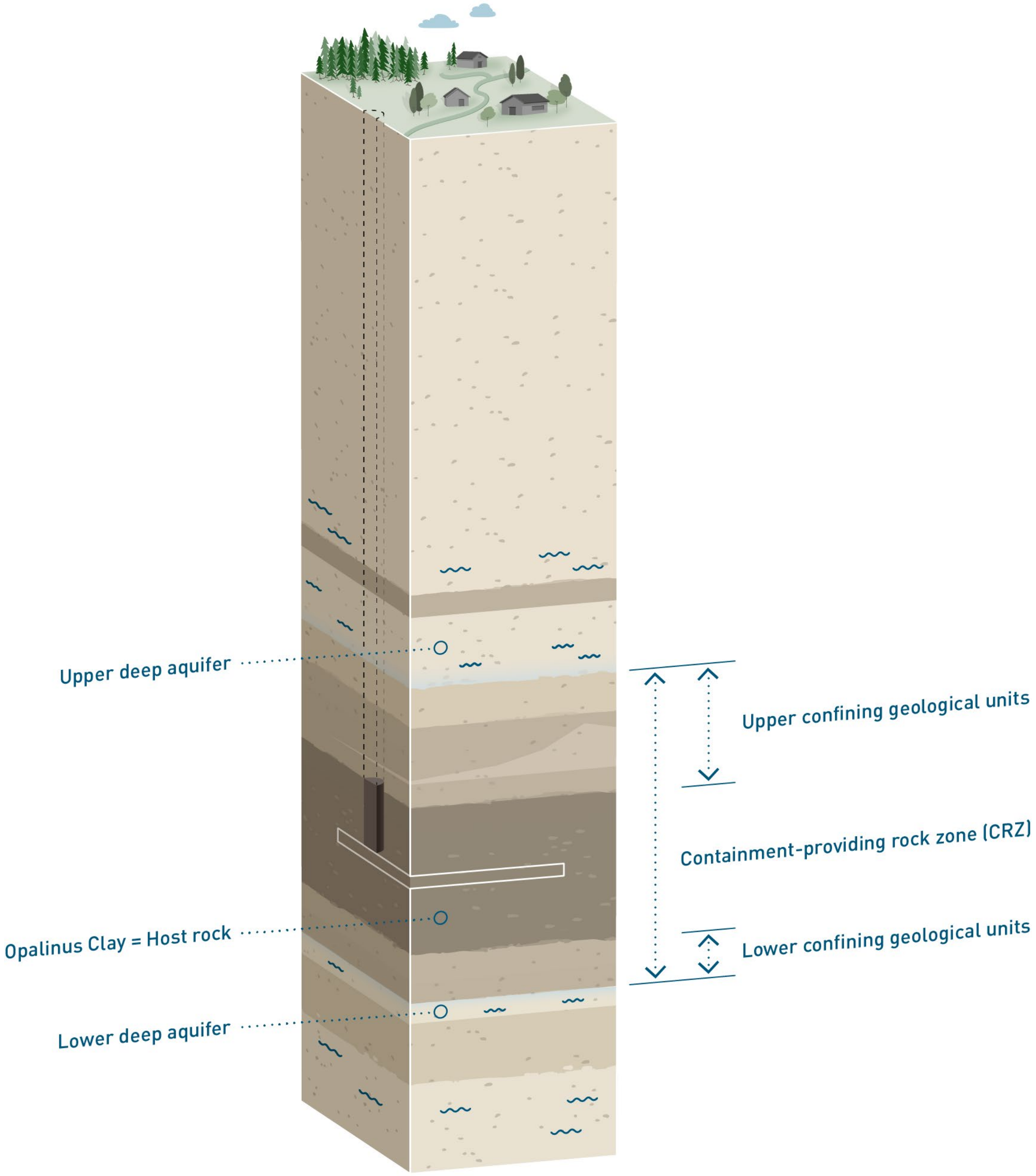

Fig. 2-2: Sketch of the location of the repository within the Opalinus Clay host rock, as well as the containment-providing rock zone (CRZ), which consists of the Opalinus Clay and its confining geological units, bounded above and below by deep aquifers

Figure is not to scale.

2.1.2 Demonstration of post-closure safety

Once the siting region has been selected, a post-closure safety case for a repository at this site must be prepared and submitted as part of the general licence application. It must be based on a comprehensive and systematic safety assessment, showing how the repository will evolve and what radiological consequences are expected, and demonstrating that the overall protection objective and the associated guidelines and protection criteria can be met.

Chapter 5 of ENSI 33/649 (ENSI 2018b) includes requirements for the demonstration of post-closure safety. This includes supplementing the more limited safety analyses that are carried out for the proposed siting region within the framework of the site comparison with a comprehensive scenario analysis and an analysis of radiological consequences. Excavation of the repository by geological erosion processes is specifically mentioned as a scenario to be evaluated.

The protection objective and the criteria by which the post-closure safety of a deep geological repository are to be evaluated are set out in ENSI Guideline G03 (ENSI 2023a). The objective of deep geological disposal is to ensure the permanent protection of humans and the environment by means of a system of staged, passively functioning engineered and geological barriers, termed the multi-barrier system. It is acknowledged that absolute containment of all radioactive substances over long periods of time is impossible, and the multi-barrier system therefore has to be designed in such a way that the release of radionuclides through the engineered and geological barriers to the biosphere remains low and the protection of humans and the environment is ensured. Quantitative protection criteria in the form of individual effective dose and risk limits are specified in the guideline. The elements to be addressed in the safety assessment, according to ENSI Guideline G03 (ENSI 2023a), are presented in Tab. 2-2. Further requirements for safety assessment and the safety case are also set out in this guideline and are referred to throughout the following sections of this report (generally as footnotes in the original German text).

The consequences of the release of chemically toxic contaminants are currently not considered in the safety assessment. However, conformance of the repository with environmental protection laws is demonstrated in the Environmental Impact Assessment[4] (Nagra 2025c). Exposure of non-human biota is also not considered in the safety assessment. This is in accordance with ENSI's explanatory report for ENSI Guideline G03 (ENSI 2020a), which states that, if exposure to humans is insufficient to cause harm, the wider environment can be presumed to be protected[5]. However, livestock and crops (including pasture) and other biota are taken into account in the safety assessment insofar as they may affect the transport and distribution of radionuclides in the biosphere, e.g., via bioturbation, and hence the dose rate to humans.

[4] *Umweltverträglichkeitsprüfung*

[5] According to ENSI (2020a): "The guideline is therefore based on the previous assumption that species are protected when the necessary precautions for the individual protection of humans have been taken."

Tab. 2-2: Elements to be addressed in the safety assessment according to ENSI Guideline G03 ENSI (2023a)

A	Description of the deep geological repository system. *Beschreibung des geologischen Tiefenlagersystems.*
B	Use of verified data on the geological conditions at the site. *Verwendung verifizierter Daten zu den geologischen Gegebenheiten am Standort.*
C	Demonstration of how the engineered and natural barriers operate, their retention capacity and their robustness. *Aufzeigen der Wirkungsweise, des Rückhaltevermögens und der Robustheit der technischen und natürlichen Barrieren.*
D	Description and evaluation of the effects of coupled processes and of gas formation and dispersion on the engineered and natural barriers and on radionuclide transport. *Darlegung und Bewertung der Auswirkungen gekoppelter Prozesse und der Gasbildung und -ausbreitung auf die technischen und natürlichen Barrieren sowie auf den Radionuklid-transport.*
E	Description of the expected long-term geological evolution. *Beschreibung der zu erwartenden geologischen Langzeitentwicklung.*
F	Description of the expected development of the materials contained in the deep geological repository, including the radioactive waste and the engineered and natural barriers. *Beschreibung der zu erwartende Entwicklung der im geologischen Tiefenlager befindlichen Materialien, einschliesslich der radioaktiven Abfälle und der technischen und natürlichen Barrieren.*
G	Scenario analysis and definition of the calculation cases used to investigate the evolution of the deep geological repository. *Szenarienanalyse und Festlegung der Rechenfälle, mit denen die zu betrachtenden Entwicklungen des Tiefenlagers untersucht werden.*
H	Justification of why the assumptions and calculation models used are applicable to the situation under consideration. *Begründung, warum die verwendeten Annahmen und Rechenmodelle auf die vorliegende Situation anwendbar sind.*
I	Systematic sensitivity and uncertainty analysis to determine the influence of uncertainties in the data, processes, and models on the calculation results. *Systematische Sensitivitäts- und Unsicherheitsanalyse zur Ermittlung des Einflusses von Unsicherheiten in den Daten, Prozessen und Modellen auf die Berechnungsergebnisse.*
J	Consideration of envelope scenarios covering possible lines of evolution, particularly regarding surface morphology and climate, within the framework of biosphere modelling. *Betrachtung umhüllender Szenarien von möglichen Entwicklungen insbesondere der Gebiets-morphologie und des Klimas im Rahmen der Biosphärenmodellierung.*

2.2 International developments and guidance on safety assessment and the safety case

Nagra's safety assessment methodology is in line with international progress and publications on the geological disposal of radioactive waste. Nagra closely observes the related development in other waste management organisations and participates in international efforts and exchanges, e.g., under the auspices of organisations such as the International Atomic Energy Agency (IAEA), the Nuclear Energy Agency of the Organisation for Economic Co-Operation and Development (OECD/NEA) and the European Commission. In the following, the most recent or important international activities and documents related to the safety assessment methodology are summarised.

At an overarching level, safety principles and provisions are laid down in the IAEA Joint Convention on the Safety of Spent Fuel and on the Safety of Radioactive Waste Management (IAEA 1997), to which Switzerland is a signatory. Moreover, there has been a long history of international collaboration in developing the approaches and methods for analysing the post-closure safety of deep geological disposal. This work is documented in numerous publications by the IAEA and the NEA. A concise summary with work up to 2014 is provided by the OECD/NEA Sourcebook of International Activities Related to the Development of Safety Cases for Deep Geological Repositories (OECD/NEA 2017b). Of particular relevance are the three IAEA safety standards SSG-14 (IAEA 2011b), SSR-5 (IAEA 2011a) and SSG-23 (IAEA 2012). More recently, work has preliminarily concentrated on specific subtopics of the safety case such as scenario development (OECD/NEA 2016) or communication aspects (OECD/NEA 2017a), and on practical applications of the proposed approaches, such as the third stage of the IAEA GEOSAF project (IAEA 2017).

A key conclusion, stated in many of the documents, is that reasonable assurance of post-closure safety is a prerequisite for the implementation of a repository system. As specified, e.g., in IAEA Safety Standards SSR-5, Paragraph 2.15 (IAEA 2011a): "*The safety objective is to site, design, construct, operate and close a disposal facility so that protection after its closure is optimized, social and economic factors being taken into account. A reasonable assurance also has to be provided that doses and risks to members of the public in the long term will not exceed the dose constraints or risk constraints that were used as design criteria*". Safety assessment (or, more generally, the development of a convincing safety case) is the procedure by which reasonable assurance is provided. Evaluations of the radiological consequences of a repository system made during a safety assessment are always subject to uncertainty. In practice, conclusions with respect to safety are not based on an exact prediction of the actual future evolution of the system, but rather on the consideration of a broad range of representative cases addressing different assumptions regarding the possible characteristics and evolution of the system.

With respect to safety assessment methodology, the outcome of the NEA Initiative Methods for Safety Assessment for Geological Disposal Facilities for Radioactive Waste (MeSA) (OECD/NEA 2012b) was a significant milestone. The assessment strategy is defined as the approach to safety assessment and the compilation of the safety case. In its safety case brochure (OECD/NEA 2013), the NEA states that part of the assessment strategy should be to provide "*a range of arguments and analyses for the safety case that are well-founded, and supported, where possible, by multiple lines of evidence*". The development of a wide range of arguments and evidence, including model-based analysis, is a key feature of the safety assessment methodology described in Chapter 5.

In the same publication, it is noted that the safety case must include an adequate treatment of uncertainty and that processes relevant to safety should be well understood and reliably modelled. Furthermore, "*potentially detrimental processes or features or events should be disclosed and directly taken into account in the safety assessment, if their probability warrants it*". Similarly, ENSI Guideline G03 (ENSI 2023a) states that the safety case must provide information on the reliability of the claims made and on the safety relevance of uncertainties[6]. In the present methodology, potentially detrimental processes, features or events are systematically analysed in the safety assessment.

Much of the work of the NEA Integration Group for the Safety Case (IGSC), which was set up to develop, review and update safety cases for geological repositories, has focused on clarifying the nature of the multiple lines of evidence within the safety case and providing specific examples of their use (see, e.g., the IGSC 20th Anniversary Brochure (OECD/NEA 2021)). Multiple lines of evidence, which may include, for example, performance and safety indicators in addition to dose and risk and the use of natural and archaeological analogues, are seen as a way of increasing the robustness of the safety case and are features of the methodology set out in the present report. Thus, ENSI Guideline G03 (ENSI 2020b) notes that complementary arguments can be used to support the assessment basis and the safety assessment results and that, where available, observations from natural analogues can be used to support the claims made in the safety case[7].

Other key areas in the work of the IGSC summarised in the brochure include:

- **integration** of the wide-ranging information that contributes to the safety case,
- **safety functions**, which play an increasing role in many national programmes in response to challenges associated with demonstrating and communicating post-closure safety and its link to design,
- **handling of uncertainty**, with a key challenge being to show that any residual uncertainty that could call the safety case into question can be avoided, mitigated, or reduced at least to the extent needed to justify a positive decision to proceed to the next programme phase, and
- **scenario development**, with the trend being the increasingly widespread use of safety functions in scenario development and the recognition of the wide range of roles scenarios can play in a disposal programme.

All these aspects are inherent parts of the methodology presented in this report.

Nagra's approach and methodology are further inspired by disposal programmes in other countries. Safety cases that were recently compiled by other waste management organisations and are of relevance for the methodological aspects discussed in the present report are listed in Tab. 2-3.

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[6] *Der Sicherheitsnachweis hat Aufschluss über die Zuverlässigkeit der getroffenen Aussagen und über die sicherheitstechnische Relevanz von Unsicherheiten zu geben.*

[7] *Gegebenenfalls können weitere Argumente, welche die Grundlagen und Ergebnisse der Sicherheitsanalyse sowie die Schlussfolgerungen des Sicherheitsnachweises zusätzlich stützen, aufgeführt werden. Nach Möglichkeit sind die Aussagen der Sicherheitsanalysen durch Naturanaloga zu stützen.*

Tab. 2-3: Recent safety cases for deep geological disposal, their main objectives in terms of the project milestones they support and the main aspects relevant to this report

Organisation, country	<u>**Name**</u> **Main *objectives* and main aspects of relevance**	**Reference**
Andra, France	<u>DAC</u> *Preliminary safety report supporting the construction licence application (original title : Dossier d'autorisation de création de l'installation nucléaire de base (INB) CIGEO. Pièce 7: Version préliminaire du rapport de sûreté).* Repository for high-level and long-lived waste in Callovo-Oxfordian **clay host rock** with a similar **multi-barrier system.**	Andra (2022)
Andra, France	<u>DOS-AF</u> *Summary of knowledge related to post-closure safety in view of finalising the pre-project for the construction licence application (original title: Dossier d'option de sûreté. Partie après fermeture).* Repository for high-level and long-lived waste in Callovo-Oxfordian **clay host rock** with a similar **multi-barrier system.**	Andra (2006)
Posiva, Finland	<u>SC-OLA</u> *Safety case for the operating licence application.* **Safety concept and design development process** with link to requirements, some **engineered barriers.**	Posiva (2021)
SKB, Sweden	<u>TR-21-01, PSAR</u> *Post-closure safety for the final repository for spent nuclear fuel at Forsmark* in support of a construction licence application. **Safety concept and design development process** with link to requirements, some **engineered barriers.**	SKB (2022)
SKB, Sweden	<u>TR-23-01, PSAR</u> *Post-closure safety for SFR, the final repository for short-lived radioactive waste at Forsmark* in support of an application for extension of the repository. **Safety concept and design development process** with link to requirements, some **engineered barriers.**	SKB (2023)
NWMO, Canada	<u>TR-2022-15</u> *Confidence in Safety – South Bruce Site* demonstrating suitability of the site to host a repository for spent fuel. Repository for high-level waste in **argillaceous** (shaley) limestone with a partially similar **multi-barrier system.**	NWMO (2022)

2.3 Safety and repository concept and provisional design

The project for implementing deep geological disposal in Switzerland has developed over several decades and is in line with the legal and regulatory requirements and international advancements described above. The project has reached the maturity level required for the general licence application by virtue of extensive RD&D in line with the periodically published RD&D Plan, e.g., NTB 16-02 (Nagra 2016b), NTB 21-02 (Nagra 2021d) and specific studies on safety, design, cost, etc. that are periodically documented in the Waste Management Programme, e.g., NTB 16-01 (Nagra 2016a), NTB 21-01 (Nagra 2021a). Along the way, Nagra's work has regularly been reviewed by the authorities (HSK 1996, HSK 2005, ENSI 2017) that have also formulated recommendations for future programme stages (ENSI 2018a, ENSI 2023b).

For the discussion of the safety assessment methodology, it is important to consider the safety-related features of the planned deep geological repository. These concern, on the one hand, the underlying safety concept with its links to design requirements (for details see Nagra (2024r)) and, on the other hand, the provisional design and implementation (for details see Nagra (2023a, 2024c)). Both considerations are summarised below.

As shown on the left-hand side of Fig. 2-3, there is an overarching protection objective, as well as design principles and protection criteria, that underlie the high-level safety and repository concept, which in turn provides the basis for the iterative design development process yielding the provisional design and implementation plan. The overarching protection objective, design principles and protection criteria comprise:

- The general protection objective stated in the Nuclear Energy Act (KEG 2003) and in ENSI Guideline G03 (ENSI 2023a) of permanent protection of humans and the environment from ionising radiation from the emplaced waste after final closure of the repositories without imposing undue burdens and obligations on future generations.
- Design principles that any acceptable concept and design must fulfil, including the principle of providing passive safety (e.g., through multiple barriers performing a set of safety functions), and the related principle of robustness.
- Protection criteria in terms of dose and risk limits set out in ENSI Guideline G03 (ENSI 2023a).

The safety concept explains how the deep geological repository ensures the protection of humans and the environment, through the safety barriers and the safety functions they perform. The repository concept describes the repository safety barriers and their properties, which contribute to the repository safety functions. The safety concept and repository concept are thus closely intertwined and are referred to collectively as the safety and repository concept. The safety and repository concept includes:

- The safety functions of the repository system as a whole that collectively ensure post-closure safety. These safety functions consist of:
  - **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 with regard to long-term geological and climatic evolution.

- The main features of the repository concept contributing to these safety functions, termed "pillars of safety"; Fig. 2-4 and Fig. 2-5 illustrate schematically how the pillars of safety contribute to the various safety functions.
- A more 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, termed, component-specific functions.
- Performance objectives, which describe how the system components, including both engineered and geological barriers, are envisioned to evolve over time and perform their individual, component-specific functions and thus collectively the safety functions.

