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ARBEITSBERICHT NAB 24-18 Rev.1

Safety and Repository Concept and Provisional Design

September 2024

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KEYWORDS
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In this report official documents have been quoted verbatim and can differ slightly from Nagra's terminology and spelling.

Excerpts from legal documents are English translations from official documents. As English is not an official language of the Swiss Confederation, these translations are provided for information purposes only and have no legal force.

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Abstract

This report is part of the documentation that forms the general licence application. It firstly defines the overarching protection objective, design principles and protection criteria, as well as other boundary conditions for the development of the current safety and repository concept. These include international frameworks such as International Atomic Energy Agency Safety Standards, and Swiss legal and regulatory frameworks. The discussion also covers institutional decisions and strategic choices made in Switzerland regarding radioactive waste disposal. The scientific and technical foundation, crucial for the repository design and safety demonstration, is explained in detail.

Secondly, the report describes Nagra's safety and repository concept, i.e., the repository safety barriers and their properties and how, through the safety barriers and safety functions they perform, the geological deep repository ensures the protection of humans and the environment. The safety functions apply to the repository as a whole, but can also be assigned to its individual components, including "pillars of safety", which are repository barriers. and their properties that are considered well understood and insensitive to perturbations and are the main contributors to these safety functions.

Thirdly, the report sets out a provisional repository design for a geological geological repository for both HLW and L/ILW, established for the purposes of the general licence application, that is consistent with, and based upon, the safety and repository concept. It includes details about the accessways, repository sections, and the engineered barrier system.

The document concludes with a discussion of the key aspects of the safety and repository concept and associated provisional repository design.

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List of Acronyms

ATW	Alpha-toxic waste
BWR	Boiling water reactor
CRZ	Containment-providing rock zone
EDZ	Excavation-damaged zone
ENSI	Swiss Federal Nuclear Safety Inspectorate (*Eidgenössisches Nuklearsicherheitsinspektorat*)
IAEA	International atomic energy agency
ICRP	International commission on radiological protection
HLW	High-level waste
HSK	Principal nuclear safety sivision (*Hauptabteilung für die Sicherheit der Kernanlagen*) – replaced by ENSI in 2009
KEG	Nuclear energy act (*Kernenergiegesetz*)
KEV	Nuclear Energy Ordinance (*Kernenergieverordnung*)
L/ILW	Low- and intermediate-level waste
MIRAM	Model inventory of radioactive materials
NEA	Nuclear energy act
NEA/OECD	Nuclear energy agency of the organisation for economic co-operation and development
NPP	Nuclear power plant
PWR	Pressurised water reactor
RD&D	Research, development and demonstration
RMC	Requirements management concept
RP-HLW	Reprocessed high-level waste
SF	Spent fuel assemblies
SFOE	Swiss Federal Office of Energy (*Bundesamt für Energie, BFE*)
SSG	Specific safety guide
SSR	Specific safety regulations
StSG	Radiological protection act (*Strahlenschutzgesetz*)
StSV	Radiological protection ordinance (*Strahlenschutzverordnung*)
USG	Environmental Protection Act (*Umweltschutzgesetz*)

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 (2002a).

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

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

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

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

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

[2] From the German *Rahmenbewilligungsgesuch*

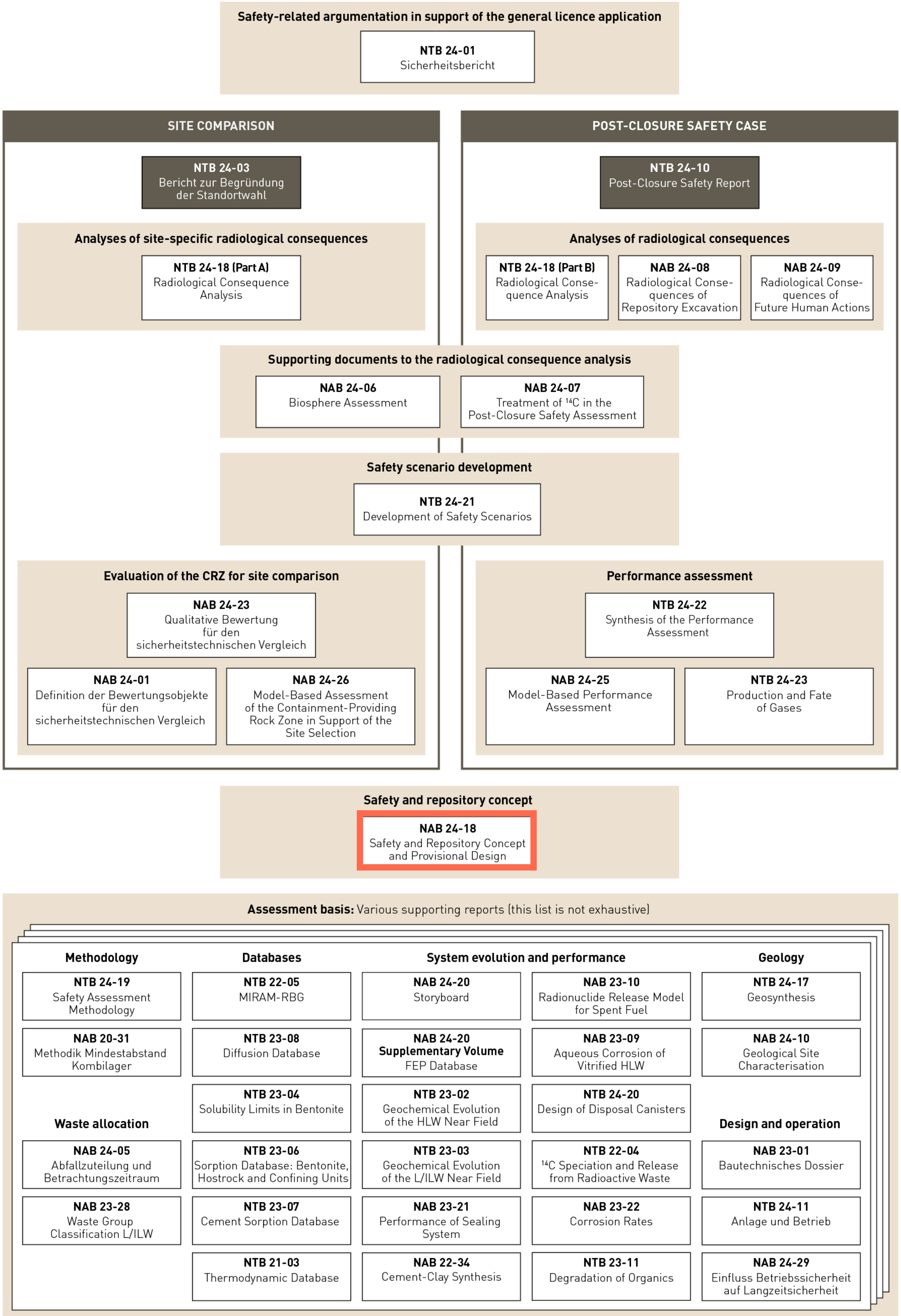

Fig. 1-1: Structure of reports covering post-closure safety aspects of the site comparison and the post-closure safety case

1.2 Scope and structure of the present report

The present report defines the safety and repository concept and the provisional repository design for a geological repository for both HLW and I/ILW that provide the basis for the safety assessment for the general licence application. Their development is part of the workflow leading to a safety case that provides a demonstration of post-closure safety, as illustrated in Fig. 1-2. All elements of the workflow are described in NTB 24-19 (Nagra 2024j).

As shown on the left-hand side of Fig. 1-2, which is the focus of the present report, there is an overarching protection objective, as well as design principles and protection criteria, that underlie a high-level safety and repository concept for geological disposal, which in turn provides a basis for an iterative design development. The overarching protection objective, design principles and protection criteria, as well as other boundary conditions for the development of the safety and repository concept, are described in Chapter 2.

Chapter 3 then describes the safety and repository concept. In Nagra's terminology, the safety concept explains how, through the safety barriers and safety functions they perform, the geological deep repository ensures the protection of humans and the environment. 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 current safety and repository concept is considered stable and mature, being iteratively developed by Nagra over the past 20 years. It is also sufficiently general, and the siting regions sufficiently similar, to apply the same safety and repository concept to all the siting regions.

By contrast, the more detailed repository design for a repository for both HLW and L/ILW, as set out in Chapter 4, is provisional and specifically developed for the purposes of the general licence application. As also shown in Fig. 1-2, it represents the current outcome of an ongoing iterative process entailing:

- 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 protection objectives, protection criteria, safety functions, component-specific functions, performance objectives and design requirements together constitute a hierarchy of safety requirements that guide design development. At earlier stages, the design development process has mainly focused on these safety requirements. Requirements regarding engineering feasibility, compatibility and efficiency are, however, becoming increasingly more important as the project progresses and the repository design becomes more detailed, but these requirements need to be met without compromising post-closure safety. This design development process is elaborated further in NTB 24-11 (Nagra 2024c).

Finally, Chapter 5 summarises the key aspects of the safety and repository concept and provisional repository design, placing them in the broader context of future project development. In particular, more profound knowledge of the geology at the site and advances in materials science and other fields are expected to impact the final design, as well as the corresponding 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 the 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.

Possible alternative concepts, such as the emplacement of disposal containers in vertical boreholes drilled from horizontal drifts, are not considered in this report. Alternative concepts have been studied previously and the reasoning behind selecting the current provisional design for the deep geological repository is explained in (Nagra 2016c). The principles presented in this report provide a framework for detailed development and optimisation of the repository design if the general licence is granted. Optimising the repository design with regard to long-term safety is a regulatory requirement (ENSI 2020b, ENSI 2020b). However, other requirements or considerations, e.g., regarding operational safety, feasibility, or cost, will also have to be taken into account. Where this is the case, they are mentioned in this report and reference is made to documents relevant to these aspects. They are, however, not systematically addressed here. In addition, there are requirements with regard to the waste itself that are not covered by this report. These are mainly laid down in the waste acceptance criteria of Nagra.

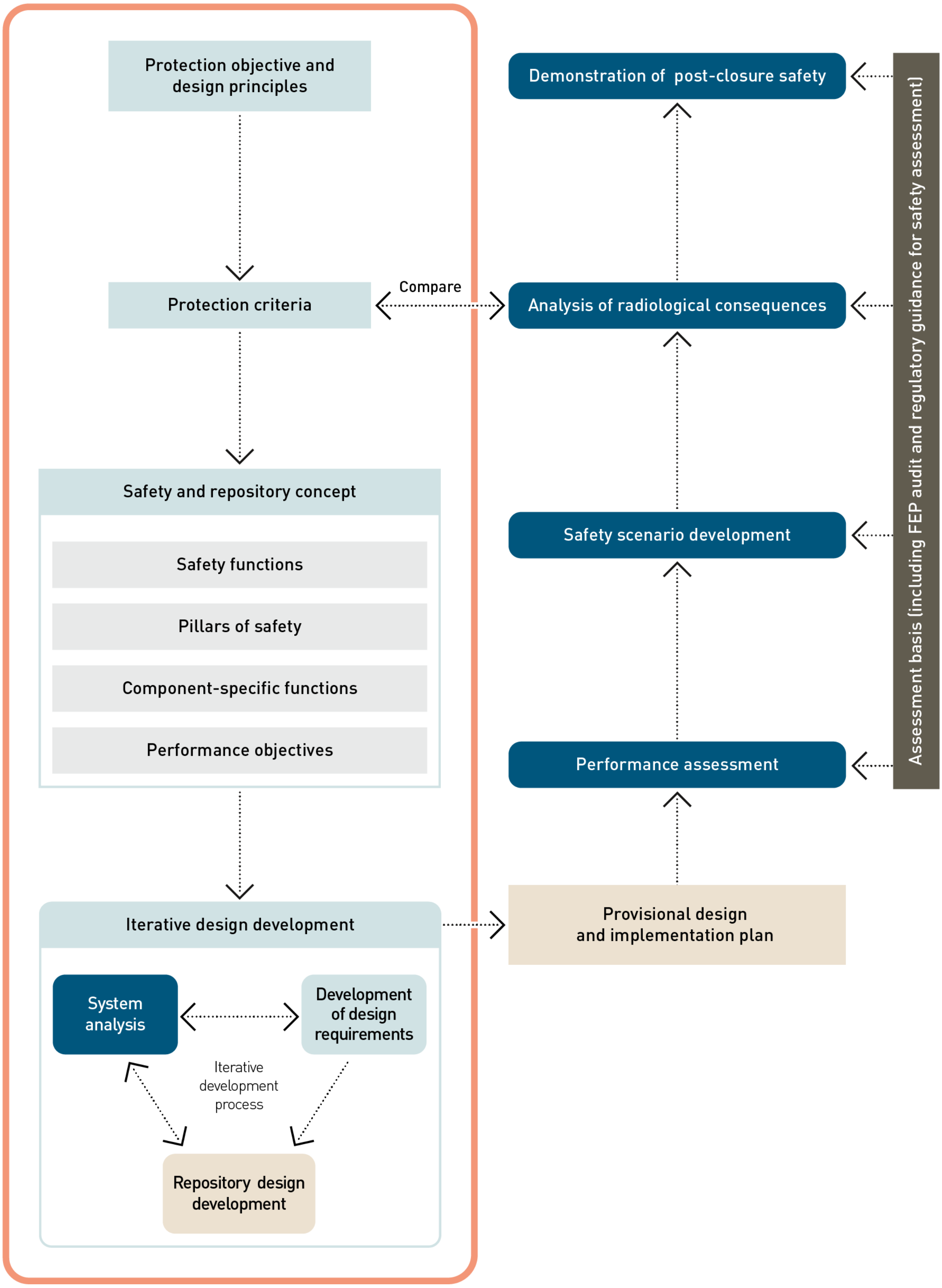

Fig. 1-2: Workflow for the post-closure safety case, highlighting, in the orange box, the process for developing a safety and repository concept which leads to development of a provisional design and implementation plan

2 Boundary conditions for the development of the safety and repository concept

Boundary conditions can broadly be split into:

- the waste to be dealt with and institutional decisions on the waste management options;
- the geological setting available, in particular the host rock as part of the containment-providing rock zone (CRZ) in the siting region;
- the international framework of treaties, agreements and standards to which Switzerland is a signatory or has agreed to comply with;
- the Swiss laws and regulations applicable to radioactive waste disposal;
- the scientific and technical foundation.

These boundary conditions are discussed in more detail in the following sections.

2.1 Waste types and waste management options

The types and quantities of radioactive waste produced in Switzerland can be regarded as the first and most fundamental boundary condition in the development of adequate waste management options and, more stringently, repository development.

The inventory of all of Switzerland's radioactive waste that exists today and that will be produced in the future has been compiled in the database MIRAM-RBG ("Model Inventory of Radioactive Materials for the RBG") and is documented in Nagra (2023). The calculation of the waste volumes assumes a 60-year operating lifetime for the existing nuclear power plants (NPPs). Switzerland has five nuclear power plants: Beznau I and II, Gösgen, Leibstadt and Mühleberg[3]. In addition, the generation and collection of waste from various applications in medicine, industry, and research (MIR) up to the year 2065 (the expected end of operation of the L/ILW repository) has been included in the database.

While a wide range of concepts to deal with radioactive waste have, over the past decades, been proposed internationally (a list of key studies is given in Tab. 2-1) and studied nationally (EKRA 2000), the conclusion was consistently drawn that deep geological disposal is the best available option for the disposal of HLW. In Switzerland, this option is preferred for all the radioactive waste, which forms a boundary condition given by the Swiss legal framework.

Tab. 2-1: Example of key international studies reviewing alternative waste management options

SKB project on alternative systems study (PASS) (Ageskog & Högbom 1992)
NDA review of geological disposal options for SF and HLW (Baldwin et al. 2008)
Andra's Dossiers Argile (ANDRA 2005), (ANDRA 2013)
NWMO watching brief on reprocessing, partitioning and transmutation, and alternative waste management technology (Jackson & Ian 2008)
SKB evaluation of strategies and systems for SF disposal (SKB 2010) and SKB review of concepts for repositories for SF and ILW (Elfwing et al. 2013)

[3] The Mühleberg reactor was shut down in 2019 after 50 years of operation.

2.2 Available geology for deep geological disposal

Besides the waste, the available geological setting in Switzerland forms an equally important external boundary condition. Within this boundary condition, an optimal host-rock and siting region is found through the site selection process guided by the sectoral plan. While, during site selection process, the safety and repository concept have evolved along with the selection of the host rock and siting region, the host rock (Opalinus Clay), the containment-providing rock zone (CRZ) within and the broader geological setting of the siting region can now be considered boundary conditions.

2.3 International framework

The international framework is mainly provided by the International Atomic Energy Agency (IAEA), the International Commission on Radiological Protection (ICRP) and internationally recognised principles.

2.3.1 International radiological protection principles

The system of radiation protection that is used worldwide is based on the recommendations of the ICRP. Substantially revised and updated in 2007, the conceptual framework adopted by the ICRP in its publication 103 (ICRP 2007) builds on the system of dose limitation central to earlier ICRP documents such as ICRP 60 (ICRP 1991) and ICRP 26 (ICRP 1977). Radiation protection recommendations, as applied to the disposal of long-lived solid radioactive waste, are set out in ICRP publication 81 (ICRP 1998a), which is an update of its publication 77 (ICRP 1998b), and in ICRP publication 122 (ICRP 2013).

The ICRP system of radiation protection is based on three fundamental principles:

- **Justification**

The principle of justification requires that any decision that alters the radiation exposure situation should do more good than harm; in other words, the introduction of a radiation source should result in sufficient individual or societal benefit to offset the detriment it causes. Regarding waste disposal, ICRP publication 81 states in Par. 31 (ICRP 1998a): "*waste management and disposal operations are an integral part of the practice generating the waste. It is wrong to regard them as a free-standing practice, needing its own justification. The waste management and disposal operations should therefore be included in the assessment of the justification of the practice generating the waste*".

- **Optimisation**

The principle of optimisation requires that the likelihood of incurring exposure, the number of people exposed, and the magnitude of their individual doses should all be kept as low as reasonably achievable, taking into account economic and societal factors. The optimisation principle is one of the key principles guiding the development of a repository design.

- **Dose limitation**

This principle requires that the total dose to any individual from regulated sources in planned exposure situations, other than medical exposure of patients, should not exceed the respective limits recommended by the Commission. Regarding waste disposal, ICRP publication 81 states in Par. 38 (ICRP 1998a): *In the context of protecting future generations, the relevant indicators* *are the annual individual dose to a critical group*[4] *for normal exposure and the annual individual risk to a critical group for potential exposure*". Quoting the earlier publication 77, it further states in Par. 69 (ICRP 1998b): "*These will together provide an adequate input to a comparison of the limiting detriment to future generations with that which is currently applied to the present generation*".

ICPR publication 81 acknowledges in Par. 80 that (ICRP 1998a):"*A major issue in evaluating the acceptability of a disposal system for long-lived solid radioactive waste is that doses or risks may arise from exposures in the distant future. There is uncertainty surrounding any estimate of these doses or risks due to lack of knowledge about future conditions. Such exposures are treated as potential exposures as their magnitude depends on future processes and conditions that have probabilities associated with them*". In publication 81, the ICRP also recognises in Par. 81 that (ICRP 1998a): "*individuals and populations in the future should be afforded at least the same level of protection from the action of disposing of radioactive waste today as is the current generation. This implies use of the current quantitative dose and risk criteria derived from considering associated health detriment. Therefore, protection of future generations should be achieved by applying these dose or risk criteria to the estimated future doses or risks in appropriately defined critical groups*".

2.3.2 IAEA Safety Standards

Switzerland is a signatory of the IAEA Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (IAEA 2005). This means that the legal framework for managing radioactive waste in Switzerland has to be consistent with the requirements of the IAEA Joint Convention and that the IAEA Safety Standards apply.

The principle of protecting humans and the environment from ionising radiation is anchored in the international framework on the management of radioactive waste. IAEA Safety Standard SF-1 states the fundamental safety objective of all radioactive waste management activities, which is "*to protect people and the environment from harmful effects of ionizing radiation*" (IAEA 2006). This safety standard also defines ten associated safety principles that provide the basis for requirements and measures for the protection of humans and the environment against radiation risks and for the safety of facilities and activities that give rise to those risks. These include, in particular, nuclear facilities, uses of radiation and radioactive sources, the transport of radioactive material and the management of radioactive waste.

IAEA Specific Safety Requirements SSR-5 establishes requirements applicable to all types of radioactive waste disposal facilities (IAEA 2011a). It is linked to the fundamental safety principles for each disposal option and establishes a set of strategic requirements that must be in place before facilities are developed.

Specific Safety Requirements SSR-5 sets out specific criteria for the protection of humans and the environment after closure of a disposal facility that fed into the formulation of Switzerland's own regulations.

[4] ICRP Publication 101 (Par. 25; ICRP 2007) introduced the "representative person", which is defined, for the purpose of protection of the public, as an individual receiving a dose that is representative of the more highly exposed individuals in the population. The dose this individual might be exposed to is equivalent to, and replaces, the mean dose in the "critical group" described in previous ICRP recommendations.

Tab. 2-2: Radiation protection criteria for the post-closure period given in Para. 2.15 of IAEA Specific Safety Requirements SSR-5

From IAEA (2011a)

(a)	The dose limit for members of the public for doses from all planned exposure situations is an effective dose of 1 mSv in a year. This and its risk equivalent are considered criteria that are not to be exceeded in the future.
(b)	To comply with this dose limit, a disposal facility (considered as a single source) is so designed that the calculated dose or risk to the representative person who might be exposed in the future as a result of possible natural processes[1] affecting the disposal facility does not exceed a dose constraint of 0.3 mSv in a year or a risk constraint of the order of 10^{-5} per year[2].
(c)	In relation to the effects of inadvertent human intrusion after closure, if such intrusion is expected to lead to an annual dose of less than 1 mSv to those living around the site, then efforts to reduce the probability of intrusion or to limit its consequences are not warranted.
(d)	If human intrusion were expected to lead to a possible annual dose of more than 20 mSv […] to those living around the site, then alternative options for waste disposal are to be considered, for example, disposal of the waste below the surface, or separation of the radionuclide content giving rise to the higher dose.
(e)	If annual doses in the range 1 – 20 mSv […] are indicated, then reasonable efforts are warranted at the stage of development of the facility to reduce the probability of intrusion or to limit its consequences by means of optimisation of the facility's design.
(f)	Similar considerations apply where the relevant thresholds for deterministic effects in organs may be exceeded.

1 Natural processes include the range of conditions anticipated over the lifetime of the facility and events that are less likely to occur. However, extremely low probability events would be outside the scope of consideration.

2 Risk due to the disposal facility in this context is to be understood as the probability of fatal cancer or serious hereditary effects.

