



ARBEITSBERICHT NAB 24-20 Rev.1

Phenomenological Description of the
Evolution of a Geological Repository for
Radioactive Waste in Opalinus Clay

September 2024

**Nagra | National Cooperative for the
Disposal of Radioactive Waste**

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KEYWORDS

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L/ILW, HLW

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Nagra Arbeitsberichte ("Working Reports") present the results of work in progress that have not necessarily been subject to a comprehensive review. They are intended to provide rapid dissemination of current information.

The present report has evolved over several years as a synthesis of phenomenology. Over this time period, many different authors contributed their expertise to this report, which is internally referred to as "*Storyboard*".

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This report has been revised due to findings made during the course of the project development. As a result, certain formulations have been adjusted to reflect updated information and ensure consistency across the reports.

Abstract

The present report outlines the expected evolution of a repository for both HLW and L/ILW, with surface facilities at the Haberstal site (municipality of Stadel, ZH). It provides a high-level description of the expected evolution and behaviour of the repository system, its components, and its surrounding environment over extended periods, as well as noting the main uncertainties.

Key elements of this description include the waste inventory, the location and layout of the deep geological repository the engineered repository components, the long-term safety-related impact of construction, operation and closure of the repository, the evolution of underground openings prior to backfilling, and the long-term interactions between components, including repository-induced effects on the host rock. The description also accounts for geological and climatic processes over extended timescales, such as erosion, uplift and fault activation.

The narrative of the expected evolution of the repository presented in the following sections is based on current scientific understanding, including uncertainty, documented in the assessment basis reports and brought together within the present report.

This comprehensive description of the expected evolution provides a robust foundation for assessing post-closure safety of a combined repository for radioactive waste that is based on a provisional design to ensure the protection of both human health and the environment for millennia to come.

Table of Contents

Abstract	I
Table of Contents	III
List of Tables.....	VI
List of Figures	VI
List of Acronyms.....	IX
1 Introduction	1
1.1 Context.....	1
1.2 Scope of the present report	2
1.3 Supplementary volume to the present report: handling of features, events, and processes in the safety assessment.....	2
1.4 The safety assessment process.....	5
1.5 Approach to developing the storyboard.....	6
1.6 Structure of this report.....	6
2 Repository system and post-closure safety considerations.....	7
2.1 Background to repository system currently under consideration	7
2.1.1 Current Nagra project for deep geological disposal of radioactive waste in Nördlich Lägern siting region.....	7
2.1.2 Monitoring and maintenance	10
2.2 HLW underground facilities and barriers	11
2.2.1 Waste encapsulation	11
2.2.2 Emplacement underground.....	12
2.2.3 Barriers for SF/HLW and their safety roles.....	15
2.3 L/ILW underground facilities and barriers	18
2.3.1 Waste containers.....	18
2.3.2 Emplacement underground.....	20
2.3.3 Barriers for L/ILW and their safety functions	22
2.4 Sealing system	24
2.5 Staging of deep geological repository construction, operation and closure.....	27
2.6 Alternative repository concepts	28
3 Processes during the construction and pre-emplacement phase and related uncertainties.....	29
3.1 Baseline conditions at the site.....	29
3.2 Construction-induced processes and uncertainties	29
3.2.1 Evolution of regional hydrology and geochemistry	29
3.2.2 Mechanical evolution of the host rock.....	30
3.2.3 Other construction-induced effects.....	31

3.3	Waste- and packaging-related processes and uncertainties	31
3.3.1	SF-/HLW-related processes.....	31
3.3.2	L/ILW-related processes.....	36
3.4	Potential impact of storage and transport on the waste packages	37
4	Processes during the pre-closure phase	39
4.1	Overview	39
4.2	Key events and processes and their consequences	42
4.2.1	Excavation and consequent mechanical unloading of the rock	42
4.2.2	Installation of rock support.....	43
4.2.3	Ventilation and cooling.....	45
4.2.4	Installation of canisters/containers and backfill material.....	46
4.2.5	Heat generation.....	47
5	Interactions between sealed and unsealed deep geological repository structures	49
5.1	Potential impact of imperfect manufacture and installation of emplacement drift and cavern components	51
5.1.1	HLW bentonite buffer emplacement	51
5.1.2	HLW voids behind the segmented lining (reference design).....	51
5.1.3	L/ILW cementitious backfill.....	51
5.2	Summary of main processes and key factors that influence them	51
6	Early post-closure processes	53
6.1	HLW emplacement drifts	54
6.1.1	Heat generation and its effects.....	55
6.1.2	Buffer saturation.....	56
6.1.3	Corrosion, gas generation and redox conditions.....	58
6.1.4	Swelling pressure development, tunnel convergence and evolution of the EDZ	60
6.2	L/ILW emplacement caverns.....	60
6.2.1	Saturation conditions and initial gas generation	60
6.2.2	Near-field evolution: cement degradation stages and processes.....	63
6.3	Access tunnels, plugs and auxiliary underground facilities.....	66
6.4	Potential impact of imperfect manufacturing and emplacement of closure components	66
6.5	Summary of main THM processes and key factors influencing these.....	66
7	Processes during the post-closure period.....	69
7.1	HLW underground facilities	69
7.1.1	Evolution while significant radiogenic heat is produced.....	70
7.1.2	Evolution after the non-isothermal period.....	72
7.2	L/ILW underground facilities	75
7.2.1	Saturation scenarios for the L/ILW underground facilities	75
7.2.2	Internal degradation of cement-based elements.....	77

7.2.3	External degradation of concrete elements: presence of water under partially saturated conditions	79
7.2.4	Corrosion of steel waste disposed of in MOSAIK containers	81
7.3	Access tunnels and auxiliary underground facilities	81
8	Robustness of the barriers	87
9	Migration of radionuclides.....	95
9.1	Transport in the near-field	95
9.2	Transport to the host rock and CRZ	96
9.3	Assessing the radionuclide release in the biosphere.....	98
10	Summary of the geological long-term evolution of Northern Switzerland.....	99
10.1	Tectonic evolution of Northern Switzerland	99
10.1.1	Climate evolution in Northern Switzerland.....	99
10.1.2	Erosion in Northern Switzerland	100
10.1.3	Hydrogeology and hydrochemistry of Northern Switzerland.....	100
10.2	Expected geological long-term evolution at the Nördlich Lägern siting region.....	101
10.3	Impacts of the long-term geological evolution on exposure to radiation	103
11	Conclusions.....	105
12	References.....	107
App. A	Expected evolution as input for the performance assessment	A-1
A.1	Waste inventory and acceptance.....	A-1
A.2	Location, construction, operation, and closure of the underground facilities	A-1
A.3	Evolution of underground openings prior to backfilling	A-2
A.4	Saturation of the access structures.....	A-2
A.5	Evolution of the L/ILW disposal area and connected underground structures after backfilling.	A-3
A.6	Evolution of the HLW disposal area after backfilling.....	A-4
A.7	Evolution driven by climatic and geological processes.....	A-4

List of Tables

Tab. 2-1:	Requirements for the HLW disposal canisters	11
Tab. 2-2:	Requirements on bentonite used as buffer in emplacement drifts	14
Tab. 2-3:	Staging of repository construction, operation and closure.....	27
Tab. 5-1:	Processes during cavern excavation, ventilation and emplacement	52
Tab. 6-1:	Processes occurring in the HLW emplacement drifts prior to deep geological repository closure	67
Tab. 6-2:	Processes occurring in the L/ILW emplacement cavern prior to deep geological repository closure	67
Tab. 7-1:	Long-term post-closure processes occurring when significant radiogenic heat is produced	71
Tab. 7-2:	Processes relevant to canister breach and corrosion of spent fuel baskets	75