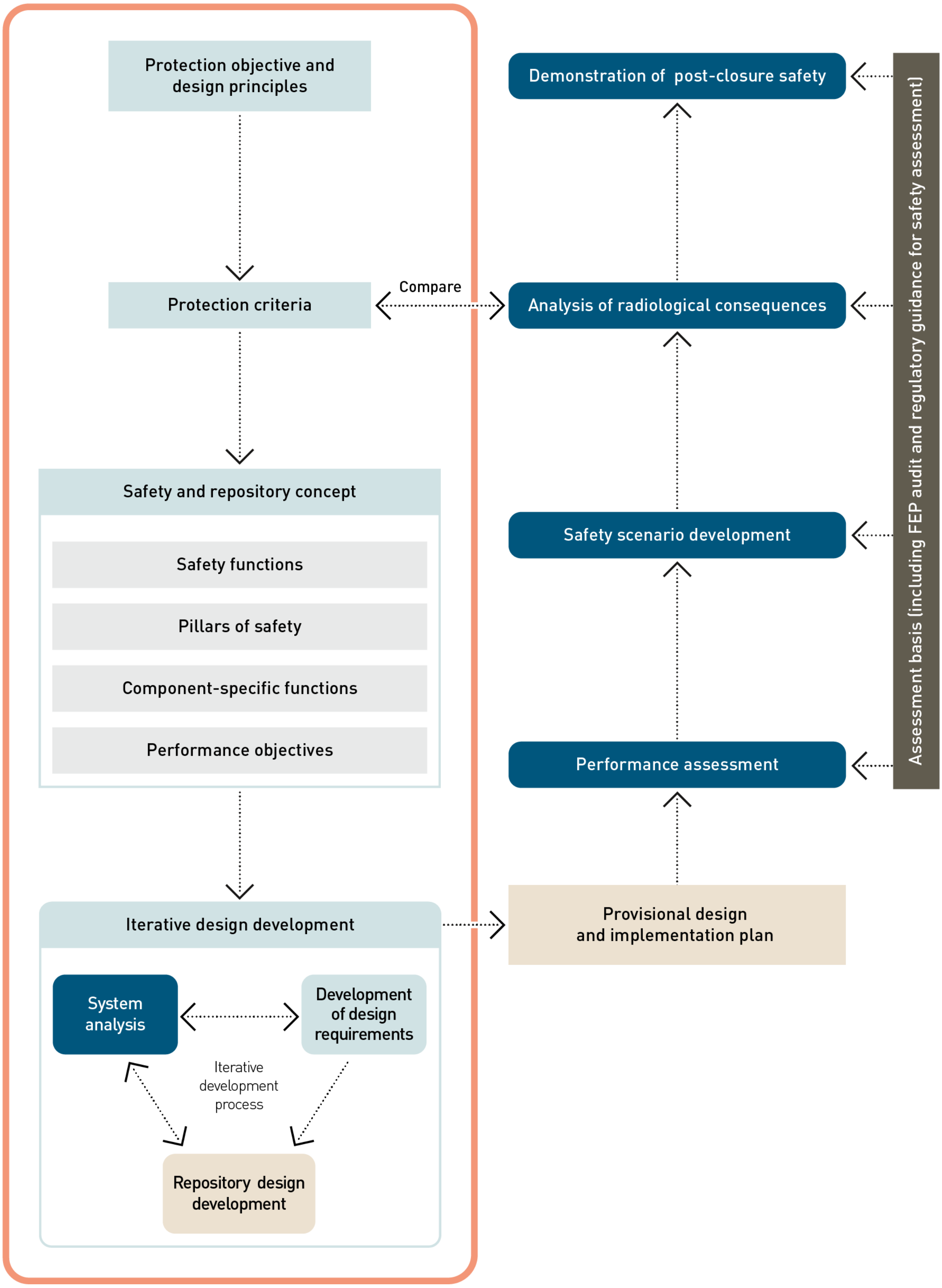

Fig. 2-3: Workflow for the post-closure safety case, highlighting, in the orange box, the process for developing safety and repository concept which leads to development of a provisional design and implementation plan to support the general licence application

Cementitious near field

- 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.

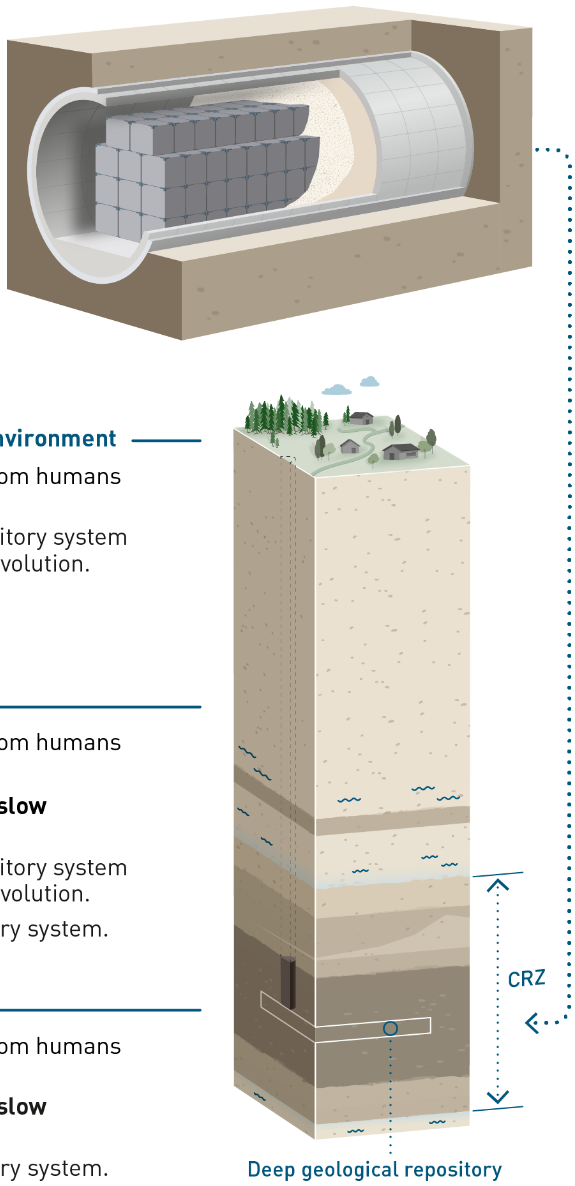

Fig. 2-4: Pillars of safety for the L/ILW repository and their contributions to the safety functions

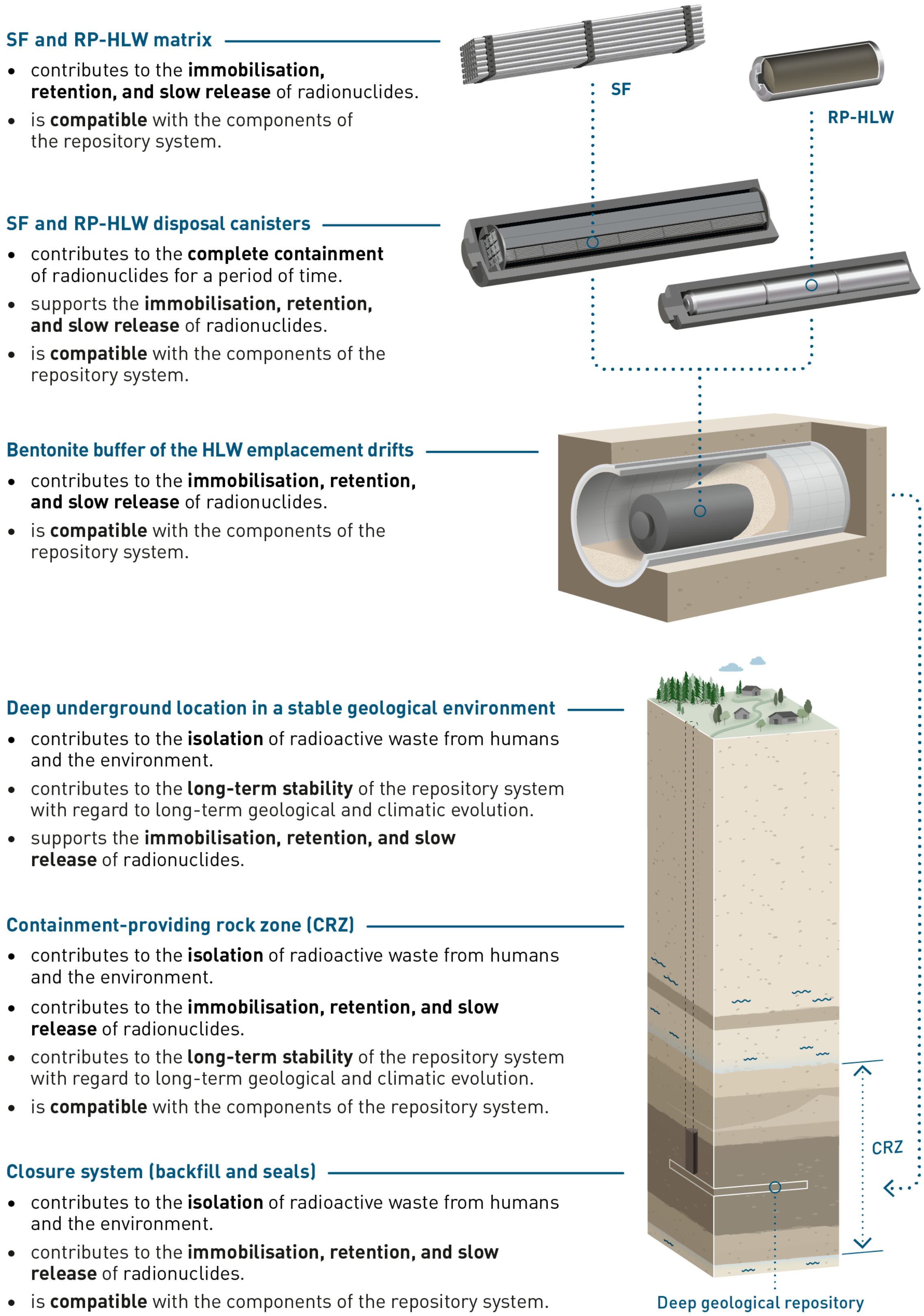

Fig. 2-5: Pillars of safety for the HLW repository and their contributions to the safety functions

The relationships between safety functions, component-specific functions and performance objectives are key elements of Nagra's safety and repository concept and are described in detail in NAB 24-18 (Nagra 2024r). The safety and repository concept is considered stable and mature and is sufficiently general, and the siting regions sufficiently similar, to apply the same concept to all the siting regions considered in Stage 3 of the Sectoral Plan.

Starting with the safety and repository concept, the development of a provisional design and implementation plan suitable for the purposes of the current project milestone, i.e., the general licence application, is an iterative process (as also illustrated in Fig. 2-3). The process entails:

- the identification and development of a set of design requirements to be met, including, but not limited to, those related to post-closure safety,
- design development itself, whereby solutions (design specifications) are proposed and refined to meet these requirements, and
- analyses of the system as a whole and its various subsystems to test whether the requirements are met and to guide the further modification of the design.

The process is also guided by existing experience in the design of system components related to construction, operation and post-closure safety, by principles of robustness, and by other requirements related to, for example, engineering feasibility and operational safety.

System analyses are at first comparatively informal and take, for example, the form of scoping calculations. However, once a reasonably stable set of design requirements has been identified and the design solutions are considered to have reasonable prospects of meeting the requirements to the extent needed for the milestone at hand (currently the general licence application), more formal analyses are undertaken. Finally, to reach the milestone, these analyses become part of the formal safety assessment (Fig. 2-3, right).

Note that there could also be feedback from design development to the performance objectives and other elements of the safety concept, i.e., it may be necessary to adjust performance objectives, without jeopardising the protection criteria, in order to reach a viable design. For simplicity, and because, as noted above, the safety and repository concept is considered to be stable and mature, this type of feedback is not depicted in Fig. 2-3.

The iterative design development process is supported by Nagra's assessment basis, which has been progressively expanded to support design development activities. As illustrated in Fig. 2-6, for the general licence application milestone, which includes both safety assessment and site comparison; the outcome of the design development process is twofold:

- a set of site-specific repository configurations for each repository type (HLW and L/ILW), and
- a design and implementation plan for a combined repository in the proposed siting region.

Based on these two outcomes, a safety-based site comparison is carried out, together with a formal safety assessment for the proposed site. The methodologies for these are further described in Chapters 5 and 6 of this report. Repository design is also documented in several design and operation reports (Nagra 2023a, Nagra 2024c).

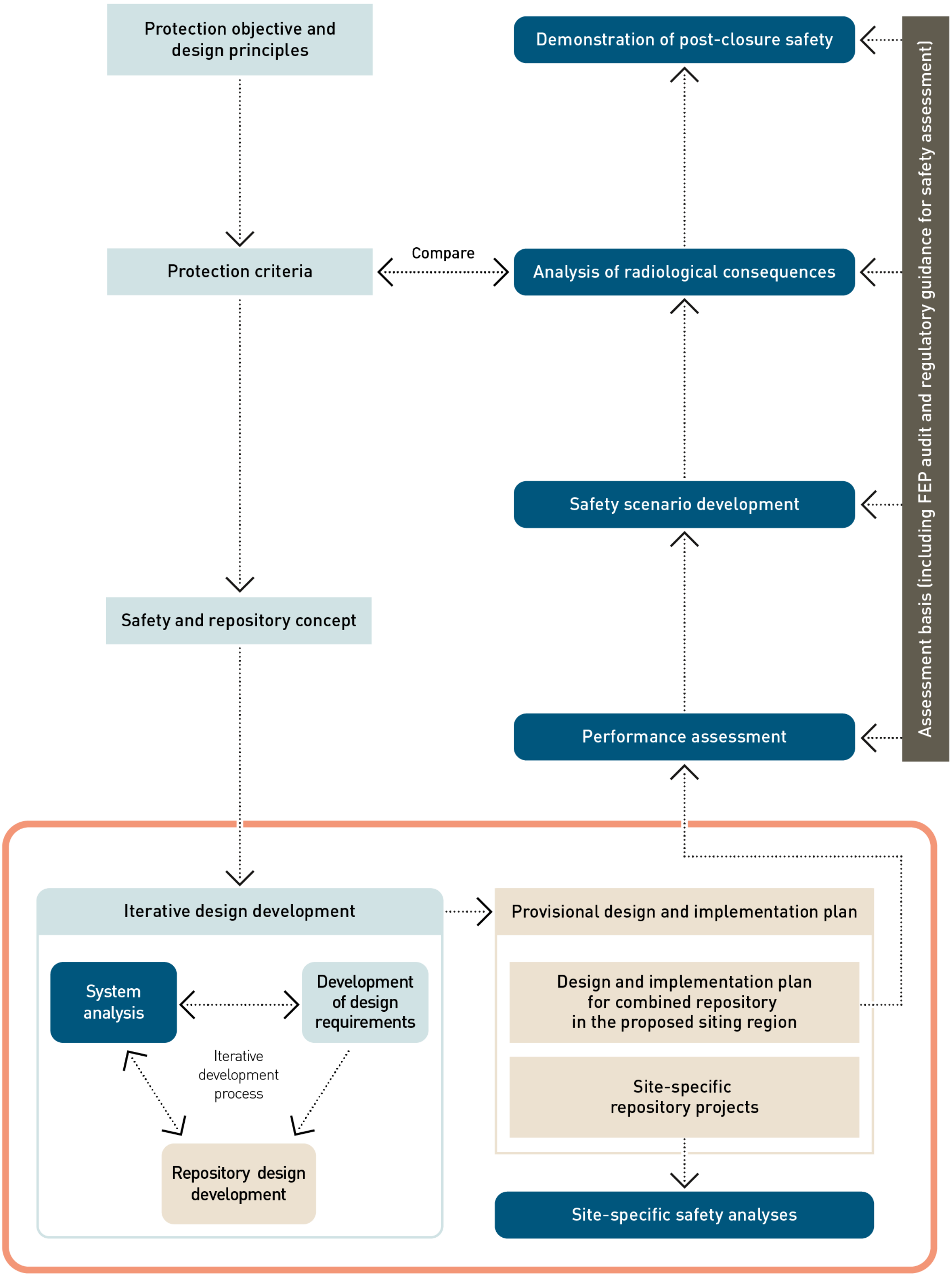

Fig. 2-6: Workflow for the post-closure safety case, highlighting the process and outcome of development of the provisional design and implementation plan

The provisional design for a combined repository for HLW and L/ILW is illustrated in Fig. 2-7. The repository provides safety by means of a multi-barrier system, i.e., a set of geological and engineered barriers. The repository system operates passively, meaning that, after closure of the repository, no further measures are required to ensure post-closure safety. The engineered barriers for HLW disposal (right) comprise SF assemblies with fuel rods (UO_2 or mixed oxide fuel (MOX) pellets in cladding tubes) and RP-HLW (not shown) that are packaged in steel canisters. The HLW canisters are emplaced in drifts, which are subsequently backfilled with a compacted bentonite buffer and sealed. For L/ILW disposal (left), L/ILW waste packages are placed inside waste containers, which are in turn emplaced in caverns that are backfilled with cement-based mortar.

Concerning the provisional implementation plan, it is sufficient to note that procedures for constructing, operating and closing the repository are established, available and affordable. Nevertheless, deviations between the "as-built" state and the "design" specifications must be anticipated, and measures to deal with such situations should be foreseen. The safety assessment methodology, with its adequate uncertainty management, contributes significantly to developing such measures.

As described above, the safety and repository concept underlying the design and implementation plan for the general licence application is considered mature and stable. However, the design requirements, and the details of the design and implementation, are defined more tentatively and should be viewed as provisional examples for the purposes of the general licence application. More profound knowledge of the geology at the site and advances in materials science and other fields are expected to impact the final design and implementation plan. Furthermore, even though state-of-the-art technology for constructing, operating and closing the repository (e.g., further exploration of the site, excavation, handling of the waste, manufacturing / emplacing the engineered barriers, backfilling) is established, available and affordable, significant technological progress, e.g., in robotics and control, must be expected in near future. Consequently, refinement and optimisation are an ongoing process that will continue in subsequent steps, triggered by and triggering future RD&D activities in various domains and likely leading to further improvements in the design and implementation plan.

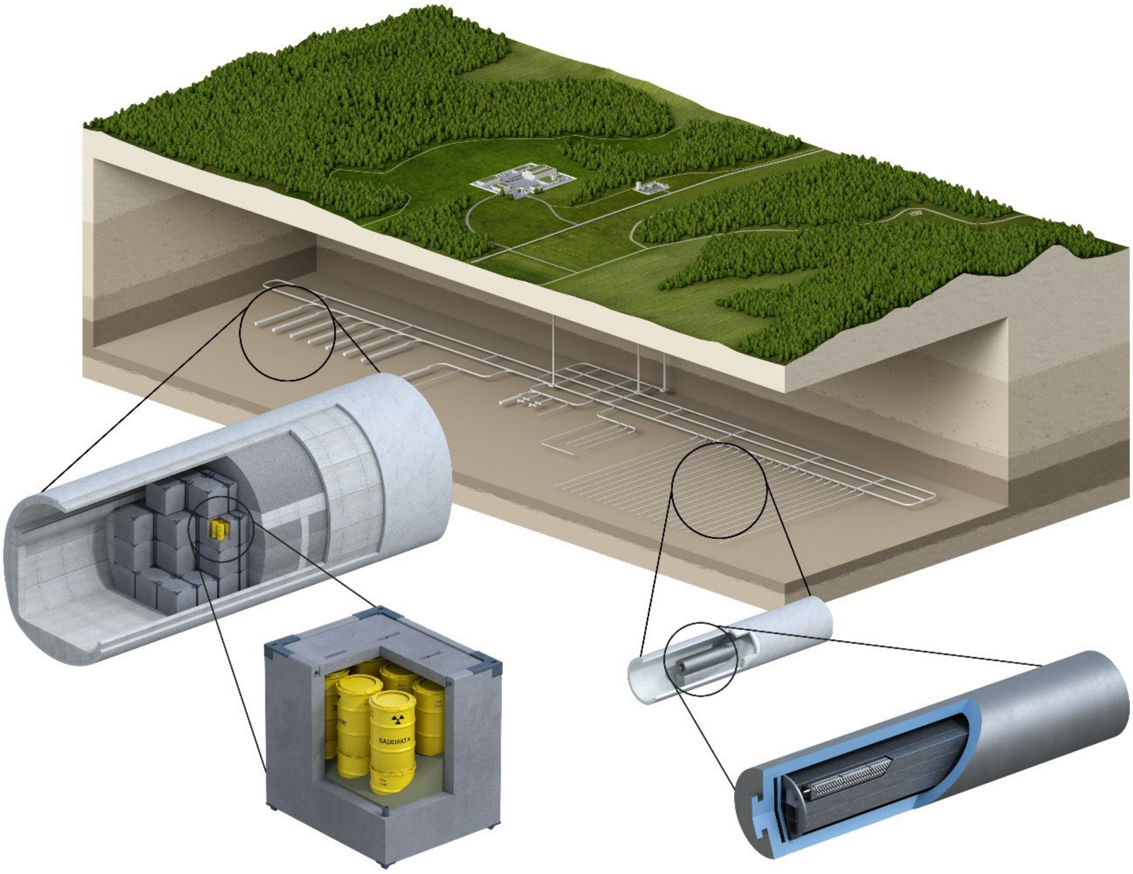

Fig. 2-7: Illustration of the provisional repository design for a co-disposal of L/ILW (left side) and HLW (right side)

3 Safety assessment features and principles

3.1 Safety assessment principles

Based on international developments and guidance (Chapter 2), as well as on Nagra's own experience from past safety assessments, principles and objectives relevant to a safety assessment include:

- **A systematic approach to information gathering and integration** – The assessment relies on a systematic approach to information gathering and integration to assemble the assessment basis, as described in Section 4.2.
- **Rigorous consideration and treatment of uncertainty** – As far as possible, all potential sources of uncertainty must be considered. Uncertainty management is described in general terms in Section 3.2 and is a feature of all processes within the safety assessment methodology described in this report.
- **Assurance of completeness** – All reasonably foreseeable possibilities for the characteristics and evolution of the repository system are considered when developing safety case arguments, and the various sources of bias must be recognised when conducting and interpreting the analyses. The assurance of comprehensiveness, i.e., the minimisation of "completeness uncertainty" is discussed further in Section 3.3.
- **Development, validation and verification of models and databases** – Appropriate quality assurance and control measures are adopted to ensure that the models and databases developed and applied in the analyses are suitable for their intended purpose. Each computer code used to perform analyses is verified. Model abstraction, including the use of simplification and conservatism in modelling, is discussed in Section 3.2.2. Validation and verification are part of quality assurance and control in safety assessment, as described in Section 3.2.4. An overview of some of the main models and codes used in safety assessment is given in Section 4.4, and databases are summarised in Section 4.5.
- **Use of stylised approaches** – Stylised approaches are adopted for the modelling of the biosphere and the nature of future human behaviour and activities, on account of the largely irreducible and unquantifiable uncertainties associated with predictions regarding these aspects, even over relatively short timescales. Biosphere modelling is described briefly in Section 5.4.2.4 and in detail in Nagra (2024k). Safety scenarios involving future human actions safety scenarios are discussed briefly in the context of scenario development (Sections 5.3) and in detail in Nagra (2024q).
- **Multiple lines of arguments for safety** – Claims related to the performance and safety of the repository system are supported, as far as possible, by multiple lines of arguments and wide-ranging evidence. The development of arguments and evidence supporting a set of high-level claims is a key element of the performance assessment methodology described in Section 5.2. Multiple lines of argument within the overall safety case are summarised in Section 5.5.
- **Internal and external reviews** – All important issues within the safety assessment are subject to internal and/or external review, which form part of quality assurance and control (Section 3.2.5).