The requirements are complemented by IAEA Specific Safety Guide SSG-14, which provides guidance on prevailing good practices for meeting and demonstrating compliance with Specific Safety Requirements SSR-5 (IAEA 2011b). It covers aspects related to siting, design, construction, operation and closure, including the safety case, its supporting safety assessments and the regulatory process. The publication addresses both the operational and post-closure safety of geological disposal facilities for waste that pose a hazard for at least several thousand years.

In addition, there are IAEA Specific Safety Guides SSG-23 and SSG-16. The first provides specific guidance on meeting the safety requirements with respect to the safety case and supporting safety assessment for the disposal of radioactive waste (IAEA 2012). The second provides more general leadership and management recommendations on how to comply with IAEA safety requirements throughout all steps of radioactive waste management (IAEA 2022).

2.3.3 Internationally recognised principles

There is international consensus that the safest permanent solution for management of HLW and SF declared as waste is disposal in the deep geological underground (NEA 2020). Geological repositories safely isolate and contain the waste with a multi-barrier system, preventing radioactivity from reaching the surface in levels that could cause harm.

The three following principles underlie disposal concepts and designs in Switzerland and internationally:

- **Passive safety**

The principle of **passive safety** is stated in requirement 5 in IAEA SSR-5 (IAEA 2011a):

"*the operator shall evaluate the site and shall design, construct, operate and close the disposal facility in such a way that safety is ensured by passive means to the fullest extent possible and the need for actions to be taken after closure of the facility is minimized.*"

Passive safety is related to the wider principle of intergenerational equity and is consistent with IAEA principle 7 (IAEA 2006), requiring that:

"*radioactive waste must be managed in such a way as to avoid imposing an undue burden on future generations…*".

Passive safety does not preclude active measures that can be implemented for a limited period of time after repository closure (i.e., surveillance and monitoring). It implies, however, that such measures are not required to ensure the post-closure safety of humans and the environment. A passive component is defined, according to the IAEA glossary as "*a component whose functioning does not depend on an external input such as actuation, mechanical movement or supply of power*". In Nagra's concept, the geological barrier and the various engineered barriers are all classified as passive components.

- **Optimisation of protection**

Optimisation of protection is a key, internationally recognised principle guiding the development of a repository concept and design and site selection. ICRP publication 81 notes that (ICRP 1998a): "*Optimisation of protection is a judgmental process with social and economic factors being taken into account*" and "*should be conducted in a structured, essentially qualitative way. The goal is to ensure that reasonable measures have been taken to reduce future doses to the extent that required resources are in line with these reductions. The optimisation principle should be applied in an iterative manner during the disposal system development process and should particularly cover both the site selection and the repository design phases*".

Since its inception, the optimisation principle has been progressively broadened to tackle several issues including, among others, the long timescales specific to the disposal of radioactive waste, and to incorporate concepts such as the use of **best available technology** or **best available technology not entailing excessive cost**. A study by the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development OECS/NEA noted that (OECD/NEA 2010): "*One way to reach system optimisation for geological disposal facilities might be to consider that the normal process of stepwise development of a repository from a conceptual basis to its implementation – whereby designs are subject to analysis, are discussed within the implementing organisation and between the latter and its reviewers, including regulators, and evolve with time – is by itself a sufficient process of optimisation. Other factors than radiological protection will be typically taken into account during the stepwise decision-making process. For instance, factors dealing with the quality of the design and its conception, such as predictability,* *demonstrability, feasibility of construction, flexibility of operation, maintenance and retrievability. Factors of more societal nature will include availability of transport routes, public acceptance and cost.*"

According to the IAEA, the optimisation of protection is defined as follows (IAEA 2012):

"*The optimisation of protection for a disposal facility is a judgemental process that is applied to the decisions made in the development of the facility design. Good engineering and technical solutions should be adopted, and good management principles should be applied to ensure the quality of all safety related work throughout the development, construction, operation and closure of the disposal facility.*"

In ICRP publication 122, the ICRP presents a similar definition of optimisation (ICRP 2013): "*Optimisation has to be understood in the broadest sense as an iterative, systematic, and transparent evaluation of protective option, including Best Available Techniques, for enhancing the protective capabilities of the system and reducing its potential impacts (radiological and others)*". ICRP Publication 122 also states that (ICRP 2013): *"Optimisation of protection is the central element of the stepwise design, construction, and operation of a geological disposal facility"*.

The iterative approach adopted by Nagra, with interactions between the safety requirements, repository design and safety assessment is consistent with this view of optimisation as an iterative, systematic and transparent evaluation and refinement of protective options.

- **Robustness and defence in depth**

According to the NEA, a siting and design strategy should be adopted that aims to develop a reliable and robust system. This concept of robustness is discussed, for example, in (OECD/NEA 1999), (OECD/NEA 2004) and (OECD/NEA 2012). The NEA states that (OECD/NEA 2012): "*Robust systems are characterised by a lack of complex, poorly understood or difficult to characterise features and phenomena, demonstrated quality control, and an absence of, or relative insensitivity to, detrimental phenomena arising either internally within the repository and host rock, or externally in the form of geological and climatic phenomena that introduce processes with the potential to compromise safety*". In other words, a robust system is one in which known detrimental phenomena, as well as uncertainty in the initial state and future evolution of a deep geological repository, do not have the potential to compromise the demonstration of safety.

The NEA furthermore states that, to favour robustness, repository host environments are generally selected such that they are (OECD/NEA 2012):

- "*Unlikely to be affected by major tectonic movements, volcanic events or other geological phenomena that could give rise to rapid or sudden changes in geological or geochemical conditions;*
- *Largely decoupled from events and processes occurring near the surface, including the effects of climate change;*
- *Lacking in scarce natural resources that may attract exploratory drilling, thus minimising the possibility of inadvertent human intrusion in the future, when the location of the repository may no longer be known*".

All the siting regions considered in Northern Switzerland possess these robust properties.

Regarding the engineered barrier system, it is stated in (OECD/NEA 2012) that: "*repositories employ materials for their engineered barrier systems that are, in general, well understood, tested, well characterised, and resistant to physical and chemical degradation under the* *conditions that are expected in the geological environment for as long as necessary to assure long-term safety*", and that: "*engineered components can also be designed to minimise the consequences of uncertainties so that the required performance is demonstrable. For example, the performance of canisters durable for several hundred to some thousand years, which are envisaged for most high-level waste repositories, can mitigate the effects of uncertainties associated with the complex and coupled thermal, hydraulic, mechanical, and chemical processes that could occur during an initial transient phase following repository closure".* Furthermore, (OECD/NEA 2012) states that: *"robustness is favoured by the multi-barrier concept, i.e., the concept of multiple components that operate in concert to isolate the waste, and prevent, delay and attenuate potential radionuclide release to the biosphere*". These are all characteristics of the provisional repository design considered in Switzerland.

Related to the principle of robustness is the principle of "defence in depth". According to IAEA SSG-23 Par. 6.30 (IAEA 2012):

"*... the focus of implementation of the concept of defence in depth for a disposal facility lies in ensuring that the design and construction of the facility will fulfil multiple complementary safety functions*".

Robustness and optimisation are interlinked. Specifically, the assessment of the robustness of a disposal system has been linked to its optimisation by the ICRP in publication 122 (ICRP 2013):

"*Assessment of the robustness of the disposal system can contribute to system optimisation because it provides insight, quantitative or qualitative, into the performance of the disposal system and its components, and into the relative contributions of the various components to the overall system. Therefore, the value of such an assessment for the optimisation process is mainly through the insights it provides on the relative contributions of the various components to the overall system objectives of containment and isolation, and how these contributions can be affected by disturbing events and processes or by remaining uncertainties. The uncertain nature of calculated effective dose and risk that is estimated to arise in the very distant future reduces their usefulness for the optimisation process.*"

According to IAEA SSG-23 Par. 6.40 (IAEA 2012):

"*The assessment of the robustness of a disposal system relies on several elements:*

- *Demonstration of the robustness of individual barriers and their safety functions;*
- *Evaluation of the defence in depth, i.e., the presence of multiple diverse safety functions, to ensure that the overall performance of the disposal system does not rely on a single safety function, the failure or unexpected poor performance of which would lead to unacceptable radiological consequences;*
- *Verification that good engineering practices (demonstrability and feasibility) have been applied;*
- *Demonstration that safety is achieved through passive means."*

2.4 Legal and regulatory framework

The Federal Constitution of the Swiss Confederation (Art. 90) states that nuclear energy legislation in Switzerland is a federal matter. The Nuclear Energy Act (KEG 2003) and the Nuclear Energy Ordinance (KEV 2004) form the legal basis on which management of radioactive waste arising from the peaceful use of nuclear energy and from specified medical, industrial and research applications is founded. The Radiological Protection Act (StSG 1991) and the Radiological Protection Ordinance (StSV 2017) govern the management of all activities, installations, events, and conditions that could give rise to hazards related to ionising radiation and that are not specifically regulated by the Nuclear Energy Act and Ordinance. These laws state that radioactive waste arising in Switzerland shall be disposed of in Switzerland.

The producers of radioactive waste are legally responsible for its safe management and disposal. The waste producers established Nagra as the responsible entity for research and development work associated with the deep geological disposal of Swiss radioactive waste. According to the Nuclear Energy Ordinance, the Federal Government plays a leading role in the disposal of radioactive waste in Switzerland. The disposal facilities must be licenced and supervised by the Federal Government. The Swiss Federal Nuclear Safety Inspectorate ENSI is the supervisory authority. The Swiss Federal Nuclear Safety Commission is responsible for evaluating projects for nuclear facilities, including radioactive waste repositories, and for submitting statements on the licensing applications and reviews from ENSI to the Swiss Federal Office of Energy (SFOE).

The Nuclear Energy Act defines a deep geological repository as "*an installation located deep underground, which may be closed, if the permanent protection of humans and the environment through passive barriers is ensured*" (Art. 3) and stipulates that "*radioactive waste shall be managed in such a manner as to ensure the permanent protection of humans and the environment*" (Art. 30) (KEG 2003). The design principles for a deep geological repository are set out in Article 11, Para. 2 of the Nuclear Energy Ordinance of 2004 (KEV 2004). A deep geological repository must be designed to ensure that:

a. It complies by analogy with the principles of Article 10 paragraph 1 [Basic principles for the design of nuclear power plants];

b. It guarantees long-term safety through multiple passive safety barriers;

c. Steps to ease surveillance and repairs of the repository, or for the recovery of the waste, in no way impair the effectiveness of the passive safety barriers after closure of the repository;

d. It can be closed within a period of a few years.

Several additional principles and requirements relating to geological disposal defined in the Nuclear Energy Ordinance are listed in Tab. 2-3.

Tab. 2-3: Regulatory principles and requirements in the Nuclear Energy Ordinance of 2004 relevant for geological disposal

From KEV (2004). The English excerpts are translations from the Nuclear Energy Ordinance. English is not an official language of the Swiss Confederation. This translation is provided for information purposes only and has no legal force.

Art. 11: Design principles for deep geological repositories	1) In order to guarantee long-term safety, the site for a deep geological repository must meet the following requirements: a. sufficient extent of suitable host rock; b. favourable hydro-geological conditions; c. long-term geological stability.
Art. 51: Categories of radioactive waste	For the purpose of management and disposal, radioactive waste is classified in the following categories: a. HLW: 1. SF which is no longer used; 2. vitrified fission product solutions resulting from the reprocessing of SF; b. ATW: waste in which the content of alpha emitters exceeds 20,000 becquerels per gram of conditioned waste; c. L/ILW: all other radioactive waste.
Art. 64: Elements of a deep geological repository	3) A deep geological repository comprises a main installation for the emplacement of the radioactive waste, a pilot installation and test areas.
Art. 66: Pilot installation	4) The following principles must be observed in connection with the design of the pilot section: a. The geological and hydro-geological conditions must be comparable to those of the main section. b. The pilot section must be spatially and hydraulically separated from the main section. c. The construction of the pilot section and the emplacement procedure of waste and backfill material must correspond to those of the main section. d. The pilot section must contain a small but representative quantity of waste.
Art. 67: Backfilling	1) The owner of a deep geological repository must backfill the storage caverns and galleries after the waste packages have been emplaced. 2) Backfilling must be carried out in such a manner that long-term safety is assured and the recovery of the waste is possible without undue effort.

Tab. 2-3: Cont.

Art. 69: Closure	1) When closing a deep geological repository, its owner must backfill all excavations and seal the sections relevant for long-term safety and security. 2) The closure project must describe the following aspects in particular: a. the backfilling and sealing of the accesses to the disposal areas; b. the transformation of the pilot section into a state suitable for long-term safety; c. the backfilling and sealing of the accesses to the repository; d. the assurance of long-term safety. 3) When closing the repository, the owner must in particular ensure that: a. No inadmissible release of radionuclides takes place via the back-filled accesses. b. The separation of water-conducting rock layers existing prior to the construction of the deep geological repository is restored over the long-term. c. The marking of the deep geological repository is permanent.

The main stages of Nagra's current disposal programme are also legally stipulated. The procedural requirements are defined in the Nuclear Energy Act (KEG 2003), the Nuclear Energy Ordinance (KEV 2004), the guideline for Swiss deep geological repositories (ENSI 2020b), the related explanatory report (ENSI 2020b), and the conceptual part of the Sectoral Plan (SFOE 2008), as well as the Environmental Protection Act (USG 1983). These define that a general licence application must be submitted to the authorities to request approval of a selected site.

This general licence application must include a safety report ("*Sicherheitsbericht*") that encompasses the demonstration of post-closure safety of the deep geological repository (see Annex 3 in KEV 2004). This is to be based on a comprehensive and systematic analysis showing how the repository at the selected site will evolve, what the radiological consequences will be and how the overall protection objective and the associated guidelines and protection criteria are met in accordance with ENSI's guidelines.

ENSI regulates the design principles specific to deep geological repositories through the provision of guidelines and provides further requirements to be considered in the general licence application for the selected site. These include requirements for the operational and post-closure safety cases, siting suitability criteria and requirements for the CRZ.

ENSI has published several guidelines defining the design principles specific to deep geological repositories and the protection criteria that determine whether the protection objective has been fulfilled. ENSI Guideline G03/d specifies four design principles for geological deep geological repositories as presented in Tab. 2-4.

Tab. 2-4: Specific design principles for deep geological repositories

According to (ENSI 2020b). The English excerpts are translations from the ENSI guidelines which are only available in German. English is not an official language of the Swiss Confederation. This translation is provided for information purposes only and has no legal force.

Passive safety	A deep geological repository has to be designed so that no further measures are necessary to ensure long-term safety.
Transboundary protection	Possible future effects of deep geological repository in Switzerland may not be higher in other countries than is permissible in Switzerland.
Protection principle	Possible future effects of deep geological repository in Switzerland must not be greater than those permissible in Switzerland today.
Protection of humans and the environment	The natural basis for the existence of humans and other living organisms has to be protected.

ENSI Guideline G03/d states that the protection objective for deep geological repositories is "*to ensure the long-term protection of humans and the environment from the effects of ionising radiation, without imposing undue burdens and obligations on future generations.*"

ENSI sets out the following quantitative protection criteria for the post-closure phase:

a. *Any future evolution of a deep geological repository must not lead to the release of radionuclides causing an individual dose exceeding 0.1 mSv per year, nor cause the risk value according to criterion (b) in paragraph 2.15 of IAEA Safety Standard SSR-5 to be exceeded.*

b. *During the assessment period, the radiological consequences of inadvertent human intrusion into the deep geological repository have to be assessed on the basis of criteria (c) and (e) as set out in paragraph 2.15 of IAEA Safety Standard SSR-5.*

c. *After the end of the assessment period, the effects on the surface must not be significantly higher than the average current radiation exposure of the Swiss population.*

The purpose of the quantitative protection is to assess whether the protection objective has been fulfilled. Compliance with the protection criteria has to be shown in a safety case.

ENSI Guideline 33/649 (ENSI 2018) specifies the safety-related requirements relating to the repository design. The main requirements are summarised in Tab. 2-5.

Tab. 2-5: Safety requirements relating to the repository design, according to ENSI Guideline 33/649

According to (ENSI 2018). The English excerpts are translations from the ENSI guidelines which are only available in German. English is not an official language of the Swiss Confederation. This translation is provided for information purposes only and has no legal force. The original German text is added in italics.

Arrangements to facilitate monitoring and repairs of the repository or to retrieve the waste may not interfere with the post-closure performance of the passive safety barriers. *Vorkehrungen zur Erleichterung von Überwachung und Reparaturen des Lagers oder zur Rückholung der Abfälle dürfen die passiven Sicherheitsbarrieren nach dem Verschluss des Lagers nicht beeinträchtigen.*
In accordance with the Sectoral Plan, the waste producers must develop proposals for the layout and design of the required surface infrastructure and the underground parts of the repository that take into account the construction feasibility of the repository. *Gemäss Sachplan erarbeiten die Entsorgungspflichtigen, abgestimmt auf die bautechnische Machbarkeit, Vorschläge zur Anordnung und Ausgestaltung der notwendigen Oberflächeninfrastruktur und ordnen die untertägigen Teile des Lagers an.*
The basis for the provisional repository design of a deep geological repository is the existence of a repository concept that meets safety requirements. This includes the emplacement concept, the barrier concept optimised for long-term safety with the multi-barrier system consisting of both geological and engineered barriers, a concept for the repository components, and other specifications (e.g., complete containment of the radioactive substances for 1,000 years in HLW canisters). *Grundlage für die Auslegung eines Tiefenlagers ist das Vorliegen eines sicherheitstechnisch geeigneten Lagerkonzepts. Dieses umfasst das Einlagerungskonzept, das bezüglich Langzeitsicherheit optimierte Barrierenkonzept mit dem Mehrfachbarrierensystem aus natürlichen und technischen Barrieren, ein Konzept für die Untertagebauwerke, sowie weitere Vorgaben (z. B. vollständiger Einschluss der radioaktiven Stoffe während 1000 Jahre in Lagerbehältern für hochaktive Abfälle).*
For the site comparison, the repository concept is to be reviewed on the basis of the current state of knowledge, which has been expanded since Stage 2 was completed, and updated if necessary. *Für den Standortvergleich ist das Lagerkonzept basierend auf dem aktuellen, gegenüber Etappe 2 erweiterten Kenntnisstand zu überprüfen und gegebenenfalls zu aktualisieren.*
When determining the lateral and vertical positions of the repository within the CRZ, facies variations and the retention capacity of the rock formations they include must be taken into account. *Bei der lateralen und vertikalen Lagerplatzierung innerhalb des EG sind fazielle Variationen und das Rückhaltevermögen der enthaltenen Gesteinsbereiche zu berücksichtigen.*
For the CRZs used in the site comparison, site-specific repository designs are to be developed based on the repository concept that adequately considers aspects related to long-term safety, repository construction, operation and closure and the potential retrieval of waste without undue effort. The basis for this is the updated overall picture of the properties and processes in the respective CRZs. *Für die im Standortvergleich verwendeten EG sind aus dem Lagerkonzept standortspezifische Lagerauslegungen zu entwickeln, in denen die Aspekte von Bau, Betrieb, Rückholung ohne grossen Aufwand, Verschluss und Langzeitsicherheit angemessen berücksichtigt werden. Basis dafür bildet das aktualisierte Gesamtbild der Eigenschaften und Prozesse in den jeweiligen EG.*

Tab. 2-5: Cont.

If variants of a component of the repository design are considered for the site comparison (e.g., different types of backfill material or disposal containers), all aspects of safety and engineering feasibility affected by it are to be discussed, and the safety-related consequences for the overall system are to be shown. Components of the repository design that are relevant to long-term safety are to be optimised and their selection justified. *Falls für den Standortvergleich Varianten einer Komponente der Lagerauslegung berücksichtigt werden (z. B. Zementverfüllung als Alternative zur Bentonitverfüllung in den HAA-Lagerstollen oder kupferbeschichtete Stahlbehälter als Tiefenlagerbehälter anstatt von Stahlbehältern für HAA, verschiedene Zwischensiegeltypen in den HAA-Lagerstollen), so sind alle davon betroffenen Aspekte der Sicherheit und technischen Machbarkeit zu diskutieren und die sicherheitstechnischen Konsequenzen für das Gesamtsystem aufzuzeigen. Für die Langzeitsicherheit relevante Komponenten der Lagerauslegung sind zu optimieren und deren Wahl zu begründen.*

Once the general licence has been granted, further nuclear licences are required in accordance with the Nuclear Energy Act and Nuclear Energy Ordinance (i.e., a construction licence and an operating licence). At each of these major project milestones and once the operational and monitoring phases are complete – an order for repository closure from the Federal Government, a formal safety assessment will be presented, as well as the compilation of a safety case (if needed for the milestone at hand).

2.5 Scientific and technical foundation

For more than forty years, many organisations and institutions worldwide have conducted research, development and demonstration (RD&D) into the geological disposal of radioactive waste. Demonstrating that deep geological disposal is a safe and feasible solution requires expertise in a wide range of scientific and engineering disciplines such as geology, groundwater hydrology, material sciences, chemistry, mining, nuclear engineering, and others.

Today, mature deep geological repository concepts exist or have been implemented and there is confidence that these provide a safe and feasible long-term solution to the management of radioactive waste. This confidence is based on the extensive amount of RD&D conducted in this field, including assessing and modelling of cement degradation, corrosion, radionuclide dissolution and migration in the geosphere and biosphere, site characterisation activities, design and engineering work and feasibility demonstrations. Various safety assessments and safety cases have been prepared and favourably reviewed by the authorities in Switzerland and abroad.

These RD&D outcomes form the scientific and technical foundation for the design and safety demonstration of a range of deep geological repository concepts. As such, they bound and guide the disposal solutions that are being developed and form an important component of the assessment basis to analyse the performance of these solutions.

Nagra regularly publishes RD&D reports that present the progress made and identify key remaining research priorities. The Nagra RD&D report from 2002 (Nagra 2002c) was part of the basis for the conclusion by the Swiss Federal Government in 2006 that Nagra had demonstrated the technical feasibility of deep geological repositories in Switzerland. The most recent research achievements are published in the latest RD&D report from 2021, together with the latest research goals (Nagra 2021c). The status of knowledge is judged by Nagra to be profound and adequate for the selection of NL as the most suitable siting region for implementing the disposal project (Nagra 2022c) and the submission of a general licence application.

Future RD&D activities concern reducing uncertainties further where needed and optimising safety and the repository design (see Chapter 3).