List of Figures

Fig. 1-1:	Reporting structure for site comparison and the post-closure safety case	4
Fig. 2-1:	Current Nagra project for deep geological disposal of radioactive waste	9
Fig. 2-2:	Current design profile of emplacement drift.....	12
Fig. 2-3:	Construction and operational phase in the HLW drift.....	13
Fig. 2-4:	Illustration of the barrier system for HLW, showing how the properties and/or processes of the individual barriers contribute to post-closure safety.....	17
Fig. 2-5:	L/ILW disposal containers (LC) filled with waste drums	19
Fig. 2-6:	MOSAIIK-II cast steel container with an inner volume of approximately 1.3 m ³	20
Fig. 2-7:	Schematic view of container emplacement in an L/ILW cavern.....	21
Fig. 2-8:	Schematic representation of a cross-section of the L/ILW cavern	22
Fig. 2-9:	Illustration of the barrier system for ATW and L/ILW, showing how the properties and/or processes of the individual barriers contribute to post-closure safety	23
Fig. 2-10:	Arrangement of the V1, V2 and V3 seals and the VF1 and VF2 backfill within a generic deep geological repository layout	25
Fig. 2-11:	Generic illustration of a seal, showing its principal components (not to scale).....	26

Fig. 3-1:	Thermal power evolution per average final disposal canister (ELB) for the three canister types. The above-illustrated thermal power evolution was calculated on the basis of (Nagra 2023b)	32
Fig. 3-2:	Thermal power in Watt on double logarithmic scale as a function of time for HLW. The above-illustrated thermal power evolution was calculated on the basis of (Nagra 2023b).....	33
Fig. 3-3:	The macro- and microstructures of a fuel pellet after its irradiation	34
Fig. 3-4:	Conceptual distribution of radionuclides in a spent fuel rod	35
Fig. 4-1:	Expected interdependencies of processes and phenomena during the construction and operational phases of an HLW emplacement drift.....	40
Fig. 4-2:	Principal THM processes in an emplacement drift during excavation (top row), ventilation (centre row) and emplacement (bottom row)	41
Fig. 4-3:	Conceptual figure of the shape and extent of an EDZ around an emplacement drift	43
Fig. 4-4:	Activities, ground and support conditions for the construction of HLW emplacement drifts.....	44
Fig. 5-1:	Interactions between HLW drifts during the operational phase of the repository	50
Fig. 6-1:	An illustrative representation of a fully saturated HLW drift hundreds of years after deep geological repository closure	53
Fig. 6-2:	Expected interdependencies of processes and phenomena in a sealed SF emplacement drift prior to deep geological repository closure	54
Fig. 6-3:	Expected THM processes during the first 100 years after closure of an HLW emplacement drift.....	55
Fig. 6-4:	Schematic illustration of coupled processes associated with vapour transport.....	57
Fig. 6-5:	Schematic illustration of coupled processes associated with vapour transport.....	58
Fig. 6-6:	Current understanding of the processes occurring at the canister-bentonite interface	60
Fig. 6-7:	Schematic sketch showing the evolution of the cavern near-field during the operational phase and after closure.....	62
Fig. 6-8:	Schematic representation of the generic degradation stages of cement.....	63
Fig. 6-9:	Gas generation rates as a function of time for a model waste package	65
Fig. 7-1:	Expected interdependencies of processes and phenomena in the HLW repository section after closure.....	69
Fig. 7-2:	Expected THM processes during the period of 100 – 1,000 years after deep geological repository closure for an SF emplacement drift	70
Fig. 7-3:	An illustrative representation of an HLW emplacement drift in the period following deep geological repository closure.....	72
Fig. 7-4:	An illustrative representation of the drift when no metal remains.....	73

Fig. 7-5:	Temporal evolution of liquid saturation of an L/ILW emplacement cavern and neighbouring materials extracted from the base-case model in Papafotiou & Senger (2016a)	77
Fig. 7-6:	Time dependence of the Ca/Si ratio of C-S-H phases for two different waste types (a) BA-PH-PF and (b) SA-L-MX, using siliceous or calcareous aggregates	78
Fig. 7-7:	Estimates of aggregate dissolution with time (upper figure) and pH evolution with time due to aggregate dissolution only (lower figure).....	80
Fig. 7-8:	Temporal evolution of liquid saturation for a V1-L/ILW seal and adjacent cavern	82
Fig. 7-9:	Temporal evolution of liquid saturation at the top and bottom interfaces between tunnel backfill/EDZ halfway between the V1-L/ILW seals and the V2 seals	83
Fig. 7-10:	Top: temporal evolution of liquid saturation for a V2-L/ILW seal and adjacent backfill material. Bottom: temporal evolution of liquid saturation at the top and bottom interfaces halfway between the V2 and V3 seals.....	84
Fig. 8-1:	Overview of the expected evolution of the main processes in the HLW section of a combined repository, based on a compilation of modelling reports and experimental data	89
Fig. 8-2:	Overview of the expected evolution of the main processes in the L/ILW section of a combined repository	93

List of Acronyms

ATW	Alpha-toxic waste
CI	Cement interaction
CRZ	Containment-providing rock zone
EdZ	Excavation-disturbed zone
EDZ	Excavation-damaged zone
ELB	Disposal canister (<i>Endlagerbehälter</i>)
ENSI	Swiss Federal Nuclear Safety Inspectorate
FE	Full-scale experiment
FEP	Feature, Event and Processes
FGR	Fission gas release
HLW	High-level waste (spent fuel assemblies and high-level waste from reprocessing)
IRF	Instant release fraction
JO	Jura Ost
L/ILW	Low- and intermediate-level waste
LEB	Local Erosion Basis
LGM	Last Glacial Maximum
NAB	Nagra Arbeitsbericht (Nagra Work Report)
NL	Nördlich Lägern siting region
NPP	Nuclear power plant
NTB	Nagra Technical Report
OPA	Opalinus Clay
OPC	Ordinary Portland cement
RH	Relative humidity
RN	Radionuclides
SF	Spent fuel (assemblies)
SF/HLW(RP)	High-level waste from reprocessing
SFOE	Swiss Federal Office of Energy
SGT	Sectoral Plan for Deep Geological Repositories
Sr	Saturation degree
THC	Thermo-hydro-chemical
THM	Thermal-hydraulic-mechanical

UGI	Underground geological investigations
URL	Underground research laboratory
VA	Encapsulation plant
VE	Ventilation experiment
WAC	Waste acceptance criteria
ZNO	Zürich Nordost
ZWILAG	Zwischenlager Würenlingen AG

1 Introduction

1.1 Context

In Switzerland, legal regulations (Nuclear Energy Act (KEG 2003), the 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 waste¹ (ATW), and high-level waste (HLW), comprising spent fuel (SF) and vitrified HLW from reprocessing (RP-HLW). The Nuclear Energy Act (KEG) requires the disposal of all these types of radioactive waste in deep geological repositories. The feasibility of this disposal solution has been demonstrated for L/ILW in Nagra (1985) and for long-lived intermediate-level waste and HLW in Nagra (2002).

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

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

The justification for this selection and the safety demonstration for a repository in the proposed siting region NL are submitted as part of the general licence application (RBG²). The reports that relate 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 2025c) shown at the top of Fig. 1-1.
- The upper left side of Fig. 1-1 shows the reports justifying Nagra's selection of NL as the proposed siting region. The available options are compared with respect to safety and technical feasibility and the results are synthesized in NTB 24-03 (Nagra 2025a) ("*Bericht zur Begründung der Standortwahl*").
- The upper right side of Fig. 1-1 shows the reports documenting the post-closure safety case for the combined repository in NL, including its synthesis in the post-closure safety report NTB 24-10 (Nagra 2024f).
- The lower part of Fig. 1-1 shows a report that presents the safety and repository concept, including the provisional design, and reports which provide the assessment basis.

The present report is highlighted in Fig 1-1 with a red box.

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*

1.2 Scope of the present report

The present report aims to provide a clear and structured overview of the evolution of such a combined repository, contributing to the specific requirement for the demonstration of safety within the framework of the general licence applications that the long-term behaviour of the deep geological repository barrier system must be understood (KEV 2004). The general licence application will include the justification for the choice of the proposed site and a safety report, which forms the basis for the post-closure safety case for the deep geological repository. The present report plays a key supporting role for both of these elements. As illustrated in Fig. 1-2, there are multiple, safety related reports that document the site comparison, the selection of a preferred site and the post-closure safety case that will support the general licence application. Additional reports document the evidence, knowledge, assessment tools, and methodologies developed or acquired by Nagra in support of these activities, i.e., the assessment basis. The present report is part of this assessment basis and is highlighted in the figure with a red box.