3.2 Uncertainty management

For a complex problem, such as analysing the future evolution, performance and safety of a geological repository and its environment, exact predictions are unachievable. Some level of uncertainty can, however, be accepted, provided the uncertainties do not compromise safety. Uncertainty in safety assessments is discussed, for example, in OECD/NEA (2012b).

Uncertainties differ in the degree to which they can be quantified or bounded, the degree to which they can be avoided or reduced in the course of a repository programme, and in the extent to which they affect the evaluated performance of the system.

The impact of uncertainty on the assessment outcome must be evaluated because this determines the level of confidence with regard to the post-closure safety of the repository system and the demonstration of compliance with requirements. ENSI Guideline G03 (ENSI 2023a) states the need to minimise uncertainty, while also acknowledging the inevitability of uncertainty and the need to understand its influence on the safety assessments. It states, in particular, that the safety case must provide information on the reliability of the claims made and on the safety relevance of uncertainties, and that uncertainties must be reduced, as far as necessary and possible, by research and data collection[8].

3.2.1 Sources and types of uncertainty

It is common practice to categorise uncertainty based on its source, typically as data uncertainty (also termed parameter uncertainty), model uncertainty (also termed conceptual uncertainty), and scenario uncertainty (OECD/NEA 2012b, Nummi 2019, IAEA 2012). The sources of uncertainty in each category are numerous and varied, and include (but are not necessarily limited to) the following:

1. Data:
    - deficiencies, incompleteness and inaccuracy in experimental data, field observations, design information, test data and waste specifications (e.g., missing data, missing values, random measurement errors),
    - faultiness, unreliability and ambiguity of experimental data, field observations, design information, test data and waste specifications (e.g., as a result of ill-defined experimental conditions, single measurements, systematic measurement errors, inconsistency between data from various sources),
    - apparent randomness (variability) of features, events, and processes (e.g., earthquakes, distribution of radionuclides in waste forms, lithological variability),
    - the need to upscale or average data, to extrapolate data due to limited spatial and temporal scales of experiments and field measurements, or more generally to apply data measured under one set of conditions to a different set of conditions,
    - (related to the above) difficulty in characterising spatial variability and capturing it adequately in models; and
    - inaccuracies in elicitation procedures, misrepresentation of elicitation results, problems in expressing an individual's beliefs quantitatively, alternative perceptions of evidence by different individuals, lack of consensus (disagreement, controversy) among experts, group dynamics, bias and anchoring.

[8] *Der Sicherheitsnachweis hat Aufschluss über die Zuverlässigkeit der getroffenen Aussagen und über die sicherheitstechnische Relevanz von Unsicherheiten zu geben. Unsicherheiten sind, soweit notwendig und möglich, durch Forschung und Datenerhebung zu reduzieren.*

2. Model:
   - lack or plurality of suitable and manageable conceptual, mechanistic, stochastic (empirical) or computational models that are consistent with the available data,
   - overly simplified and overly parameterised models,
   - applicability of models outside their ranges of demonstrated or assumed validity, e.g., validity of models over the timescales or geological extent relevant to a deep geological repository; and
   - numerical errors (e.g., discretisation errors, matrix inversion errors, round-off and truncation errors).
3. Scenario:
   - the possibility of unrecognised failure (e.g., in manufacturing and installing engineered repository components),
   - alternative paths for the evolution of the repository system in terms of its main components and their safety functions that are not captured by the reference safety scenario,
   - uncertainty in the occurrence and impact of possible future geological and climatic conditions and events (e.g., timing of glaciation and the potential for significant earthquakes), and
   - uncertainty related to future human actions that could impact the performance of the repository (e.g., drilling boreholes once records of the repository are lost).

Uncertainty may also be classified by its nature as epistemic (caused by deficiencies in knowledge) or aleatory (due to the apparent randomness of relevant phenomena) (Nummi 2019). In principle, the former relates to uncertainty that can be avoided, reduced, or eliminated (e.g., by site characterisation, research, and design modifications) and the latter relates to uncertainty that cannot be reduced or eliminated in this way. In practice, it may be difficult to make a clear distinction between aleatory and epistemic uncertainties. However, both types of uncertainty can be quantified through uncertainty analysis. The results of uncertainty analysis are typically used to identify the most likely or the expected outcome, to assess the level of confidence that a certain threshold is or is not exceeded, and to quantify the level of contribution of different sources of uncertainty to the uncertainty in assessment outcomes. The results of uncertainty analysis can then be used to inform decisions or to quantify a risk.

Uncertainty is present in the assessment basis (Chapter 4) where it is quantified and treated as described in Section 4.2. The uncertainty in the assessment basis is propagated through the safety assessment, where additional sources of uncertainty such as scenario and model uncertainties are also introduced. Uncertainties in the safety assessment are handled in a variety of ways, as described in the following sections.

3.2.2 Model abstraction and the use of simplification and conservatism

The safety assessment methodology presented in this report is supported by two broad types of models:

- performance assessment models for the analysis of the THM-C evolution of the repository system. Within the context of the post-closure safety case, such models are used to evaluate claims regarding system or subsystem performance (see Section 5.2) and, in the context of site comparison, for the assessment of individual siting criteria (see Section 6.2.5), and
- radiological consequence analysis models for the evaluation of radionuclide release, retention, and transport. Such models evaluate the radiological consequences, expressed as dose rate over time, and are used, in the context of the safety case, to demonstrate safety (see Section 5.4) and, in the context of site comparison, for site-specific safety analyses (see Section 6.2.4).

Conceptual models of each type are implemented in computer codes (computational models) that solve sets of algebraic and differential equations (mathematical models) using input parameters that define initial and boundary conditions, material properties, the rates of processes, and the timing of events.

By definition, both categories of models incorporate a substantial degree of simplification. Simplification is needed because of the complexity of the repository system, the impossibility of complete system characterisation and the currently limited understanding of some processes. If appropriately justified, simplification provides a way of handling both complexity and the associated uncertainty.

Simplifications include the use of a sequence of individual models, which pass information across their interfaces, rather than basing the assessment on a single integrated model of all relevant phenomena. This type of simplification must be well justified to avoid introducing substantial additional uncertainty into the assessment outcome. Simplifications and assumptions subject to uncertainty also include those made in formulating and applying individual models. The specific calculation endpoints under consideration determine the required level of detail, and hence complexity, of the models with respect to:

- geometric abstraction: 1D, 2D or 3D representations of the repository system or components thereof can be considered,
- process abstraction: different physical processes and their couplings can be implemented to represent the relevant phenomena and processes,
- homogenisation: distributions of properties can be expressed in terms of representative values at the scale of interest, and
- boundary and initial conditions: different representations of the initial state and constraints imposed on the system can be assessed.

Regarding process abstraction, simplification can include, for example, the omission of some poorly understood phenomena. Moreover, where omission of a phenomenon cannot be justified, the approach is often to incorporate the complex or poorly understood phenomenon in a relatively simple form in the mathematical models and codes, while applying relatively pessimistic ranges to the parameter values to address the resulting uncertainty. Simplifications and assumptions that are subject to uncertainty may be justified on the grounds that they either have a negligible impact on the calculation endpoints (e.g., performance and safety indicators), or that they are conservative[9].

In the case of performance assessment models for the analysis of the THM-C evolution of the repository system, a model simplification or conservative assumption can be taken to be one that results in a calculation endpoint (performance metric) that tends to either underestimate the margin, whereby the corresponding performance target is met, or make it more likely that the target is violated. In the case of the models used for the evaluation of radionuclide release, retention, and transport and for the evaluation of dose, a conservative simplification or assumption is one that leads to an overestimation of radiological consequences. Conservatism can also be applied in the selection of parameter values for a model.

It is not appropriate to treat all uncertainties in modelling using conservative simplifications and assumptions, and by selecting conservative parameter values. This is because:

- the excessive use of conservatism could make it impossible to identify a suitable site that satisfies regulatory requirements, including constraints on dose rates and risk,
- even if regulatory constraints were met, the safety margins would remain unknown, resulting in a distorted view of the safety of the repository system, the relative roles of individual barriers and the relative favourability of different siting regions, and
- the excessive use of conservatism would also hide information about the significance of different types of uncertainty treated in this way, and hence provide no useful guidance to RD&D, design choices, and site selection and characterisation.

Furthermore, it may not always be clear *a priori* whether an assumption, simplification or parameter value is conservative, without also calculating the consequences of using alternative assumptions or parameter values, or more realistic models. For uncertainties not treated in this way, the impact of uncertainty on model output is assessed using deterministic or probabilistic uncertainty analysis, as described in the following section.

It is crucial that simplifying assumptions in the models do not lead to inconsistencies between them, or with experimental evidence, or with models built for data analyses and subjected to comprehensive testing and calibration. In this context, consistency means that the loss of accuracy introduced by model abstractions is justified and can be expressed quantitatively in terms of uncertainties. This justification is supported by model abstraction workflows that include model verification, validation, and benchmarking using different codes and experimental data. Models used in Nagra's safety assessment and the abstraction workflows developed for that purpose are described in detail in numerous supporting reports (Tab. 4-1). Specific examples of the application of these workflows include those employed in performance assessment (Chapter 4 in Nagra (2024h) and Chapter 5 in Nagra (2024s)), and for the analysis of radiological consequences (Appendices A, B and E in Nagra (2024o)).

[9] The term "conservative" applies to simplifications, assumptions, parameter values, etc., that are confidently expected to lead to calculated 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). On the other hand, an assumption or parameter value that is "pessimistic" is taken to be one that is possible, but leads to calculated consequences that are less favourable than the most likely consequences.

Measures taken to ensure models and codes used in the safety assessment are fit for purpose are briefly described in the context of quality assurance and control in Section 3.2.5.

3.2.3 Deterministic and probabilistic uncertainty analysis

Uncertainty in model output arises from the uncertainty in input data as well as from the model uncertainties of the types listed in Section 3.2.2. There are principally two complementary techniques to quantify the uncertainty in the model output due to the uncertainty in the input data: deterministic and probabilistic uncertainty analyses.

In a deterministic uncertainty analysis, uncertainty in model output is explored by defining and testing specific input parameter values. The starting point for deterministic uncertainty analysis is usually a reference (or base) case, against which a series of alternative cases is compared. The reference case builds upon reference model formulations and reference parameter values, the choice of which generally depends on the purpose of the uncertainty analysis. If the aim is to demonstrate adherence to established criteria (e.g., the analysis of radiological consequences), then more pessimistic choices could – in theory – be applied for the reference case in comparison with a study that evaluates different alternatives (e.g., in the context of siting or design optimisation). Combinations of multiple, highly unlikely possibilities are, for the most part, excluded when carrying out deterministic uncertainty analysis. Care is needed, however, that correlated phenomena or parameter combinations are not excluded on this basis (e.g., if there is a common cause for certain conditions or events). Care is also needed in view of the long timescales considered in safety assessments. Possibilities that are, for example, unlikely to occur on an annual basis, could nonetheless be likely over the course of a million years.

In a probabilistic uncertainty analysis, the selection of input data (referred to as sampling for each probabilistic "run" of a model) is carried out based on the probabilities assigned to the data (e.g., using the Monte Carlo method), and the model output is analysed using standard graphical and statistical methods of sensitivity analysis. These techniques are used, for example, in the analysis of radiological consequences, in line with ENSI Guideline G03[10] (ENSI 2023a), which states that a sensitivity analysis is to be carried out to identify the most sensitive parameters (or, more precisely, those parameters whose variance most affects variance in the results). In principle, alternative model assumptions can also be sampled probabilistically, although Nagra favours the use of either a deterministic approach or conservative assumptions to handle model uncertainty, because of the difficulty inherent in assigning probabilities to alternative models. Combination of multiple uncertainties, including where correlations exist between them, can be quantified using probabilistic uncertainty analysis, in which the entire range of input parameters judged to have non-zero probability is used as input.

Due to the use of model simplifications and conservative assumptions, especially to handle those uncertainties that cannot readily be quantified, the outcome of probabilistic uncertainty analyses should not be interpreted as the absolute probability of, for example, a performance target or safety criterion being met, but rather the probability of these being *conditionally met based on certain assumptions*. Since most of these assumptions and simplifications are conservative, the calculated probability of a criterion or target being met can be viewed as a lower bound.

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[10] *Die Sicherheitsanalyse hat mindestens die folgenden Elemente zu umfassen: […] systematische Sensitivitäts- und Unsicherheitsanalyse zur Ermittlung des Einflusses von Unsicherheiten in den Daten, Prozessen und Modellen auf die Berechnungsergebnisse.*

3.2.4 Scenario uncertainty

Uncertainty in the broad evolution of the repository system and in how the safety functions are achieved (i.e., scenario uncertainty) is handled in the safety assessment by defining and evaluating a set of safety scenarios.

In radioactive waste management, as in everyday language, the term "scenario" can have different meanings, the most relevant of which in the present context are:

- A postulated sequence of events or states as a system develops over time.
- The context or environment in which something (e.g., a waste management programme) is set.

Nagra uses the term "safety scenarios", in accordance with Swiss regulatory guidelines (ENSI 2023a), to refer to possible variants of the development of waste, engineered and geological barriers, the biosphere and the human way of life under the influence of assumed features, events and processes (FEPs)[11]. Care is taken in the selection of the set of safety scenarios to reduce scenario uncertainty by bounding and representing the possible evolutions of the repository. The development of safety scenarios as part of the safety assessment methodology is described in Section 5.3.

Some scenario uncertainties regarding possible changes in commercial and government policies (e.g., potentially for different types or volumes of waste to require disposal) are examples of uncertainties not considered within either site comparison or safety assessment.

3.2.5 Quality assurance and control

The possibility of human error in applying the methodologies presented in this report are an additional source of uncertainty. To minimise this type of uncertainty, measures of quality assurance and control (QA and QC, respectively) must be applied to all activities that use or produce models and data.

QA may be defined as encompassing all measures to check that the process of producing an outcome (e.g., a dataset) or delivering a service (e.g., doing an assessment) meet the requirements set forth on the process. QA measures used by Nagra in safety assessment include check lists, audits, and process evaluations, and they are usually carried out by the persons involved in the process. By contrast, QC may be defined as checking the product after it has been produced. QC measures used by Nagra in the safety assessment include product tests, peer reviews and inspection tests, and these are preferably carried out by persons that are not involved in the model development and analysis.

Specific measures to ensure that the models and databases used in safety assessment are fit for purpose, that the mathematical models are implemented correctly in computational models, that the computational models are reliable and that they are applied correctly and without error are presented in Nagra (2024o) and Nagra (2024s). These include a comparison of model outputs with the results of experiments covering a range of spatial and temporal scales and with observations of natural systems and verification of numerical codes, e.g., by benchmarking against analytical solutions and against other codes that address similar problems.

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[11] *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 the analysis of radiological consequences, specific QA and QC workflows are presented in Appendix F of Nagra (2024o) and, where necessary, with respect to individual codes in Appendix D of Nagra (2024o).

3.3 FEP audit and issue of completeness

A prime concern in safety analyses and safety assessment is the issue of phenomenological "completeness", that is, the need to demonstrate that:

- FEPs and their interactions that could affect post-closure safety have been thoroughly identified.
- These FEPs have been adequately managed in the safety assessment.

Although it is impossible to prove beyond all possible doubt the completeness of a safety assessment, that is, "completeness uncertainty" can never be eliminated, measures can be taken to ensure the inclusion of a comprehensive set of potentially relevant phenomena and, equally importantly, to ensure that the safety-relevant phenomena have been represented appropriately in the assessment.

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. Understanding of the initial state and post-closure evolution of the repository, on which performance assessment, safety scenario development and the analysis of radiological consequences are based, is synthesised in the description of the phenomenological evolution of the repository (Nagra 2024j) together with the more detailed account of the characteristics and evolution of the site provided by the geosynthesis (Nagra 2024g). The description of the phenomenological evolution of the repository has been developed iteratively over many years, with each version having been peer reviewed, drawing on Nagra's extensive RD&D programme (Nagra 2021c). Similarly, the geosynthesis is one of the central results of the systematic site selection process, which also followed a step-wise approach with regular quality assurance and peer reviews. The comprehensiveness of the descriptions is further assured by effective information exchange between safety assessors and technical experts within Nagra and between these experts and the wider scientific community.

A FEP audit has been carried out to confirm that all FEPs are either included in the safety assessment or that their omission is well justified. As described in Section 4.5.3, a database of FEPs has been developed iteratively over many years, largely independently of the main safety assessment process[12]. Each version has been reviewed by internal Nagra experts and external third-party experts, and compared with other relevant FEP databases compiled by national organisations in other countries and by international bodies. The FEP audit then considers whether all the FEPs in the FEP database have been adequately treated in the safety assessment. More specifically, the audit consists of assigning each FEP to one of the groups defined in Tab. 3-1.

[12] One exception is that part of the methodology dealing with the development of future human action (FHA) safety scenarios, where FHA FEPs provide the starting point for development (see Section 5.3.5). For these particular safety scenarios, the FEP audit does not, therefore, provide an additional completeness check.

Tab. 3-1: Grouping of FEPs according to their handling in the safety assessment

Each group is described in Nagra (2024i)

<table>
<tr><th colspan="2" rowspan="2"></th><th colspan="2">Handling in the safety assessment</th></tr>
<tr><th>Included</th><th>Excluded</th></tr>
<tr><td colspan="2">FEPs outside the assessment scope or not relevant to the safety assessment</td><td>×</td><td>0</td></tr>
<tr><td rowspan="2">Features of the initial state or FEPs affecting the initial state of the repository system</td><td>Safety-relevant site and design features and planned implementation</td><td>1</td><td>×</td></tr>
<tr><td>Other site and design features and deviations from design</td><td>2</td><td>3</td></tr>
<tr><td rowspan="3">FEPs occurring during the post-closure period</td><td>Geological and climatic</td><td rowspan="3">4</td><td rowspan="3">5</td></tr>
<tr><td>Repository-related</td></tr>
<tr><td>Future human actions and activities</td></tr>
<tr><td colspan="2">Biosphere and surface / near-surface environment FEPs</td><td>6</td><td>7</td></tr>
</table>

Each FEP is assigned to a category ranging from 0 to 7, according to its type and its handling in the safety assessment. A FEP can be excluded if it is outside the scope of the safety assessment (Category 0) or because it can be shown to be irrelevant to performance and safety for the site and design under consideration (Categories 3, 5 and 7). FEPs that are outside the scope of the assessment are clearly not included (as indicated by a red cross). Furthermore, all identified safety-relevant site and design features or features of the planned implementation are included – none are excluded (as also indicated by a red cross).