In addition, developments in other countries will continue to inform the Swiss programme. In particular, Finland, Sweden and France are making progress in implementing geological disposal facilities for HLW and long-lived ILW. In 2015, POSIVA obtained a construction licence for a geological disposal facility for Finland's SF and submitted its operating licence application in December 2021 (POSIVA 2022). In Sweden, the government granted the Swedish Nuclear Fuel and Waste Management Company (SKB, *Svensk Kärnbränslehantering AB*) a construction licence for a similar facility in 2022, and in France, Andra submitted a construction licence application for the geological disposal of HLW and long-lived ILW in January 2023 (ANDRA 2022).

3 Safety and repository concept

The safety concept explains how, through the multi-barrier components and the safety functions they perform, the geological deep repository ensures the protection of humans and the environment. The repository concept describes the 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, which is the subject of the present chapter.

3.1 Overview of the multi-barrier system and safety concept

The repository provides safety by means of multiple geological and engineered safety barriers, i.e., the multi-barrier system. These barriers operate passively, meaning that, after closure of the repository, no further measures, such as for maintenance, control, or monitoring, are required to ensure post-closure safety. This relieves future generations of the burden of having to manage or monitor the disposed waste.

Waste is disposed of in emplacement rooms, located deep underground, roughly in the middle of the Opalinus Clay host-rock layer, between its confining units (Fig. 3-1). The engineered barriers for HLW disposal consist of SF assemblies with fuel rods (UO_2 or mixed oxide fuel (MOX) pellets in cladding tubes) and vitrified RP-HLW that are packaged in steel canisters. The HLW canisters are emplaced in drifts, which are subsequently backfilled with a buffer and sealed. For L/ILW disposal, L/ILW waste packages are placed inside waste containers and voids filled with cementitious material. The waste containers are in turn emplaced in caverns that are backfilled with cement-based mortar.

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

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

The geological units above or below the Opalinus Clay include units with heterogeneous distribution of clay mineral contents and locally lower clay contents, are nonetheless contributing to the retardation of the radionuclide release.

The geological barrier is complemented by a mutually compatible set of engineered barriers. A key role of the engineered barriers is the minimisation and mitigation of disturbances to the CRZ caused by the waste and its emplacement, including, for example, the effects of heat generated by the waste and the disturbance to the rock caused by the excavation and ventilation of underground openings. The engineered barriers around the HLW waste, with the waste disposal canister playing the central role, are expected to provide a period of complete containment of radionuclides. Although some eventual release of radionuclides and migration through the multi-barrier system cannot be excluded, most radionuclides will remain immobilised in the waste forms and waste containers until they decay.

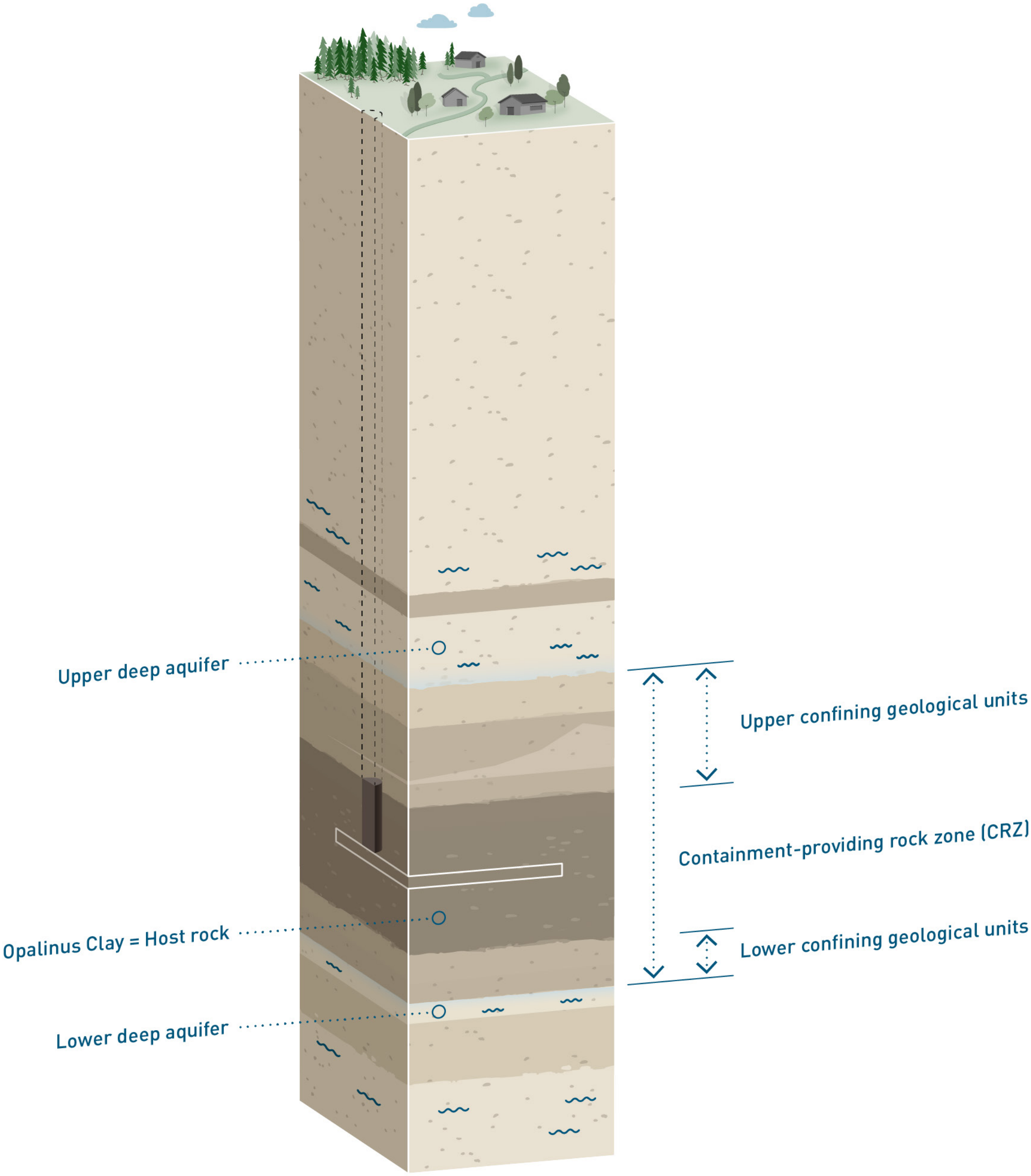

Fig. 3-1: Placement of the repository deep underground within the Opalinus Clay, between its confining units

Furthermore, the radionuclides that are released will migrate only slowly towards the surface environment, with substantial attenuation by radioactive decay of many radionuclides first within the engineered barriers and then, for any that penetrate these barriers, within the surrounding geological barrier. The location of the geological repositories will be such that the risk of future inadvertent human intrusion is small. Nonetheless, because the possibility of inadvertent human intrusion or disturbance of the repository in the distant future cannot be completely excluded, repository design features are incorporated that mitigate its potential impact. These also form part of the safety concept. These various aspects of the safety concept are described in later sections of this report.

A qualitative description of the expected phenomenological evolution of the repository is presented in (Nagra 2024f). Prior to closure, and after the completion of waste emplacement operations, a monitoring phase will start. After roughly ten years of monitoring, the disposal area accessways will be backfilled and sealed. This will be followed by another observation period that is currently assumed to last 50 years (Nagra 2021a). After this observation period, the whole repository will be closed[5] and the post-closure period will begin. Evolution in the post-closure period can be described in terms of five periods (which to some extent overlap):

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

The phenomenology highlights that a large proportion of the radionuclides is not expected to leave the repository and would decay in there, due to their retention in the engineered barriers. The radionuclides reaching the host rock will very slowly diffuse toward the CRZ and further decay. Once in the groundwater aquifers and further in the biosphere, the remaining radionuclides will be diluted in different compartments (e.g., soil, atmosphere, plants…). Due to the combined effect of the safety barriers, radiological consequence analyses show that potential doses to humans or the environment are expected to be well below the protection criterion specified by the regulatory authority (Nagra 2024i).

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[5] This will involve backfilling the central area, the facilities for underground geological investigations and the observation drifts; these system features are described in Ch. 4.

3.2 Safety functions and related safety requirements

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

- **S1: Isolation** of radioactive waste from humans and the environment;
- **S2: Complete containment** of radionuclides for a period of time;
- **S3: Immobilisation, retention, and slow release** of radionuclides;
- **S4: Compatibility** of the components of the repository system;
- **S5: Long-term stability** of the multi-barrier system regarding long-term geological and climatic evolution.

These safety functions are used to derive a set of safety requirements on the system components, including the "pillars of safety" described in Section 3.3; the Level 2 safety requirements listed in App. A (Level 1 requirements are related to the boundary conditions for the development of the safety and repository concept described in Ch. 2).

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

3.3 Pillars of safety

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

- The **deep underground location** of the waste emplacement rooms **in a stable geological environment** that lacks exploitable resources ensures that the repository is not susceptible to geological events and processes relevant to post-closure safety and that inadvertent human intrusion remains unlikely.
- The **containment providing rock zone** (CRZ) includes the host rock as well as upper and lower confining units. The host rock, Opalinus Clay, is characterised by a fine and homogeneous pore structure, extremely low hydraulic permeability, a homogeneous and high clay mineral content and the associated high sorption capacity for many radionuclides. The CRZ is characterised by favourable properties (especially self-sealing ability) for long-term stability, forming a very effective and stable barrier against radionuclide transport and a compatible (physical and chemical) environment for the engineered barriers (Nagra 2024r).
- Both the **SF and RP-HLW matrices** are chemically stable in the expected environment.
- The **HLW disposal canisters** are mechanically stable and corrosion-resistant in the expected environment. They ensure complete containment of the radionuclides for at least as long as the heat generated by the waste has significant potential to affect transport processes in the surrounding barriers and satisfy the regulatory requirement of complete containment for at least 1,000 years (ENSI 2020b).

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

Each pillar of safety can contribute directly and/or indirectly to the safety functions. For example, the HLW disposal canisters contribute directly to the containment of radionuclides, while the surrounding buffer contributes indirectly as it helps to protect the canisters. Compatibility between the different pillars based upon a solid technical and scientific understanding of the geological and engineered components.

The contributions of these seven pillars to the five safety functions are summarised schematically in Fig. 3-2 and Fig. 3-3 elaborated in the discussion of component-specific functions in Section 3.4.

SF and RP-HLW matrix

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

SF and RP-HLW disposal canisters

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

Buffer of the HLW emplacement drifts

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

Deep underground location in a stable geological environment

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

Containment-providing rock zone (CRZ)

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

Closure system (backfill and seals)

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

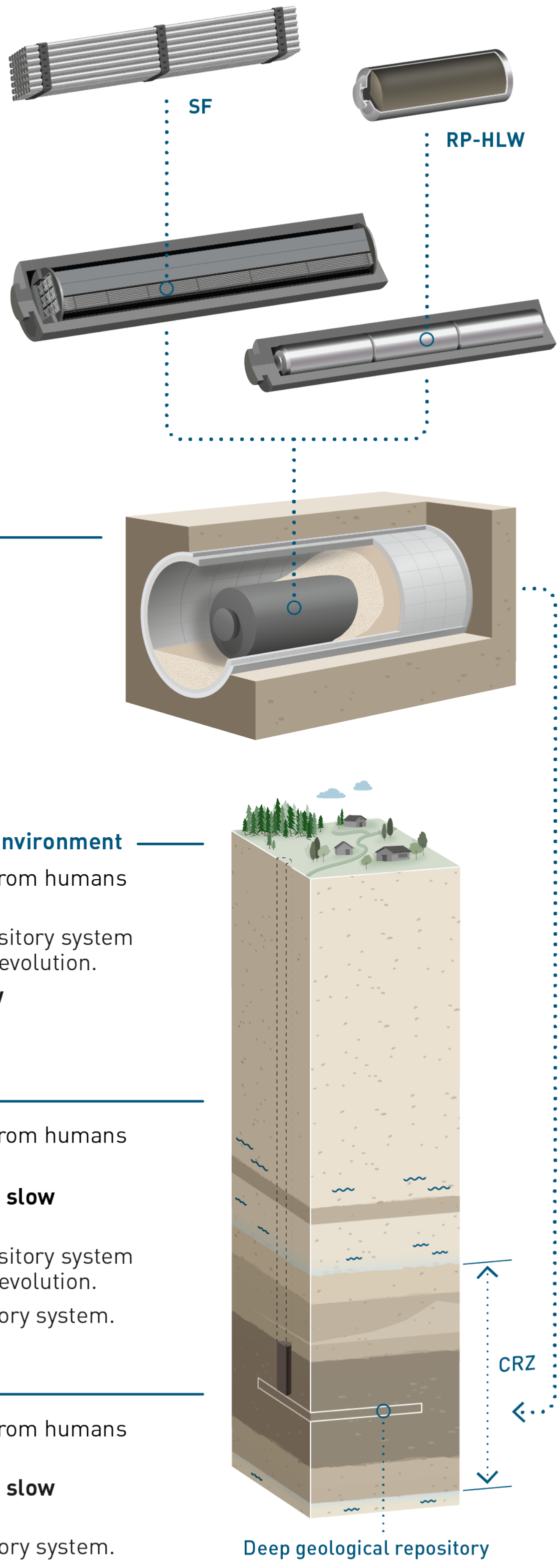
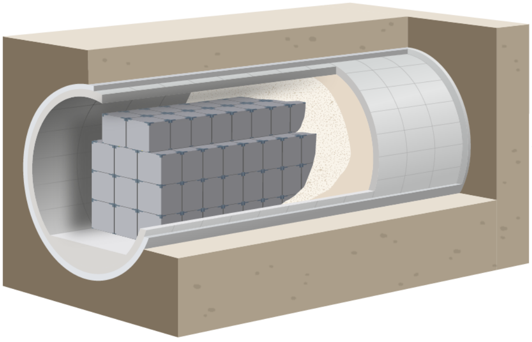


Fig. 3-2: Summary of the functions of the pillars of safety for HLW disposal



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.

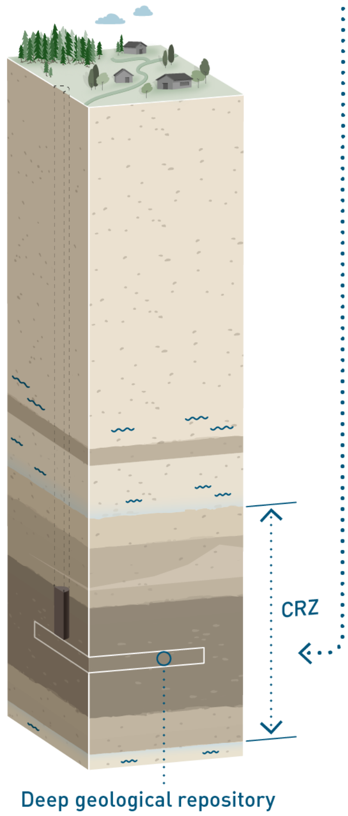


Fig. 3-3: Summary of the functions of the pillars of safety for L/ILW disposal

3.4 Functions of the pillars of safety

Specific properties of, or actions to be performed by, one or more system features, including the pillars of safety, that contribute directly or indirectly to the safety functions are termed component-specific functions (though some apply to the repository system as a whole).

The main component specific functions for HLW and L/ILW disposal are illustrated in Fig. 3-2 and Fig. 3-3, respectively, and describe further in the following sections. The component specific functions are associated with particular Level 2 safety requirements in Nagra's hierarchy of safety requirements. These requirements are listed in the text and are each assigned a code. The codes begin with the characters "L2", which refers to Level 2, then an abbreviation for the related safety function and finally to a unique number. An overview of all component-specific functions and their links to both the safety functions and the system components is presented in App. A.

3.4.1 Deep underground location in a stable geological environment

The deep underground location of the waste emplacement rooms in a stable geological environment contributes to:

- waste isolation (safety function S1);
- immobilisation, retention, and slow release of radionuclides (safety function S3);
- long-term stability (safety function S5).

Once backfilled, specific underground structures, including the emplacement drifts and caverns and various accessways, also contribute to compatibility (S4), as described in Section 4.1 in the discussion of specific elements of the layout.

3.4.1.1 Contributions to waste isolation

The depth of the repository contributes to waste isolation by placing the waste beyond the depth of common excavation activities, such as mining, tunnelling, or quarrying. The depth of the repository minimises the effects of surface events and processes on the repository and the likelihood and consequences of future human actions. The consequences of inadvertent human intrusion are also reduced by compartmentalising the repository (i.e., individually sealed waste emplacement rooms). Furthermore, compartmentalisation helps to limit the propagation and impact of potential incidents and accidents.

The deep underground location in a stable geological environment thus contributes to the following Level 2 requirements related to waste isolation:

L2-ISO-02	Consequences of inadvertent human intrusion are limited
L2-ISO-03	Effects of events and processes at the surface are minimised
L2-ISO-04	Likelihood and consequences of future human actions are minimised

3.4.1.2 Contributions to immobilisation, retention, and slow release

The repository design can contribute to the immobilisation, retention, and slow release of radionuclides by avoiding any preferential release pathways to the boundary of the CRZ and thus optimising the radionuclide retention within the repository. Such pathways can be formed by naturally occurring fractures but can also arise from the construction of the repository.

The deep underground location in a stable geological environment thus contributes to the following Level 2 safety requirements related to immobilisation, retention, and slow release of radionuclides:

L2-IRR-01	The system provides long transport times that result in attenuation of radionuclide releases by decay
L2-IRR-02	The system provides dilution and dispersion of radionuclides during transport

3.4.1.3 Contributions to long-term stability

The repository location and layout are selected with a view to long-term stability of the geological setting, i.e., in a stable geological environment away from faults and deep underground. The repository layout is also arranged in such a way as to prevent mutual interactions between different repository components that could be detrimental to safety. Potential interactions to consider include:

- geomechanical aspects such as overlapping excavation damaged zones (EDZ),
- repository-induced effects, in particular, those due to:
  - heat released by HLW and, to a shorter and lesser extent, heat released from cement hydration during the construction or closure of the repository,
  - gas generation by corrosion of metals present in the waste and construction materials, and by degradation of organic materials mainly present in L/ILW, and
  - chemical and microbiological interactions between different parts of the repository, although these are generally of secondary importance as they occur at a smaller scale than the above-mentioned aspects.

Such mutual interactions are mainly prevented or minimised by ensuring that the different components of the repository are sufficiently far apart. The impact of heat is minimised by spatially distributing heat-emitting waste. Tunnel convergence and EDZ development are minimised by orienting the underground openings in the direction of the principal stress. Finally, unfavourable mutual interactions (e.g., overlapping EDZs or interactions between gas, thermal or chemical processes) between different parts of the repository must be avoided by placing them sufficiently far apart.

The deep underground location in a stable geological environment thus contributes to the following Level 2 safety requirement related to long-term stability:

L2-STB-02	The layout and placement of the repository are such that it is unlikely to be affected by processes at the surface, by the reactivation of faults or by the creation of new faults that intersect the underground facilities

3.4.2 Containment-providing rock zone

The CRZ contributes to:

- waste isolation (safety function S1);
- immobilisation, retention, and slow release of radionuclides (safety function S3);
- compatibility (safety function S4);
- long-term stability (safety function S5).

Although the CRZ clearly contributes to the containment of the radionuclides, containment as a safety function (S2) is reserved for complete containment within waste packages, and specifically within the HLW disposal canisters. Containment of radionuclides within the CRZ occurs as a result of the limited movement of porewater and of immobilisation and retention due to sorption, and so is captured by the safety function S3.

3.4.2.1 Contributions to waste isolation

A CRZ with limited geological or groundwater resources will reduce the likelihood of future human actions and, in that way, contributes to waste isolation. In addition, the self-sealing properties of the host rock will mitigate the consequences of inadvertent human intrusion, due to radionuclide retention.

The CRZ thus contributes to the following Level 2 safety requirement related to waste isolation:

L2-ISO-02	Consequences of inadvertent human intrusion are limited

3.4.2.2 Contributions to immobilisation, retention, and slow release

The CRZ is characterised by low hydraulic conductivities, low hydraulic gradients and low diffusion coefficients, ensuring sufficiently long transport times from the repository to the CRZ boundaries for the radionuclides. The mineralogy and porewater composition of the CRZ also promote radionuclide precipitation. Hence, the CRZ contributes to the immobilisation, retention, and slow release of radionuclides. The Opalinus Clay formation in particular is characterised by:

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

The geological units above or below the Opalinus Clay include units with a lower or more heterogeneous clay mineral content, participating in the retardation of the radionuclide release.

The CRZ contributes to the following Level 2 safety requirement related to immobilisation, retention, and slow release of radionuclides:

L2-IRR-01	The system provides long transport times that result in attenuation of radionuclide releases by decay

3.4.2.3 Contributions to compatibility

The safety function of compatibility is fulfilled by selecting a suitable host rock (and implementing excavation and design controls), such that the performance of the CRZ is not adversely affected by the repository itself. A CRZ with sufficiently high thermal conductivity and a gas storage capacity can enhance the dissipation of heat and gas, respectively, and limit or prevent heat- or gas-induced fracturing of the CRZ. The extent of fracturing caused by repository excavation (EDZ formation) will depend on the excavation method and the hydromechanical properties of the CRZ. Selecting a CRZ with the capacity to seal fractures will reduce the impact of these processes on the CRZ performance. Furthermore, the CRZ properties favour low permeability in the EDZ, e.g., good rock strength to provide mechanical stability and creep closure to heal fractures. The mineralogy and porewater composition of the CRZ provide a chemical environment which limits the corrosion of the HLW disposal canister. Furthermore, the low permeability of the CRZ constrains the water flow towards the canisters, required for corrosion.

The properties of the CRZ thus contribute to the following Level 2 safety requirements related to compatibility:

L2-CMP-01	Detrimental effects of repository-generated gas are avoided
L2-CMP-02	Detrimental effects of repository-generated heat are avoided
L2-CMP-03	Detrimental hydromechanical effects of excavation are limited
L2-CMP-06	Unfavourable chemical interactions between different parts of the repository are avoided or limited

3.4.2.4 Contributions to long-term stability

The CRZ provides long-term stability to ensure that the diffusion-dominated conditions, porewater composition and self-sealing capacity are preserved. This requires that the stress conditions, porewater composition, permeability, and diffusion coefficients in the CRZ are stable with respect to processes such as decompaction, erosion, glacial loading and unloading, seismic activity, tectonic regime change, and dissolution phenomena.

However, there are no specific L2 safety requirements for the CRZ related to long-term stability.

3.4.3 SF and RP-HLW matrix

RP-HLW is the product of the calcination of highly radioactive liquids from reprocessing operations, mixed at high temperatures with borosilicate glass and poured into steel flasks. This mix is melted into a glass matrix, which contains the radionuclide inventory, and enclosed in stainless-steel flasks. In SF, most radionuclides are enclosed in the fuel pellets and the cladding.