The focus of the report is on the processes that occur during the construction, operation and closure of the combined repository, as well as during the post-closure period. The report examines the safety-related impact of repository-induced effects on the geological and engineered barriers, such as thermal effects, the formation of an excavation-damaged zone, cement-clay interaction and the effects of gas generation and gas pressure build-up. However, it does not address the potential impact of future human actions, or the radiological consequences of any radionuclides that may be released from the deep geological repository over time. These topics will be covered in other reports such as the post-closure safety report (Nagra 2024f) as part of the safety case accompanying the planned general licence applications (Nagra 2025c).

1.3 Supplementary volume to the present report: handling of features, events, and processes in the safety assessment

A prime concern in safety assessment is the issue of phenomenological comprehensiveness. That is:

- Have all the features, events, and processes (FEPs) that could affect the post-closure safety been thoroughly identified?
- Have these features, events and processes been adequately treated in the safety assessment?

Although it can never be proven that an assessment is complete, actions can be taken to encourage the identification of all potentially relevant phenomena and equally important, once identified, to ensure that the safety-relevant phenomena have been represented appropriately in the assessment.

In the safety assessment that supports the general licence application, an assurance of phenomenological completeness and appropriate treatment is provided by:

- the development of a comprehensive database of FEPs that may be relevant to the safety assessment, and a careful auditing of the phenomena included in the safety assessment against the FEP database in a process termed FEP management.

These activities are described in detail in the supplementary volume of the present report. In particular, the report indicates which FEPs can be excluded a priori, based on the existing scientific understanding of their negligible likelihood and/or consequences, or on the grounds that they are outside the scope of the safety assessment, and which need to be propagated either to performance assessment, or directly to the analysis of radiological consequence for further consideration. The report can thus be viewed as a “filter” as to which FEPs are to be considered in detail in the safety assessment and which can be excluded from the outset.

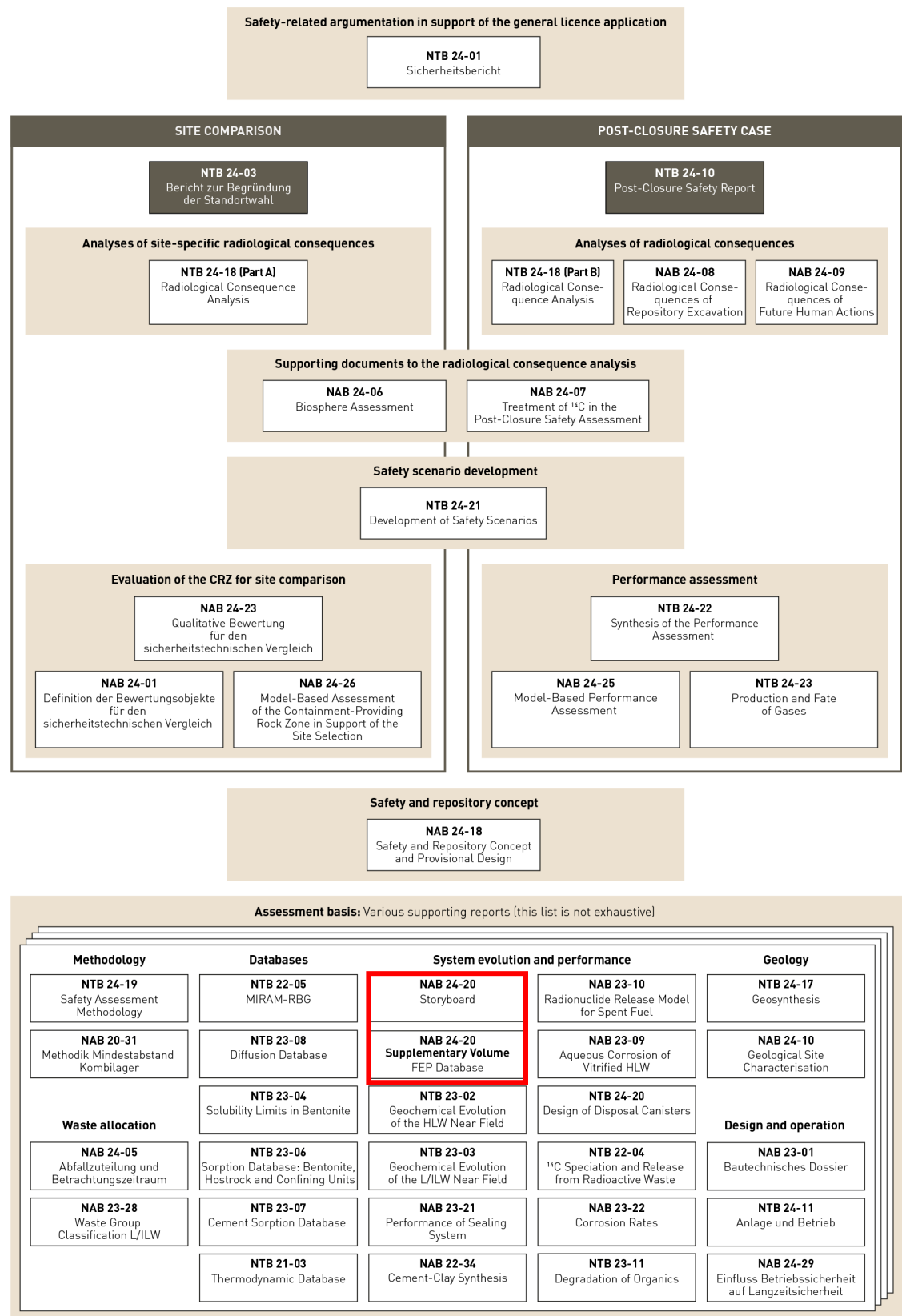


Fig. 1-1: Reporting structure for site comparison and the post-closure safety case

The present report, which is part of the assessment basis, is highlighted with a red box.

1.4 The safety assessment process

Safety assessment is defined by Nagra as the process of developing the safety case by gathering the evidence and arguments and carrying out analyses for the safety of the disposal system during the post-closure phase. Safety assessment consists of four main elements:

- **performance assessment** consists of an analysis of the thermal, hydraulic, mechanical, and chemical evolution of the repository system, including an evaluation of the fulfilment of performance objectives,
- **safety scenario development** entails the identification and description of a set of safety scenarios that capture uncertainties in the broad spectrum of how the disposal system may evolve over time, considering all relevant sources of uncertainty, as well as the identification of additional “what-if?” cases to test system robustness,
- **analysis of radiological consequences** consists of an evaluation of radionuclide release rates to the surface environment as a function of time in the safety and “what-if?” cases, and the conversion of these release rates into either annual individual effective doses or annual individual risks, for comparison with regulatory protection criteria, and
- **a safety demonstration** in which evidence, arguments, and analyses from the three previous steps are brought together for the safety case.

By providing a description of the expected evolution of the deep geological repository over time, the storyboard supports the definition of a reference safety scenario³. The storyboard also supports safety assessment by:

- identifying relevant phenomena that are examined in the performance assessment and, if found to be potentially safety-relevant, propagated to reference or alternative safety scenarios and to the analysis of their radiological consequences,
- providing a conceptual basis for the development of the models to assess the impact of these phenomena on deep geological repository evolution, and
- providing a basis for targets or evaluation scales to assess when impacts could become relevant to deep geological repository performance and safety.

The comparison of siting regions consists of both site-specific safety analyses, i.e., an evaluation of radionuclide release rates to the surface environment as a function of time in a defined set of safety scenarios, and a qualitative evaluation of the containment-providing rock zone (CRZ) in each siting region. Given the similarity in the geological characteristics and expected evolution of all three siting regions, the reference safety scenario and alternative safety scenarios developed for Nagra’s proposed siting region can be assumed to be applicable the other siting regions. The qualitative evaluation of the CRZ is made against a set of siting criteria, which, among others, concern the expected evolution of the CRZ during the period under consideration due to the effects of geological and climatic long-term processes, repository-induced effects and human actions. The impact of repository-induced effects on the CRZ is one of the main focuses of the present report.

³ The reference safety scenario is defined in Nagra (2024j) as a general description of the initial state of the repository barriers at the time of repository closure, of their expected evolution over time and of the assumptions made regarding the biosphere for the analysis of radiological consequences.