FEPs can be included in different ways, for example:

- 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 must be 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.

A similar FEP audit was also undertaken in Project *Entsorgungsnachweis* (demonstration of disposal feasibility), as described in detail in Nagra (2003). For the present safety case, the FEP audit is documented along with the phenomenological evolution of the repository in Nagra (2024j, 2024i).

As a final point on the topic of completeness, as discussed in Section 5.3.2.3, "what-if?" cases are defined and analysed as part of the safety assessment. These "what-if?" cases involve extreme and hypothetical assumptions. The primary aim is to illustrate the robustness of the system, but such analyses may also pre-empt potential criticism that the selected ranges of parameter values are too narrow or that some detrimental FEPs are either unknown or have been overlooked.

3.4 Time period for assessment

The time period for assessment refers to the main period of concern from the perspective of post-closure safety. Regulatory guidance in ENSI Guideline G03 (ENSI 2023a) states that a period of up to one million years shall be addressed by the safety case, and that the temporal development of the radiological hazard potential of the emplaced waste and the predictability of the long-term geological evolution shall be taken into account[13]. In Nagra (2008), based on the decrease in radiotoxicity that occurs over time, the time period for assessment (referred to in the context of site comparison as the time period under consideration) was defined as extending up to 100,000 years for a L/ILW repository and up to one million years for a HLW repository. These time frames have been confirmed and are also adopted during Stage 3 of the Sectoral Plan and for the general licence application (Nagra 2024a).

Specifically, they are adopted in the site comparison for Stage 3 of the Sectoral Plan, when considering separate HLW and L/ILW repositories. The shorter period considered for the L/ILW repository based on considerations of radiotoxicity is also consistent with ENSI guidelines[14] (ENSI 2018b). For the safety assessment, which considers a combined repository for HLW and L/ILW at the Haberstal site, a period extending up to one million years is considered, although, when considering specific processes which may, in some cases, become insignificant much earlier than the defined time period for assessment (such as, e.g., the heat output from the waste), a shorter timeframe can be chosen that is appropriate to the process at hand.

ENSI Guideline G03 (ENSI 2023a) also requires that dose calculations carried out to determine the release, retention and transport of radionuclides shall be performed up to the time of the maximum radiological impact of the deep geological repository[15]. To meet this requirement, the timeframe covered by the calculations is extended, where necessary, to 10^7 years for releases from the HLW disposal area and to 10^6 years for releases from the L/ILW disposal area.

Finally, beyond the time period for assessment, ENSI Guideline G03 (ENSI 2023a) requires that the range of potential radiological impacts of a deep geological repository be determined, taking into account inherent uncertainties, and that scenarios in which the deep geological repository area is increasingly exposed to influences from the earth's surface due to geological processes should be included in these considerations[16]. The main concern here is glacial and fluviatile erosion, which affect the repository barrier system and may ultimately lead to excavation of the remnants of the waste itself, albeit most likely on a timescale of well in excess of one million years. This is addressed in a dedicated report on the radiological consequences of deep geological excavation by erosion processes, where time frames beyond the defined time period for assessment are taken into consideration (Nagra 2024p).

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[13] *Für den Sicherheitsnachweis ist ein Nachweiszeitraum von bis zu einer Million Jahre festzulegen. Die zeitliche Entwicklung des radiologischen Gefährdungspotenzials der eingelagerten Abfälle und die Prognostizierbarkeit der geologischen Langzeitentwicklung sind zu berücksichtigen.*

[14] *Falls gezeigt werden kann, dass durch das geologische Tiefenlager aufgrund des radiologischen Gefährdungs-potenzials der Abfälle bereits nach weniger als einer Million Jahre nur noch vernachlässigbar kleine radiologische Auswirkungen für Mensch und Umwelt zu erwarten sind, kann der Nachweis für einen kürzeren Betrachtungs-zeitraum geführt werden.*

[15] *In der Sicherheitsanalyse sind Dosisberechnungen bis zum Zeitpunkt der maximalen radiologischen Auswirkungen des geologischen Tiefenlagers durchzuführen, mindestens jedoch bis zum Ende des Nachweiszeitraums.*

[16] *Für die Zeit nach Ablauf des Nachweiszeitraums ist der Variationsbereich der möglichen radiologischen Auswir-kungen eines geologischen Tiefenlagers unter Berücksichtigung der inhärent vorhandenen Unsicherheiten zu ermitteln. Szenarien, in denen der Tiefenlagerbereich aufgrund geologischer Vorgänge zunehmend Einflüssen der Erdoberfläche ausgesetzt wird, sind in diese Betrachtungen einzubeziehen.*

4 Assessment basis

4.1 Development and documentation of the assessment basis

ENSI Guideline G03 (ENSI 2023a) states that, for the safety case, data, processes, and model concept shall be used that are in accordance with the state of the art in science and technology, and that their uncertainties shall be identified[17]. It also states that the available technical and scientific data on the deep geological repository and its surroundings, the information on the emplaced waste packages, the findings obtained during operation and the results of monitoring shall be taken into account in the safety case[18]. Nagra considers these items to be part of the "assessment basis", which is taken to include the evidence, knowledge, assessment tools and methodologies developed or acquired in support of site selection and safety assessment. The main elements of the assessment basis are summarised in Fig. 1-1.

The methodologies described in the present report are part of the assessment basis. Other key elements of the assessment basis include the general scientific understanding of the waste inventory, an integrated understanding of the host rock and its geological setting, also termed the "geosynthesis" (Nagra 2024g), and an understanding of the phenomenological evolution of the repository (Nagra 2024j). The assessment basis also includes the models, codes and databases used in the quantitative analyses supporting both the comparison of the siting regions and the safety assessment for the combined repository in the proposed siting region (see Sections 4.4 and 4.5).

4.2 Information gathering and integration

The body of information that is contained within the assessment basis includes information gathered from a variety of sources, and the associated uncertainty represents a mixture of epistemic and aleatory types (see Section 3.2.1). The process of information gathering may be broadly subdivided into:

- field observations and monitoring activities,
- laboratory experiments, field testing and demonstration / verification activities,
- modelling studies,
- literature surveys, and
- expert elicitation.

Each of these is summarised in the following sections, with emphasis on the origin and handling of uncertainty.

4.2.1 Field observations and monitoring activities

Field observations and monitoring are continuous, single, or recurrent, relatively passive measurement activities to assess the geological and environmental conditions at the proposed site, or sites, prior to repository implementation. Their purpose is to establish an initial base level for relevant parameters, and to track changes during the implementation period and possibly for some time

[17] *Für den Sicherheitsnachweis sind Daten, Prozesse und Modellkonzepte gemäss Stand von Wissenschaft und Technik zu verwenden und deren Unsicherheiten aufzuzeigen.*

[18] *Die verfügbaren technisch-wissenschaftlichen Daten über das geologische Tiefenlager und seine Umgebung, die Informationen über die eingelagerten Abfallgebinde, die während des Betriebs gewonnenen Erkenntnisse und die Ergebnisse der Überwachung sind im Sicherheitsnachweis zu berücksichtigen.*

beyond. Given that the properties of natural media feature a certain degree of random variation in space and time, and given that environmental influences on the measurement processes can neither be fully determined nor fully eliminated, the data obtained include relatively large amounts of aleatory uncertainty. Additional uncertainty arises from systematic measurement errors due to improper calibration procedures or long-term drift of measurement devices. Missing data (e.g., due to remote device failure) or missing metadata (e.g., non-recorded location and time of measurement) may substantially contribute to the overall level of uncertainty. Such uncertainty must usually be accepted and cannot be reduced.

Irreducible uncertainty in field observations and monitoring is handled by using averaging (reporting a reference value), reporting the bounding values or by defining probability density functions (PDFs), which are carried through to the modelling performed in support of the site selection and the post-closure safety assessment.

When the number of observations is large, as is the case for minerology, porosity and temperature of the geological formations in the siting regions, a range of possible values including reference value is estimated directly from the data. When the number of observations is limited as for, e.g., hydraulic head measurements, the estimation of reference and bounding values is achieved by including conceptual models and expert judgement (Nagra 2024f).

Additionally, in the case of diffusion coefficient and sorption limits for each radionuclide in each geological unit, the parameter values and the corresponding PDFs are inferred directly from the available geological dataset (Glaus et al. 2024, Marques Fernandes et al. 2024).

4.2.2 Laboratory experiments, field testing and demonstration / verification activities

Laboratory experiments, field testing, and demonstration / verification activities are single or recurrent and constitute relatively short measurement activities performed at the sites under consideration or at similar sites (e.g., at the Mont Terri Rock Laboratory). These activities are commonly designed with high levels of intrusion or perturbation to the system under study. In contrast to field observations and monitoring, these activities occur in a setting with a higher degree of control over environmental influences on the measurement processes (e.g., diffusion experiments in the laboratory). Additionally, this may include an enhanced level of perturbation to accelerate the process being measured or to mimic conditions that are expected to pertain under repository conditions (e.g., heater experiments). The greater control of external influences and higher stimulation may result in a higher signal-to-noise ratio in measured data compared with more passive activities. However, other sources of uncertainty in passive activities are equally relevant for more active measurements. Uncertainty is handled using the same methods as those used for more passive activities, as described above.

4.2.3 Modelling studies

In the context of the assessment basis, modelling studies are carried out to analyse specific aspects of the behaviour of the repository system or similar systems, to design passive and active measurement activities, to process or interpret measured raw data (parameter estimation), to predict data that have not yet been obtained, and to test different model formulations.

The model uncertainties are managed through comparison of available models, documenting the justification for choosing the specific model, validating the chosen model against experimental data, benchmarking the results of the model against other available models or data, and ensuring appropriate QA and independent review processes.

4.2.4 Literature surveys

Literature surveys are useful for gathering and interpreting existing, documented information that may be relevant to the repository system under consideration, including information on other systems with comparable features (e.g., natural and anthropogenic analogues, other repository systems in similar host rocks) and also past studies on the repository system under consideration. Common sources are published literature, technical reports from international waste management organisations, and electronic databases.

Uncertainty regarding literature surveys can be divided into uncertainty in the reported information and uncertainty in the process of gathering the reported information. Uncertainty in the reported information relates to incomplete information, outdated information, false information, insufficiently quantified information, lack of reported uncertainty, etc. Uncertainty in the process of gathering data from literature refers to expert judgement on relevance, credibility, correctness, bias, comprehensiveness, applicability, and transferability of the reported information. Nagra keeps such uncertainty in check via good documentation and management of documentation, which are both key to maintaining credibility and traceability of information from literature surveys that feed into the assessment basis. One example of such documentation is the report on corrosion rates of metals relevant for the provisional repository design (Diomidis et al. 2023).

4.2.5 Expert elicitation

The goal of expert elicitation is often to quantify uncertainty in key parameter values, especially where these have to be based on a range of evidence of different types, different quality or different or uncertain degrees of applicability to the problem at hand, and so an element of subjective judgement is needed. Expert elicitation may also be used to evaluate the confidence in, and potential applicability of, competing alternative conceptual models (Gosling 2018). Uncertainty in expert elicitation arises from:

- Anchoring, which is the tendency to rely too heavily on, or to be biased in favour of, pre-conceived notions, "typical" values of a parameter, or views formed based on early information received on a topic.
- Over-/under-confidence related to the experts' false understanding of what they do not know.
- Motivational biases (e.g., experts may try to be excessively conservative or, by contrast, may be unduly optimistic due to a conviction that the system is safe or a desire for it to be so).
- Application of heuristics (e.g., practical methods, or "rules of thumb", for making judgements that are often based on past experience and may be widely used, but are not guaranteed to be optimal, logical or rational in the context of disposal).

These uncertainties can be minimised by using a structured elicitation approach that, for instance, provides some training before the actual elicitation takes place and/or focuses first on the unlikely values of a parameter to avoid value anchoring (e.g., the structured elicitation approach outlined in RWM (2017)). As of today, a number of different types of structured expert elicitation procedures have been developed for different purposes, all with their own advantages and disadvantages in terms of complexity, duration, and resources needed (e.g., Budnitz et al. (1997) Cooke (1991) and O'Hagan (2019)).

The elicitation process helps to identify strengths and weaknesses in the available data and arguments, thereby supporting uncertainty assessment. As for literature surveys, good documentation of the elicitation process is key to maintaining the credibility and traceability of the resulting information that feeds into the assessment basis.

For the assessment basis used in the present methodology, Nagra has employed expert elicitation in the context of climatic and geological long-term evolution (Nagra 2024g).

4.2.6 Integration / synthesis of information

Where different types or sources of information are available, an ensemble of information, possibly with different representations of uncertainty, must be integrated to provide, as far as possible, a coherent, logical, realistic, and defensible description of the repository system and its environment, including statements of uncertainty. Where the integration of information involves the evaluation of a quantity that is a function of several variables, each of which has its own attendant uncertainty, these sources of uncertainty must be combined to obtain a measure of the overall uncertainty in the quantity of interest. This is generally achieved using computer-based deterministic and probabilistic methods of uncertainty analysis (see Section 3.2.3).

Where no formal methods are used to integrate uncertain information, the synthesis of information is carried out by a single expert, or by a team of experts, judged to have a good overview of the topic at hand. Integration may therefore involve a substantial amount of subjective judgement. To keep linked uncertainty in check, all steps involved in this synthesis, along with their respective input and output information, must be documented in a clear and traceable manner. Independent reviews ensure that the information that feeds into the assessment basis is coherent and as unbiased as possible.

4.3 General scientific understanding

4.3.1 Geosynthesis

The current, integrated understanding of the geology of Northern Switzerland in the three potential siting regions considered in Stage 3 of the Sectoral Plan is provided in a geosynthesis (Nagra 2024g), which includes information on:

- the past geological evolution of Northern Switzerland,
- the current properties of the CRZ and other relevant geological elements, including their mineralogical composition, porosity, porewater and groundwater composition, geomechanical behaviour and tectonic overprint, hydraulic and diffusion properties and self-sealing capacity, and
- long-term climatic, tectonic, erosion, hydrogeological and geochemical evolution in the future.

Aspects of long-term geological evolution that are addressed include future climate evolution and glaciations, future tectonic evolution, future erosion, hydrological and hydrogeochemical evolution and changes to the barrier properties of the host rock and confining units arising from natural climatic and geological events processes. The geosynthesis is supported by complementary geological datasets, which include detailed geological information on the three siting regions (Section 4.5.2).

4.3.2 Initial state and phenomenological evolution of the repository

The expected initial state of a combined repository for HLW and L/ILW in the Opalinus Clay at the time of excavation of the underground openings and emplacement of the waste and engineered barriers and its subsequent phenomenological evolution is described in Nagra (2024j) and summarised in Nagra (2024e) as part of the description of the reference safety scenario. Although this description assumes a combined repository, much of it is also applicable to two separate repositories for L/ILW and HLW. The phenomenological evolution of the repository addresses the safety-relevant impacts of repository-induced effects on the engineered and geological barriers, such as thermal effects, the formation and development of disturbed zones around the underground openings, and the interaction between cement and clay, as well as the effects of gas generation and gas pressure development. It also covers the impact of geological and climatic processes.

The report does not address the potential impacts of FHAs or the release, retention, transport, and fate of radionuclides in the engineered and geological barriers or in the biosphere. These topics are extensively covered in other detailed reports (Nagra 2024o, Nagra 2024q, Nagra 2024k, Walke & Thorne 2023, Nagra 2024t).

4.4 Safety assessment models and codes

Multiple different models and codes are used in the safety assessment, as well as in the comparison of siting regions. Model development inevitably involves a degree of simplification or abstraction, as discussed in Section 3.2.2. Tab. 4-1 shows some of the most important codes and their purposes.

Tab. 4-1: Examples of some of the most important computer codes used in site-specific safety analyses and in safety assessment

Code	**Main purpose**	**References**
STMAN 5.10	Evaluation of radionuclide release, retention and transport in the aqueous phase in the HLW repository near-field.	Robinson (2022)
VPAC 1.1	Evaluation of radionuclide release, retention and transport in the aqueous phase in the L/ILW repository near-field.	Holocher et al. (2008)
PICNIC 1.5.1	Evaluation of radionuclide release, retention and transport in the aqueous phase in the geosphere.	Robinson & Chittenden (2022)
TOUGH3 EOS 75r	Evaluation of volatile C-14 release, retention and transport in the repository system and the geosphere.	Zhang et al. *(in prep.)*
TOUGH3 EOS5	Assessment of gas and thermal repository-induced effects.	Jung et al. (2018)
SwiBAC 2.0	Biosphere modelling for different climates and geomorphologies.	Nagra (2024k)
AMBER 6.7	Assessment of the radiological consequences of repository excavation by erosive processes.	Nagra (2024p)
PhreeqC	Aqueous geochemical calculations, including speciation, batch reaction, and one-dimensional reactive transport.	Fernández et al. (2014)

4.5 Databases

Over the past ten years, Nagra has built up a comprehensive metadata catalogue, the so-called General Data Management System (GDMS). This is a software tool especially developed for Nagra for the collection and management of metadata on all types of raw technical and scientific data that Nagra has collected or acquired in the course of the Sectoral Plan process. The data themselves are stored on various servers in file formats that comply with industry standards and can therefore be opened by all common software packages. The metadata are managed in an SQL server database and can be accessed via a local desktop client or special plug-ins, e.g., the geographic information system (GIS). The desktop client supports Nagra employees in searching for data, entering metadata for their own research results and submitting data to third parties. All data are linked to the corresponding reports or other information via the GDMS. All data that flows from Nagra to external users are logged in the system. The GDMS contains over 100,000 metadata records on all types of data, such as seismic measurements, logging, core photos, GIS, geological 3D models, computer-aided design (CAD) including building information modeling (BIM), geodetic and hydrological measurement series, results of safety analyses, waste inventories and much more. Entire databases, as well as physical data such as cores, samples etc., can be managed with the GDMS. The Nagra GDMS makes all important data findable, accessible, interoperable and reusable (so-called FAIR principle). Examples of the databases maintained in Nagra GDMS are provided in Sections 4.5.1 and 4.5.2.

4.5.1 Waste and nuclide inventory databases

The current description of the waste and of the nuclide inventory is based on MIRAM, the "Model Inventory of Radioactive Materials". This database quantifies and characterises all existing and future radioactive waste in Switzerland, including SF assemblies. The current MIRAM database for the general licence applications (MIRAM-RBG) was published in 2023 (Nagra 2023b). The calculation of the waste volumes assumes a 60-year operating lifetime for the existing nuclear power plants Beznau I and II, Gösgen and Leibstadt, and a 47-year operating lifetime for the Mühleberg nuclear power plant, which was shut down in 2019 and is currently being decommissioned. In addition, the generation and collection of radioactive waste from medicine, industry and research up until 2065 are considered in MIRAM-RBG (Nagra 2023b). A consistency check of this model inventory is made by reassessing the underlying assumptions of this waste inventory projection for each project milestone.

4.5.2 Geological characterisation of the siting regions

The geological characterisation of the siting regions (Nagra 2024f) provides the description of the three siting regions as input for their quantitative comparison and for the safety assessment of a combined repository in Nagra's proposed siting region. It includes:

- **stratigraphic abstraction**, which divides the CRZ into units with similar characteristics with regard to key parameters for safety assessment (e.g., diffusive and advective transport),
- **stratigraphic surfaces** defining the geometry of these units in 3D, including their thickness,
- **faults** mapped in 3D seismics,
- mineralogy, porosity and density of the units,
- **hydrogeological and geochemical information**, such as hydraulic conductivity of the units, heads, hydraulic gradients and the porewater hydrochemistry, and
- **geomechanical properties** of the Opalinus Clay and of overlying and underlying units, including information on the stress field (orientation and magnitude).

4.5.3 Nagra FEP database

The Nagra FEP database, which has been developed over many years, is presented in brief in this section.