The SF (i.e., fuel pellets and claddings) and RP-HLW matrix (i.e., borosilicate glass) contribute to:

- immobilisation, retention, and slow release of radionuclides (safety function S3);
- compatibility (safety function S4).

3.4.3.1 Contributions to immobilisation, retention, and slow release

The matrices immobilise most radionuclides in stable forms which can only start to degrade (at very slowly rates) when they come into contact with porewater. In the case of SF, after breaching of the HLW disposal canisters, a small proportion of the radionuclides may then be released rapidly (e.g., gaseous fission products present in the gap between the fuel matrix and the cladding, and activation products from the cladding). Most radionuclides, however, remain in the SF and RP-HLW waste matrices for a long time as they are uniformly distributed within them; they are congruently released with the degradation of these matrices once they come into contact with porewater. The degradation of the fuel matrix and borosilicate glass occurs very slowly in the reducing environment that prevails in the repository near field. Furthermore, as the waste matrices degrade, the composition of the porewater will change and promote the precipitation and co-precipitation of radionuclides, limiting the radionuclide release into porewater. The waste matrices thus contribute to the immobilisation, retention, and slow release of radionuclides.

The SF and RP-HLW waste matrices contribute to the following Level 2 safety requirements related to immobilisation, retention, and slow release of radionuclides:

L2-IRR-06	Once in contact with water, the waste forms remain stable and release most radionuclides congruently with slow degradation
L2-IRR-11	The waste forms immobilise most radionuclides until contacted by porewater
L2-IRR-12	Once released from the waste forms, some radionuclides may be immobilised by precipitation and co-precipitation

3.4.3.2 Contributions to compatibility

The compatibility between the waste matrices and the other engineered barriers is ensured by imposing requirements based on certain properties of the waste (waste acceptance criteria).

There are no specific L2 safety requirements on the SF and RP-HLW waste forms related to compatibility.

3.4.4 Disposal canisters

Before emplacement, HLW (including SF and RP-HLW) will be packaged into stable and corrosion-resistant canisters. These disposal canisters contribute to three safety functions:

- complete containment (safety function S2);
- immobilisation, retention, and slow release of radionuclides (safety function S3);
- compatibility (safety function S4).

3.4.4.1 Contributions to complete containment

The HLW disposal canisters must guarantee complete containment of the radionuclides for the required minimum of 1,000 years, corresponding to the following Level 2 safety requirement:

L2-CC-02	The HLW disposal canisters provide complete containment for the required minimum period of 1,000 years under expected conditions

This implies that they will resist to the mechanical stresses and corrosion for at least this period.

3.4.4.2 Contributions to immobilisation, retention, and slow release

The HLW disposal canisters also contribute to the immobilisation, retention, and slow release of radionuclides, as, during their corrosion, the generation of H_2 affects the local porewater chemistry in a way that promotes the stability of the SF matrix (and hence the slow release of embedded radionuclides) and precipitation, immobilisation, or retardation of some radionuclides.

There are no specific L2 safety requirements on the HLW disposal canisters related to immobilisation, retention and slow release.

3.4.4.3 Contributions to compatibility

The safety function of compatibility is fulfilled by ensuring that canister corrosion occurs slowly, resulting in low gas generations rates, and by providing sufficient radiation shielding to limit radiolysis around the canisters (Nagra 2016d, Leupin et al. 2016, Poller et al. 2016). In addition, the HLW disposal canister is designed such that the thermal density in the HLW disposal area is low enough to protect the engineered and geological barriers from damage caused by the thermal load. This requires a limit on the thermal load of the HLW placed in each individual canister. It also requires that the -HLW disposal canisters are emplaced sufficiently far apart to limit the temperature increase in the surrounding buffer and CRZ (see Section 4.1.6).

The HLW disposal canisters thus contribute to the following Level 2 requirements related to compatibility:

L2-CMP-15	The heat output of the HLW disposal canisters does not result in irreversible damage of the geological or engineered barriers
L2-CMP-23	The gas generated by corrosion of the HLW disposal canisters and its transport through engineered and geological barriers does not result in irreversible damage of these barriers

3.4.5 HLW buffer

The ENSI regulatory guidelines (ENSI 2020b) require all underground openings to be backfilled. The backfill used within the HLW drifts is termed the buffer. The buffer contributes to:

- immobilisation, retention, and slow release of the radionuclides (safety function S3);
- compatibility (safety function S4).

3.4.5.1 Contributions to immobilisation, retention, and slow release

As the buffer forms a physical and chemical barrier around the HLW disposal canisters, it contributes to the immobilisation, retention, and slow release of radionuclides. The physical barrier is provided by selecting a buffer material with a low permeability and through which colloids cannot be transported. The chemical barrier provided by selecting a buffer material with a mineralogy and porewater that promotes the sorption and immobilisation by precipitation of many of the radionuclides that may be released after breaching of the canisters.

The buffer contributes to the following Level 2 safety requirement related to immobilisation, retention, and slow release of radionuclides:

L2-IRR-04	The buffer retains many radionuclides once released from the HLW disposal canisters

3.4.5.2 Contributions to compatibility

The buffer needs to have chemical and mineralogical compatibility with adjacent components, including the Opalinus Clay host rock. It needs to provide a stable environment around the HLW disposal canisters that limits corrosion and protects them against mechanical stress damage. This implies that its chemical and mineralogical composition remain unchanged under the expected conditions, so that the buffer can protect the HLW disposal canisters for a sufficient period. The buffer must ensure that the mechanical loads on the canisters are evenly distributed. It must also inhibit microbial activity in order to limit the risk of microbially induced corrosion at the surface of the HLW disposal canister. Care must be taken that any corrosive substances in the buffer are only present in low concentrations.

Canister corrosion is not only an important factor for the lifetime of the canister; it also leads to the generation of gas. Gas is transported through the buffer to the EDZ and from there into the host rock. The buffer must ensure sufficient gas transport to its surroundings, preventing an unfavourable gas pressure buildup and associated damage of the barriers. The gas permeability of the buffer has therefore to be sufficient. However, due to the low corrosion rate and associated gas generation rate, diffusion-dominated transport is expected. The buffer must also efficiently transfer heat to its surroundings with a sufficiently high thermal conductivity to protect the engineered and geological barriers from damage caused by the thermal load. When evaluating the performance of the buffer in transferring heat, it is important to consider how the properties of the buffer evolve shortly after repository closure when the buffer becomes saturated. After a certain amount of time, the tunnel support will degrade. The mechanical stabilisation of the host rock is then ensured by the buffer. This requires that compressibility of the is sufficiently low to provide stability to the tunnel support and to limit tunnel convergence.

The buffer contributes to the following Level 2 safety requirements related to compatibility:

L2-CMP-07	The buffer allows for sufficient gas transport to its surroundings
L2-CMP-08	The buffer favours efficient heat transfer between it and its surroundings
L2-CMP-09	The buffer limits tunnel convergence
L2-CMP-10	The buffer provides a protective environment for the HLW canisters
L2-CMP-29	The buffer is chemically and mineralogically compatible with adjacent components

3.4.6 Cementitious L/ILW near field

In general, L/ILW is placed in concrete containers filled with a cement-based mortar. The L/ILW emplacement caverns in which the containers and placed are also backfilled with a cement-based mortar. The concrete containers and the cement-based mortar create a cementitious L/ILW near field around the waste which contributes to two safety functions:

- immobilisation, retention, and slow release of the radionuclides (safety function S3);
- compatibility (safety function S4).

3.4.6.1 Contributions to immobilisation, retention, and slow release

The cementitious near field contributes to the immobilisation, retention and slow release of radionuclides by creating a physical and chemical barrier around the waste. The physical barrier ensures that porewater movement in the emplacement caverns is slow and diffusion-dominated. The cementitious near field also creates a hyper alkaline environment that limits the solubility of many radionuclides and provides a suitable environment for retaining many radionuclides by sorption.

The cementitious L/ILW near field contributes to the following Level 2 safety requirement related to immobilisation, retention and slow release of radionuclides:

L2-IRR-05	The cementitious L/ILW near field retains many radionuclides

3.4.6.2 Contributions to compatibility

The cementitious near field needs to have chemical and mineralogical compatibility with adjacent components. The degradation products of the cementitious materials do not significantly affect the performance of adjacent barriers and radiation-induced effects are limited in the L/ILW repository section. The L/ILW emplacement caverns are foreseen to be fully backfilled with cement-based mortar, which is sufficiently stiff to limit tunnel convergence after the tunnel support has degraded.

Gas will be formed by the corrosion of the metallic L/ILW and construction materials and by the degradation of organic materials. The cementitious near field must be designed with a high gas-accessible porosity and sufficient storage capacity to prevent an unfavourable gas pressure buildup and associated damage of the barriers. The cementitious environment also limits the corrosion rates of metals and the degradation of organic L/ILW and hence the rate of gas generation.

Low amounts of heat are expected to be generated by the waste stored in the L/ILW repository section. Nonetheless, the heat generation by the cementitious L/ILW near field, e.g., due to cement hydration or radioactive decay in the L/ILW, needs also to be limited. It is expected that the release of hydration heat from cement leads to a relatively short-term temperature increase and low heat emitting waste is foreseen to be stored in the L/ILW repository section.

The cementitious L/ILW near field contributes to the following Level 2 safety requirements related to compatibility:

L2-CMP-05	The cementitious L/ILW near field provides a limited source of heat
L2-CMP-11	The cementitious L/ILW near field favours gas transport and storage
L2-CMP-13	The L/ILW cavern backfill limits tunnel convergence
L2-CMP-14	The L/ILW near field is chemically and mineralogically compatible with adjacent barriers
L2-CMP-16	The cementitious L/ILW near field limits the rate of gas generation

3.4.7 Closure system

The closure system includes the sealing of the emplacement rooms, accessways and shafts, and the backfilling of these accessways and shafts. This system contributes to three safety functions:

- waste isolation (safety function S1);
- immobilisation, retention, and slow release of the radionuclides (safety function S3);
- compatibility (safety function S4).

The design of the different components of the closure system is described in Ch. 4, where further component-specific functions are described.

3.4.7.1 Contributions to isolation

In accordance with ENSI G03 (ENSI 2020b), the emplacement rooms will be sealed immediately after backfilling. Other underground openings are backfilled and sealed at the end of the monitoring period. The resulting closure system contributes to waste isolation as it would require effort and resources to dismantle it, thus deterring inadvertent future human intrusion. Installing seals at the entrance of each emplacement room after waste emplacement also limits the consequences of the abandonment of the repository. Sealing and backfilling compartmentalises the repository which limits the consequences of inadvertent human intrusion.

The closure system contributes to the following Level 2 safety requirements related to isolation:

L2-ISO-01	Likelihood and consequences of abandonment of the repository are minimised
L2-ISO-02	Consequences of inadvertent human intrusion are limited
L2-ISO-04	Likelihood and consequences of future human actions are minimised

3.4.7.2 Contributions to immobilisation, retention, and slow release

The system also contributes to the immobilisation, retention, and slow release of radionuclides because many will be retained within the closure system. The radionuclides not retained within the closure system will slowly diffuse away. The closure system of the shaft also creates a barrier for gaseous radionuclide-bearing species (e.g., $^{14}CH_4$) in order to contain them for a longer time within the accessways and shafts.

The closure system contributes to the following Level 2 safety requirements related to immobilisation, retention, and slow release of radionuclides:

L2-IRR-01	The system provides long transport times that result in attenuation of radionuclide releases by decay
L2-IRR-02	The system provides dilution and dispersion of radionuclides during transport
L2-IRR-08	The closure system retains any radionuclides released from the disposal areas

3.4.7.3 Contributions to compatibility

In terms of compatibility, the closure system must ensure sufficient gas transport to its surroundings and provide for sufficient gas storage volume. The system itself must also be a limited source of gas. This means that the rate and extent of gas generation from metallic structural materials in the closure system will have to be limited. Finally, the closure system must limit tunnel convergence by providing stability to the tunnel support resp. the rock after tunnel support degradation and be chemically and mineralogically compatible with adjacent barriers.

The closure system contributes to the following Level 2 safety requirements related to compatibility:

L2-CMP-19	The closure system favours gas transport and storage
L2-CMP-20	The closure system does not contribute significantly to gas generation
L2-CMP-21	The closure system limits tunnel convergence
L2-CMP-22	The closure system is chemically and mineralogically compatible with adjacent barriers

3.5 Performance objectives

Safety functions and component-specific functions can be supplemented with performance objectives. Performance objectives constitute Level 3 in Nagra's hierarchy of safety requirements that guide design development.

Performance objectives 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. For example, it is a component-specific function of the bentonite to supports the HLW disposal canisters in containing the waste**,** by limiting corrosion and protecting them against mechanical stress damage (Section 3.4.5). This function is fulfilled by bentonite swelling upon saturation with porewater. The bentonite buffer is expected to evolve in such a way that it protects the HLW disposal canister mechanically for as long as possible. The performance objective leads to design requirements that define, for example, what minimal swelling pressure bentonite must exert on the HLW disposal canister to fulfil this function.

Developing a sufficiently quantified design and demonstrating that this design meets the more detailed performance objectives and design requirements is planned at a later stage of licensing when the selected disposal site has been approved. A provisional design developed for the purposes of the general licence application and the related safety case is, however, described in the following chapter.

4 Provisional repository design and additional component-specific functions

The provisional design for a geological repository for both HLW and L/ILW with surface facilities at the Haberstal site at a depth of ca. 900 m, is the basis of the corresponding safety case, i.e., the current implementation of the safety and repository concept, is described in the following sections. Nagra has compared previously a combined geological repository with two distinct geological repositories for L/ILW, including ATW, and for HLW. It was concluded that a geological repository for both HLW and L/ILW has the same radiational operational and long-term safety requirements as two separate ones, but has clear advantages in terms of construction-related risks, resource consumption and greenhouse gas emission, as fewer facilities have to be constructed and operated (Nagra 2021a).

As illustrated in Fig. 4-1, the repository is foreseen to consist of two separate sections: one for the disposal of L/ILW (including ATW), and the other one for HLW (including both SF and RP-HLW).

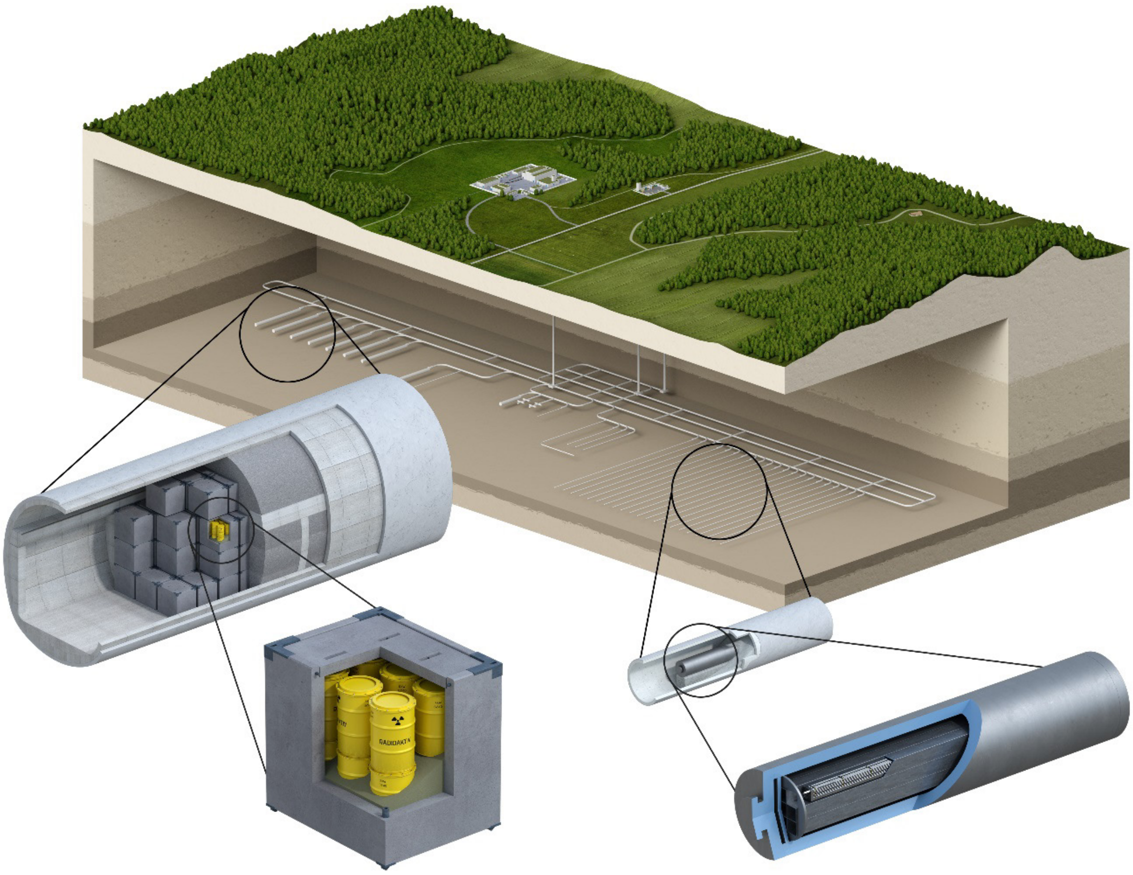


Fig. 4-1: Illustration of engineered barriers for a co-disposal of L/ILW (left side) and HLW (right side)

Additional Level 2 safety requirements, over and above those described in Chapter 3 for the pillars of safety, are again identified in this chapter in tables. The requirements described here in Chapter 4 are expected to support the definition of more specific and quantified design requirements, which will be derived in detail in the future licensing stages (i.e., for construction or operating licence applications), by means of the iterative design development process.

Design choices do not only have long-term safety implications. Other requirements or considerations related to operational safety, engineering practicability or cost may also come into play. These considerations are discussed where relevant in the following sections, albeit more briefly. As the surface infrastructure is not relevant for long-term safety, it is not included in this chapter. Decisions on the final repository design will be taken when the construction licence application is prepared, on the basis of the state of knowledge at that time.

4.1 Repository layout

The following sections present the current repository layout, and also include the safety implications of the construction of the repository, as well as its impact on the host rock surrounding the repository.

Specific repository components described in the following are as follows:

- accessways,
- repository sections,
- pilot repository and central area,
- disposal area accessways,
- disposal areas, and
- emplacement rooms.

4.1.1 Accessways to the deep geological repository

The accessways to the deep geological repository can take the form of tunnels (ramps), shafts (with a shaft head at the surface) or blind shafts (underground shaft head with connecting tunnel). The number of accessways and their specific functions (e.g., emplacement operations, staff and material transfer, ventilation, evacuation route, etc.) can also vary. The actual design choices also depend on the site characteristics.

In the current repository layout, the geological repository for both HLW and ILW will have three shafts (Fig. 4-2): an access shaft, an operation shaft and a ventilation shaft.

The accessways must be designed, constructed, operated and closed in such a way that:

- they do not form a preferential release pathway for radionuclides along the repository components, and
- they do not cause unfavourable interactions with other parts of the repository.

Preventing the shafts from becoming a preferential pathway for radionuclide transport can be achieved by ensuring that:

- there is a sufficient lateral distance between the shafts and the HLW emplacement drifts and between the shafts and the L/ILW emplacement caverns, and
- the closure system (i.e., seals and backfill of repository structures) limits radionuclide migration in the repository.

The closure system will also contribute to preventing an increased flow through the repository sections as well as hydraulic short-circuits (see Section 4.2.5) (Nagra 2024d).

The host rock will desaturate around the shafts, which can in turn affect the hydromechanical, thermal, chemical and mineralogical properties of the CRZ. Here too, a sufficient distance between the shafts and the disposal areas must be implemented to minimise or avoid any long-term safety consequences related to desaturation (Nagra 2024f).

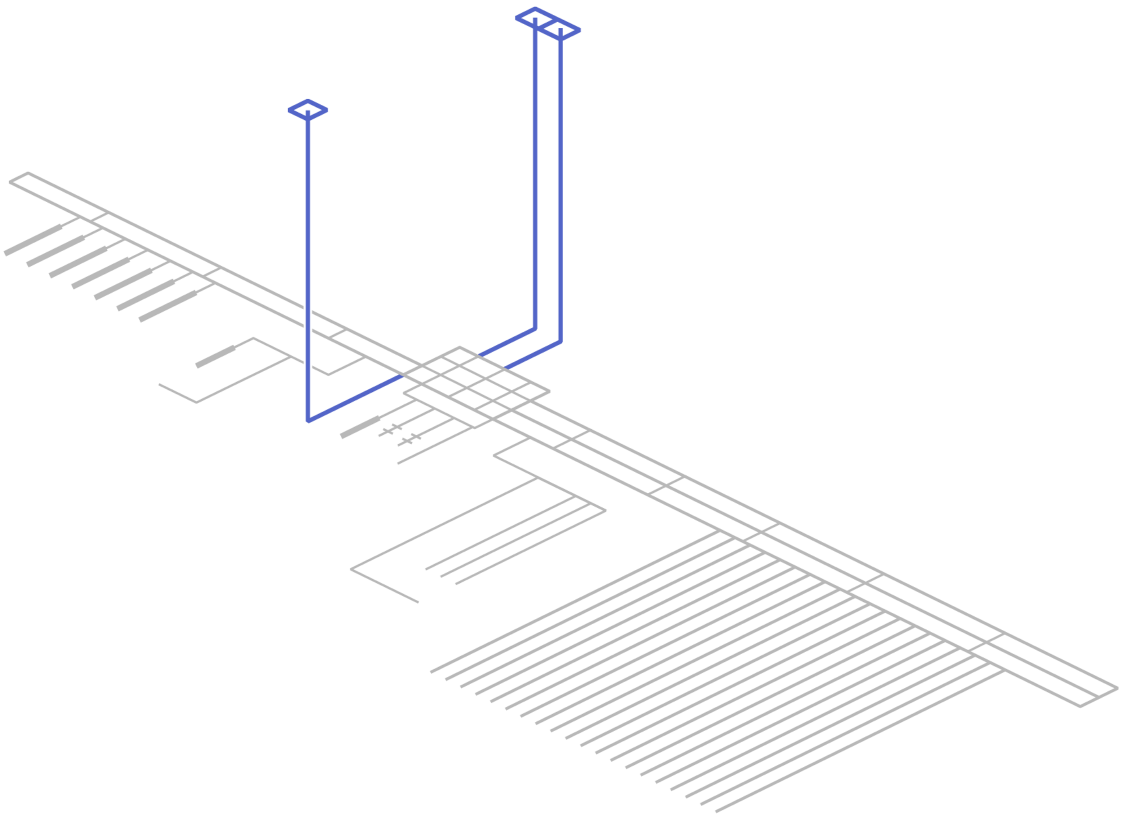


Fig. 4-2: Representation of the accessways, including an access shaft, an operation shaft and a ventilation shaft (coloured in blue), in the provisional layout for a geological repository for both HLW and I/ILW

The (backfilled and sealed) accessways contribute to the following Level 2 safety requirements related to the immobilisation, retention, and slow release of radionuclides:

L2-IRR-01	The system provides long transport times that result in attenuation of radionuclide releases by decay
L2-IRR-02	The system provides dilution and dispersion of radionuclides during transport

They also contribute to the following Level 2 requirements concerning compatibility:

L2-CMP-01	Detrimental effects of repository-generated gas are avoided
L2-CMP-02	Detrimental effects of repository-generated heat are avoided
L2-CMP-03	Detrimental hydromechanical effects of excavation are limited
L2-CMP-06	Unfavourable chemical interactions between different parts of the repository are avoided or limited

4.1.2 Repository sections

The current repository layout for a geological repository emplaces the L/ILW (including ATW) and HLW in two separate repository sections (Fig. 4-3). These sections contain the disposal areas plus the pilot repositories for that waste category.