1.5 Approach to developing the storyboard

There are different possibilities to describe the evolution of a deep geological repository. Two bounding approaches are (1) to describe the evolution of each component in turn, or (2) to describe the evolution of the entire system in a sequence of discrete time frames. Both approaches have advantages and disadvantages. In particular, the evolution of each of the various repository components can be strongly interrelated, which favours the holistic second approach. However, especially during the early evolution of the repository, the evolution of one emplacement room and the materials within and around it may lag behind that of another, since the rooms⁴ will be constructed, filled and closed at different times. This favours a more component-wise description of evolution. The “storyboard” approach adopted in the present report lies closer to the second bounding approach in that the description is divided into broad time frames based on key phases in the development of the deep geological repository. However, to avoid the drawbacks of this approach, the start and end of each phase are defined by specific events or milestones, such as the sealing of an emplacement room, rather than by absolute times. Thus, for example, a description is given of the evolution of an emplacement room prior to its sealing. This description is applicable to all emplacement rooms of a given type, irrespective of when, within the repository schedule, they are constructed, filled and sealed.

No attempt has been made to define an “initial state” for the deep geological repository as a starting point for subsequent evolution. This is because, in principle, the evolution of each engineered component starts at the time of its manufacture, and the evolution of the host rock is an ongoing, albeit gradual, process that occurs over a geological timescale. However, significant perturbations on a much shorter timescale begin with the start of excavation. A discussion thus includes all significant pre-emplacement processes for each engineered component and the baseline conditions for the host rock, as well as the impact of excavation.

1.6 Structure of this report

The remaining chapters of this report are structured as follows:

- Chapter 2 describes the repository system and safety concept.
- Chapter 3 gives an account of pre-emplacement processes and attendant uncertainties.
- Chapter 4 presents the evolving conditions within and around the HLW emplacement drifts and L/ILW caverns during construction and operations.
- Chapter 6 presents the further evolution of the repositories up to the time of deep geological repository closure.
- Chapter 7 addresses post-closure evolution.
- Chapter 8 assesses the robustness of the barriers.
- Chapter 9 provides an overview of the transport processes affecting the transport of radionuclides.
- Chapter 10 addresses the potential impact of the long-term geological evolution of the siting region on the deep geological repository evolution.
- Chapter 11 offers some conclusions and a discussion of uncertainties.

⁴ “Room” and “emplacement room” are general terms for those underground openings where the waste will be emplaced, namely the SF/HLW emplacement drifts and the L/ILW emplacement caverns.

2 Repository system and post-closure safety considerations

A repository system is currently defined by Nagra as comprising the underground structures, the emplaced waste and the engineered barriers that will have been installed at the time of deep geological repository closure, along with the part of the geological environment that provides safety functions. In the following, the background to the repository systems under consideration by Nagra in its project for the general licence applications⁵ is described.

2.1 Background to repository system currently under consideration

The concepts currently under consideration for implementing deep geological disposal in Switzerland are the result of many years of RD&D, as well as of safety, design, cost, site evaluation and other studies performed by Nagra (literature summarised in Nagra (2021b) and the corresponding reviews by the authorities in, e.g., HSK 1986, HSK 1996, HSK 2004, HSK 2005 and (Nagra 2008a). They also take into account the relevant national legal and regulatory guidance (e.g., KEG 2003, KEV 2004, ENSI 2009), as well as input from related international projects.

The following subsection describes the current Nagra project for a deep geological repository in Nördlich Lägern siting region for the general licence application. New findings made before construction work begins (underground geological investigations, advances in technology and materials science, experience from other programmes, etc.), could lead to the project being adapted for purposes of optimisation and industrialisation.

2.1.1 Current Nagra project for deep geological disposal of radioactive waste in Nördlich Lägern siting region

The current Nagra project envisages a geological repository with a repository section for SF and RP-HLW and one for L/ILW. As illustrated in Fig. 2-1, the underground part of the repository will be constructed in the Opalinus Clay (OPA) at a depth between 850 and 900 m b.g.l. It will include a series of dead-end emplacement drifts for SF and RP-HLW and dead-end emplacement caverns for L/ILW. The HLW emplacement drifts will be spatially separated from the L/ILW emplacement rooms to minimise interactions between the two sections of the repository.

The underground facilities of the repository will be constructed roughly in the middle of the OPA stratum or, if confining units on either side of this stratum exhibit excellent barrier properties, in the middle of the containment-providing rock zone (CRZ), which consists of the OPA stratum plus those confining units.

In determining the extent of the Nördlich Lägern siting region, regional fracture zones have already been accounted for and excluded accordingly. To provide for optimum use of the available space at deep geological repository level (constrained by the geometric configuration of the OPA host rock and important geological features), the current concept for the HLW repository section foresees several spatially separated disposal areas, each with multiple emplacement drifts, possibly with different lengths. In this way, smaller-scale unfavourable geological features can be considered in the layout and usage of the disposal areas and the emplacement drifts. Furthermore, even minor potentially unfavourable geological features can be avoided by not using the affected section of an emplacement drift for waste emplacement. Following the definition of the HLW repository section, the L/ILW repository section is defined making the best use of the available geology.

⁵ The repository concept for the general licence application is to be understood as an example (in German: *beispielhafte Umsetzung*) of how a repository could be realised.

Minimum threshold distances are envisaged between the individual underground structures as well as between these structures and important geological elements or other relevant features (e.g., existing or future deep boreholes). In particular, the repository-induced effects of both sections of the repository and potential interactions between them (e.g., mechanical stress fields or thermal heat pulses) must be accounted for and minimised by specifying minimum allowable separation distances (see below for more information).

Access to the disposal areas is provided through the operations and the construction shafts, which allow for simultaneous waste emplacement and construction activities. The current concept for the main facility foresees a dead-end topology, i.e., the connections both from the disposal areas and from the emplacement drifts to other parts of the repository are single or are at least concentrated at single locations.

State-of-the-art technology and procedures for implementing the concepts currently under consideration (e.g., constructing the repositories, handling the waste, exploring the selected sites, manufacturing/emplacing the engineered barriers) are established, available and affordable (Nagra 2023a). Nonetheless, the implementation of deep geological disposal will take considerable time and it is likely that significant technological progress, e.g., in robotics and control, will be made by the time construction begins. Furthermore, the outcome of characterisation activities at the selected sites, which include geological investigations both at the surface and underground over several years, will have an influence on the concepts finally adopted. Therefore, the concepts currently under consideration are unlikely to be the final versions that will support a construction licence application. Rather, they are likely to be refined and optimised for subsequent programme milestones, in conjunction with future RD&D activities in various domains.

The main characteristics of the repository in terms of the surface infrastructure, access structures, central area, repository accesses and disposal areas are as follows:

- The deep geological repository has a surface facility and a joint auxiliary access facility for operations and ventilation.
- The HLW repository section has three parallel tunnels (for operations, ventilation and construction), whereas the L/ILW section of the repository has two (operations and ventilation tunnels).
- The central area of a repository includes a joint area serving the two sections of the deep geological repository. It consists of joint underground operation rooms, a manoeuvring area, joint structures for underground geological investigations (UGI) and a ventilation branch. There will also be two areas serving the two repository sections individually. These consist of UGI structures for either L/ILW or HLW and an underground construction logistics area.
- The L/ILW repository section consists of emplacement caverns, and that for HLW consists of emplacement drifts.