The FEP database for Project *Entsorgungsnachweis* (termed the OPA FEP List) was developed based on an earlier Nagra FEP list related to the disposal of RP-HLW in a crystalline host rock (Sumerling et al. 1993) and on several ancillary FEP lists compiled by Nagra and Nagra's consultants, which considered various specific aspects of the proposed repository system. The ancillary FEP lists focused on those aspects of the repository system and its assessment that differed from earlier Nagra safety assessments (i.e., FEPs related to disposal of SF and ILW, and FEPs related to the performance of the Opalinus Clay as a host rock and migration barrier).

The OPA FEP List was developed internally by Nagra through a process of accumulation, addition, organisation, and rationalisation based mainly on the experience of Nagra staff. To promote comprehensiveness of the OPA FEP List, an audit was performed, where the OPA FEP List was compared with two independently derived FEP lists:

- The NEA International FEP List (OECD/NEA 2000), which provided a comprehensive list of relatively generically described FEPs that were intended as either a starting point, or an audit tool, for the assessment of any solid radioactive waste repository system.
- The NEA FEPCAT catalogue of FEPs related to natural clays (Mazurek et al. 2003), which was based on a compilation and review of observations and results from experimental studies on natural clay samples in the laboratory and in underground testing facilities.

Following Project *Entsorgungsnachweis*, the FEP database was further updated by Nagra based on RD&D work carried out in the intervening years. A formal completeness check of the updated database was then carried out, as reported in Metcalfe et al. (2020). This check involved comparing the database against the FEPs in the following four FEP lists:

- the NEA International FEP (IFEP) list V3.0 (OECD/NEA 2019),
- the Canadian Nuclear Waste Management Organization's (NWMO's) FEP list for the Seventh Case Study for a deep geological repository for used CANDU fuel at a hypothetical site in a sedimentary rock environment (Garisto 2018),
- Ontario Power Generation's (OPG's) FEP list for the post-closure safety assessment of the proposed low- and intermediate-level radioactive waste disposal facility at the Bruce site in Ontario (Quintessa Ltd. et al. 2011), and
- the Belgian radioactive waste management organisation's (ONDRAF/NIRAS's) FEP list (ONDRAF/NIRAS 2018).

The database was updated based on this completeness check, reviewed and, where necessary, modified. It is this version of the FEP database that is used in the safety assessment in support of the general licence application and is documented in Nagra (2024i).

4.5.4 Other databases

Several other databases are used as sources of data for safety assessment. Tab. 4-2 shows some of the most important of these. Details and justifications related to specific data used for performance assessment and the analysis of radiological consequences are provided in Nagra (2024h), Nagra (2024m) and Nagra (2024o), respectively.

Tab. 4-2: Examples of some of the most important databases used as data sources for safety assessment

Database	Description and main purpose	References
Biosphere sorption database	Sorption coefficients for use in the biosphere assessment.	Metcalfe et al. (2023)
PSI/Nagra thermodynamic database	Thermodynamic data for various elements, aqueous species, solids, and gases for safety assessments.	Hummel & Thoenen (2023)
Solubility limits	Solubility limits for model Opalinus Clay porewaters as input for sorption and diffusion databases.	Kulik & Miron (2024)
Sorption database	Sorption data for clay as input of transport models for safety assessments.	Marques Fernandes et al. (2024)
Diffusion database	Diffusion data for Opalinus Clay as input of transport models for safety assessments.	Glaus et al. (2024)
CEMDATA 19	Thermodynamic database for the modelling of cement hydration, cement mineral equilibria, cement porewater (in connection with the PSI database) for use in safety assessment.	Lothenbach et al. (2019)
Solubility limits	Solubility limits for the cementitious near-field, including effect of EDTA.	van Laer et al. (2022)
Cement sorption database	Sorption coefficients to calculate radionuclide transport in the cement-based near-field of the L/ILW repository section.	Tits & Wieland (2023)
Solubility limits	Solubility limits for the bentonite near-field.	Hummel et al. (2023)

5 Methodology for the safety assessment in support of the post-closure safety case for a combined repository

5.1 Main steps in safety assessment

The high-level workflow required for carrying out the safety assessment for a combined repository in the proposed siting region in support of the general licence application is illustrated in Fig. 1-2. As shown on the right-hand side of the figure, the safety assessment consists of the following main processes:

- **Performance assessment**, defined by Nagra as an analysis of the THM-C evolution of the repository system. Performance assessment tests whether the expected evolution of the repository system, as provided by the assessment basis (Nagra 2024j), is indeed the expected evolution based on the arguments and evidence available. Performance assessment also identifies uncertain, potentially detrimental phenomena and other uncertainties that could degrade the functionality of the components of the repository system or of the repository system as a whole, as input to safety scenario development.
- **Safety scenario development**, which entails the identification and description of a set of safety scenarios that capture uncertainty in the initial state of the repository system and different ways in which it could evolve over time. Based on the knowledge provided by the assessment basis and the findings of the performance assessment, safety scenario development aims to systematically shift the emphasis of the safety assessment to the phenomena that might put the post-closure safety of the repository in question.
- **Analysis of radiological consequences,** which consists of an evaluation of radionuclide release rates to the surface environment as a function of time for calculation cases identified in the safety scenario development. The analysis includes the conversion of these release rates into safety indicators, such as annual individual effective doses (Section 5.4.2.3), which are compared with regulatory protection criteria to assess the available safety margin.
- **Demonstration of post-closure safety,** in which evidence, arguments and analyses from the three previous steps are brought together with other information supporting the quality of the safety assessment, the safety and robustness of the repository system, and the strength of the stepwise repository siting, design and implementation processes, in the safety case.

These safety assessment processes are elaborated further in the following sections. As also illustrated in Fig. 2-3, these processes have a close relationship to the objectives, principles and criteria that lead to the development of a safety concept and, eventually, the repository design. In principle, the analysis of the system as designed begins before the performance assessment and with a verification that requirements on the site, design and waste can be met, including, for example, an assessment of deviations from design specifications that may occur when the repository is constructed, operated, and closed. Work to date on this step is documented in the assessment basis and will be completed within the context of future licensing steps. At the current stage, it is generally assumed that suitable waste acceptance criteria are applied, a suitable location for the repository within the siting region can be identified and suitable engineering methods are used to implement the repository in accordance with the requirements on the site, design, and waste. However, some postulated deviations from design specifications are also considered. It is expected that the impact of such deviations will be bounded through systematic safety scenario development and analysis.

5.2 Performance assessment

5.2.1 Performance assessment workflow

Performance assessment is the first process carried out in the general safety assessment workflow leading to a robust post-closure safety case for the combined repository at the proposed site (Fig. 1-2). Following international standards of transparent and traceable assessment workflows (OECD/NEA 2002), performance assessment evaluates the long-term performance of the repository at a level of simplification which bridges the gap between the real-world repository system and its highly abstracted representation in the analysis of radiological consequences.

The performance assessment part of the general safety assessment workflow is elaborated in Fig. 5-1. Performance assessment involves four main steps:

1. assessment of barrier performance for each of the pillars of safety of the multi-barrier system,
2. assessment of the entire system (total system performance), to account for any possible THM-C interactions between the individual barrier components,
3. assessment of uncertainties associated with the simplified representation of the real-world repository system in an abstracted performance assessment framework (uncertainty propagation associated with the abstraction process), and
4. assessment of deviations from expected repository performance by barrier and by interaction ("screening of performance assessment scenarios").

The auditability of the assessment workflow is ensured with a traceable method of proof. For this, claims are formulated, which concern the contribution of each component of the multi-barrier system, and of the repository system as a whole, to the repository safety functions defined in Section 2.3. The claims, which are closely related to the component-specific functions also discussed in Section 2.3, are supported by suites of arguments. A claim can be deemed robust if it is well substantiated using sound arguments, which are themselves supported by convincing evidence. The robustness of a claim is strengthened by seeking a wide spectrum of arguments which can be assigned broadly to the following categories: (i) empirical knowledge, such as experience from other radioactive waste disposal programmes, (ii) dedicated scientific and technical knowledge that has been acquired specifically in the context of the repository project, and (iii) a safety-oriented repository design.

The evidence that supports these arguments can also come from multiple sources (empirical evidence from desk studies and collaborations with other radioactive waste disposal programmes, experimental evidence from targeted site investigation programmes, model-supported evidence derived from sensitivity and robustness analyses); see the discussion of information gathering and integration in Section 4.2. A balanced evaluation of arguments and evidence provides important insights to the limitations of repository performance when the multi-barrier system is subjected to internal or external perturbations.

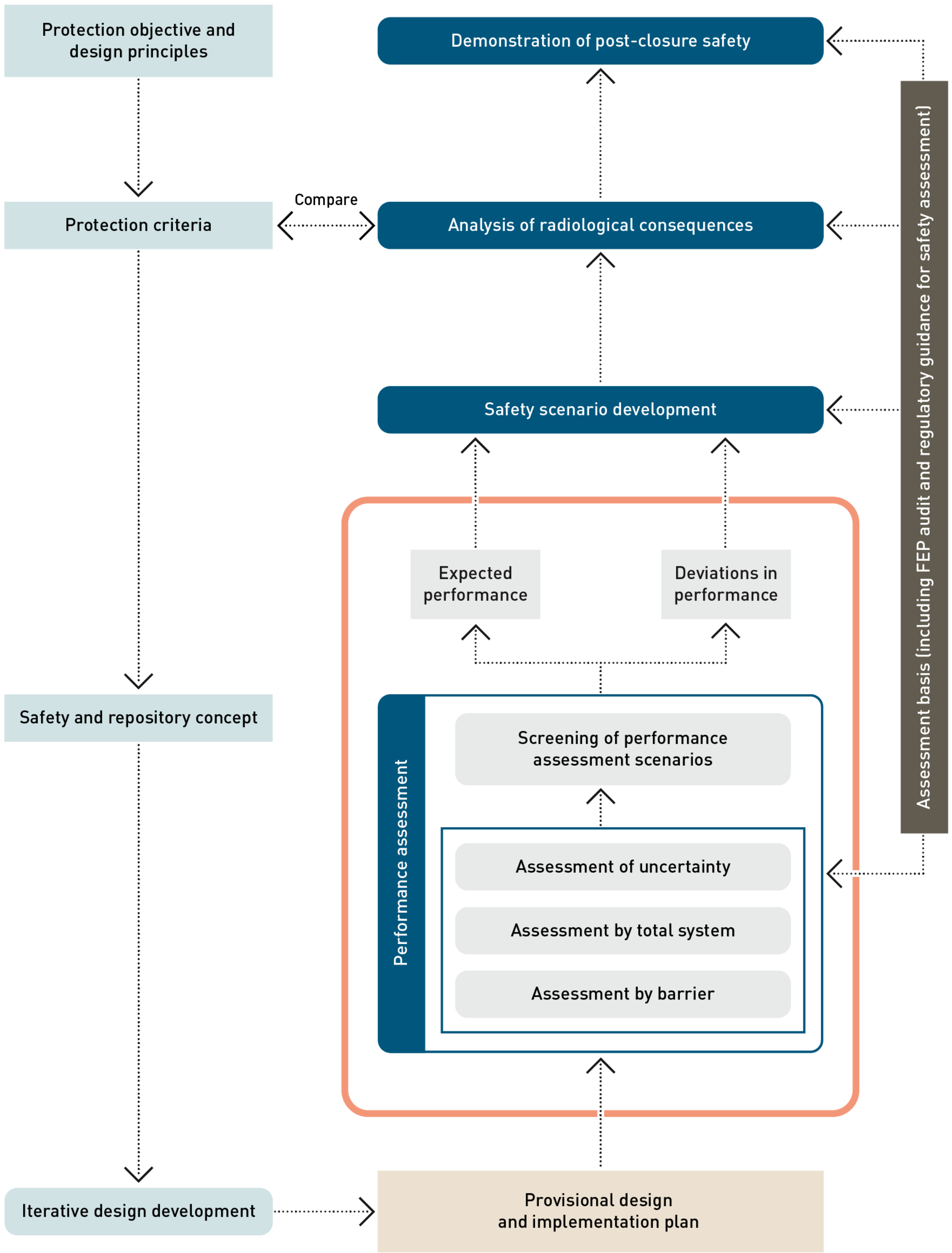

Fig. 5-1: Workflow of post-closure safety assessment, highlighting the workflow and outcomes of the performance assessment process

As discussed in general terms in Section 3.2, the traceable handling of uncertainty is an indispensable element of safety assessment and of the assessment workflow. In the case of performance assessment, evidence must be provided that the modelling tools and approaches applied for the quantitative assessment of barrier performance at both the component and total system level adequately represent the safety-relevant processes and phenomena identified through the general scientific understanding of the repository and its environment (Section 4.3). Adequate consideration of uncertainty propagation along the performance assessment model chain allows for uncertainty quantification with the aim of bracketing the confidence bounds on the expected system response.

It is the role of performance assessment to screen the possible paths of repository evolution and to identify, bundle and formulate safety-relevant deviations from expected repository performance as input to safety scenario development. From the performance assessment perspective, the possible paths of repository evolution are classified in terms of the expected performance of the multi-barrier system and deviations thereof. Deviations from expected performance are analysed at the component level and at the level of the entire repository system with emphasis on the likelihood of occurrence and on their relevance for safety.

5.2.2 Assessment by barrier

Recalling the general safety and repository concept for the combined repository set out in Section 2.3, the main barriers and other features contributing to the safety functions are termed "pillars of safety". Fig. 2-4 and Fig. 2-5 illustrate schematically how the pillars of safety contribute to the various safety functions. Performance Assessment claims are formulated on how each of these pillars of safety contributes to the safety functions, and the supporting arguments for these claims are collected. For example, the following claim is made for the SF matrix regarding its contribution to the safety function of immobilisation, retention and slow release of radionuclides:

- Claim – *The SF near-field (SF pellets) represents an environment which ensures immobilisation, retention and slow release of radionuclides.*

This claim is supported by the following arguments (note, this list of arguments is not exhaustive):

- Argument I – *The majority of radionuclides are bound in the* UO_2*, MOX mineral phases.*
- Argument II – *The instant release fraction from SF corresponds to only a small fraction of the total radionuclide inventory.*

These arguments are, in turn, supported by dedicated SF dissolution experiments, many general studies on fuel dissolution and activation calculations. Model-based assessments of tracer transport in the CRZ confirm the important role of the SF matrix, contributing to the immobilisation and slow release of radionuclides. These and other lines of arguments and evidence, taken together, strengthen the claim that there is effective radionuclide retention in the SF matrix, building confidence in the performance of the SF matrix as a pillar of safety.

In a similar manner, claims, arguments and evidence are developed for each pillar of safety. Subsequently, their contribution to the overall performance of the repository is assessed.

5.2.3 Assessment by total system

The construction and operation of the repository and the emplacement of waste, backfill and other materials change the environmental conditions in the vicinity of the underground structures and create a thermal, hydraulic, geomechanical and geochemical disequilibrium in the repository near-field over an extended period of time. This perturbation of the physico-chemical conditions can give rise to THM-C interactions between the repository components. The impact of such THM-C interactions on the overall performance of the repository system ("total system performance") is addressed in the performance assessment of the total system behaviour.

The performance assessment workflow at the total system level is executed similarly to the assessment at the component level. However, claims are postulated only for those safety functions that are relevant at the level of the total system, most notably the safety function of "*compatibility of the multi-barrier-system elements*" (Fig. 2-4 and Fig. 2-5). Compatibility is of particular significance because THM-C interactions between the repository components could potentially impair the overall barrier integrity of the repository system.

The claims are postulated for each type of interaction. Arguments are elaborated which support the claims on a qualitative or quantitative level. Convincing evidence is sought to confirm the line of arguments in a robust manner. For example, the following claim is made regarding the safety function of "*compatibility of the multi-barrier system elements and the radioactive waste types among each other and with other materials*" (Fig. 2-5):

- Claim – *Thermal impacts do not perturb the stable geochemical and geomechanical environment to an extent that it would impair safety.*

The claim is supported by the following arguments (again, this list of arguments is not exhaustive):

- Argument I – *The safety-oriented design of the HLW near-field ensures that the temperature in the near-field does not impair the barrier function of the bentonite buffer.*
- Argument II – *The safety-oriented design of the HLW repository ensures that thermally induced overpressures in the host rock do not create mechanical rock failure.*

These arguments are, in turn, supported by model-based assessments, which confirm that the performance of the HLW near-field is in accordance with the above claim. Probabilistic numerical simulations allow for a quantitative evaluation of the associated safety margins and the possibility of any deviations from the expected performance. Further empirical and experimental evidence stems from international research programmes and also from dedicated laboratory and in-situ experiments performed as part of Nagra's own RD&D programme.

5.2.4 Assessment and quantification of uncertainty

A model is a simplification of a real-world system achieved by eliminating unnecessary detail, i.e., it is an abstraction (Section 3.2.2). Any type of model abstraction, or "conceptualisation", may introduce inaccuracy and additional uncertainty by reducing the degrees of freedom existing in the real-world system. In performance assessment, the "elimination of unnecessary detail", i.e., the adoption of simplifications, is required and desirable as it improves the traceability of claims made regarding system behaviour. At the same time, it must be proven that these simplifications do not impair the capability of the models to make unbiased assessments of repository performance. This calls for a traceable analysis of the uncertainty and uncertainty propagation arising from model abstraction. As described in Section 3.2.2, conceptual uncertainty may arise from the following types of abstraction:

- geometric abstraction,
- process abstraction,
- homogenisation and
- boundary and initial conditions.

The aggregation of uncertainties arising from multiple model abstractions is a complex process that starts with the abstractions used in the model-supported interpretation of field observations, site characterisation data and dedicated laboratory experiments. The interpreted field data, expressed in terms of expected parameters and uncertainty ranges, form an important part of the assessment basis that provides input to performance assessment. At the other end of the abstraction chain are the model abstractions used when evaluating performance of the repository system in terms of predefined performance indicators, which each quantify the performance of the repository system with respect to a given performance objective. The uncertainty in the input parameters, together with the conceptual uncertainty introduced by the model abstraction process, determine the uncertainty range for the calculated performance indicators and the associated safety margins that are present with respect to the corresponding performance objective.

Notably, the goodness of a model for representation of the real-world system is subjective and depends on the intended use. Nevertheless, the goodness of a model can be judged by a well-planned and executed Code and Calculation Verification and Model Validation (V&V) programme formulated in terms of qualitative and quantitative performance measures. The performance assessment synthesis report (Nagra 2024s) documents Nagra's efforts associated with the analysis of uncertainty propagation at the performance assessment level.

5.2.5 Screening of performance assessment scenarios and the link to safety scenario development

The iterative process of repository development (lower part in Fig. 2-3) is used to develop a provisional design and implementation plan for the purposes of the general licence application. By design, the multi-barrier system of the repository is expected to provide its intended safety functions and component-specific functions, both at the component and the total system level, and all performance assessment claims are expected to be met, i.e., the *expected performance*. *Deviations from expected performance* may occur if one or several barrier components do not provide their intended safety functions and component-specific functions. In such cases, the inherent redundancy that is part of the robustness of the multi-barrier system should ensure that other properly functioning barrier components still provide an adequate overall performance of the repository system, although this may need to be verified through the development of safety scenarios and the analysis of radiological consequences.

The initial state of the repository is generally well-constrained (although there may be uncertainty regarding, e.g., the presence of initial defects in one or more barriers). Then, the subsequent evolution of the system under the action of the expected source terms, initial and boundary conditions corresponds to the "expected performance" scenario, which is closely related to the reference safety scenario described in Section 5.3. It encompasses all paths of repository evolution which arise from the intended fulfillment of the safety functions of all barrier components. These paths share a common description of the characteristics of the system and the broad evolution of its safety functions, but may differ in specific details, such as the properties of a key feature like a groundwater aquifer or the rate of a key process like overburden erosion, reflecting parameter uncertainty.

Deviations from the expected performance occur if a barrier component fails to perform its assigned safety functions. These may arise from phenomena that cause detrimental impacts, including the unfavourable evolution of internal or external processes, which may also impair the performance of the entire repository system. For each barrier component and for all the interactions between the repository components, the paths of repository evolution related to deviations from expected performance can be merged to form specific performance assessment scenarios. 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, and the source terms associated with the repository induced effects, such as heat and gas generation.

For each performance assessment scenario, probabilistic simulations are carried out. This evaluation procedure encompasses a comparison of performance indicators (e.g., temperature, pore pressures and tracer fluxes) and their calculated values against corresponding performance targets. Hence, the impact of uncertainties or deviations in performance can be quantified, providing insight into the contribution of each barrier component to the overall performance of the multibarrier system.