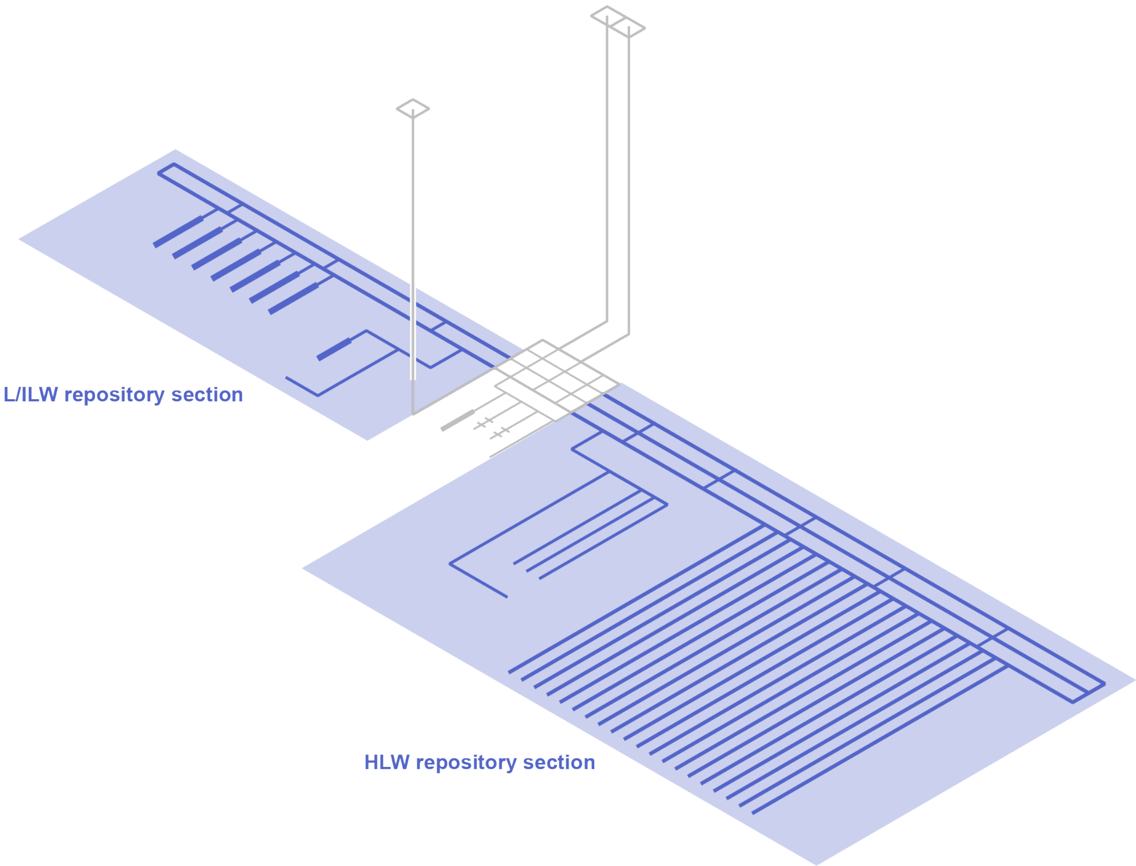


Fig. 4-3: Representation of two distinct repository sections (both coloured in blue) in the provisional design for a geological repository for both HLW and I/ILW

Placing different categories of waste in different repository sections contributes to waste isolation because it compartmentalises the repository and ensures no safety relevant interaction between the waste types. As the two categories of waste also require different engineered barriers, it makes sense to have two repository sections. Indeed, L/ILW and ATW will be placed in concrete containers before being emplaced in L/ILW emplacement caverns. Due to the similarities in the way in which L/ILW and ATW will be disposed of, synergies can be achieved by placing both waste categories in a single repository section. The same applies to HLW, which must be contained for the required minimum period of 1,000 years and will be therefore placed in corrosion-resistant canisters surrounded by a bentonite buffer. Design variants are conceivable in which the waste is compartmentalised into more than two sections. However, the question is whether benefits of a further subdivision of the repository sections outweigh the potential additional complexity and cost of a more compartmentalised facility.

The choice of adopting a lateral layout of the repository sections (i.e., side by side and not on top of one another) makes optimum use of the thickness of the host rock for both repository sections. In this way, the vertical distances for radionuclide transport are as large as possible.

Phenomenological analyses have shown that no safety-relevant interactions between the L/ILW and HLW repository sections are to be expected when both sections are placed at a distance of at least around 125 m (Nagra 2021b). At that distance, thermal or gas-induced interactions do not affect the long-term safety functions of the multi-barrier system. It was even demonstrated that, depending on the repository conceptual design, the maximum gas pressures in the L/ILW repository section of the combined repository could be lower than those for an individual L/ILW repository because of the additional potential gas storage volume provided by the repository components linking the disposal areas. However, at that distance higher temperatures in the L/ILW repository section would result compared to a respective distance of 210 m. Hence, a safety requirement for a more stringent specific distance between the repository sections is not mandatory from a radiological point of view (Nagra 2021b).

From practical perspectives it has therefore been decided to maintain a minimum lateral distance of 200 m between the two repository sections.

Compartmentalising the repository into sections contributes to the following Level 2 safety requirement related to isolation:

L2-ISO-02	Consequences of inadvertent human intrusion are limited

It also contributes to the following Level 2 requirements concerning compatibility:

L2-CMP-01	Detrimental effects of repository-generated gas are avoided
L2-CMP-02	Detrimental effects of repository-generated heat are avoided
L2-CMP-03	Detrimental hydromechanical effects of excavation are limited
L2-CMP-06	Unfavourable chemical interactions between different parts of the repository are avoided or limited

Finally, making optimum use of the thickness of the host rock contributes to the following Level 2 requirements regarding immobilisation, retention, and slow release of radionuclides:

L2-IRR-01	The system provides long transport times that result in attenuation of radionuclide releases by decay
L2-IRR-02	The system provides dilution and dispersion of radionuclides during transport

4.1.3 Pilot repositories and central area

At the base of the shafts, a central area will be constructed, which will serve as the starting point for the excavation of the L/ILW and HLW repository sections (Fig. 4-4). This central area will also contain a test area and the L/ILW and HLW pilot repositories with observation drifts.

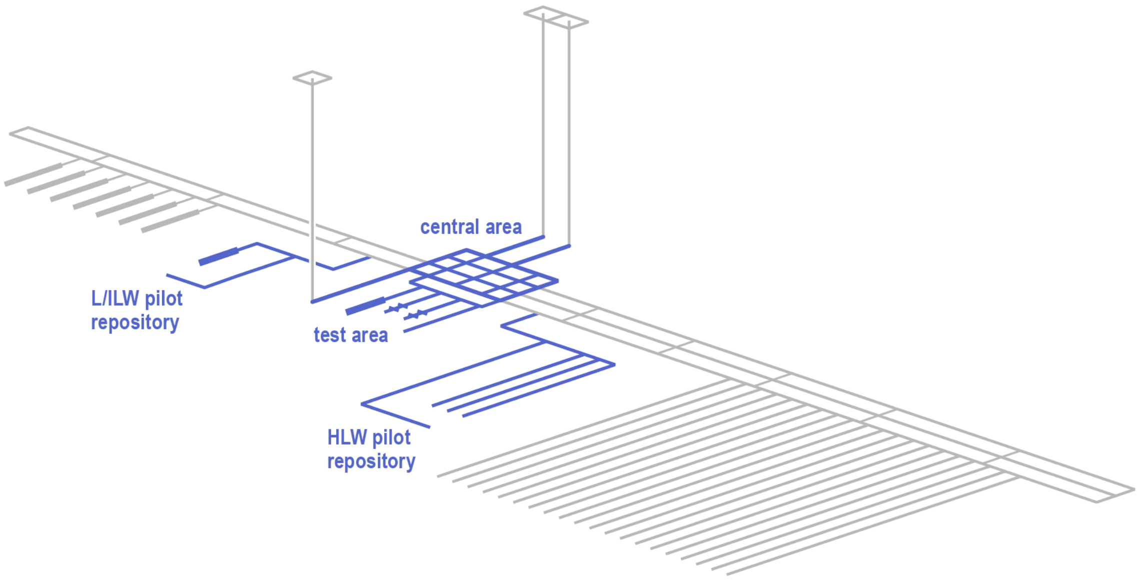


Fig. 4-4: Representation of the repository central area (coloured in blue), including a test area and the L/ILW and HLW pilot repositories, in the provisional design for a geological repository for both HLW and I/ILW

The test areas must be configured and designed in such a way that the characterisation of the underground geological situation and evaluation of safety are possible without compromising the functions of the safety barriers (see Art. 35 in KEG 2003).

The pilot repositories must be representative of the corresponding HLW emplacement drifts and L/ILW emplacement caverns. Their design, excavation and closure will therefore be identical to those emplacement rooms. To prevent any detrimental interactions between the disposal areas and the pilot repositories, the current repository layout provides for a minimum distance of 200 m between the emplacement rooms and the pilot repositories, and also between the pilot repositories and the central area. The distance of 200 m has been chosen based on the engineering argumentation made in Section 4.1.2.

The distance between the emplacement rooms and the pilot repositories contributes to the following Level 2 requirements concerning compatibility:

L2-CMP-01	Detrimental effects of repository-generated gas are avoided
L2-CMP-02	Detrimental effects of repository-generated heat are avoided
L2-CMP-03	Detrimental hydromechanical effects of excavation are limited
L2-CMP-06	Unfavourable chemical interactions between different parts of the repository are avoided or limited

4.1.4 Disposal area accessways

The disposal area accessways connect the shafts and central area with the emplacement rooms (Fig. 4-5). These accessways include an operations tunnel for waste transfer and a ventilation tunnel in both repository sections. A third tunnel is included in the HLW repository section to enable the continuous construction of additional HLW emplacement drifts in parallel with the emplacement of HLW disposal canisters (Nagra 2020). Continuous construction in parallel with waste emplacement is foreseen to limit the time the HLW emplacement drifts remain open. The period during which these drifts are open is limited as ventilation leads to desiccation of the clay around the drift. This in turn results in the precipitation of salts which could enhance the corrosion of the HLW disposal canisters. This is not an issue for the L/ILW emplacement caverns due to the highly alkaline cementitious near field. Therefore, the construction of the L/ILW repository section will be completed before emplacement operations start, and the tunnel used for the construction can also serve as operations tunnel.

The design of the disposal area accessways may affect the performance of the repository. For example, the layout of the construction and operations tunnels has an impact on water inflow along the repository components, and could lead to possible hydraulic "short-circuits". The tunnel volume has an impact on the amount of desaturation, resaturation time, and the possibility of developing gas-induced porewater overpressures. The design of the disposal area accessways must therefore include an evaluation of the expected impact of desaturation and gas pressure buildup on the repository performance.

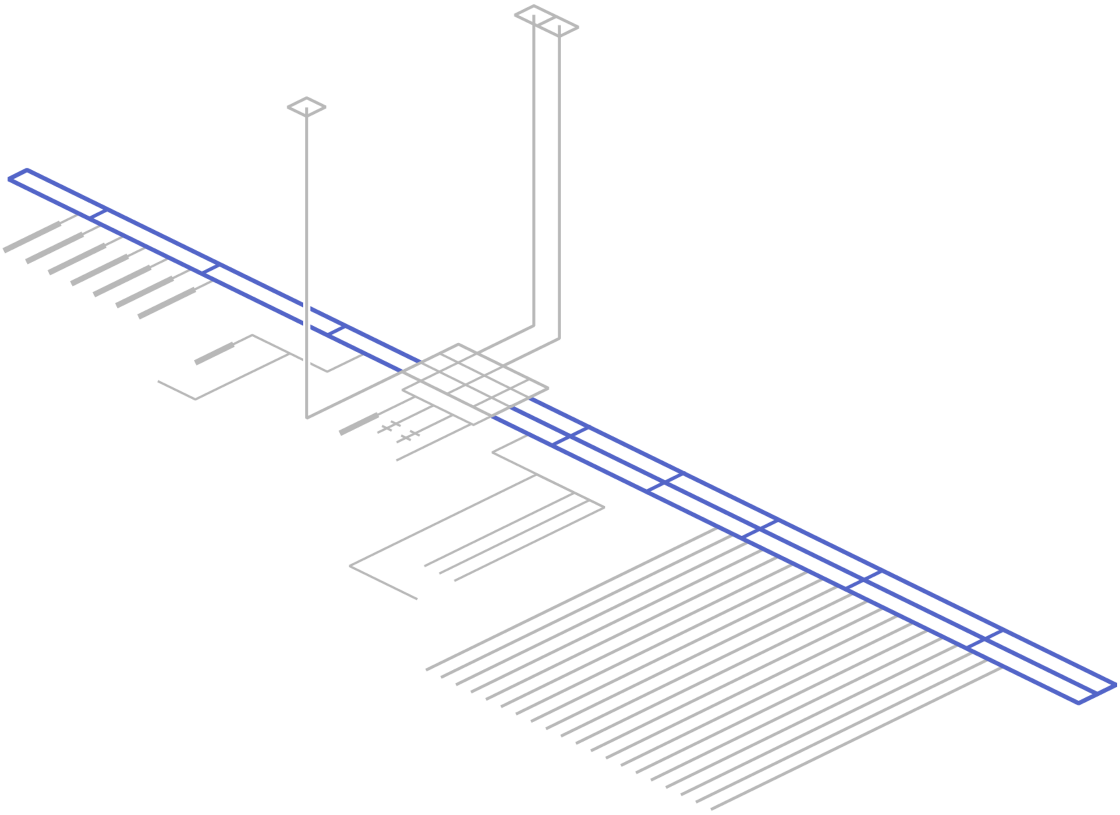


Fig. 4-5: Representation of two disposal area accessways for the L/ILW (left) and HLW (right) repository sections (both coloured in blue) in the provisional design for a geological repository for both HLW and I/ILW

The design of the disposal area accessways contributes to the following Level 2 requirement concerning compatibility:

L2-CMP-03	Detrimental hydromechanical effects of excavation are limited

4.1.5 Disposal areas

Each disposal area encloses a group of adjacent emplacement rooms for one repository type, including a minimum distance around these emplacement rooms. The layout of these areas is determined as part of an iterative process together with the definition of the boundaries of the CRZ.

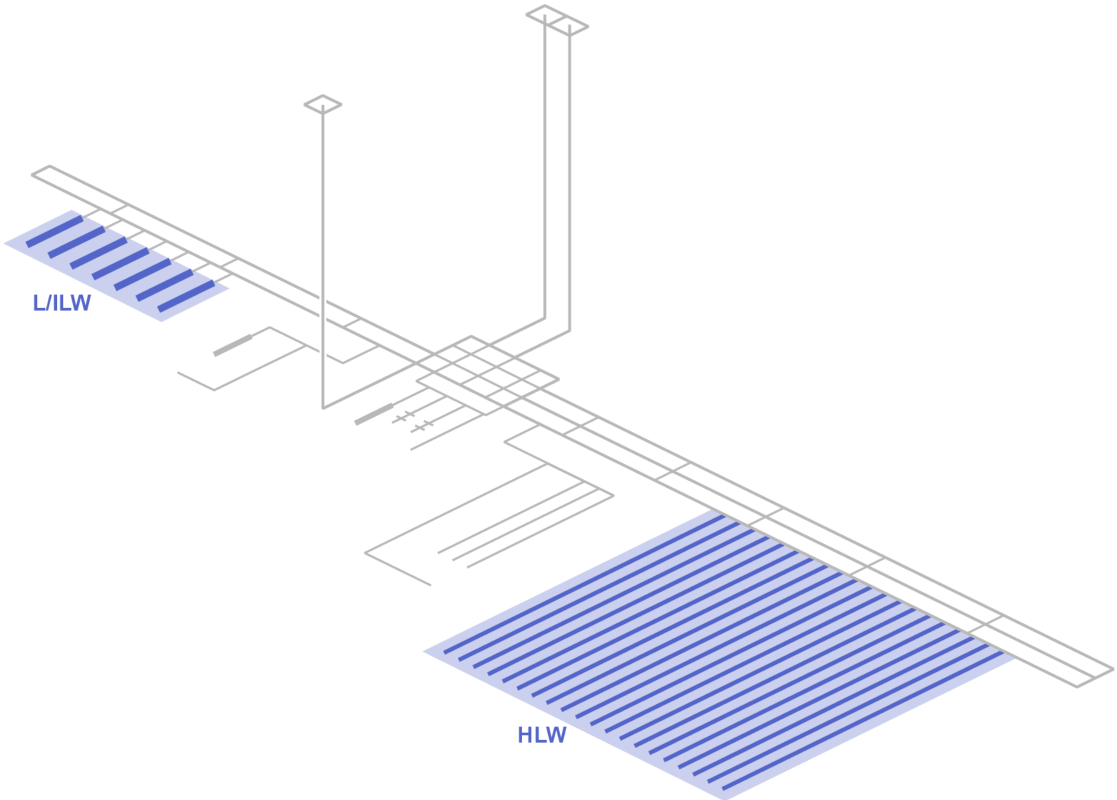


Fig. 4-6: Representation of the L/ILW (left) and HLW (right) disposal areas (both coloured in blue) in the provisional design for a geological repository for both HLW and I/ILW

The location of the disposal areas can be optimised to achieve the longest possible residence time of radionuclides in the CRZ and, in particular, within the Opalinus Clay. To achieve this, they should be located at:

- a sufficient depth, approximately at the centre of the host rock, and
- a sufficient distance from faults and existing deep boreholes.

Positioning the disposal areas approximately at the centre of the host rock maximises the vertical distance for radionuclide transport in the CRZ and delays their release into the biosphere, assuming a diffusion of radionuclides in all directions and the presence of water-bearing rock formations in the confining geological units above and below the host rock. These confining units should, in practice, provide an effective barrier to advective radionuclide transport, in addition to that provided by the host rock. However, due to the greater uncertainties about their properties compared with the host rock, e.g., heterogeneities in clay mineral content and hydraulic conductivity, they are considered to a lesser extent in the repository conceptual design.

The depth of the disposal areas also contributes to the isolation of the waste. This depth must be sufficient to protect the disposed waste from surface processes such as erosion or glaciation. This requirement could in principle result in the disposal area being located below the centre of the host rock layer, conflicting with the requirement favouring repository placement at the centre of the host rock. However, this requirement is met for the current siting regions, even if the repository is placed at the centre of the host rock layer.

The disposal area should also be located away from faults and boreholes. Deformation zones should also be avoided, but these are expected to be of minor relevance due to the self-sealing capacity of the host rock. The anisotropy in the transport properties of the host rock caused by stratification means that vertical radionuclide transport is slower than horizontal transport. Hence, larger horizontal distances need to be maintained. With respect to the current repository layout, a minimum distance of 175 m to faults and 50 m to deep boreholes has been demonstrated to be sufficient.

Thus, optimisation of the location of the disposal areas contributes to the following Level 2 safety requirements regarding immobilisation, retention, and slow release of radionuclides:

L2-IRR-01	The system provides long transport times that result in attenuation of radionuclide releases by decay
L2-IRR-02	The system provides dilution and dispersion of radionuclides during transport

and also contributes to the following Level 2 safety requirement regarding stability:

L2-STB-02	The layout and placement of the repository are such that it is unlikely to be affected by processes at the surface, by the reactivation of faults or by the creation of new faults that intersect the underground facilities

whereas the depth of the disposal areas also contributes to the following Level 2 requirements regarding isolation:

L2-ISO-03	Effects of events and processes at the surface are minimised
L2-ISO-04	Likelihood and consequences of future human actions are minimised

4.1.6 HLW emplacement drifts

The HLW emplacement drifts will be constructed perpendicular to the access tunnels and parallel to each other (Fig. 4-7).

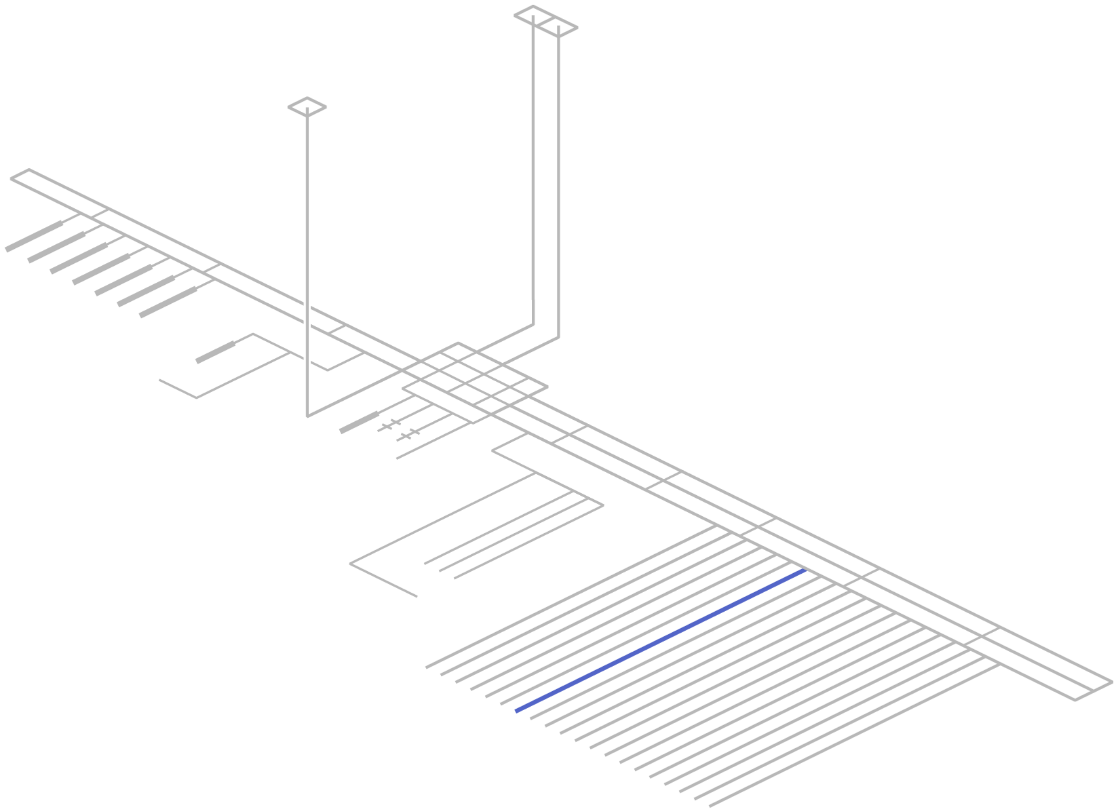


Fig. 4-7: Representation of one HLW emplacement drift (coloured in blue) in the provisional design for a geological repository for both HLW and I/ILW

The choice to use dead-end drifts (only accessible from one side), limits the gradient that drives the axial water inflow along emplacement rooms. This in turn extends the transport times for radionuclides to the disposal area accessways.