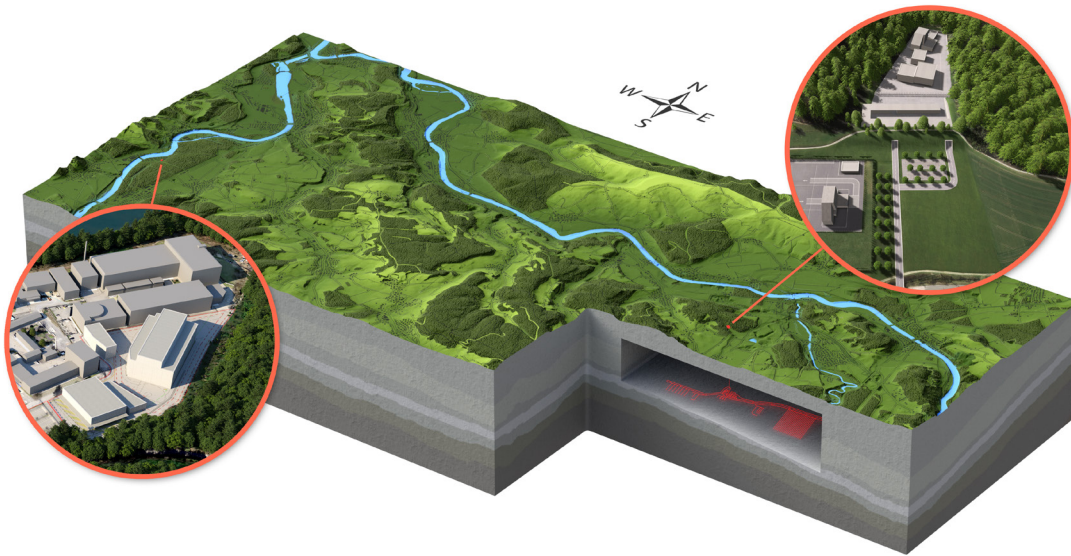


Fig. 2-1: Current Nagra project for deep geological disposal of radioactive waste

General comments on the required minimum distance between the L/ILW and HLW sections of the repository

For planning purposes and using phenomenological analysis (Nagra 2021a), interactions between the L/ILW and HLW repository sections due to the mechanical effects of repository-generated heat and gas, as well as additional thermo-hydro-chemical (THC) interactions, have been evaluated.

It has been shown that, at a minimum distance of about 125 m between the L/ILW and HLW repository sections, there are no interactions that could compromise the mechanical integrity of the engineered and geological barriers. In particular, neither thermal- nor gas-related interactions are expected to negatively affect the post-closure safety functions of the barrier systems. It can even be shown that the maximum gas pressures in the L/ILW repository section of the repository are slightly lower than those in an individual L/ILW repository, because of the addition gas storage volume provided by connecting tunnels.

Thermo-hydro-chemical (THC) interactions also have the potential to impact the safety of a combined repository, especially in the L/ILW repository section, if distance separating the two sections is too small. Comparative calculations show that a distance of 125 m between the two repository sections results in significantly higher temperatures in the L/ILW caverns than would be expected with a distance of about 210 m. Qualitatively, a minimum distance of about 210 m between the L/ILW and HLW repository sections appears sufficient to avoid safety impairments of the L/ILW repository section due to THC interactions.

2.1.2 Monitoring and maintenance

A possible set of timelines for the monitoring of the deep geological repository and its environment is presented in (Nagra 2025b).

Monitoring activities will be carried out at and from the surface (e.g., measurement of radionuclide concentrations in the environment, continuous measurements of state variables in deep boreholes) and underground, particularly in the pilot repositories during the main monitoring period.

Pilot repositories are foreseen for HLW and for L/ILW, respectively. Each contains a small but representative fraction of the waste and is the focus of the monitoring programme. The aims of the pilot repository are:

- to serve as a demonstration facility for emplacement technology;
- to provide information on the behaviour of the barrier system and to check predictive models;
- to allow early detection of any unexpected and undesirable system evolution; and
- to provide input for decisions regarding the commencement of operations and eventually the closure of the entire deep geological repository.

It is foreseen that the pilot repositories will be backfilled and sealed without delay to ensure that conditions represent those foreseen for the final state of the respective section of the repository as closely as possible.

Prior to the main monitoring period, i.e., during shaft construction, the rock properties and conditions will be continuously monitored to update safety assessment models to be used for the next licensing steps. Host-rock properties and thermal-hydraulic-mechanical (THM) state conditions (pore pressure, stress, temperature and saturation) will be further assessed in the UGI (later re-designated as the test area of the repository). This facility allows for an extensive experimental programme and for a refined set of host-rock parameter values to be determined. The test area will also be used to study aspects such as excavation damage, tunnel support techniques and interaction of backfill materials with the host rock.

The main monitoring period consists of two phases. During the first phase, construction and operations tunnels will remain open. In a second phase, these excavations will be backfilled, and only the test area and pilot repositories will remain accessible. These two monitoring phases are expected to last for about 70 years prior to final closure. Continued monitoring after closure is considered to be a decision for future generations. Any monitoring after closure will, however, not take place underground (except possibly via deep boreholes).

In view of the long timescales involved in deep geological repository operation, a concept for maintenance of important installations and replacement of components (e.g., waste reception and handling facilities, monitoring instrumentation, etc.) will be developed. Retrieval of SF and HLW – should the need arise – would make use of the mechanical properties of the proposed bentonite backfill (lower strength compared with the disposal canisters and the tunnel lining), thus facilitating the excavation of the disposal canisters to an extent that allows their safe removal (Nagra 2021d).

2.2 HLW underground facilities and barriers

The following paragraphs outline the currently envisaged concepts for the underground facilities and operations/closure of the HLW repository section (i.e., including both SF and HLW from reprocessing) with the focus on the currently proposed implementation of the individual underground facilities and activities.

2.2.1 Waste encapsulation

SF and vitrified HLW will either be delivered to the surface facilities from one of the interim storage facilities or directly from the (decommissioned) nuclear power plants (NPPs). In both cases, waste-specific reusable transport casks will be used. For waste to be accepted, so-called waste acceptance criteria (WAC) must be fulfilled.

SF assemblies and flasks containing vitrified HLW will be loaded into steel disposal canisters without further prior treatment in the encapsulation plant⁶. Loading will be carried out with the objective of optimising the emplacement procedure to provide an evenly distributed thermal load (i.e., heat output restriction is a maximum of 1,500 W per canister at emplacement) and an optimum use of the available space underground. For this reason, the encapsulation plant must have several input and output docking stations to enable the mixing of SF assemblies with different heat outputs to be loaded into the disposal canisters. Aspects determining the repository thermal load (maximum heat output per canister and layout aspects such as drift spacing) will be revisited in the work leading up to the application for the construction licence, when the thermal conditions and parameters at the selected site will be confirmed by research in the facility for underground geological investigations.

The basic requirements for the HLW disposal canisters are listed in Tab. 2-1 and are discussed in more detail in Nagra 2024b).

Tab. 2-1: Requirements for the HLW disposal canisters

-
- Sufficiently low general corrosion rates under in-situ repository conditions (Diomidis et al. 2023)
 - Low probability of localised damage processes (e.g., stress-corrosion cracking, pitting corrosion, etc.) under in-situ deep geological repository conditions.
 - Well-developed methodologies for predicting the (chemical) long-term corrosion and mechanical canister breach modes and their interactions.
 - Adequate structural strength under in-situ deep geological repository conditions and under normal and abnormal handling operations during the operational phase, including possible retrieval from the emplacement position.
 - Reliable closure sealing. In addition, the method for sealing a canister must not result in the maximum temperature permitted for the waste being exceeded.
 - Compatibility with the size of spent fuel assemblies, which are up to about 4.5 m in length. From this requirement, it follows that a satisfactory method for fabrication of a canister must exist or be possible to develop at the scale of interest.
 - Processes arising from the canister and its waste and their interaction with the barriers in the repository (e.g., gas production, radiation emission, corrosion products) should not cause significant damage over the long term to these barriers.
 - Depending on the material and canister design selected, the more detailed requirements derived may vary. An example of a more detailed elaboration of requirements for the concept of carbon steel canisters for SF/HLW is given by Patel et al. (2012).
-

⁶ The current overall waste management concept foresees the location of the encapsulation plant at the interim storage facility for radioactive waste of the Zwischenlager Würenlingen AG (ZWILAG).

Fig. 2-3 shows the steps involved in the emplacement of an HLW canister in a section of an HLW drift, including subsequent backfilling. (a) shows the emplacement of the tunnel support with prefabricated concrete liner segments. Any external voids are backfilled with a low-viscosity grout. The expected secondary porosity in the excavation-damaged zone (EDZ) is shown with fine dark lines indicating the probable extent of the EDZ around the excavation. In (b), the canister is emplaced on a pedestal made of compacted bentonite blocks.

Shortly afterwards, as shown in (c), the tunnel is backfilled with granular bentonite material (pellets) with a water content about 5%⁷ to ensure that the required compaction density of the bentonite pedestal and granular material is reached after saturation and swelling of the bentonite.