Following quantitative evaluation, a systematic screening of the performance assessment scenarios is performed based on the likelihood of the identified deviations occurring and their relevance to repository safety. This facilitates 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.

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, the relative impact of the phenomenon on the performance margins can be quantified.

The screening process and outcome is documented in Nagra (2024s). The decision on propagation of a performance assessment scenario to a specific category of safety scenario is described in the following sections.

5.3 Safety scenario development

5.3.1 Safety scenario development workflow

Safety scenario development is the second process carried out in the general safety assessment workflow leading to a robust post-closure safety case for the combined repository at the proposed site (Fig. 1-2). The development of safety scenarios is based on the general scientific understanding within the assessment basis (Section 4.3) and the findings of the performance assessment (Section 5.2). It "*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 bounding and representing the possible ways in which the repository might evolve, providing for an integral part of the treatment of uncertainty in the safety assessment, as noted in Section 3.2.4.

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, as well as the less likely events and processes that may lead to deviations from expected performance or compromise the safety functions of one or more pillars of safety.

Specifically, safety scenario development involves the definition of:

1. A **reference safety scenario**, providing a general description of the initial state of the repository barriers, their expected performance over time and the assumptions made regarding the biosphere for the analysis of radiological consequences.
2. A set of **alternative safety scenarios**, derived from a consideration of potentially detrimental phenomena and associated uncertainties that could result in a degraded functionality of the main components of the repository system or of the repository system as a whole compared with that assumed in the reference safety scenario.
3. A set of **"what-if?" cases**, which represent extreme, often purely hypothetical situations where each pillar of safety (Fig. 2-4 and Fig. 2-5) is considered in turn, with a degraded performance.
4. A set of **FHA safety scenarios**, which concern the impact of potential actions undertaken by human society in the long term on the performance and safety of the repository.

The FHA safety scenarios are treated as a separate class of safety scenarios, due to their particularly speculative nature. This means, for example, that they cannot reasonably be assessed in terms of likelihood of occurrence. Therefore, the methodology for development of the FHA safety scenarios is presented separately in Section 5.3.2.4.

A definition of safety scenarios and their variants is provided in Section 5.3.2, which then goes on to describe the details of the workflow for developing each of the categories of safety scenarios, as well as "what-if?" cases, described above (the blue box inside the orange box in Fig. 5-2). The determination of the evaluation approach for the safety scenarios and "what-if?" cases, whether quantitative or qualitative, is described in Section 5.3.3.

The application of this methodology and the resulting safety scenarios are described in detail in Nagra (2024e) and Nagra (2024q).

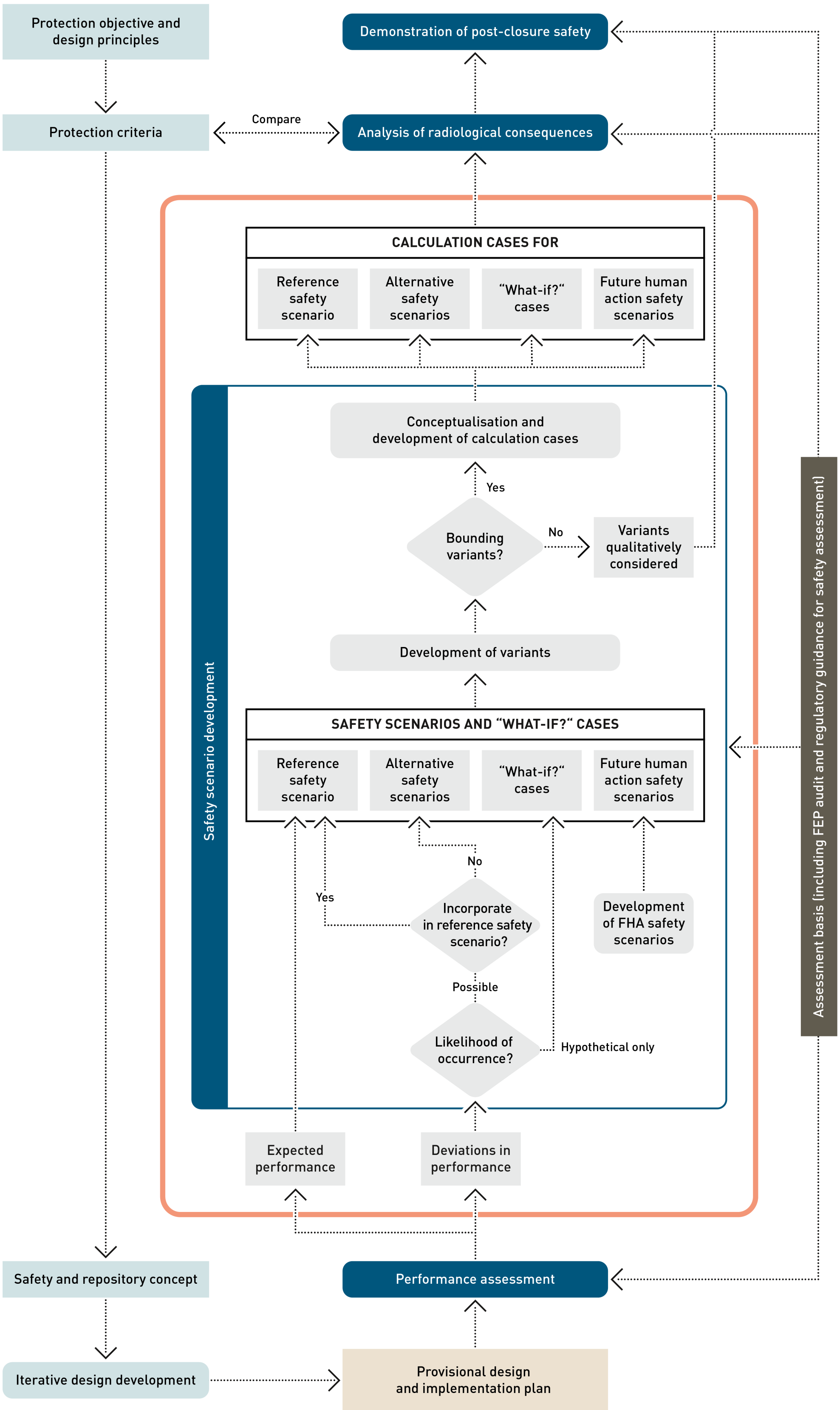

Fig. 5-2: Workflow of post-closure safety assessment, highlighting the workflow and outcomes of the safety scenario development step

5.3.2 Safety scenarios, their variants and calculation cases

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. It should be noted that the description of safety scenarios accounts for geological scenarios, which describe possible ways in which the geological environment of the repository may evolve over time without considering consequences for the evolution of the repository. Safety scenarios describe the possible paths for the evolution of the repository system and its environment under the effects of an assumed geological scenario.

A safety scenario can have one or more variants. Variants of a given safety scenario mostly share the same general description of FEPs 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. For example, safety scenarios that involve consideration of a fracture or fault intersecting the repository can have variants concerning the position of intersection of the fracture / fault either in the HLW or L/ILW section of the combined repository. In addition, each safety scenario or variant will typically have associated with it one or more cases – termed "calculation cases". The calculation cases define specific calculations that are carried out to analyse the radiological consequences of a particular safety scenario or variant, including parameter values that are taken from the assessment basis or from the results of performance assessment, for example (Section 5.2).

5.3.2.1 The reference safety scenario

The reference safety scenario provides a general description of the initial state of the repository barriers, their expected performance over time and the assumptions made regarding the biosphere for the analysis of radiological consequences. In the context of the general licence application, a single reference safety scenario is established for the combined repository at the proposed site. However, due to the similarity of the geological system and the initial state and design of the repository, the same description is broadly applicable to the other siting regions considered in the site comparison. The reference safety scenario describes the expected phenomenological evolution of the repository, based largely on the phenomenological description provided in Nagra (2024j), as well as the arguments and evidence underpinning key claims in the performance assessment (Nagra 2024s). The reference safety scenario provides a point of reference for the development of other safety scenarios. More specifically, to be considered a separate safety scenario, other safety scenarios must differ qualitatively from the reference safety scenario in the broad way in which they describe repository evolution.

5.3.2.2 Alternative safety scenarios

Alternative safety scenarios 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. The development of alternative safety scenarios involves a screening process, guided by the assessment basis and the results of performance assessment. The starting point is the deviations in performance, identified in performance assessment, that could occur, for example, as a result of detrimental phenomena and their attendant uncertainties. These could adversely affect the functionality of pillars of safety (Fig. 2-4 and Fig. 2-5), or of the repository system as a whole. The screening process considers the following:

- The likelihood of occurrence at a site:

  The assessment basis and the results of performance assessment provide estimations for likelihood of occurrence for specific deviations in performance. If the occurrence of such deviations cannot be ruled out with confidence, they are propagated to the next step in the screening process. On the other hand, if it can be shown that such phenomena could not plausibly occur at a given site within the one-million-year "time period for assessment" defined in ENSI Guideline G03 (ENSI 2023a) (see Section 3.4), they can still be considered as a hypothetical "what-if?" case, to demonstrate the robustness of the system (Section 5.3.2.3).

- Impact on the safety functions:

  If the functionality of individual components of the disposal system or of the disposal system-as-a-whole could be negatively affected by detrimental phenomena in a manner that is not captured by the reference scenario, then these possible deviations in performance give rise to alternative safety scenarios and variants. It should be noted, however, that even if some impact cannot be ruled out, the general description of the evolution of the disposal system provided by the reference safety scenario may still apply. If the impact is, in this sense, minor, then the deviation in performance can be subsumed within the reference safety scenario and potentially accounted for in the analysis of radiological consequences, e.g., by the definition of additional calculation cases.

5.3.2.3 "What-if?" cases

In addition to calculation cases corresponding to the reference and alternative safety scenario, additional hypothetical "what-if?" cases are defined that are intended to test the robustness of the repository, even in the event that some favourable features and processes hypothetically fail to operate as expected. Furthermore, as noted in Section 3.3, they may also mitigate possible "completeness uncertainty", pre-empting possible criticism that some detrimental FEPs are either unknown or have been overlooked.

As noted in the previous section, "what-if?" cases may represent deviations in performance associated with specific phenomena that, according to current understanding, could not plausibly occur at a given site within the million-year "time period for assessment". Additional "what-if?" cases are also defined, based around the pillars of safety shown in Fig. 2-4 and Fig. 2-5. These hypothetical cases are not associated with any causal physical phenomena. Each pillar of safety is considered in turn, with a degraded performance postulated in order to define a full set of "what-if?" cases.

5.3.2.4 Methodology for the development of future human action safety scenarios

ENSI Guideline G03 (ENSI 2023a) requires that the safety assessment includes "*scenarios in which the safety of the deep geological repository is influenced by human actions [...] as appears credible with regard to today's society*"[19].

The methodology for addressing FHA in the post-closure safety assessment is shown in Fig. 5-3. It is similar to that for the alternative safety scenarios, as described in Section 5.3.2.2, but with some notable differences. The methodology follows a development process initially established

[19] *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.*

for the safety assessment in Nagra's *Entsorgungsnachweis*. This methodology has evolved through subsequent safety assessments, including Nagra (2008) and Nagra (2014), and is further refined in the current safety assessment.

In the context of the optimisation of the repository against potential human intrusions for the general licence application, it is acknowledged that the extensive exploration and assessment of speculative intrusion scenarios offers limited practical benefits. Instead, the focus shifts towards current practices and technological knowhow, which provide the basis for specifically selected stylised scenarios. This involves the identification of current human activities in the regional vicinity of the site, combined with state-of-the-art technological applications (e.g., drilling equipment and techniques).

Rather than the deviations in barrier performance from the performance assessment, FHA safety scenario development takes, as its starting point, the Nagra FEP catalogue (Section 4.5.3), which includes, among others, a set of FEPs specific to FHAs. Each individual FHA FEP is evaluated for the potential to impact the safety functions of the repository. At this point, many FEPs are screened out by argument, establishing that they will not lead to any deviation from the expected performance of the repository, as described in the reference safety scenario. The remaining FEPs, which cannot be excluded by argument alone, are then developed into FHA safety scenarios.

Once the set of FHA safety scenarios are developed, the procedure to define variants and calculation cases is followed, as illustrated in Fig. 5-2 and detailed in Section 5.3.2.

The full description of Nagra's FHA methodology for the general licence application, its application, and the assessment of the identified FHA safety scenarios can be found in Nagra (2024q).

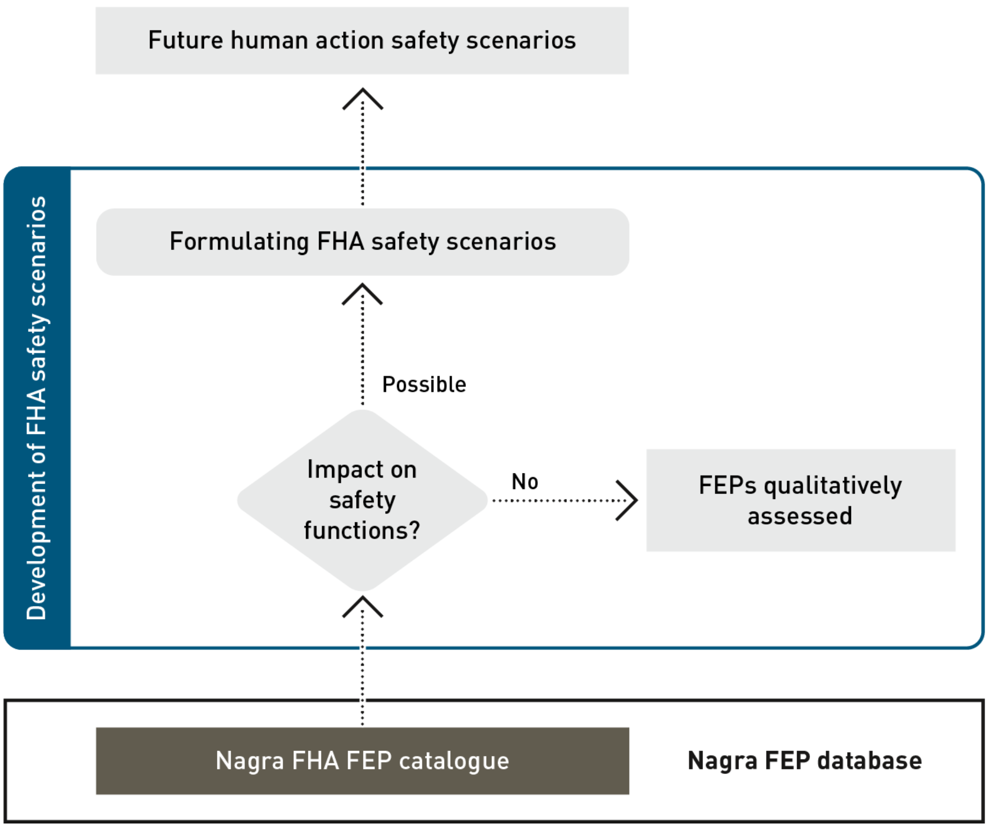

Fig. 5-3: Methodology for the development of FHA scenarios and FHA safety scenarios

Nagra (2024q)

5.3.3 Evaluation approaches

As a final step in the process of safety scenario development, the evaluation approach for each of the calculation cases is decided. Specifically, when it is possible to argue that certain calculation cases need not be evaluated quantitatively, since their radiological consequences will clearly be less than, or very similar to, another case, a qualitative approach suffices (Nagra 2024e). Calculation cases that are to be analysed quantitatively are propagated to the analysis of radiological consequences.

5.4 Analysis of radiological consequences

5.4.1 Workflow for the analysis of radiological consequences

The analysis of radiological consequences is the third process carried out in the general safety assessment workflow in support of a robust post-closure safety case for the combined repository at the proposed site (Fig. 1-2). The part of the general safety assessment workflow that covers the analysis of radiological consequences is elaborated in Fig. 5-4. It addresses the calculation cases identified in safety scenario development as requiring quantitative evaluation.

For each safety scenario, one or more deterministic calculation cases are, at a minimum, analysed. The "what-if?" cases are also analysed deterministically. This includes, for the reference safety scenario, a reference calculation case which considers reference (best estimate) parameter values. In addition, for the reference safety scenario, additional calculation cases are defined to address parameter uncertainty. First a probabilistic uncertainty analysis is performed to quantify the range of uncertainty in computed radiological consequences and to identify the parameters to which the computed radiological consequences are most sensitive. A calculation case is then defined which assumes the most pessimistic parameter values for the identified sensitive parameters. Finally, the results of all the radiological consequence analyses, including the probabilistic sensitivity analysis and the pessimistic reference calculation case, are compared with the regulatory dose criterion (see below) and the safety margin for each calculation case is evaluated.

In the following section, an overview of the modelling approach used for both the deterministic and probabilistic analysis is presented. The details of specific models and the parameter values that are selected are documented in Nagra (2024q) for FHA safety scenarios and in Part B of Nagra (2024o) for other safety scenarios and "what-if?" cases. The results of the analyses are also presented in these reports.

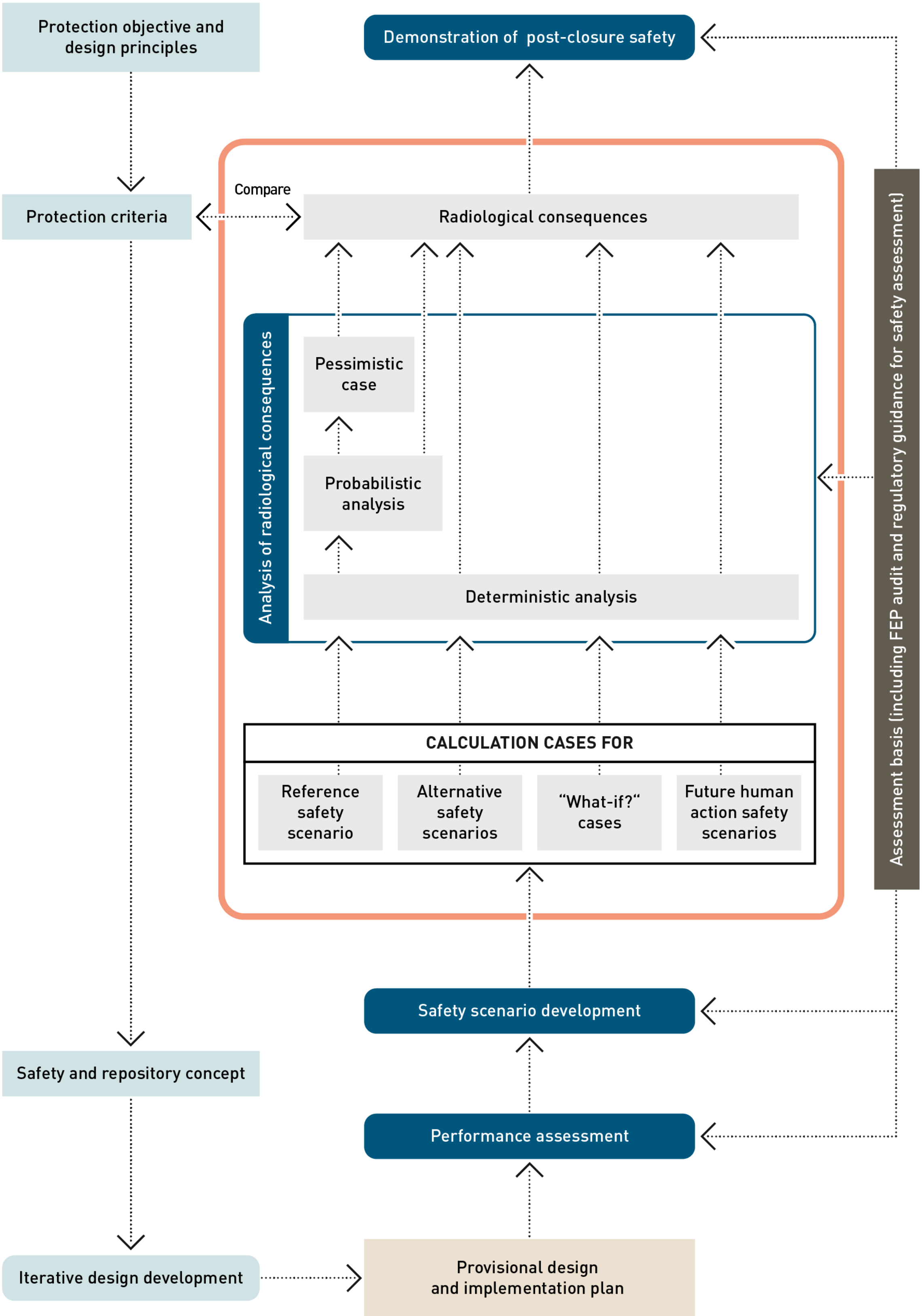

Fig. 5-4: Workflow of the radiological consequence analysis performed for safety scenarios and "what-if?" cases

5.4.2 General modelling approach for deterministic and probabilistic analyses

5.4.2.1 Modelling of radionuclide migration pathways

The analysis of radiological consequences uses quantitative models to evaluate relevant safety indicators, i.e., annual individual dose and certain complementary safety indicators, as described in Section 5.4.2. Suitable models are formulated for the analysis of the safety scenarios, as well as the additional "what-if?" cases. The models are developed based on the specifics of the safety scenarios and "what-if?" cases and employ a range of model assumptions and abstractions, including those justified in the performance assessment by either demonstrating their limited impact on radiological consequences or by showing that they lead to conservative radiological consequences (i.e., that they tend to over-estimate radiological consequences).