The requirement to achieve the largest possible vertical distance for radionuclide transport applies not only to the disposal area, but also to the individual HLW emplacement drifts. Using a layout that is parallel to the host rock layer maximises the vertical distance for radionuclide transport in the host rock. Ideally, the emplacement drifts should follow the same slope as the host rock layer to maximise this distance.

Orienting the HLW emplacement drifts in the direction of the principal stress increases their mechanical stability. In conjunction with a suitable excavation technique and rock support measures, this avoids any unnecessary degradation of the geological barrier and limits the extension of the EDZ, thereby reducing the uncertainties associated with radionuclide transport times in the EDZ. Furthermore, the HLW emplacement drifts must be placed at a minimum distance from each other, so that the impact of heat output, gas production and chemical interactions on the different barriers remains small. This also prevents the EDZs of adjacent drifts from overlapping. An axial distance of 40 m between the HLW emplacement drifts is considered sufficient to prevent mutual interactions.

The HLW emplacement drifts will have to be long enough to allow the construction of the seals and to provide enough space for a sufficient number of HLW disposal canisters. In the current repository layout, the drifts are planned to be 900 m long from the seal to the end of the drift. This length results from considerations of both spatial requirements and ventilation (> 300 m) and occupational safety, in particular escape route restrictions (< 1,000 m). The emplacement drifts must also take account of the spacing that is required between the HLW disposal canisters. These canisters must be placed sufficiently far apart to limit detrimental thermal effects on the engineered and geological barriers (see Section 3.4.4). The distance required between the HLW disposal canisters also depends on the spacing between the emplacement drifts. Determining the optimal spacing between the canisters and between emplacement drifts is an optimisation issue that will be addressed in a later phase. In the current provisional design, the distance between two canisters has been set at 3 m and the distance between drifts to about 40 m.

The inner diameter of the HLW emplacement drifts must be large enough to allow the emplacement of both HLW disposal canisters and enough bentonite buffer. At the same time, the diameter of the emplacement drifts must be limited so that the (vertical) distance for radionuclide transport through the intact host rock is maximised and the extent of the EDZ remains limited. In the current repository layout, the internal diameter has been set at about 2.80 m due to constructional reasons.

Thus, the choice to use dead-end drifts and their limited diameter contribute to the following Level 2 requirements regarding immobilisation, retention, and slow release of radionuclides:

L2-IRR-01	The system provides long transport times that result in attenuation of radionuclide releases by decay
L2-IRR-02	The system provides dilution and dispersion of radionuclides during transport

while the orientation of the drifts, their diameter, the separation between them and the chosen excavation technique contributes to the following Level 2 requirements regarding compatibility:

L2-CMP-01	Detrimental effects of repository-generated gas are avoided
L2-CMP-02	Detrimental effects of repository-generated heat are avoided
L2-CMP-03	Detrimental hydromechanical effects of excavation are limited
L2-CMP-06	Unfavourable chemical interactions between different parts of the repository are avoided or limited

4.1.7 L/ILW emplacement caverns

The L/ILW emplacement caverns will be constructed perpendicular to the access tunnels and parallel to each other (Fig. 4-8).

Like the HLW emplacement drifts, the L/ILW emplacement caverns will be dead-end structures and oriented in the direction of the maximum principal stress. In the current repository layout, the L/ILW emplacement caverns will have a maximum length of 250 m and an inner diameter of approximately 11 m. This is large enough to stack several L/ILW containers on top of each other and backfill the L/ILW emplacement caverns, while the extent of the EDZ and the loss of (vertical) distance for radionuclide transport through intact host rock are limited.

As the diameter of the L/ILW emplacement caverns is larger than the diameter of the HLW emplacement drifts, the EDZ around these caverns will be considerably larger as well. Therefore, to avoid overlapping between the EDZ of adjacent caverns, these caverns should be placed further apart than the HLW emplacement drifts. Based on the current provisional design the minimum distance between the L/ILW emplacement caverns (axis to axis) is 85 m.

Unlike the HLW emplacement drifts, which are constructed parallel to the slope of the host rock, the L/ILW emplacement caverns are constructed horizontally because the containers will be stacked on top of each other. Since the host rock has a slope of a few degrees, the length of the L/ILW caverns is constrained by the need to limit the loss in (vertical) distance for radionuclide transport through the intact host rock.

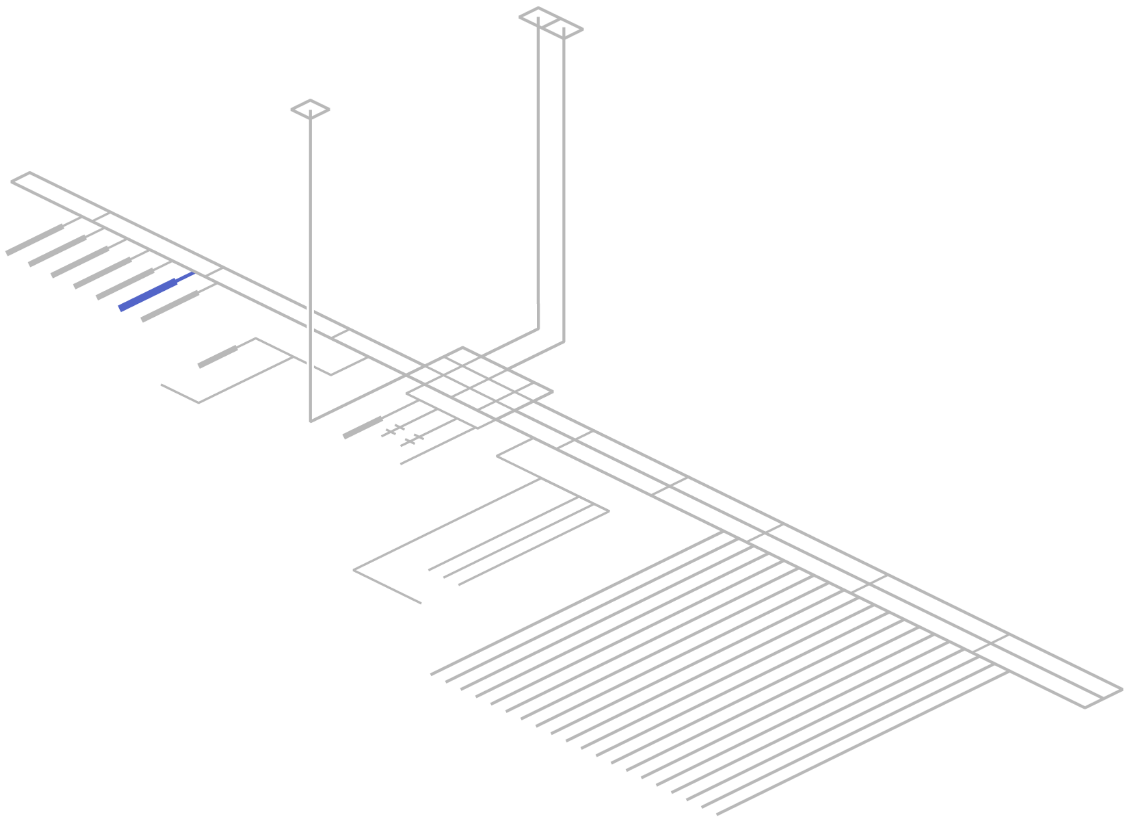


Fig. 4-8: Representation of one L/ILW emplacement cavern (coloured in blue) in the provisional design for a geological repository for both HLW and I/ILW

Thus, the choice to use dead-end caverns and their limited lengths contribute to the following Level 2 requirements regarding immobilisation, retention, and slow release of radionuclides:

L2-IRR-01	The system provides long transport times that result in attenuation of radionuclide releases by decay
L2-IRR-02	The system provides dilution and dispersion of radionuclides during transport

while the orientation of the caverns and their diameter contributes to the following Level 2 requirements regarding compatibility:

L2-CMP-01	Detrimental effects of repository-generated gas are avoided
L2-CMP-02	Detrimental effects of repository-generated heat are avoided
L2-CMP-03	Detrimental hydromechanical effects of excavation are limited

4.2 Component design

The following sections present the provisional designs for the various components of the engineered barrier system. Starting from the waste and moving outward toward the host rock, these components comprise:

- HLW disposal canisters,
- bentonite buffer,
- L/ILW waste packages, containers, infill and backfill,
- tunnel support, and
- the closure system.

The HLW and L/ILW waste forms are not included in this section, since they are not part of the repository design. The SF and RP-HLW waste matrices are, nonetheless, a pillar of safety and are discussed in Section 3.4.3 of the previous chapter.

4.2.1 HLW disposal canisters

The HLW disposal canisters are designed to be 120 to 140 mm thick in order to withstand the mechanical loads placed on them during the containment period, taking into account the loss of thickness due to corrosion (Nagra 2024e). Several possible canister materials have been evaluated: carbon steel, cast iron, different types of ceramics and specific alloys and coatings made of copper, titanium and nickel (Nagra 2012). The current design assumes HLW disposal canisters made of carbon steel (without coating).

The canisters are cylindrical with an outer diameter of 110 cm and a length of approximately 5 m (Fig. 4-9). This is enough to accommodate 12 BWR SF assemblies, 4 PWR SF assemblies or 3 HLW flasks in one canister. After the HLW is placed in a disposal canister, it is closed by welding in such a way that a chemically inert atmosphere (e.g., argon gas) prevails inside the canister. Quality assurance procedures will limit the number of undetected defects.

The contributions of the HLW disposal canisters to the Level 2 safety requirements are described in Section 3.4.4.

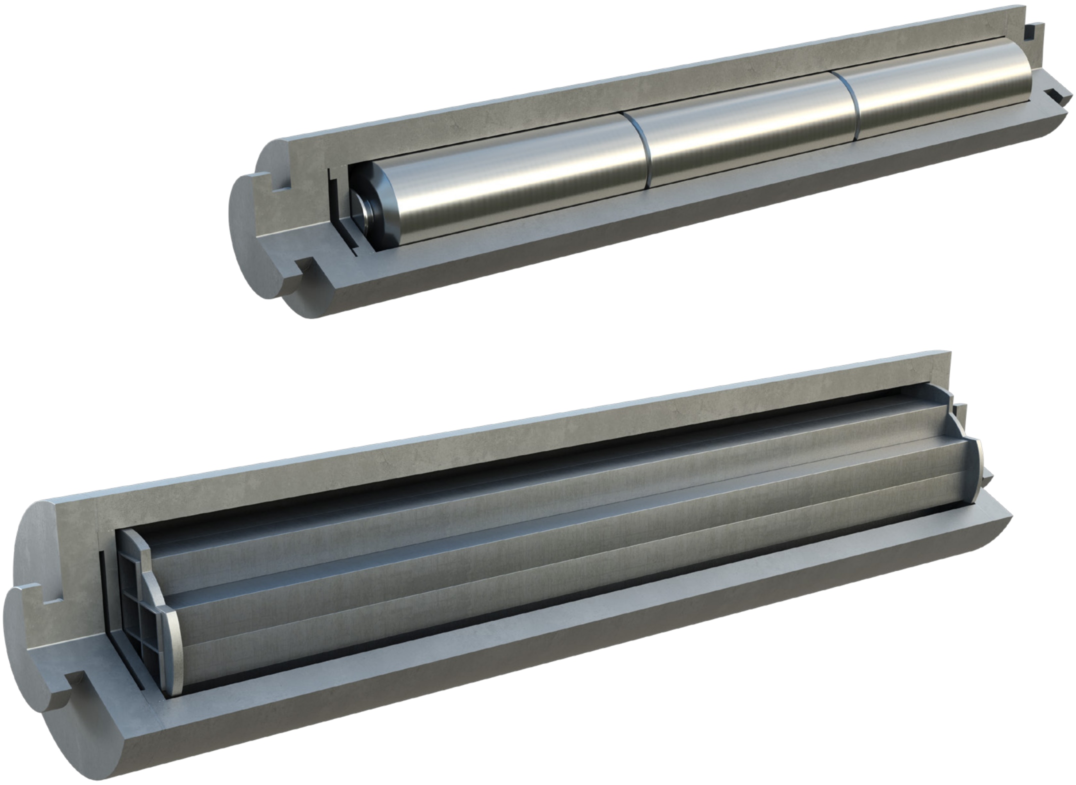


Fig. 4-9: Schematic cross-section of the current canister containing RP-HLW (top) and SF assemblies (bottom)

In addition to the canisters themselves, the RP-HLW stainless-steel flasks could form a barrier and delay the time the waste matrix comes into contact with porewater. Similarly, the SF cladding could delay the time that the SF fuel pellets come in contact with porewater. However, due to the significant uncertainties about the performance of these components, their function in delaying contact with porewater is omitted in the safety assessment dose calculations. Rather, water is assumed to come into contact with the waste matrices once the HLW disposal canisters are breached.

4.2.2 Bentonite buffer

As noted in Section 3.4.5, the spaces around the HLW disposal canisters will be filled with a buffer material. Various materials have been considered and tested as possible buffer material: pure bentonite, bentonite-additive mixtures (e.g., bentonite/sand mixtures), cement-based mortar or other clay materials (Nagra 2002b, Nagra 2016a).

In an early stage of the repository conceptual design development, Nagra selected compacted pure bentonite as the reference material for backfilling the HLW emplacement drifts (Nagra 2014, Jenni et al. 2019). When saturated, compacted bentonite has a low permeability, which ensures that movement of the porewater in the emplacement drifts is slow and diffusion dominated. Saturated compared bentonite also has a fine pore structure, which immobilises colloids and limits microbial activity. Because bentonite is a clay-rich material, it has a good geochemical compatibility with the Opalinus Clay host rock and has a high sorption capacity for many radionuclides. When confined, it develops a swelling pressure as it saturates, which provides stability to the tunnel support and to limits tunnel convergence after the tunnel support degrades. Its swelling capacity also allows any gas pathways that are formed to reseal. Limitation of uneven mechanical forces on the canisters requires that the bentonite saturates as homogeneously as possible and develops a relatively uniform swelling pressure. This in turn implies requirements on the homogeneity of the dry buffer density and on the backfilling process. Corrosion rates of carbon steel embedded in compacted bentonite have been assessed and found to be low using corrosion experiments (Diomidis et al. 2023).

The current provisional buffer design consists of:

- prefabricated bentonite blocks that are placed on the floor of the emplacement drift; the canisters will then be placed on these blocks so that they are in the centre of the drift, and
- granular bentonite material used to backfill the voids around and between the canisters.

Fig. 4-10 presents a schematic representation of an HLW emplacement drift backfilled with bentonite.

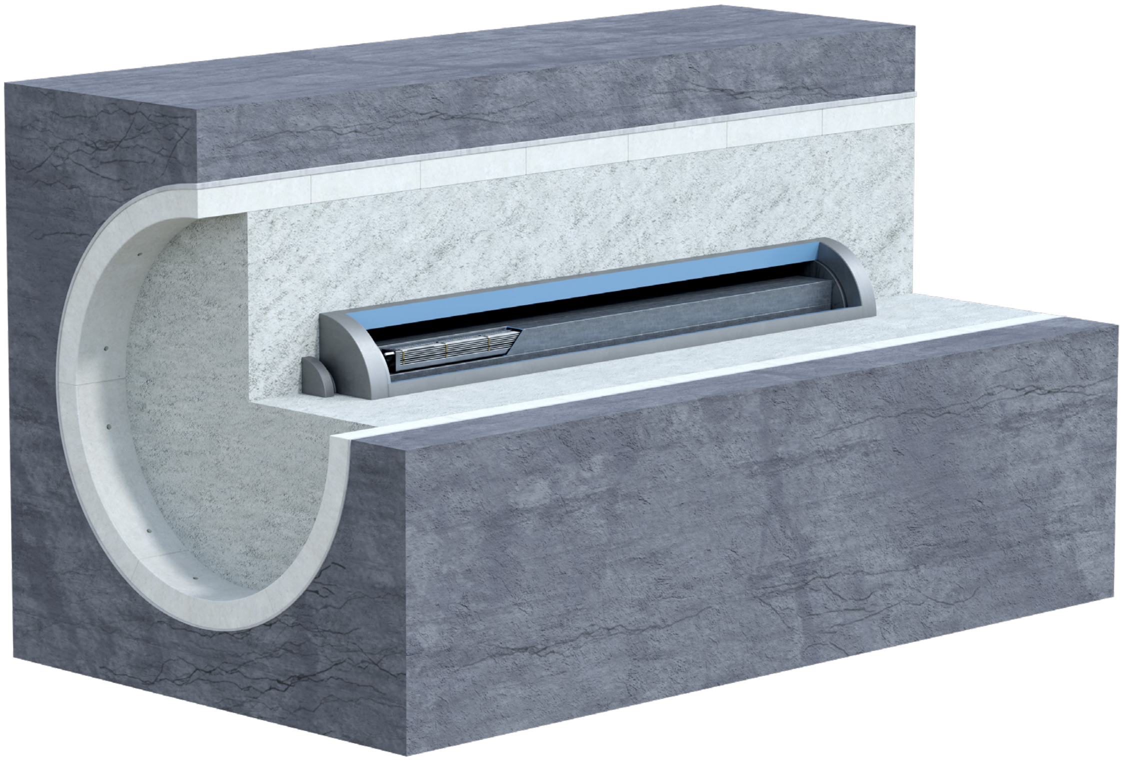


Fig. 4-10: Schematic representation of an HLW emplacement drift backfilled with bentonite

The contributions of the bentonite buffer to the Level 2 safety requirements are described in Section 3.4.5.

4.2.3 L/ILW waste packages, containers, infill and backfill

Most of the L/ILW is pressed, embedded in a cement/mortar matrix[6] and placed in standardised 200 L drums, MOSAIK-II-type casks made of cast iron, or steel casks. No safety functions or L2 requirements are assigned specifically to these waste packages, but the cementitious matrix inside them will contribute to the safety functions assigned to the cementitious L/ILW near field, which is further described in Section 3.4.7.

The L/ILW waste packages and placed inside containers are made of reinforced concrete and infilled with a cement-based mortar. Fig. 4-11 shows an example of two L/ILW containers, one containing directly packaged waste (e.g., from decommissioning) and one containing 200 L drums.

[6] Ion exchange resins can be solidified into three different types of matrices: cement, bitumen or styrene, according to their usage and the relevant conditioning facility.

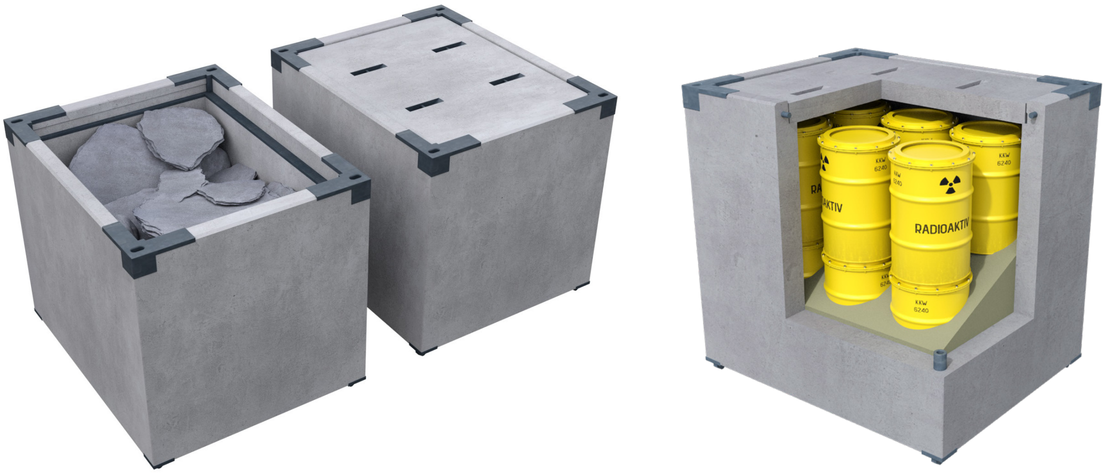


Fig. 4-11: Examples of an L/ILW container, one filled with directly packaged L/ILW (left), and one containing 200 L drums (right)

Various options are being considered regarding the size of these containers and the way they are handled, transported, and emplaced.

In addition, various infill materials and techniques are being investigated. Particularly for the waste packaged in MOSAIK casks, adding a layer of packaging to the L/ILW container which does not appear to have any long-term safety benefit. As a result, the direct emplacement of the MOSAIK casks remains a possible variant.

Once the L/ILW containers are emplaced in the repository, the L/ILW emplacement caverns will be backfilled (Fig. 4-12). This will limit the consequences of abandoning the repository as removing the cement-based backfill requires effort and resources but still remains possible.