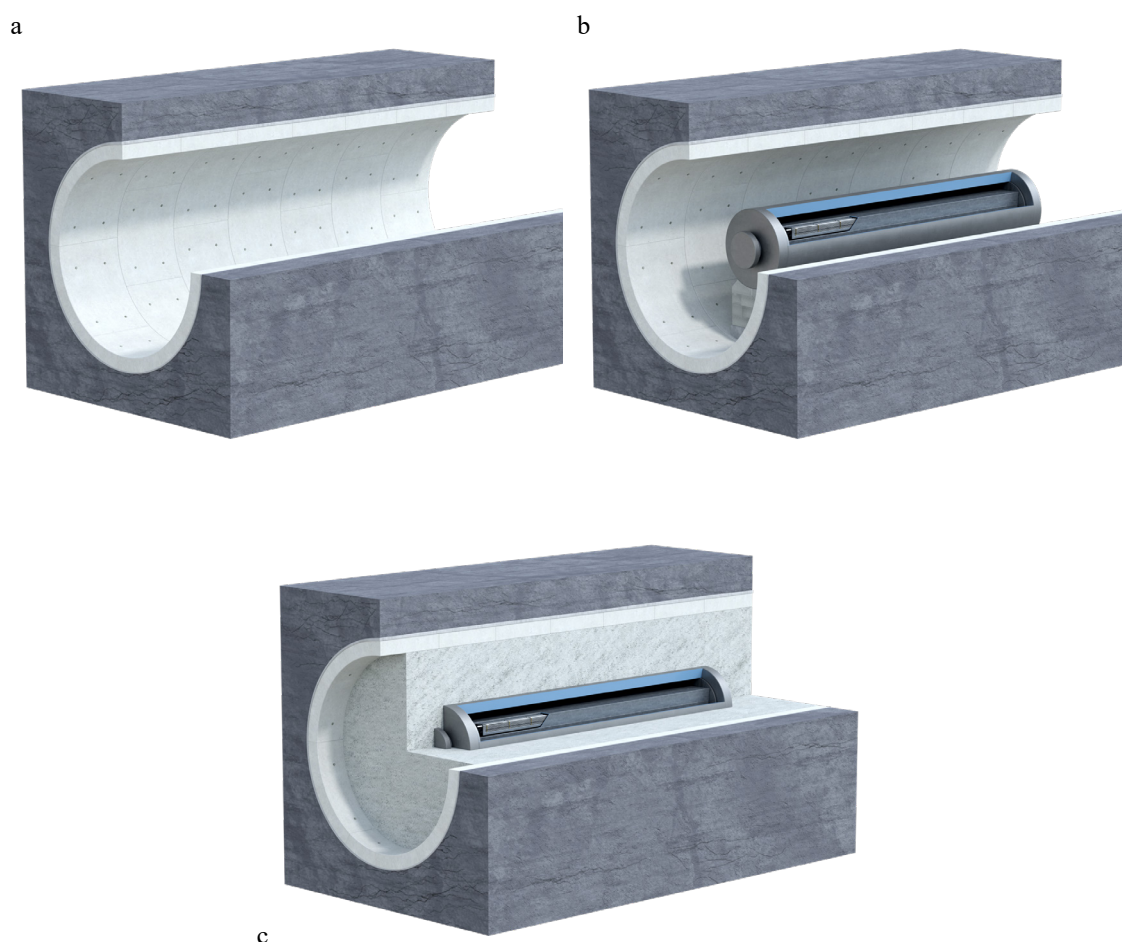


Fig. 2-3: Construction and operational phase in the HLW drift

⁷ For comparison, bentonite blocks typically have around 18 wt.% water content.

These steps are repeated as successive canisters are emplaced. The spacing between adjacent canisters along the drifts is foreseen to be about 3 metres.

The bentonite blocks and pellets together form a protective mechanical, thermal⁸ and chemical buffer around the disposal canisters. Requirements on the bentonite buffer are derived and justified in Leupin et al. (2014). The required properties are listed in Tab. 2-2 and are described in more detail in Jenni et al. (2019).

They are formulated in terms of safety-relevant buffer properties and preferred values for the indicators that quantify these properties (notably, the current requirement criterion on hydraulic conductivity after full saturation is $< 10^{-11} \text{ m s}^{-1}$).

Other backfill materials remain possible; the final decision on the backfill material and its safety-relevant properties will be taken prior to the construction licence application.

Tab. 2-2: Requirements on bentonite used as buffer in emplacement drifts

-
- The hydraulic parameters of the saturated buffer should prevent advective flow through the buffer and therefore result in an effective transport barrier. Possible cracks in the buffer should close through self-sealing.
 - Chemical retention of radionuclides from the buffer.
 - Sufficient density so that the resulting microporous structure provides an effective barrier for colloid transport.
 - Sufficient swelling pressure will limit convergence, prevent canister sinking and, given the rheological properties of the saturated bentonite, protect the canister from deviant stresses.
 - Sufficient gas transport capacity to transport corrosion gases without significant reduction of its function as a hydraulic barrier.
 - Minimum microbial corrosion to protect the canister.
 - Resistance to mineral transformation to protect the canister and attenuate the release of radionuclides.
 - Suitable thermal conductivity so that the waste form, canister and buffer do not experience conditions detrimental to the performance of their safety functions.
-

In accordance with ENSI (ENSI 2020b), seals will be emplaced at the end of each drift after the waste has been emplaced and the cavern backfilled. Excavation, waste emplacement, backfilling and sealing of the drifts will be organised such that a limited number of emplacement drifts will be open at any given time, i.e., the construction of further HLW emplacement drifts occurs in parallel to emplacement. The construction operations will be completely separated from emplacement operations within the respective drifts.

⁸ In the sense that they protect the rock from high temperatures.

2.2.3 Barriers for SF/HLW and their safety roles

Overview of the barriers and their safety roles

The barriers for HLW disposal comprise (from the inside out):

- the vitrified HLW matrix or SF assemblies, including fuel pellets;
- the HLW disposal canisters;
- the HLW emplacement drift backfill (bentonite buffer);
- the backfill and seals of other underground structures;
- and the host rock and confining units.

Fig. 2-4 illustrate these barriers and describe how the properties of the individual elements of the barrier systems, and/or processes occurring within, contribute to safety. These safety-relevant attributes of each barrier are discussed further in the following paragraphs.

SF assemblies

The majority of radionuclides associated with SF are incorporated in the fuel pellet matrix and, as activation products or contamination, in the Zircaloy cladding and other metal parts (structural materials) of the fuel assemblies. Following eventual breaching of the disposal canisters and ingress of water to the canister interior, the fuel matrix⁹, Zircaloy cladding and other metal parts will degrade and corrode very slowly in the expected environment. The spent fuel dissolution rate proposed for use in safety assessment calculations is 10^{-7} a^{-1} , with upper and lower limits of 10^{-6} a^{-1} , and 10^{-8} a^{-1} , respectively (cf. Johnson et al. 2022). All activation and fission products in the cladding and structural material, at fuel grain boundaries and cracks, as well as within the gaps will be more rapidly released (see discussion on instant release fraction (IRF) in Section 7.1.2; Yamaguchi et al. 1999, Necib et al. 2018, Necib et al. 2018, Mibus et al. 2018, Johnson 2014).

RP-HLW matrix

Radionuclides associated with HLW from reprocessing (RP-HLW) are uniformly incorporated in a borosilicate glass matrix that is contained in a stainless-steel flask. Following breaching of the disposal canisters and ingress of water to the canister interior, the glass matrix will dissolve¹⁰ only slowly in the expected environment, thus providing low radionuclide release rates which are, in the most pessimistic case, in the order of $9.3 \cdot 10^{-2} \text{ g m}^{-2} \text{ d}^{-1}$ for non-radioactive reference glasses from ORANO (La Hague, France) and $1.7 \cdot 10^{-1} \text{ g m}^{-2} \text{ d}^{-1}$ from Sellafield (UK), whereas in the best estimate, they dissolve with $1 \cdot 10^{-3} \text{ g m}^{-2} \text{ d}^{-1}$ for glass from ORANO and $1.5 \cdot 10^{-3} \text{ g m}^{-2} \text{ d}^{-1}$ for glass from the UK (Curti 2022).

⁹ The Zircaloy cladding of the SF could also potentially contribute to containment, although this is not taken into consideration in Nagra's safety assessment.