Two pathways for the migration of radionuclides to the surface environment are considered:

- Radionuclide migration in the aqueous phase, in which radionuclides are released to the porewater that is directly in contact with the waste. Radionuclides may migrate in the aqueous phase by diffusion or in case of porewater flow by advection.
- Radionuclide migration in the gas phase, in which gaseous radionuclides mix with, and are transported by, repository generated gases.

The two pathways are modelled separately using different computer codes for each defined calculation case associated with safety scenarios and for the "what-if?" cases.

Not all radionuclides present in the waste forms need to be included the deterministic and probabilistic analyses. The selection of radionuclides is based on a screening approach elaborated in Section 5.4.2.2.

5.4.2.2 Radionuclide screening

The list of radionuclides present in the repository at the beginning of the post-closure phase are extracted from MIRAM-RBG (part of the assessment basis; see Section 4.5.1). However, most of these radionuclides need not be considered in the calculation of dose rates and other safety indicators since they will be retained in the multi-barrier repository system, particularly in the CRZ, until they pose no radiological risk. A screening procedure is followed prior to the analysis of the radiological consequences to identify the subset of present radionuclides to be considered in the analysis of radiological consequences. The screening approach is depicted in Fig. 5-5 and elaborated in the following sections.

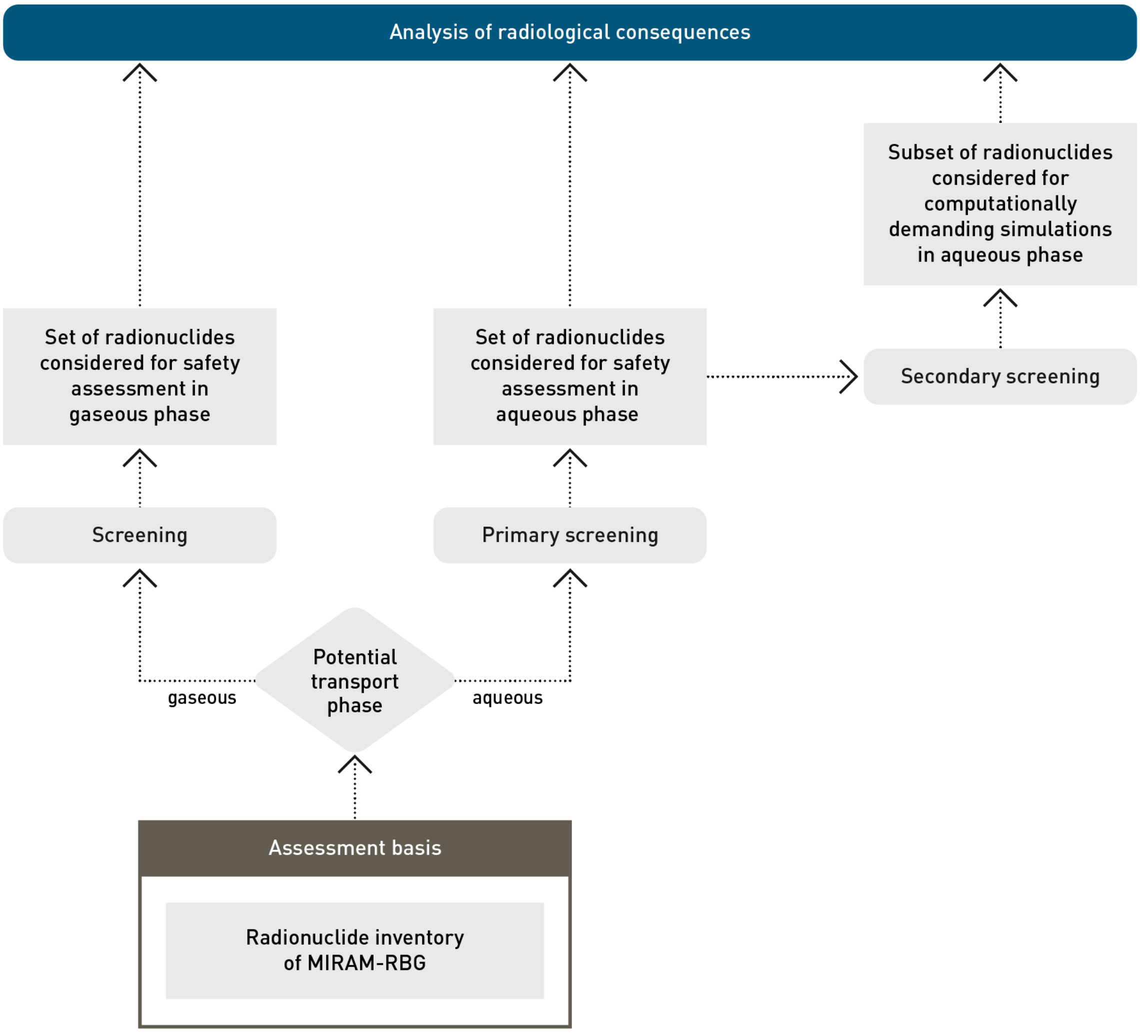

Fig. 5-5: Screening approach for the selection of radionuclides for including when calculating dose rates and other safety indicators

Radionuclide migration in the gaseous phase

Radionuclides that are highly volatile under repository conditions can, potentially, be carried through the repository barriers by repository-generated gases. However, only those radionuclides with a sufficiently long half-life to pose a radiological risk are considered in the analyses of radiological consequences. Additionally, radionuclides that are potentially gaseous but highly soluble are excluded from the calculations that consider gas-mediated radionuclide transport.

Radionuclide migration in the aqueous phase

A larger number of radionuclides can be present in the aqueous phase and have a sufficiently long-life to pose a radiological risk. To identify those that are safety-relevant, a two-stage screening is undertaken, with the first stage used to identify a larger set of radionuclides that are considered in less computationally demanding calculations, and the second stage used to identify a more limited set of radionuclides for more demanding calculations.

For the first stage of screening, a highly conservative and simplified transport model is used. The model assumes a transport path of 20 m for radionuclides through the Opalinus Clay directly to an overlying aquifer. All radionuclides are assigned the same, conservatively chosen transport parameter values and no sorption of radionuclides in Opalinus Clay is assumed. This model also assumes instant release of the entire radionuclide inventory from the repository at the time of closure. The maximum radionuclide-specific dose rates over a million-year period are calculated assuming the consumption of drinking water drawn from the aquifer. Any radionuclide that gives rise to a maximum effective dose rate of more than 10^{-8} mSv per year and has a half-life longer than 60 days is considered in the site-specific consequence analysis of radionuclide transport in the aqueous phase. For decay chains, due consideration is given to radionuclide decay and ingrowth when determining if and how chain members are included in the calculations.

The second stage uses the full site-specific transport model developed for the NL siting region. The radionuclides contributing the most to the release rate from the repository near-field, Opalinus Clay host rock and CRZ boundaries are identified, which are then taken as the set of radionuclides to be used in highly demanding calculations, such as probabilistic uncertainty and sensitivity analyses. In practice, most of the considered radionuclides that pass the first screening stage do not migrate out of the near field or the host rock, according to the more elaborate second stage model, due to their low solubility limit or high sorption characteristics. Thus, omitting them from the analysis does not cause any significant underestimation of radiological consequence.

5.4.2.3 Safety indicators to be calculated

Quantitative protection criteria in the form of individual effective dose and risk criteria are specified in guideline ENSI-G03 (ENSI 2023a). Based on the arguments presented in Smith et al. (2019), annual individual effective dose is selected as the main "safety indicator" for the analysis of radiological consequences. Annual individual effective dose represents the sum of the equivalent doses in all organs and tissues over the course of a year, weighted with factors, and is generally referred to simply as "dose" in the safety assessment.

In addition to the calculation of annual individual effective dose, the performance and safety of the repository system can further be illustrated using a range of additional, complementary safety indicators. Complementary safety indicators include:

- **radioactivity fluxes** due to radionuclides released from the repository over the course of time, which are compared with natural radioactivity fluxes in the surface environment, and
- **radiotoxicity** originating from the repository to the boundary of the CRZ, as functions of time, which are compared with the initial radiotoxicity of the emplaced waste inventory.

The consideration of these complementary indicators can provide additional arguments for safety that avoid, to some extent, the difficulties faced in evaluating and interpreting doses and risks that may occur in the far future (OECD/NEA 2004, OECD/NEA 2012b). A comprehensive review of complementary indicators used in safety cases, including the reference values for safety indicators, is reported in OECD/NEA (2012a).

The modelling of radionuclide migration through the repository system via the aqueous and gaseous pathways generates radioactivity release rates to the biosphere as its main endpoint. To compare with the regulatory dose criterion, these modelled release rates to the biosphere are converted to dose rates using biosphere dose conversion factors (BDCFs), which are derived from a biosphere assessment, as explained in the following section.

5.4.2.4 Biosphere modelling and dose conversion factors

The longevity of the hazard associated with the waste means that there is potential for some radioactivity present in, or in-grown from, the disposed inventory to reach the surface environment in the long term (tens of thousands to hundreds of thousands of years in the future). Modelling of radionuclide behaviour in the surface and near-surface (collectively referred to as the biosphere in this context) and of radionuclide exposure pathways is needed to evaluate the potential exposures arising from such releases. This modelling of radionuclide transfer and accumulation processes in the surface environment is carried out as a modelling activity separate from the modelling of release rates to the surface environment.

The biosphere modelling developed in support of the general licence application (Nagra 2024k) is based on a compartment modelling framework encoded within Nagra's SwiBAC software. A key feature of radionuclide release rates to the surface environment is that, in most safety scenarios, they vary over timescales that are much longer than the timescales that characterise the most relevant transfer and accumulation processes in the surface environment itself. This allows radionuclide concentration equilibrium to be assumed within individual biosphere model compartments. Thus, release rates to the surface environment are not used directly as a source term for biosphere modelling. Rather, SwiBAC is used to evaluate a set of BDCFs, which, by multiplication with the calculated release rates of radionuclides to the surface environment, convert these to effective dose rates. The BDCFs correspond to the calculated dose rates (Sv a^{-1}) at equilibrium for a constant unit release of radionuclides (Bq a^{-1}) in groundwater to the biosphere. Uncertainty concerning the biosphere on long timescales is unavoidable; nonetheless, the reference BDCFs are shown to provide a generally pessimistic assessment. The BDCFs provide a means for Nagra's consequence analyses to evaluate potential doses associated with radionuclide releases from the geosphere.

For the calculation of dose, according to ENSI's guideline ENSI-G03[20] (ENSI 2023a), a representative individual within the population group most affected by the potential impacts of a deep geological repository with realistic lifestyles from today's perspective must be postulated. In line with ENSI's guideline, the effect of ionising radiation on humans in the far future are based on current knowledge.

Reference BDCFs are based on potential radionuclide releases to a valley based on present-day conditions in Northern Switzerland, which allows a comprehensive range of exposure pathways to be assessed. The modelling aims to be realistic in terms of representing radionuclide migration in the biosphere, but pessimistic in evaluating potential doses. The latter is achieved by assuming that people are present close to the area of release and that they make reasonable maximal use of local resources by spending all of their time in the local area, drawing local groundwater and living a self-sufficient lifestyle.

Alternative biosphere conditions are also explored, including alternative assumptions regarding future climate, consistent with ENSI-G03. A warmer-drier climate would result in BDCFs that are higher than those based on present-day climate, due to lower water flows in the surface and near-surface and higher irrigation requirements. Conversely, releases to an area drained for

[20] *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. Bei der Analyse ist zu unterstellen:*

- *Mögliche Varianten der Klimaentwicklung und entsprechende Biosphärenmodelle sind festzulegen und ihre Bedeutung für die Langzeitsicherheit des geologischen Tiefenlagers ist zu untersuchen.*
- *Die Wirkung ionisierender Strahlung auf den Menschen hat sich nach den heutigen Kenntnissen zu richten.*

farming and releases under cold climate conditions (given that the timescale will include glacial-interglacial cycling) result in BDCFs that are lower than those of the reference biosphere. Consistent with the BDCF approach, each climate state is assumed to persist throughout the time period for assessment; no transitions between different climate states are considered. Details are provided in Nagra (2024k).

5.5 Demonstration of safety

The demonstration of safety brings together multiple lines of arguments that together make an overall safety case. These lines of argument, as shown in Fig. 5-6, include:

- the strength of the stepwise repository siting, design and implementation process,
- the favourable qualities of the siting region, the CRZ and the engineered barrier system,
- the favourable results of the safety assessment, and
- the quality of the safety assessment.

Overall, the safety case has to show that no issues have been identified that have the potential to compromise safety, and that there is sufficient confidence in this conclusion for the purpose of the programme stage at hand, namely the general licence application.

Most relevant to the present report is the quality of the safety assessment, which rests on a well-defined and sound safety assessment methodology, as described in the present report, and a sound assessment basis, including:

- a good scientific understanding of the FEPs relevant to the repository system and its evolution and the interactions between these FEPs,
- a systematic treatment of uncertainty, including arguments indicating that the actual performance of the repository system will, in reality, be more favourable than that evaluated in quantitative analyses (use of conservatism), and
- models, codes and databases used in performance assessment and in the analysis of radiological consequences that are fit for purpose.

An FEP audit also contributes to quality (Section 3.3), giving confidence that all relevant FEPs are accounted for in the safety assessment, and providing further quality measures to ensure that the models, codes, and databases are correctly applied.

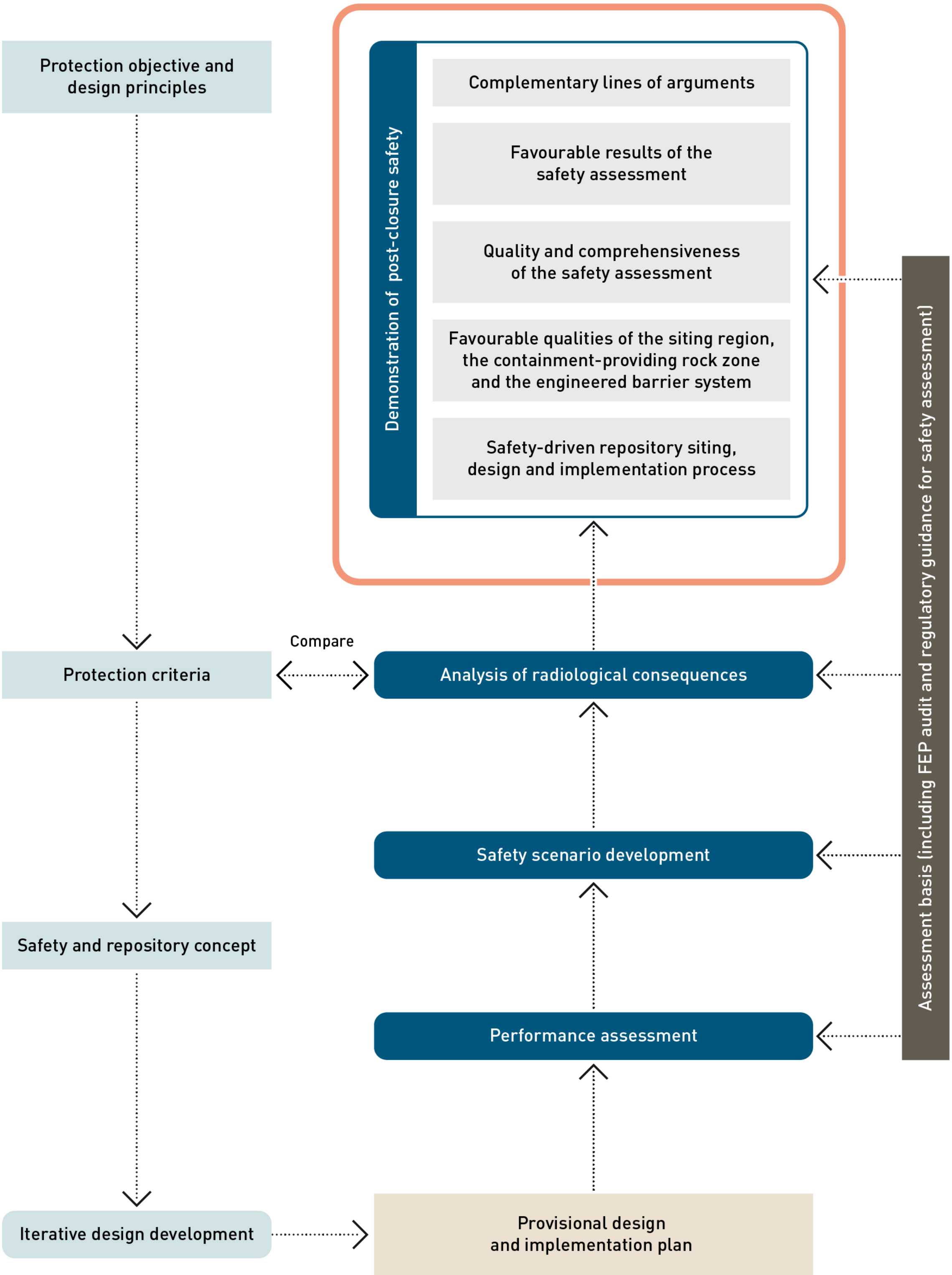

Fig. 5-6: Demonstration of post-closure safety using multiple lines of arguments within the safety assessment workflow

6 Consistency of the safety assessment methodology with the methodology for site comparison

6.1 Main steps in site comparison

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. 6-1. The figure is organised to facilitate comparison with the steps of the safety assessment methodology, as depicted in Fig. 1-2 and elaborated in the following sections of this chapter. The figure is also broadly consistent with the methodology set out in Chapter 4 of ENSI 33/649 (ENSI 2018b) (see Fig. 2-1).

The methodology is described only briefly here, emphasising its consistency with the safety assessment methodology described in Chapter 5. For a more detailed description of the methodology for site comparison and for the selection of the proposed siting region, see 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. 6-1 and is described further in Section 6.2.
- 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. These are represented in the vertical workflow on the right-hand side of Fig. 6-1 and are described further in Sections 6.3 and 6.4, respectively.

6.2 Evaluation of siting regions for HLW disposal

The evaluation of each siting region for HLW disposal, i.e., the left-hand vertical workflow path in Fig. 6-1, involves the four substeps specified in Chapter 4 of ENSI 33/649 (see Section 2.1.1), the implementation of which is described in detail in Nagra (2024d), Nagra (2024n) and Nagra (2025a), and is summarised in the following paragraphs.

6.2.1 Delimitation of the CRZ

Siting area boundaries were defined in SGT Stage 1. For the site comparison in Stage 3 of the Sectoral Plan, preferred areas for waste disposal within these boundaries were identified in a multi-stage procedure. HLW disposal is assumed to take place within these areas, with the rock zone around the disposal areas that have similarly favourable properties constituting the CRZ. Laterally, the CRZ is dimensioned in such a way that it meets the spatial requirements for HLW disposal according to the current repository concept, with additional spatial reserves for optimisation. Vertically, it includes the host rock as well as its barrier-effective confining units (Fig. 2-2), bounded above and below by aquifers.