A cement-based mortar has been chosen as buffer material for the L/ILW emplacement caverns. This mortar, together with the concrete containers and the cemented waste form, creates a cementitious L/ILW near field, the contributions of which to the Level 2 safety requirements are described in Section 3.4.6. In addition, as explained above, backfilling contributes to:

L2-ISO-01	Likelihood and consequences of abandonment of the repository are minimised

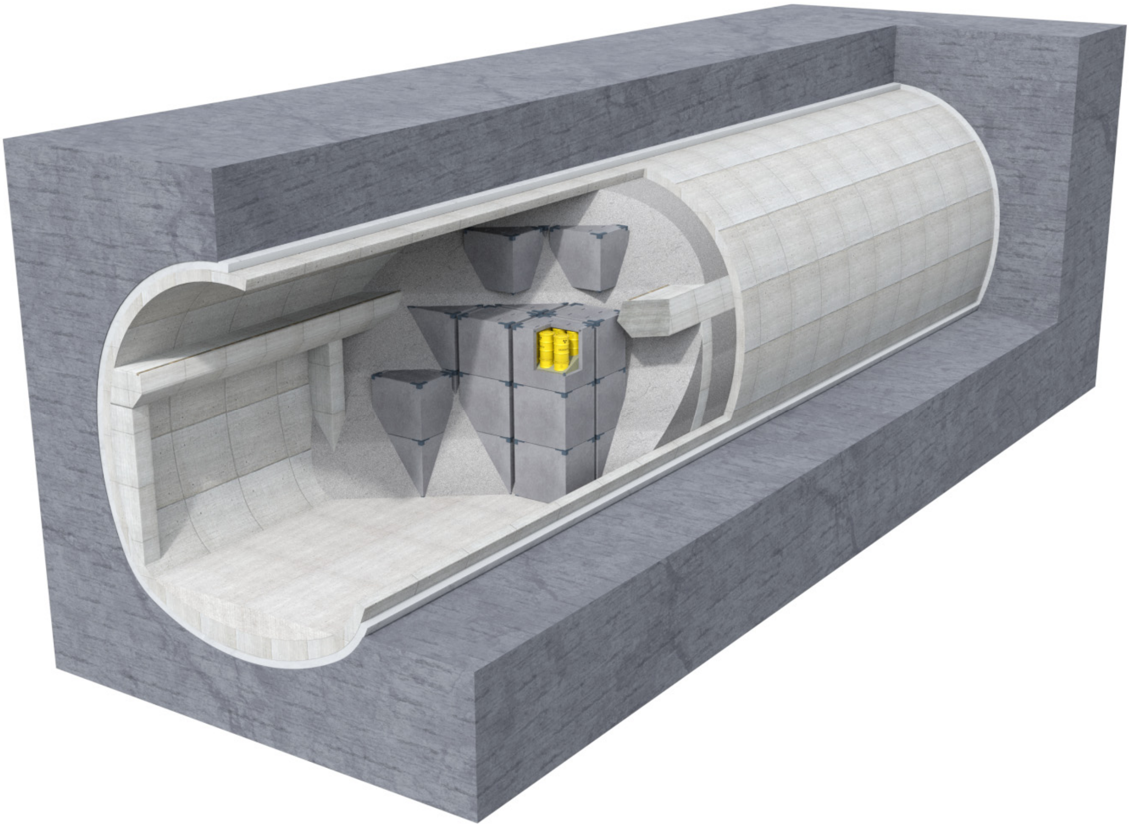


Fig. 4-12: Schematic representation of an HLW emplacement drift backfilled with bentonite (left), and an L/ILW emplacement cavern backfilled with cement-based mortar (right)

4.2.4 Tunnel support

Tunnel support in the emplacement rooms and the other repository sections is necessary to ensure the stability of the repository structures during the construction and waste emplacement operations. The tunnel support must also be chemically compatible with adjacent barriers. In safety assessment, tunnel support is conservatively assumed to neither contribute to the containment nor to immobilisation, retention, and slow release of radionuclides as it might be degraded some decades after emplacement. However, regarding compatibility, it must not generate a significant amount of gas. Thus, the amount of reinforcement steel or other metallic structures in the tunnel support, as well as organic cement admixtures, is minimised to limit the total amount of gas formed in the repository. In addition, heat must be transferred efficiently through the support of the HLW emplacement drifts. The tunnel support also provides mechanical support to the host rock, so that tunnel convergence and EDZ formation are limited, and it needs to be chemically and mineralogically compatible with adjacent barriers. Finally, the tunnel support around the bentonite buffer of the HLW emplacement drifts must be designed to allow for a sufficiently even saturation of the bentonite.

It is planned that the HLW emplacement drifts will be supported by pre-cast concrete tubbing elements (i.e., concrete tubes or rings) in order to support the rock mass around the excavation as quickly as possible and limit rock convergence. Depending on the site-specific situation, alternative methods may be considered such as shotcrete, steel arches and nets, or combinations of these. The tunnel support around the bentonite buffer of the HLW emplacement drifts must be designed so that it allows a sufficiently even saturation of the bentonite. At the same time, the tunnel support can contribute to limiting the desaturation of the CRZ.

For the L/ILW emplacement caverns, the provisional design of the tunnel support consists of an outer layer of shotcrete and an inner concrete liner constructed in-situ.

The tunnel support for the operation and construction tunnels are planned to last for the period of operation of the deep geological repository. The openings will be supported by an outer layer of shotcrete and an inner layer of precast concrete elements.

The tunnel support contributes to the following Level 2 safety requirements related to compatibility:

L2-CMP-03	Detrimental hydromechanical effects of excavation are limited
L2-CMP-26	The tunnel support system favours efficient heat transfer to its surroundings
L2-CMP-27	The tunnel support system limits tunnel convergence and EDZ development
L2-CMP-28	The tunnel support system is chemically compatible with adjacent barriers
L2-CMP-30	The tunnel support system supports sufficiently even saturation of the bentonite buffer
L2-CMP-32	The tunnel support system does not contribute significantly to gas generation

4.2.5 Seals and backfill materials of the closure system

The different types of seals that are part of the closure system are illustrated in Fig. 4-13. They comprise:

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

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

Earlier repository conceptual designs (Nagra 2010; Nagra 2016b) also included sealing sections within the HLW emplacement drifts. The impact of these seals was greatly reduced by the introduction of the dead-end emplacement drifts which, together with the extremely low porewater inflow from the surrounding host rock, prevent a dominant release pathway along the repository structures (Poller et al. 2014; Nagra 2016c). Sealing sections within the HLW emplacement drifts can therefore be omitted as the bentonite buffer itself already ensures a hydraulic separation, or compartmentalisation of the HLW disposal canisters.

The design of the different components of the closure system is described below. The design of the current closure concept is also described in more detail in Nagra (2021d), together with possible variants. The seal designs take into account that the tunnel support may locally need to be removed before emplacement. The closure system should also not unnecessarily complicate the possibility of retrieving the radioactive waste during the monitoring phase.

The contributions of the closure system as a whole to the Level 2 safety requirements are described in Section 3.4.7.

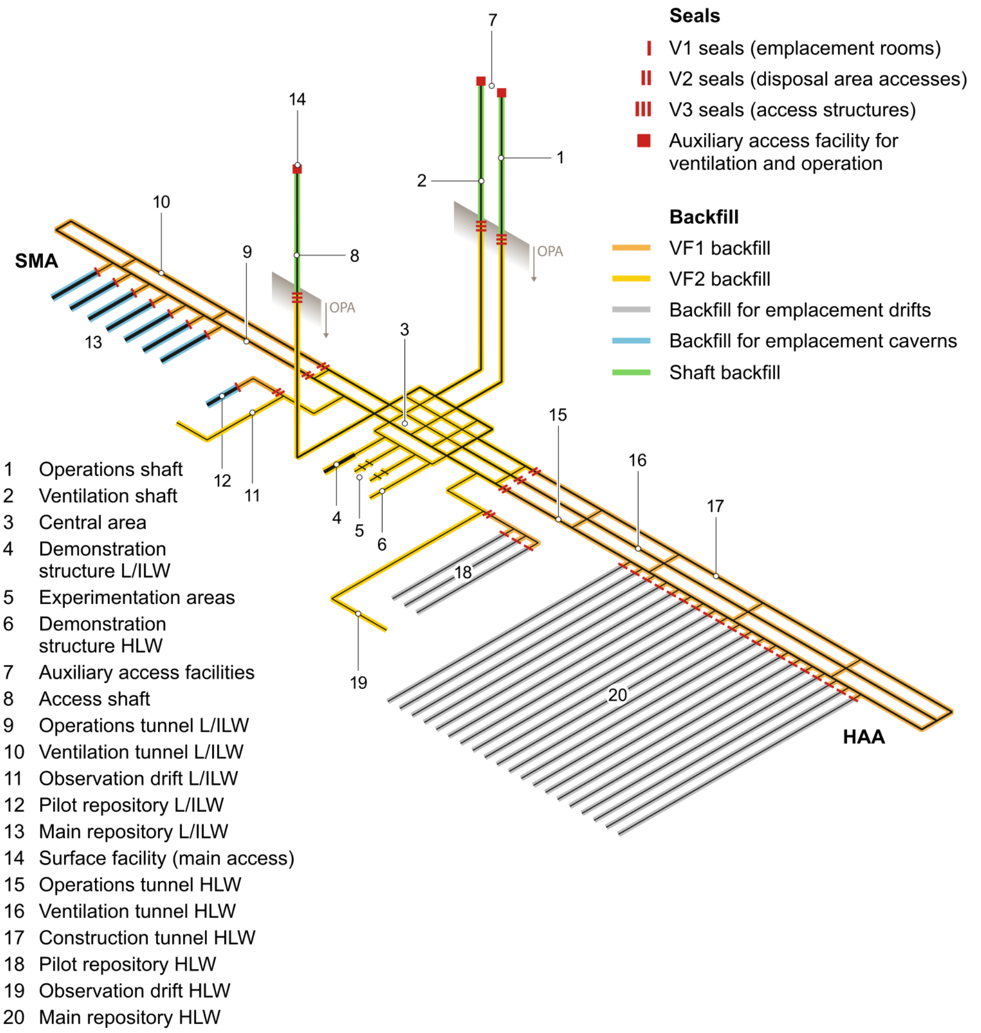


Fig. 4-13: Schematic view of the underground facilities in the provisional design for a geological repository for both HLW and I/ILW, including sealing and backfill of the repository structures

From Nagra (2021d)

4.2.5.1 V1 and V2 seals

A generic design of a V1 or V2 seals is shown in Fig. 4-14. It consists of three main elements (Nagra 2021d):

- the sealing element,
- the abutments, and
- the transition layers.

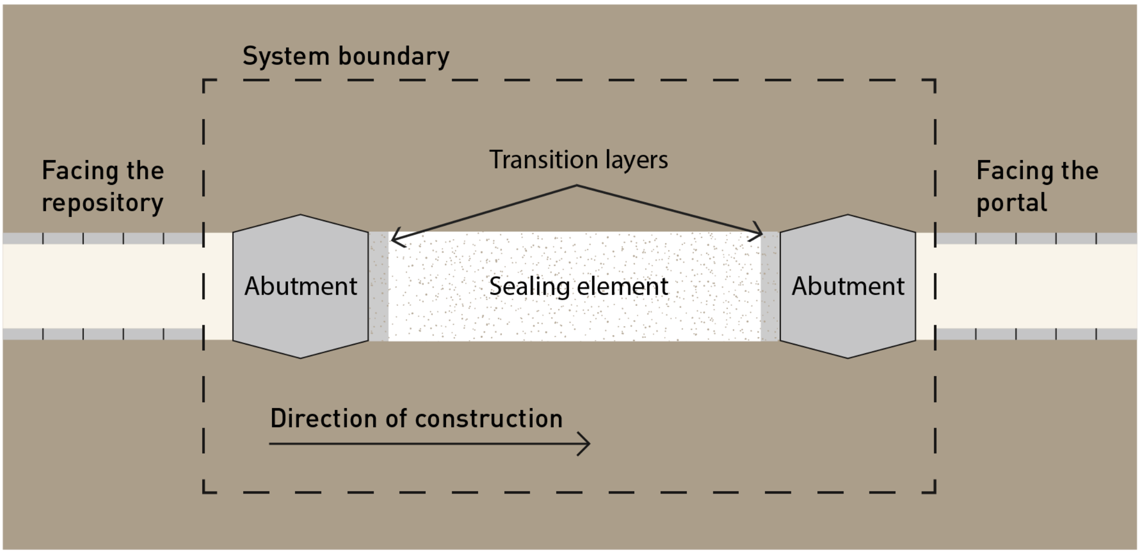


Fig. 4-14: Basic, generic schematic structure of the seal sections (not to scale)

Based on Nagra (2021d)

The sealing elements of the V1-HLW and V2-HLW seals are composed of bentonite. On the other hand, as there is a greater risk of unfavourable gas pressure building up in the L/ILW emplacement caverns, the V1-L/ILW and V2-L/ILW seals are composed of a sand-bentonite mix (80% bentonite and 20% sand), which results in a higher gas permeability than the pure bentonite. The bentonite in the sealing elements will retain radionuclides in the closure system (at least those dissolved in the porewater), as it restricts porewater flow through the closure system and promotes the sorption of some radionuclides.

The abutments are necessary to hold the seals in place, and are composed of concrete. The transition layers physically separate the bentonite and concrete abutments. This limits the possible clogging of pores in the bentonite by the precipitation of secondary minerals due to the chemical gradient between the concrete and the bentonite.

The seals contribute to the compartmentalisation of the repository, which limits the impact of inadvertent future human intrusion. The V1 seals compartmentalise the radioactive waste by sealing it in multiple emplacement rooms and the V2 seals compartmentalise (i.e., provide spatial separation of) the disposal areas.

Due to the low permeability of the sealing elements, the V1 and V2 seals close off the different parts of the repository and limit water flow along the repository components. As such, the seals contribute to slow and diffusion-dominated transport of radionuclides. The bentonite in the seal design also promotes radionuclide sorption. This means that the seals contribute to the retention of radionuclides in the closure system. By limiting the porewater flow from the entrance of the HLW emplacement drifts, the seals also prevent the bentonite buffer from becoming saturated with water coming from the entrance of the drift and promotes radial and regular saturation of the bentonite buffer.

To avoid an unfavourable gas pressure build-up and associated damage of the barriers, especially in the L/ILW repository section, the V1 and V2 seals are designed to be gas-permeable. The design should also minimise gas production by limiting the amount of metallic construction materials. The amount of steel and metal used for this temporary support is considered negligible as only temporary rock support is planned to be used during construction of the seals.

The seals contribute locally to the mechanical stabilisation of the repository components. They would be designed and constructed to withstand the (lithostatic, hydraulic and gas-induced pressure) forces acting on them. In that way, they contribute to limiting host rock convergence and EDZ extension.

Finally, choosing bentonite as a sealing material ensures chemical and mineralogical compatibility with the host rock and the bentonite buffer and stability under the expected conditions.

4.2.5.2 V3 seals

The V3 seals are designed to saturate within a few thousands of years and limit the porewater flowing through the shafts to the repository. They provide hydraulic separation of the repository from aquifers above the Opalinus Clay. Once saturated, they are gas-tight and thus reduce or prevent the release of gaseous radionuclide species (particularly $^{14}CH_4$) to the biosphere. They therefore contribute to slow and diffusion-dominated transport of radionuclides along the repository components and to the retention of radionuclides.

The V3 seals also contribute to the mechanical stabilisation of the rock around the shafts. They are designed and constructed to withstand the (lithostatic, hydraulic and gas pressure) forces acting on them. In that way, they contribute to limiting host rock convergence and EDZ extension.

4.2.5.3 VF1 and VF2 backfills

After degradation of the tunnel support, these backfills will provide stability to the host rock and limit its convergence. The backfill must also ensure sufficient gas storage and transport capacity with a sufficient gas-accessible porosity. This not only contributes to the avoidance of an unfavourable gas pressure build-up and associated damage of the barriers, but also provides storage volume for gaseous radionuclides. This in turn limits radionuclide release to the biosphere. Candidate materials for VF1 and VF2 currently include processed Opalinus Clay from the excavation of the repository or Friedland clay, both of which would be mixed with sand and/or gravel, or a sand-bentonite mixture. Such a mixture is chemically and mineralogically compatibility with the host rock and remains stable under the expected conditions.

4.2.5.4 Backfills of the accessways

The backfilling of the part of the shaft above the V3 seals contributes to isolating the waste as it will deter inadvertent future human intrusion. There are currently no specific long-term safety requirements defined for this backfill.

4.3 Repository construction, operation and closure

The actions to construct, operate and close the repository can also have safety implications, as they can affect the host rock around the repository; these are discussed in the following paragraphs.

The current concepts for constructing, operating and closing the repository (i.e., transferring and handling waste and backfilling and sealing repository structures) are based on technologies available today and detailed in separate reports (Nagra 2022a, Nagra 2022b). Progress can, however, be expected in related technological areas (robotics, electronic control systems, etc.). Optimisation based on relevant technological innovations will be therefore taken into account before construction, operation and closure of the deep geological repository.

Prior to its disposal in the repository, the waste must meet a set of waste acceptance criteria to ensure that:

- the waste is adequately characterised and sufficiently documented;
- qualitative and quantitative requirements for safety-relevant aspects or properties are met (e.g., with regard to mechanical stability, nuclide inventories, gas production rates or thermal output);
- the optimisation requirement is met, with special attention to safety-relevant aspects (e.g., assessing and possibly implementing measures to reduce gas production).

For post-closure safety, the central requirements for the construction, operation and closure of the repository are as follows.

1. Detrimental hydromechanical effects of excavation are limited (Level 2 requirement L2-CMP-03)

Limitation of the excavation damage means that the distance for radionuclide transport in the undisturbed Opalinus Clay remains as large as possible. Therefore, it is important to use cross-sections for the emplacement rooms that are adapted to the depth and geotechnical conditions. Both the construction process and the tunnel support (Section 4.2.4) must limit the mechanical damage, such as large rock detachments from the excavation sidewalls and excavation front.

2. Pathways that could potentially by-pass the host rock are closed off during operation and closure

This ensures that the distance for radionuclide transport in the undisturbed Opalinus Clay remains as large as possible. Therefore, it is important that the repository structures are backfilled. This will also limit the convergence of the Opalinus Clay.

The desaturation and resaturation of the CRZ, in combination with its thermal evolution, can also affect the properties of the geological or engineered barriers. These aspects should be considered when optimising the construction, operation and closure processes (e.g., with regard to excavation and tunnel support design and emplacement processes and in determining how long the repository should be kept open).

Furthermore, the amount of materials that could potentially damage the geological or engineered barriers should be limited. This applies in particular to gas-producing materials (e.g., metals, organic materials) or any substances that can chemically interact with the CRZ or adjacent barriers.

Finally, any measures taken in response to incidents or accidents must not significantly, or not more than absolutely necessary, impair the post-closure safety of the repository in the long-term. At the current planning stage, it is assumed that incidents and accidents during construction, operation and closure will not adversely affect the long-term safety of the closed repository (Nagra 2024b).

5 Discussion and conclusions

Nagra will apply for a general licence to the relevant authorities in 2024. This is the first step in the licensing process as defined in the Nuclear Energy Act (KEG 2003). This report is part of the documentation that forms the general licence application and:

- defines the overarching protection objective, design principles and protection criteria, as well as other boundary conditions for the development of the current safety and repository concept;
- describes these safety and repository concept, i.e., the repository safety barriers and their properties and how, through the safety barriers and safety functions they perform, the geological deep repository ensures the protection of humans and the environment, and
- sets out a provisional repository design for a geological repository for HLW and I/ILW, established for the purposes of the general licence application, that is consistent with, and based upon, these safety and repository concept.

The principles and methodology presented in this report provide a framework for detailed development and optimisation of the repository conceptual design after the general licence has been granted.

The safety concept of a deep geological repository describes how the permanent protection of humans and the environment during the post-closure phase will be achieved by means of a succession of geological and engineered barriers. It defines five safety functions that the repository must fulfil:

- **S1: Isolation** of radioactive waste from humans and the environment;
- **S2: Complete containment** of radionuclides for a period of time;
- **S3: Immobilisation, retention, and slow release** of radionuclides;
- **S4: Compatibility** of the components of the repository system;
- **S5: Long-term stability** of the multi-barrier system regarding long-term geological and climatic evolution.

These safety functions apply to the repository as a whole, but can also be assigned to its individual components, including "pillars of safety", which are repository components or features and their properties that are considered well understood and insensitive to perturbations and are the main contributors to these safety functions:

- Deep underground location in a stable geological environment;
- the containment providing rock zone (CRZ);
- SF and RP-HLW waste matrices;
- HLW disposal canisters;
- the bentonite buffer;
- the L/ILW cementitious near field;
- the closure system, i.e., the sealing and backfilling of the disposal area accessways and the shafts.

The development of the provisional repository design includes proposing and refining design choices, such as material choices, dimensions, layouts or implementation procedures, and verifying whether the design meets the requirements. The following summarises the most important safety-relevant features of the provisional repository design:

- The repository is located in an environment where the likelihood of inadvertent future human intrusion is limited and where geological events and surface processes that could adversely affect post-closure safety are avoided as far as possible. This means that it will be located at a sufficient depth and in a stable geological environment and in a host rock with no or limited mineral or other resources.
- The impact of inadvertent future human intrusion, if it were to occur, and other events such as an abandonment of the repository during operation, will be limited by compartmentalising the repository. Therefore, HLW and L/ILW will be placed in separate repository sections. The seals and backfills will also contribute to repository compartmentalisation.
- The different repository structures will be arranged in such a way that mutual interactions that could be detrimental to safety are prevented. This will be achieved by placing the different parts of the repository sufficiently far apart.
- The repository will also be located and designed to achieve the longest possible residence time of the radionuclides in the CRZ and, in particular, within the host rock. This means that the repository will be located at sufficient depth, approximately at the centre of the Opalinus Clay layer, and away from faults and deep boreholes. It also leads to the choice of a lateral layout of the repository sections (i.e., side by side and not on top of one another), and HLW emplacement drifts parallel to the host rock layer.
- The repository conceptual design and closure system ensure that the release of radionuclides takes place mainly through the geological barriers. The closure system will reduce the pore water flow through the repository structures, and the axial flow of water along the emplacement rooms will be further reduced by opting for a dead-end geometry.
- Construction of the repository will damage the Opalinus Clay as little as possible, so that the transport distance of radionuclides in the undisturbed host rock remains as large as possible. This means selecting appropriate repository-excavation techniques and types of tunnel support. It also means backfilling and sealing the repository structures, as this also limits the convergence of the host rock after the tunnel support has degraded. The use of materials that could potentially damage the geological or engineered barriers should also be minimised. This is especially true for gas-generating materials, such as metals or organic waste, or any substances that could chemically interact with the host rock or other barriers.
- The HLW disposal canisters ensure that the waste is contained for a required minimum period of 1,000 years. This is achieved by a choice of materials and a design that limit corrosion processes and can withstand the mechanical loads that will arise during the containment period. The HLW disposal canisters will be protected by the bentonite buffer which creates a geochemical environment, inhibiting corrosion. The bentonite buffer will also limit the risk of mechanical damage due to an inhomogeneous stress distribution around the canisters. In the case of L/ILW, the cement-based backfill provides mechanical stability to the host rock, even after the degradation of the tunnel support.

Once the HLW and L/ILW primary waste packages are breached, a small proportion of the radionuclides will be released instantaneously (e.g., gaseous fission products present in the gap between the fuel matrix and the cladding, and activation products from the cladding). Especially in the case of HLW, however, most radionuclides remain in the waste matrices for a long time as they are uniformly distributed within them and are congruently released with the extremely slow degradation rates of these matrices once they are in contact with porewater.