¹⁰ The stainless-steel flasks containing the vitrified HLW could also potentially contribute to containment, although this is not taken into consideration in Nagra's safety assessment.

Disposal canisters

The disposal canisters are designed to ensure the complete containment of SF and vitrified HLW and their associated radionuclides for several thousands of years (Nagra 2024b)¹¹. Eventually, however, a combination of mechanical and corrosion processes will lead to canister breaching events distributed in time, allowing the ingress of water and the release of radionuclides. However, even after breaching, the canisters contribute to the retarded release and retention of radionuclides through limited access of water to the canister interior and the favourable sorption capacity of corrosion products for many radionuclides.

Bentonite buffer

As long as the bentonite is dry, hardly any canister corrosion will take place and the integrity of the canister is assured. Gradually, OPA porewater will migrate through the lining into the buffer, but canister corrosion will remain slow (Diomidis et al. 2023). As it saturates, the buffer will expand, filling any remaining void spaces, hydraulically isolating the canisters from each other and providing a favourable environment for canister longevity and for the stability of the waste forms once the canisters are breached. The presence of the buffer will limit tunnel convergence once the lining degrades, and the use of bentonite as a buffer material is compatible with the favourable chemical conditions in the host rock. When, in the long term, the canisters are breached, the saturated buffer will also provide strong retention of radionuclides, thus attenuating any releases to the rock.

Host rock and containment-providing rock zone

The containment-providing rock zone, which consists of the OPA host rock and those confining units with similarly favourable properties, provides low water flows, a fine and homogeneous pore structure and favourable geochemical conditions, thus providing strong retention and attenuated release of radionuclides to the environment as well as a suitable hydrogeological, geochemical and geomechanical environment for the engineered barrier system over the time periods considered in the safety assessment.

¹¹ ENSI-G03 (ENSI 2009) requires that the canisters provide complete containment for at least 1,000 years.

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.

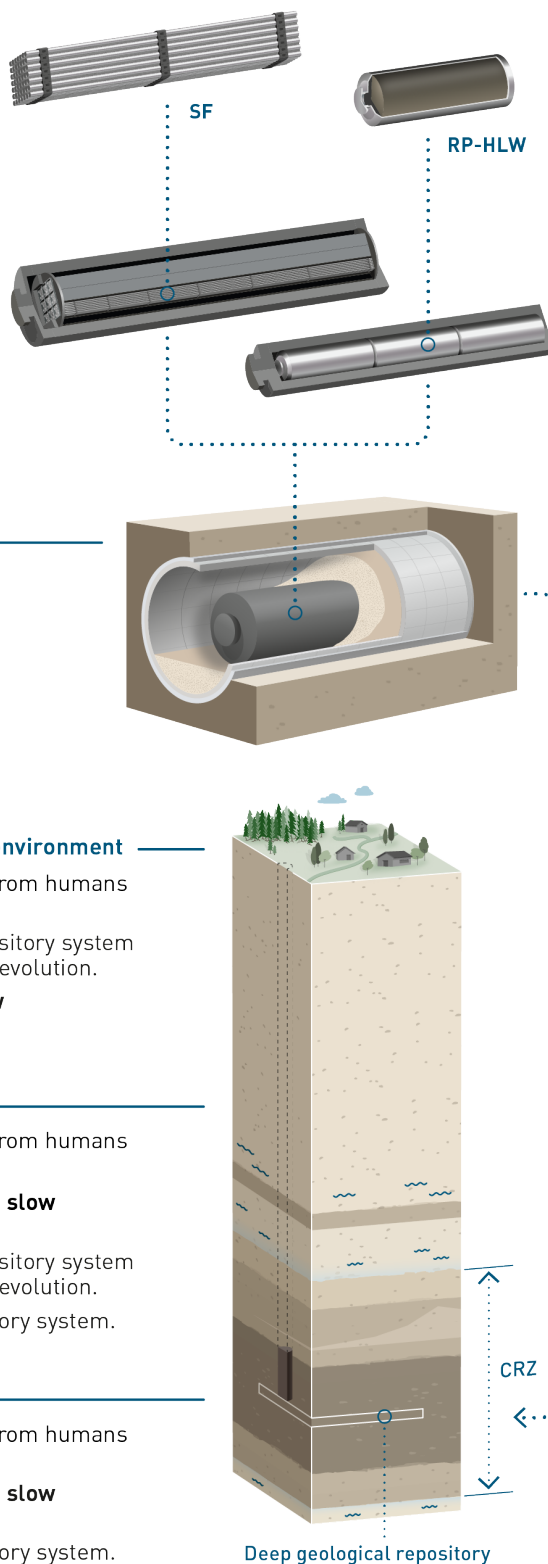


Fig. 2-4: Illustration of the barrier system for HLW, showing how the properties and/or processes of the individual barriers contribute to post-closure safety

2.3 L/ILW underground facilities and barriers

The following paragraphs outline the currently envisaged concepts for the underground facilities and operation/closure of the L/ILW repository section with the focus on the currently proposed implementation of the individual underground facilities and activities. The L/ILW repository section is characterised by high waste volumes on the one hand, and by low radiotoxicities on the other. The waste is typified by large variability and heterogeneity in physicochemical properties (Nagra 2023b). Thus, although having many features in common, the design of the engineered barrier system for an L/ILW repository section differs in some ways from that for the HLW repository section, where the waste volume is smaller, but the radiotoxicity is higher, and the range of waste characteristics is narrower. The L/ILW repository inventory includes large amounts of metals and organic materials that will generate gas as they corrode and degrade, respectively.

2.3.1 Waste containers

L/ILW is encapsulated within disposal containers of different types. The majority of the waste will be placed in barrels (mostly 200 L drums) within operational waste disposal containers (LC) (Fig. 2-5). However, activated metals or concrete from the decommissioning of NPPs will be emplaced directly into the disposal containers. Each container is made of concrete and heavily armoured with rebars to ensure its stability. The internal void space is filled with a cementitious high-pH suspension, and the concrete lid is then installed.



Fig. 2-5: L/ILW disposal containers (LC) filled with waste drums

The operational waste is, and will be, stored in barrels (mostly 200 L drums). These barrels will be packaged into operational waste containers.

Another type of container to be disposed of in the L/ILW repository is the MOSAIK container shown in Fig. 2-6. This type of container contains highly activated reactor waste. The manufacturer, GNS, has developed several types of MOSAIK containers for the interim storage and transport of radioactive waste requiring significant shielding. Some of these types are also licensed for disposal in a deep geological repository. The different container types are optimised for different types of waste. Nevertheless, they share a similar design basis, as they are all made of ductile cast iron and have a bolted lid with an elastomer seal for water and gas tightness. The main differences between the MOSAIK types appear to be their size, wall thickness, and amount of shielding added. The following discussion assumes that the MOSAIK containers contain only metallic waste that did not undergo any further conditioning.



Fig. 2-6: MOSAIK-II cast steel container with an inner volume of approximately 1.3 m³

Before a MOSAIK is emplaced in an L/ILW repository, it is inspected. Thus, it can be expected that the seal is still intact and provides the necessary water and gas tightness. However, the duration for which the container will remain tight is difficult to predict as the seal elastomer and other structural parts of the sealing system, e.g., bolts, will start degrading in the repository environment. Consequently, it is conservatively assumed that MOSAIK containers (as is also the case for other types of L/ILW containers) do not provide any barrier to gas exchange between the internals and the repository environment. This would allow vapour to enter the container and increase the relative humidity of the atmosphere in contact with the waste, thereby initiating corrosion.

2.3.2 Emplacement underground

After transport to the underground facilities, the disposal containers are stacked in dead-end emplacement caverns that, according to the current design, have dimensions of an internal width of about 11.5 m and a height of about 12 m (Nagra 2023a). Container emplacement is illustrated in Fig. 2-7. The length of each cavern is approximately 200 ± 50 m. Each cavern is connected to the operations tunnel by a branch tunnel. At the transition to the emplacement cavern, the branch tunnels are enlarged to provide sufficient space for the transfer of the disposal containers from the wagons on which they are transported underground to an overhead crane that moves them into their final positions.