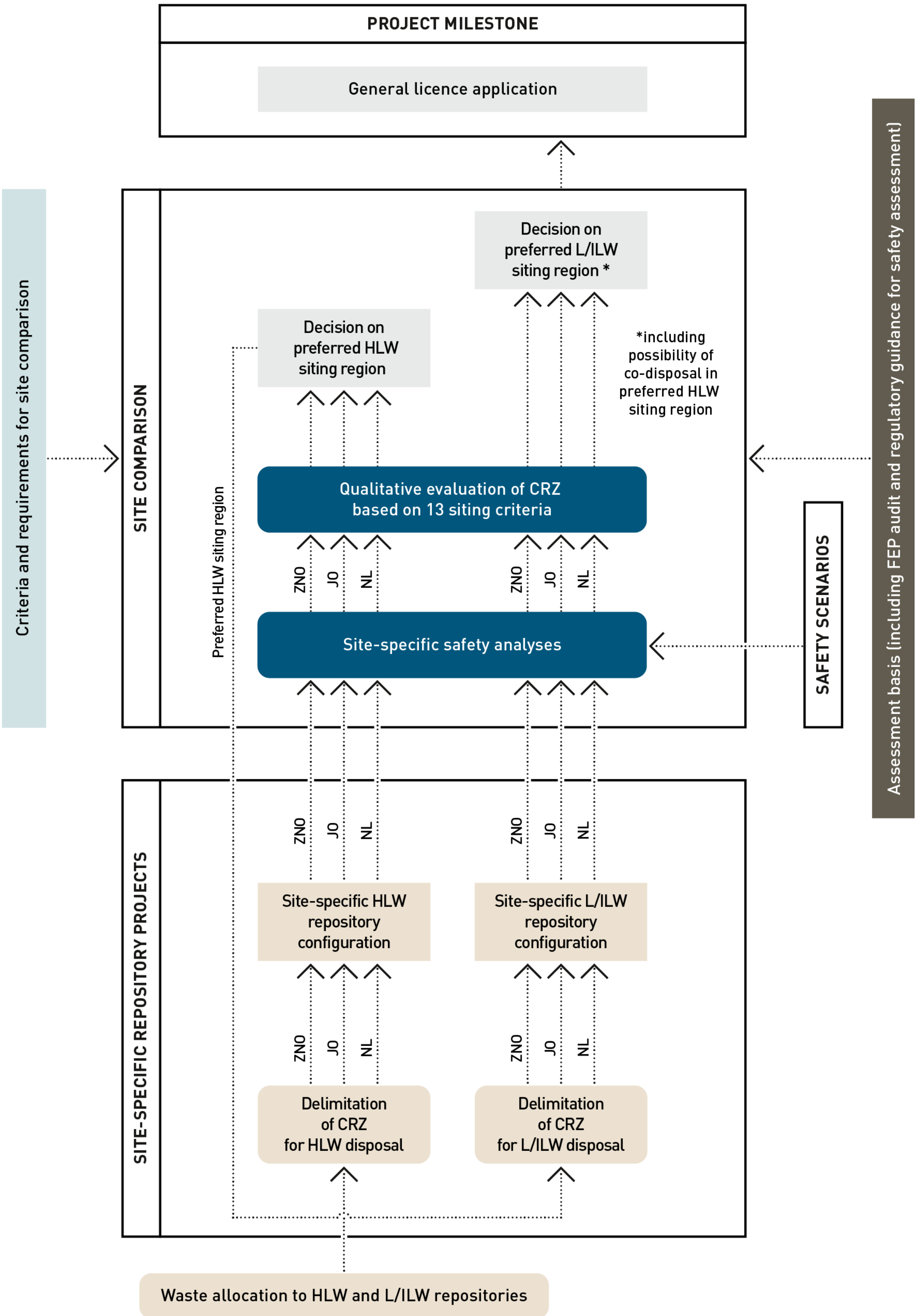

Fig. 6-1: Overview of the general approach for site comparison

6.2.2 Site-specific repository projects

The HLW repository is then configured within the space available in the CRZ. The development of site-specific configurations for an HLW repository is part of the design development process, as described in general terms in Chapter 2 (see, especially, Fig. 2-3). Site-specific repository projects are established for the planning of the repository facilities and are needed specifically for the site-specific safety analyses and for the qualitative evaluation of the CRZ, as described in Sections 6.2 and 6.3, respectively. As well as the positioning of the emplacement drifts for HLW, this involves locating the other underground structures, including access structures and the logistics area, in accordance with relevant safety, structural and operational requirements. A complete description of the repository projects for both HLW and L/ILW disposal can be found in the civil engineering dossier (Nagra 2023a).

6.2.3 Application of safety scenarios for site comparison

ENSI 33/649 (ENSI 2018b) requires that the safety analysis for site comparison includes analyses of both reference and alternative safety scenarios. Given the similarity in the geological characteristics, the engineering design of the disposal system and the expected evolution of all three siting regions, the same reference safety scenario and alternative safety scenarios are applicable to all three siting regions. Site-specific differences, e.g., in the likelihood, rates or extent of some phenomena, are, however, accounted for. There is thus no need for dedicated site-specific performance assessments to support safety scenario development. However, analyses similar to those used in the performance assessment for the safety case are among those used to support the qualitative evaluation of the CRZ (see Section 6.2.5).

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. 6-2).

Carrying out a more limited set of calculations in the site-specific safety analyses is in line with Section 5.2 of ENSI (2018b), which states that the demonstration of the effectiveness and robustness of the engineered and geological barriers, the safety scenario analysis and the sensitivity analyses in the safety assessment in support of the general licence application are more detailed than those carried out within the safety analyses supporting site selection[21]. Furthermore, the consequences of FHA safety scenarios, as well as potential measures available to reduce these consequences, are not expected to be site-specific.

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[21] *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.*

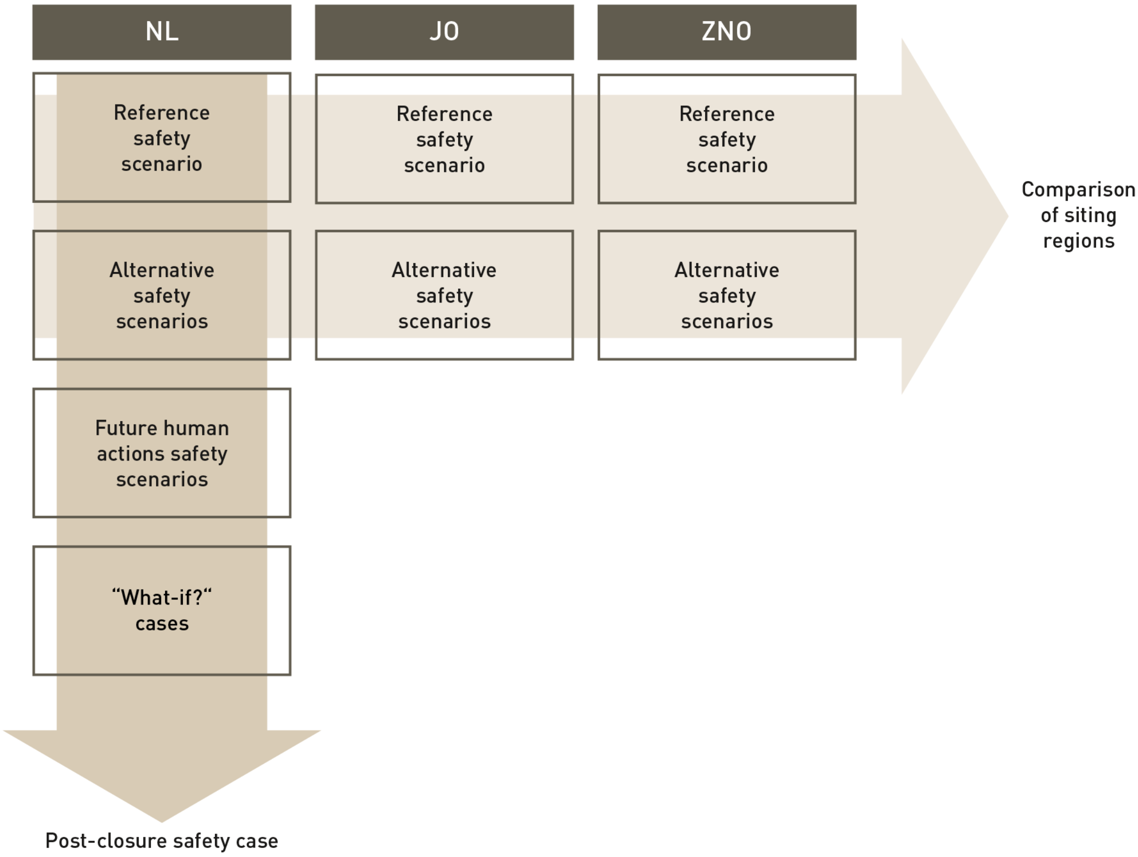

Fig. 6-2: Safety scenarios, variants and "what-if?" cases as input to the post-closure safety case and to the comparison of siting regions

6.2.4 Site-specific safety analyses

Similar to the analysis of radiological consequences for safety assessment described in Section 5.4, each site-specific safety analysis[22] consists of an evaluation of radionuclide release rates to the surface environment as a function of time in a defined set of safety scenarios. Furthermore, they also include the conversion of these release rates into either annual individual effective doses or annual individual risks, which are compared with regulatory protection criteria to assess the available safety margins. The modelling approach used in the site-specific safety analyses carried out for an HLW repository in each siting region is essentially the same as that used in the analysis of radiological consequences of releases from the HLW disposal section of a combined repository in Nagra's proposed siting region, i.e., the approach described in detail in the context of safety assessment in Section 5.4.2. However, the geosphere retention and transport model is tailored to

[22] In order to align the terminology with regulatory guidelines on site selection, the term "safety analysis" (to be understood as "Sicherheitsanalyse" in the German regulatory guidelines) is used as a synonym for "consequence analysis" in the context of site selection.

the characteristics of each siting region. Uncertainty in models and data is again accounted for by a combination of conservative assumptions and calculation cases combined with probabilistic analyses, in line with regulatory guidance set out in ENSI 33/649[23] (ENSI 2018b).

6.2.5 Qualitative evaluation of the CRZ

In the qualitative evaluation of the CRZ, as in earlier stages of the siting process, the 13 siting criteria presented in Tab. 2-1 are evaluated for each siting region using an indictor-based procedure. Some of the indicators may be quantitative and can be evaluated using models. However, the establishment of a preferred siting region for HLW disposal based on these indicators is a qualitative process, as is the evaluation of the potential for a combined repository, which is why the process as a whole is referred to as qualitative.

Nagra (2024n) contains an overview of the indicators used in Stage 3 that correspond to each criterion, as well as their justifications and their comparison against evaluation scales. As noted in Section 2.1, the Sectoral Plan (BFE 2008) specifies, for each of the criteria, the various *"aspect(s) to be evaluated"* and their corresponding *"relevance for safety"*. These form the basis for the selection of the indicators and evaluation scales. Nagra has defined different *assessment perspective*s for each of the four criteria groups. The assessment perspectives are as follows:

- **Group 1** considers the performance of the CRZ based on its characteristics at the start of the time period under consideration (i.e., at the time of repository closure), assuming that these have not been impacted by the presence of the repository.
- **Group 2** is concerned with the expected evolution of the CRZ during the time period under consideration, due to the effects of geological and climatic long-term processes, repository-induced effects and human actions.
- **Group 3** addresses uncertainties originating from limitations to the level up to which it is possible to characterise and explore the geological barrier and to predict its long-term evolution based on site investigations.
- **Group 4** concentrates on the suitability of the CRZ and overlying strata at each site from an engineering perspective, both for expected conditions and for conditions that deviate negatively from the expected.

Like the performance assessment, the analysis of the siting criteria includes an analysis of the THM-C evolution of the disposal system, with an emphasis on their relevance to post-closure safety in a given siting region. Also, as in the performance assessment, the qualitative evaluation of these criteria is, in some cases, supported by quantitative modelling, and many of the same models and data are used in the analysis of these criteria and in the performance assessment part of the safety assessment.

Finally, in the qualitative evaluation of the CRZ, the results of the evaluation carried out for individual criteria are aggregated in a multi-criteria analysis, as described in Nagra (2024n).

[23] *Wo Ungewissheiten bestehen, sind in der Sicherheitsanalyse die maximalen radiologischen Konsequenzen durch die Berechnung umhüllender Varianten oder durch konservative Annahmen abzuschätzen. Der Einfluss von Ungewissheiten auf die berechneten Ergebnisse ist systematisch aufzuzeigen, und die daraus gezogenen Schlüsse für die Langzeitsicherheit sind darzulegen.*

6.2.6 Establishment of preferred siting region for HLW disposal

A safety-based comparison of the siting options available for HLW disposal based on the steps summarised in Sections 6.2.1 to 6.2.4, and an evaluation of the characteristics that were decisive for the selection of the proposed site for this repository type, is provided in Nagra (2025a).

6.3 Evaluation of siting regions for L/ILW disposal

The evaluation of each siting region with respect to L/ILW disposal involves the same four steps as described above for HLW disposal. The demarcation of favourable siting regions and the development of site-specific repository configurations for an L/ILW repository consider the possibility of co-disposal of L/ILW in the proposed siting region for the HLW repository. As a specific example of the iterative nature of the development of repository configurations, analyses were carried out to formulate requirements on the minimum distance between the HLW and L/ILW disposal areas of the combined repository (Nagra 2021b). As in the case of the HLW repository, the modelling approach used in the site-specific consequence analyses carried out for an L/ILW repository in each siting region is similar to that used in the analysis of radiological consequences carried out as part of the safety assessment for the L/ILW repository section of a combined repository in Nagra's proposed siting region, i.e., the approach described in detail in the context of safety assessment in Section 5.4.2. The qualitative evaluation of the CRZ is again based on the 13 siting criteria presented in Tab. 2-1, and again addresses similar issues to the performance assessment part of the safety assessment, which is described in Section 5.2, and uses many of the same models and data.

6.4 Evaluation of co-disposal of HLW and L/ILW in a combined repository

When evaluating the potential for a combined repository in the same siting region, safety-related, ecological, spatial planning and economic factors are taken into account, as described in Nagra (2025a).

7 Summary and conclusions

7.1 Summary of the safety assessment methodology

The primary aim of the present report has been to describe the methodology for the post-closure safety assessment of a combined repository at the proposed site. There are four main safety assessment processes:

- **performance assessment**, in which the 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 the different ways in which the repository system could evolve 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 safety**, in which evidence, arguments and results from the three previous steps are brought together in the post-closure safety report (Fig. 1-2).

The first step in the methodology is to carry out the performance assessment. As explained in Section 5.2, the claims addressed in the performance assessment are derived from the safety concept and, in particular, from the safety functions and component-specific functions of the disposal system. Performance assessment provides a rigorous assessment of how the evolving disposal system executes these functions. The arguments and evidence that substantiate the claims begin with an understanding of the initial state of the disposal system. This, in turn, comes from the design and implementation plan, which is the outcome of the safety-orientated iterative design development process outlined in Chapter 2, as well as characteristics of the site and of the waste, which are part of the assessment basis. Other elements of the assessment basis that contribute to the arguments and evidence within the performance assessment are the available models, data and the current scientific understanding of:

- the climatic and geological evolution of the site and wider region, and
- the phenomenological evolution of the repository.

Experience from previous safety analyses, for example, in process modelling and in the management of uncertainty, is also used to support performance assessment.

Also, potential circumstances, if any, that could potentially lead to the impairment of one or more safety- and component-specific functions in a manner that does not fall within the scope of the reference safety scenario, are identified within the framework of performance assessment. The performance assessment thus supports, in the second safety assessment step, the derivation of a set of safety scenarios describing other possible paths for the evolution of the disposal system and its environment, starting from an initial state, and extending into the future, generally for as long as the radioactive waste presents a potential hazard. The outcomes of safety scenario development are a reference safety scenario, a set of alternative safety scenarios, a set of stylised FHA safety scenarios (which consider potential future actions undertaken by human society), and additional hypothetical “what-if?” cases, which are aimed at demonstrating the robustness of the disposal system.

Most safety scenarios and "what-if?" cases are carried through to the analysis of radiological consequences, where radionuclide release, retention and transport modelling as well as dose assessment are carried out. Some, however, may be handled by qualitative argumentation. These are also identified within the scope of safety scenario development. The output of the radiological consequences analysis includes the safety margin for each calculation case with respect to regulatory protection criteria, specifically the dose criterion, as well as complementary safety indicators, such as radionuclide fluxes and concentrations.

Finally, the results of the performance assessment and consequence analyses are brought together with other additional lines of argument to provide a demonstration of the safety of the system as designed. The calculated safety margins provide a key line of argument for the overall demonstration of safety in the safety case. This line of argument is, however, complemented and strengthened by additional lines of argument that address the quality of the system itself and of the analyses that are performed on the system, including their adherence to the protection objective and the safety assessment principles. Related to the quality of the analyses, an audit of the safety assessment against Nagra's FEP database is carried out to ensure that the safety assessment is comprehensive in the phenomena that it accounts for. As part of this audit, irrelevant FEPs, and FEPs that are outside the scope of the safety assessment are identified and the rationale for their exclusion is explained.

7.2 Other objectives met by this report

In addition to describing the methodology for the post-closure safety assessment, the report has also addressed the following additional objectives:

1. To present a broad perspective of the context in which the current safety assessment methodology was developed

   The context and boundary conditions for the methodology are presented in Chapter 2. These include the legal and regulatory requirements with respect to safety for the general licence application and international developments and guidance related to safety assessment and the safety case. It also includes the safety and repository concept, requirements and design of the disposal system to which the methodology is applied.

2. To provide a general overview of the common scientific and technical basis underlying both the safety assessment and the safety-related aspects of site comparison

   The general features of safety assessment and safety assessment principles are set out in Chapter 3. The common scientific and technical basis underlying both the safety assessment and the safety-related aspects of site comparison, termed the assessment basis, is described in Chapter 4. The methodologies described in the present report are part of this assessment basis. The assessment basis also includes the general scientific understanding of the waste inventory, of the host rock and its geological setting, and of the phenomenological evolution of the repository, as well as the models, codes and databases used in the quantitative analyses supporting both the comparison of siting regions and the safety assessment for the selected siting region.

3. To highlight the similarities, parallels and general consistency between the safety assessment methodology and the methodology adopted for the selection of NL as the preferred siting region, which is also to be documented as part of the general licence application

   The similarities, parallels and general consistency between the safety assessment methodology and the methodology adopted for the selection of NL as the proposed siting region are described in Chapter 6. There is a close relationship between performance assessment, one of the main elements of safety assessment, and the qualitative evaluation of the CRZ for some criteria 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 the different siting regions. Indeed, the analysis of the reference safety scenario and alternative safety scenarios carried out for the HLW section of the combined repository in Nagra's selected siting region is essentially the same as the site-specific safety analyses for an HLW repository in all three siting regions. However, consistent with regulatory guidance, the demonstration of the effectiveness and robustness of the engineered and geological barriers, the safety scenario analysis and the sensitivity analyses in the safety assessment in support of the general licence application are more detailed than those carried out within the safety analyses in support of the site selection. In particular, they include FHA safety scenarios and "what-if?" cases that are not considered in the site-specific safety analyses for the site comparison.

7.3 Conclusions

A sound methodology is presented that can be applied to the post-closure safety assessment for the combined repository at the proposed site. The methodology is consistent with Swiss legal and regulatory requirements with respect to safety for the general licence application and with international developments and guidance on safety assessment and the safety case. The safety assessment principles are based on these developments and guidance, as well as Nagra's own experience in past safety assessments. There are broad similarities, parallels and general consistency between the safety assessment methodology and the methodology adopted for the selection of NL as Nagra's proposed siting region. Both methodologies are built upon a common assessment basis.

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9 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.
Assessment perspectives	In the context of the qualitative evaluation of the CRZ during site comparison, assessment perspectives are the different viewpoints of the siting criteria (classified into four groups), from which the CRZ should be evaluated in terms of safety and engineering feasibility.
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 consisting of spatially separated HLW and L/ILW repository sections in the same siting region.

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 implementtation 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.
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 scenario*), it performs as required.
FEP	*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.
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.

Term	Definition
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 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), • spent fuel and RP-HLW matrix, • spent fuel and RP-HLW canisters, • Bentonite 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 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.
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.

Term	Definition
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.
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*.

Term	Definition
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.
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*.

Term	Definition
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 Stage 3 of the Sectoral Plan, 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.
"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.