Most radionuclides need to dissolve in the porewater before they are released into the host rock. The bentonite buffer in the HLW emplacement drifts and the L/ILW cementitious near field will limit the solubility of most radionuclides and also promote radionuclide sorption. As a result, the bentonite and cementitious components will contribute to the retention of the radionuclides in the repository.

In the HLW repository section, heat transport is an important process because the RP-HLW and SF continues to produce heat for some time due to radioactive decay. The transport of the heat from the waste through the engineered barriers will not damage these barriers. In the L/ILW repository section, gas storage capacity and gas transport are important as the L/ILW produces significant quantities of gas by corrosion of metals and degradation of organic waste. The engineered barriers are therefore designed to have a high gas storage capacity. This is necessary to prevent an unfavorable gas pressure build-up and associated damage of the barriers.

The engineered barriers are designed (i.e., the materials will be chosen) to avoid geochemical interactions that could negatively impact safety and to ensure geochemical and mineralogical compatibility between the different components. The design of the engineered barriers also takes into account the requirement of waste retrievability (see Art. 37b in KEG 2003). This means that the design of the HLW canisters or L/ILW containers, backfill and seals does not make it unnecessarily difficult to retrieve the waste during the monitoring phase.

Finally, it is important to keep in mind that this report is focused on the long-term safety requirements and how they affect the design. Requirements regarding engineering feasibility, compatibility and efficiency are, however, becoming increasingly more important as the project progresses and the repository design becomes more detailed, but these requirements need to be met without compromising post-closure safety.

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7 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 evolution 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.

Term	Definition
Combined repository	A repository comprising disposal areas for both HLW and L/ILW in the same siting region.
Compartmentalisation	Partitioning of waste, e.g., in different sections of the repository, through a designated layout of the repository and the installation of seals and backfill.
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 time period for assessment 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.
Defence-in-depth	The principle through which safety is defended at various levels, with layers of overlapping provisions so that, if a deficiency should occur in one layer it would be compensated for or corrected by others. This includes the multi-barrier system and how its safety functions ensure a robust repository system.
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,

Term	Definition
	• the favourable results of the safety assessment, • complementary lines of arguments.
Design requirements	Requirements placed on the design of system components such that they are expected to fulfil their respective performance objectives and component-specific functions. These design requirements are developed in association with the repository design and system analysis as part of an iterative design development process. For the safety assessment in support of the general licence application milestone, this process leads to the provisional design and implementation plan, for which safety is assessed.
Design specifications	Solutions to the design requirements, concerning technical, quality and organisational aspects of individual components or the whole repository system.
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 can 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.
Waste packages	Generic term for SF/RP-HLW disposal canisters and L/ILW disposal containers.
Emplacement rooms	Generic term for HLW emplacement drifts (HLW repository or combined repository section) and L/ILW emplacement caverns (L/ILW repository or combined repository section) for the long-term emplacement of radioactive waste.
Envelope scenarios	Scenarios that cover potential 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.
FEPs	*Features, events and processes.* Internal or external phenomena (or factors) that can either define the repository system or influence its evolution or radiological consequences.

Term	Definition
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 can impact repository safety, particularly regarding human intrusion into the repository (e.g., by drilling deep borehole). 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.
Optimisation of protection	A principle of radiological protection to keep radiological exposure as low as reasonably achievable (ALARA), which is also applied throughout the stepwise and iterative development of the repository design in view of post-closure safety.
Performance assessment	An analysis of the thermal, hydraulic, mechanical, and chemical evolution of the repository system. Performance assessment verifies whether the expected evolution of the repository system, as provided by the assessment basis, is indeed the expected evolution based on the arguments and evidence available. Performance assessment also identifies deviations in performance that could degrade the functionality of the components of the repository system or of the repository system as a whole, as inputs to safety scenario development.
Performance assessment scenarios	Performance assessment scenarios address features, events and processes that could potentially degrade the repository barriers and their safety functions. They permit a quantitative assessment of the impact of deviations in performance on the performance of the repository system as a whole and enable the consideration of uncertainties related to the evolutionary path. This provides information on their relevance to safety, which facilitates the identification of those deviations that require an in-depth analysis of the radiological consequences.

Term	Definition
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 the 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. While both pessimism and conservatism lead to calculated consequences that are less favourable than those that are most likely, conservatism includes the use of hypothetical assumptions or parameter values and results in consequences that are less favourable than the most likely consequences, including uncertainty.
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 post-closure 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*.

Term	Definition
Provisional design and implementation plan	The provisional layout, material choices and dimensions of all components of the repository, and the sequence of operations for repository construction, operation and closure. It results from the iterative design development process that is informed by the safety and repository concepts, system analyses and other design considerations, such as engineering practicality and operational safety.
Reference safety scenario	A general description of the initial state of the repository barriers, their expected evolution over time (including the release, retention and transport of radionuclides within the repository system), and the assumptions made regarding the biosphere for the analysis of radiological consequences. Essentially, in the reference safety scenario, the repository system will perform as expected and the pillars of safety are assumed to provide their assigned functions, in accordance with the safety and repository concept.
Repository section	In the combined repository, in addition to the main HLW and L/ILW disposal areas, the HLW and L/ILW repository sections each include a pilot facility, in which the behaviour of the wastes, the backfill, the seals and the host rock is monitored until the end of a monitoring period.
Repository system	The repository system comprises the underground structures, the emplaced waste, the installed engineered barriers, and the containment-providing rock zone.
Requirements	Conditions that must be fulfilled or attributes that must be possessed by the repository system or its components to achieve certain objectives. Requirements are organised hierarchically. At the highest level, these are overarching objectives and principles, including those specified in Swiss legislation and regulations. Low-level requirements are more detailed and specific and support the fulfilment of the overarching requirements.
Reserve FEPs	*Features, events and processes* considered likely to occur and beneficial to safety that are deliberately excluded from quantitative analysis because the level of scientific understanding is insufficient to support quantitative modelling, or because suitable models, codes or databases are unavailable. Reserve FEPs can be mobilised at a later stage of repository planning if the level of scientific understanding is sufficiently enhanced, and the necessary models, codes and databases are developed. The existence of reserve FEPs constitutes an additional, qualitative argument for reserves of safety beyond those indicated by the quantitative analysis.

Term	Definition
Robustness principle	The principle of siting and designing the repository system such that it is insensitive to detrimental processes and events and that post-closure safety can be demonstrated irrespective of the remaining uncertainty.
Safety analysis (site-specific)	A synonym for *analysis of radiological consequences* in the context of site-specific analyses performed within the framework of site comparison. As for the more detailed safety assessment in support of the general licence application, this analysis also comprises a systematic and quantitative analysis approach, including a reference scenario 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 disposal containers in long, layer-parallel emplacement rooms 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 post-closure safety. Engineered and geological 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 action 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 could 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 can 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.

Term	Definition
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. In contrast with *alternative safety scenario*.
Scenario analysis	With respect to the regulatory guidance, this refers to a combination of (in Nagra's terminology) *safety scenario development* and *radiological consequence analysis* for the defined *calculation cases.*
Sensitivity analysis	Technique to investigate 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 Guideline G03 (ENSI 2023)), 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 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 should extend up to the time of maximum radio-logical impact of the repository, 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.
Time period under consideration	The timeframe over which safety analysis calculations are performed in the frame of the 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 an HLW repository.
Uncertainty analysis	Quantification of the influence of uncertainties in data, processes and model assumptions on calculation results.

Term	Definition
"What-if?" cases	"What-if?" cases are calculation 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 one-million-year *time period for assessment,* can also be considered as a "what-if?" case.

App. A Safety functions, related safety requirements and component design aspects

The safety functions specific, together with their related safety requirements – at Level 2 in Nagra's safety requirements hierarchy – and repository design aspects, are listed in in Tab. A-1, together with how the repository conceptual design can meet these requirements. Specific requirements related to the CRZ are not included in this table as these relate to the siting process and not to the repository design process. This version of the Level 2 safety requirements dates from September 2023. At a later stage, these Level 2 requirements will be used as a basis for (quantitative) performance objectives (Level 3 safety requirements), design requirements (Level 4) and design specifications (Level 5).

Tab. A-1: Long-term safety functions and their related safety requirements and repository design aspects

Safety function		**Level 2 safety requirements**	**Related design aspects**
S1: Isolation	L2-ISO-01	Likelihood and consequences of abandonment of the repository are minimised.	L/ILW waste packages, containers, infill and backfill (Section 4.2.3): • By backfilling the emplacement caverns with cement-based mortar shortly after the waste is emplaced, the consequences of abandoning the repository are limited as removing the cement-based backfill requires effort and resources. Closure system (Section 3.4.7): • The permeability of the closure system is sufficiently low to limit the water flow from one emplacement room to another part of the repository. • Excavating the closure system requires significant effort and resources.
	L2-ISO-02	Consequences of inadvertent human intrusion are limited.	The deep underground location in a stable geological environment (Sections 3.4.1 and 4.1.2): • The repository conceptual design compartmentalises the emplaced waste which limits the impact of potential incidents to one part of the repository and might not affect the other parts. Closure system (Section 3.4.7): • The low permeability of the closure system limits the water movements across the repository and thereby also limits the impact of incidents, if they would occur, in one part of the repository to the other parts.

Tab. A-1: Cont.

Safety function		Level 2 safety requirements	Related design aspects
S1: Isolation	L2-ISO-03	Effects of events and processes at the surface are minimised.	The deep underground location in a stable geological environment (Section 3.4.1): • The repository depth is sufficient to limit the effects of surface processes, such as erosion or glaciation.
	L2-ISO-04	Likelihood and consequences of future human actions are minimised.	The deep underground location in a stable geological environment (Sections 3.4.1 and 4.1.2): • The repository depth is beyond the depth of common excavation activities, such as mining, tunnelling, or quarrying. • A CRZ with limited geological or groundwater resources will reduce the likelihood of future human actions and, in that way, contributes to waste isolation Closure system (Section 3.4.7): • The closure system forms a physical barrier to the waste which would require effort and resources to dismantle.
S2: Complete containment	L2-CC-02	The HLW disposal canisters provide complete containment for the required minimum period of 1,000 years under expected conditions.	HLW disposal canisters (Sections 3.4.4 and 4.2.1): • Manufacturing, welding, heat treatment, inspection and handling procedures can be tailored for minimising undetected defects and residual stresses. • The wall thickness of the canisters ensures sufficient corrosion margin. • The canisters are strong enough for the load cases that apply to them. • The canister manufacturing process and the related QA/QC measures guarantee ensure a sufficiently high percentage of the canisters manufactured are intact.

Tab. A-1: Cont.

Safety function		Level 2 safety requirements	Related design aspects
S3: Immobilisation, retention, and slow release	L2-IRR-01	The system provides long transport times that result in attenuation of radionuclide releases by decay.	The deep underground location in a stable geological environment (Sections 3.4.1, 4.1): • The repository sections and emplacement rooms make optimum use of the thickness of the host rock by locating them at sufficient depth, approximately at the centre of the host rock, somewhat parallel to the sedimentary stratum and at a sufficient distance from faults and deep boreholes. • The diameter of the emplacement rooms is limited so that the (vertical) distance for radionuclide transport through the intact host rock is maximised. • The shafts are designed, constructed, operated, and closed in such a way that they do not form a preferential release pathway for radionuclides. • Dead-end drifts limit the gradient that drives the axial water flow along emplacement rooms and thus extends the transport times for radionuclides to the accessways. • Repository construction, operation, and closure damage the CRZ as little as possible. Closure system (Section 3.4.7): • The permeability of the closure system is sufficiently low to contribute to slow and diffusion-dominated transport of radionuclides.
	L2-IRR-02	The system provides dilution and dispersion of radionuclides during transport.	The deep underground location in a stable geological environment location (Sections 3.4.1, 4.1): • The repository depth together with the properties of the geological environment favour dilution and dispersion. Closure system (Section 3.4.7): • The permeability of the closure system is sufficiently low to contribute to slow and diffusion-dominated transport of radionuclides.

Tab. A-1: Cont.

Safety function		Level 2 safety requirements	Related design aspects
S3: Immobilisation, retention, and slow release	L2-IRR-04	The bentonite buffer retains many radionuclides once released from the canisters.	Bentonite buffer (Sections 3.4.5 and 4.2.2): • The high clay content of the bentonite promotes radionuclides sorption and low solubility, which limit the releases of radionuclides. • The saturated bentonite has a low hydraulic conductivity which ensures slow and diffusion-dominated radionuclide transport. • The saturated compacted bentonite develops a sufficiently high swelling pressure to seal any openings in the buffer. The fine pore structure in the saturated bentonite immobilises colloids.
	L2-IRR-05	The cementitious L/ILW near field retains many radionuclides.	Cementitious L/ILW near field (Section 3.4.6): • The cementitious near field promotes radionuclide sorption and low radionuclide solubility, which limit their release. • The cementitious near field contributes to slow and diffusion-dominated porewater movement in the L/ILW emplacement caverns.
	L2-IRR-06	Once in contact with porewater, the waste forms remain stable and release most radionuclides congruently with slow degradation.	SF and RP-HLW waste matrices (Section 3.4.3): • The waste form degrades only very slowly when it comes into contact with infiltrating porewater. • A uniform distribution of most radionuclides within the waste matrix contributes to their slow release. • The chemical conditions in the near field are highly reducing (high H_2 partial pressure) and thus contribute to very slow dissolution rates.
	L2-IRR-08	The closure system retains any radionuclides released from the disposal areas.	Closure system (Section 3.4.7): • The permeability of the saturated clay in the seal and backfill materials is sufficiently low to limit water flow and advective transport. • The clay content of the seal and backfill materials promote the sorption of many radionuclides. • The gas permeability of the shaft seals is sufficiently low to limit the gas flow and advective transport.

Tab. A-1: Cont.

Safety function		Level 2 safety requirements	Related design aspects
S3: Immobilisation, retention, and slow release	L2-IRR-11	The waste forms immobilise most radionuclides until contacted by porewater.	SF and RP-HLW waste matrices (Section 3.4.3): • The waste form material is stable in the absence of water.
	L2-IRR-12	Once released from the waste forms, some radionuclides may be immobilised by precipitation.	SF and RP-HLW waste matrices (Section 3.4.3): • The dissolution of the waste form affects the porewater composition in such a way that the porewater permits the precipitation of radionuclides.
S4: Compatibility	L2-CMP-01	Detrimental effects of repository-generated gas are avoided.	Repository layout (Section 4.1): • The repository components are arranged in such a way that there are no unfavourable interactions due to gas generated in the different parts of the repository.
	L2-CMP-02	Detrimental effects of repository-generated heat are avoided.	Repository layout (Section 4.1): • Spatially distributing the heat-emitting wastes in the repository minimises the impact of heat. • The repository components are arranged in such a way that there are no unfavourable thermal interactions between the different parts of the repository.
	L2-CMP-03	Detrimental hydromechanical effects of excavation are limited.	Repository layout (Section 4.1): • Orienting the emplacement rooms in the direction of the principal stress minimises tunnel convergence and EDZ development. • The underground structures are arranged in such a way that overlapping EDZs are avoided. Repository construction methods and tunnel support (Sections 4.2.4 and 4.3): • The tunnel excavation method and the design and emplacement method of the tunnel support are optimised to limit the development of EDZs during construction. • The stiffness of the tunnel support minimises the development of an EDZ.

Tab. A-1: Cont.

Safety function		**Level 2 safety requirements**	**Related design aspects**
S4: Compatibility	L2-CMP-05	The cementitious L/ILW near field provides a limited source of heat.	Cementitious L/ILW near field (Section 3.4.6): • The cement used in the components of the cementitious near field generate a limited heat due to cement hydration.
	L2-CMP-06	Unfavourable chemical interactions between different parts of the repository are avoided or limited.	Repository layout (Section 4.1): • The repository components are arranged in such a way that there are no unfavourable chemical interactions between the different parts of the repository.
	L2-CMP-07	The bentonite buffer allows for sufficient gas transport to its surroundings.	Bentonite buffer (Sections 3.4.5 and 4.2.2): • The bentonite allows gas transport without irreversible damage to the barriers.
	L2-CMP-08	The bentonite buffer favours efficient heat transfer between it and its surroundings.	Bentonite buffer (Sections 3.4.5 and 4.2.2): • The thermal conductivity of the bentonite is sufficiently high, both during the transition phase when it becomes saturated and when it is fully saturated.
	L2-CMP-09	The bentonite buffer limits tunnel convergence.	Bentonite buffer (Sections 3.4.5 and 4.2.2): • The bentonite buffer sufficiently fills the volume of the HLW emplacement drifts. • The bentonite is sufficiently stiff to limit tunnel convergence.

Tab. A-1: Cont.

Safety function		Level 2 safety requirements	Related design aspects
S4: Compatibility	L2-CMP-10	The bentonite buffer provides a protective environment for the HLW disposal canisters.	Bentonite buffer (Sections 3.4.5 and 4.2.2): • The amounts of potentially corrosive substances (e.g., chlorides and sulphates) in the bentonite buffer are limited. • The saturated bentonite buffer has a sufficiently fine pore structure to limit microbial activity. • The saturated bentonite is sufficiently plastic to even out differential stresses on the buffer. • The bentonite homogenises upon saturation and develops a relatively uniform swelling pressure.
	L2-CMP-11	The cementitious L/ILW near field favours gas transport and storage.	Cementitious L/ILW near field (Section 3.4.6): • The gas-accessible porosity of the cementitious near field is sufficiently high to provide a sufficient gas storage volume in the buffer. • The cementitious near field has a sufficiently high gas permeability to allow gas out of the emplacement caverns.
	L2-CMP-13	The L/ILW cavern backfill limits tunnel convergence.	Cementitious L/ILW near field (Section 3.4.6): • The cement-based backfill sufficiently fills the volume of the HLW emplacement drifts. • The cement-based backfill is sufficiently stiff to limit tunnel convergence.
	L2-CMP-14	The L/ILW near field is chemically and mineralogically compatible with adjacent barriers.	Cementitious L/ILW near field (Section 3.4.6): • The properties of the cementitious near field do not significantly impair the safety-related properties of the CRZ, the tunnel support and the seals at the entrance of the emplacement caverns. • Radiation-induced effects on the cement components are limited.

Tab. A-1: Cont.

Safety function		Level 2 safety requirements	Related design aspects
S4: Compatibility	L2-CMP-15	The heat output of the HLW disposal canisters does not result in irreversible damage of the geological or engineered barriers.	HLW disposal canisters (Sections 3.4.4 and 4.2.1): • The thermal load of the canisters is sufficiently low so that the safety-related properties of bentonite buffer and CRZ are not impaired. • The canisters are emplaced sufficiently far apart to limit the temperature increase in the surrounding bentonite buffer and CRZ.
	L2-CMP-16	The cementitious L/ILW near field limits the rate of gas generation.	Cementitious L/ILW near field (Section 3.4.6): • The organic admixtures to the cement components of the near field is limited. • The alkalinity of the cementitious near field reduces the likelihood of microbial degradation of organic materials. • The corrosion rate in the alkaline environment is very low.
	L2-CMP-19	The closure system favours gas transport and storage.	Closure system (Section 3.4.7): • The gas-accessible porosity of the backfill is sufficiently high to provide a sufficient gas storage volume in the backfill of the closure system. • The backfill of the closure system and the seals of the closure system, with the exception of the shaft seals, have a sufficiently high gas permeability to evacuate gas from the repository components.
	L2-CMP-20	The closure system does not contribute significantly to gas generation.	Closure system (Section 3.4.7): • The amounts of metals and the organic content in the closure system are limited.
	L2-CMP-21	The closure system limits tunnel convergence.	Closure system (Section 3.4.7): • The seal structures are sufficiently stiff to minimise tunnel convergence. • The seal structures can be installed sufficiently quickly after the tunnel support is locally removed to enable seal installation.

Tab. A-1: Cont.

Safety function		Level 2 safety requirements	Related design aspects
S4: Compatibility	L2-CMP-22	The closure system is chemically and mineralogically compatible with adjacent barriers.	Closure system (Section 3.4.7): • The materials used in the closure system do not significantly chemically interact with the CRZ, tunnel support and bentonite buffer or cementitious near field, so that the performance of these components is not significantly reduced.
	L2-CMP-23	The gas generated by corrosion of the HLW disposal canisters and its transport through engineered and geological barriers does not result in irreversible damage of these barriers.	HLW disposal canisters (Sections 3.4.4 and 4.2.1): • The anaerobic corrosion rate of carbon steel canisters is low. • The canisters provide sufficient radiation shielding to limit radiolysis in the bentonite buffer and cementitious near field around the canisters.
	L2-CMP-26	The tunnel support of the HLW emplacement drifts favours efficient heat transfer to its surroundings.	Tunnel support (Section 4.2.4): • The materials used for the tunnel support and the thickness of this support ensure sufficient heat transfer to the surrounding CRZ.
	L2-CMP-27	The tunnel support system limits tunnel convergence and EDZ development.	Tunnel support (Section 4.2.4): • The tunnel support is sufficiently stiff to minimise tunnel convergence. • The tunnel support is installed sufficiently quickly after tunnel excavation.
	L2-CMP-28	The tunnel support system is chemically compatible with adjacent barriers.	Tunnel support (Section 4.2.4): • The materials used in the tunnel support system do not chemically interact with the CRZ, closure system and bentonite buffer or cementitious near field, so that the performance of these components is not significantly reduced. • Radiation-induced effects on the tunnel support are limited.

Tab. A-1: Cont.

Safety function		Level 2 safety requirements	Related design aspects
S4: Compatibility	L2-CMP-29	The bentonite buffer is chemically and mineralogically compatible with adjacent components.	Bentonite buffer (Sections 3.4.5 and 4.2.2): • The materials used in the tunnel support system do not chemically interact with the CRZ, closure system and bentonite buffer or cementitious near field, so that the performance of these components is not significantly reduced. • Radiation-induced effects on the tunnel support are limited.
	L2-CMP-30	The tunnel support system supports sufficiently even saturation of the bentonite buffer.	Tunnel support (Section 4.2.4): • The tunnel support can be designed such that it allows a sufficiently even saturation of the bentonite is possible.
	L2-CMP-32	The tunnel support system does not contribute significantly to gas generation.	Tunnel support (Section 4.2.4): • The amounts of gas-producing substances, such as metals and organic materials, used in the tunnel support are limited.
S5: Long-term stability	L2-STB-02	The layout and placement of the repository are such that it is unlikely to be affected by processes at the surface, by the reactivation of faults or by the creation of new faults that intersect the underground facilities.	Repository layout (Sections 3.4.1 and 4.1): • The layout of the repository provides a suitable distance to known faults. • Any faults that are not detected are unlikely to be relevant to safety. • The stresses arising from geologic processes are likely to be taken up by faults that are identified and avoided.