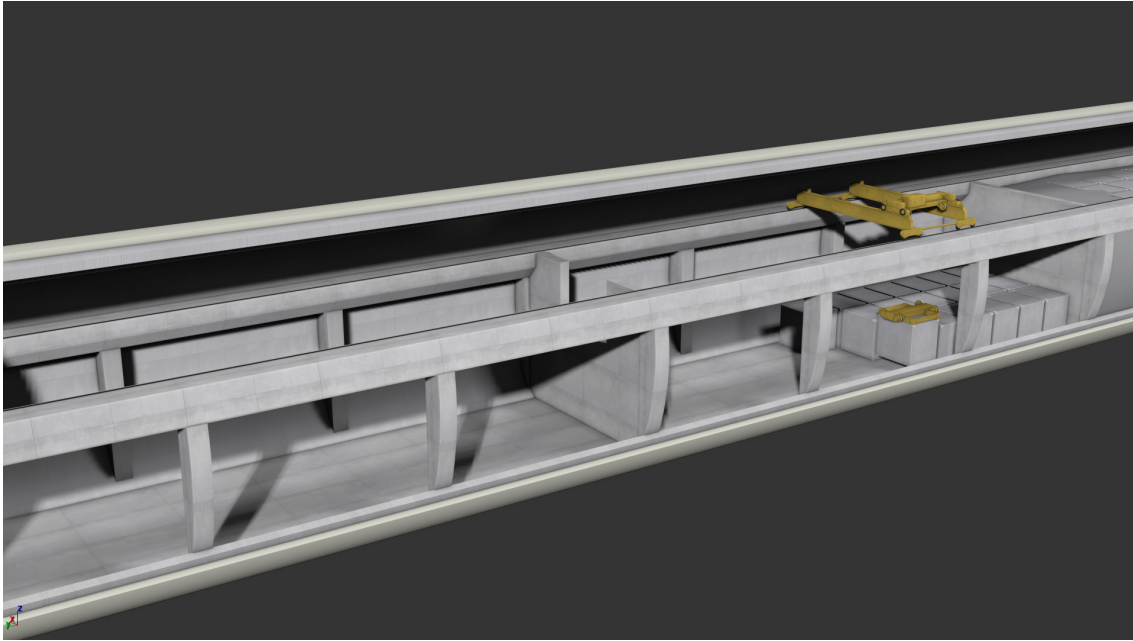


Fig. 2-7: Schematic view of container emplacement in an L/ILW cavern

According to the current stage of the project, the lining of the caverns is based on a two-shell principle (Nagra 2023a). The outer shell consists of shotcrete and gliding arches, providing a yieldable tunnel support that initially functions as short-term rock support. The inner shell lining will be installed after the convergence of the gliding arches and consists of in-situ concrete that is emplaced by formwork. The functionality of this inner shell lining is to withstand the final mechanical loads during the operational phase. For all these cement-based elements, a high-pH concrete (ordinary Portland cement; OPC) will be used (except for the outer-shell shotcrete, where the use of a low-pH cement could be considered to reduce the chemical gradient to the host rock).

As illustrated in Fig. 2-8, a highly porous mortar is used to fill any void space between the containers and the cavern lining. (Jacobs et al. 1994). To contribute to a highly alkaline near-field, the mortar will be manufactured with Portland cement, and the option of employing pure limestone aggregates remains to be evaluated (Martin et al. 2023). This could prevent the chemical interaction of the cement with the aggregates and thus contribute to maintaining the alkaline chemical milieu in the cavern. Thus, in addition to the radioactive waste and the chemically active waste matrix or waste compounds, the backfilled tunnels contain chemically hydrated cements, significant amounts of steel (from drums, tunnel support and construction materials) and concrete aggregates. The degradation and chemical interactions between these compounds are discussed in detail in Section 6.2 of this report.

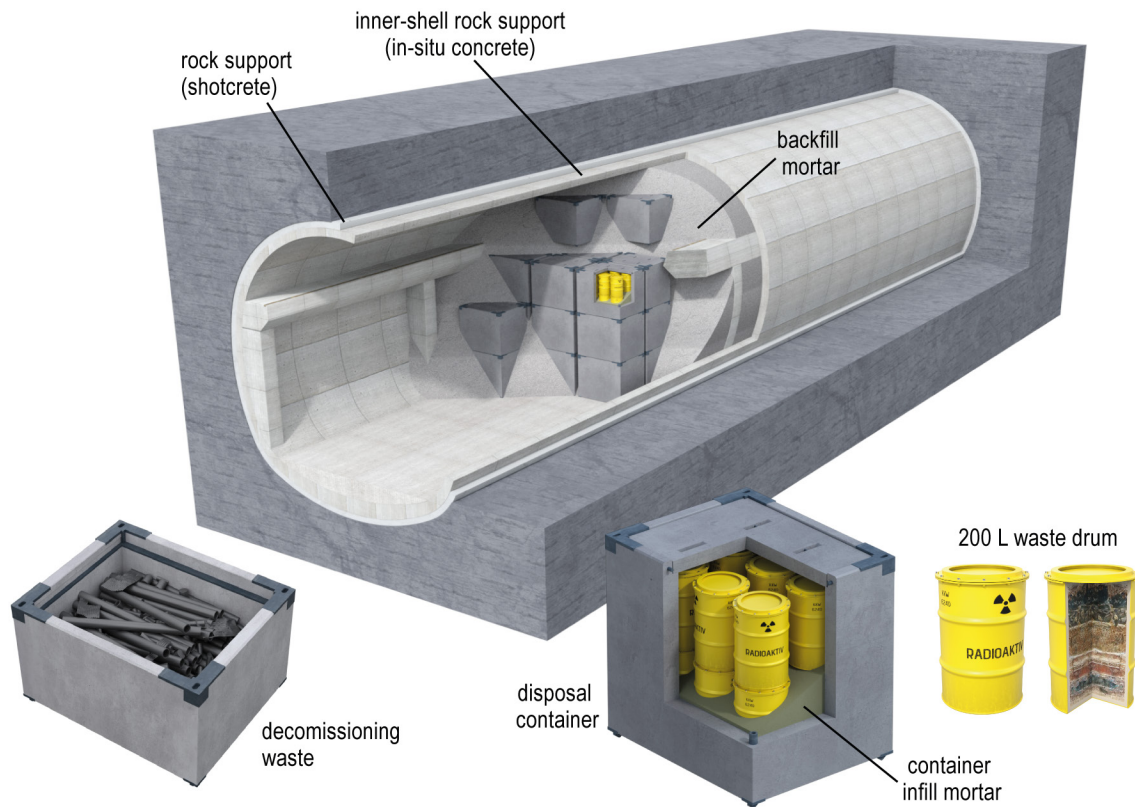


Fig. 2-8: Schematic representation of a cross-section of the L/ILW cavern

When the cavern and its top-heading have been backfilled (possibly with a flowable concrete in the top part of the cavern), the enlarged section of the branch tunnel at the cavern mouth will also be backfilled with backfill mortar (Jacobs et al. 1994).

2.3.3 Barriers for L/ILW and their safety functions

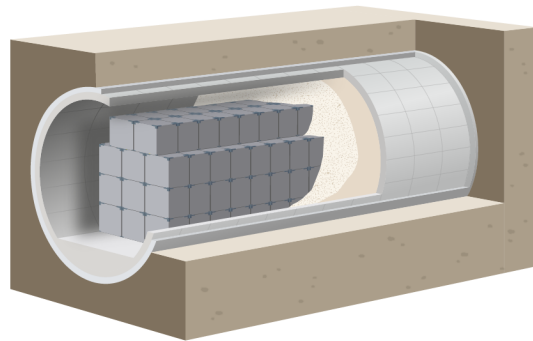
The barriers of the L/ILW section of the repository comprise:

- L/ILW waste matrices, and the waste and disposal containers, including their internal backfill;
- L/ILW emplacement cavern backfill (cement mortar);
- backfill and seals of other underground structures; and
- and the host rock and confining units.

Fig. 2-9 illustrates these barriers and describes how the properties and/or processes of the individual elements of the barrier system contribute to safety. The safety-relevant attributes of the host rock and confining units, as well as of the backfill and seals of other underground structures are identical to those described in the context of HLW in Section 2.2.3 and are thus not repeated here.

Cementitious near field

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



Repository layout and deep underground location

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

Containment-providing rock zone (CRZ)

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

Closure system (backfill and seals)

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

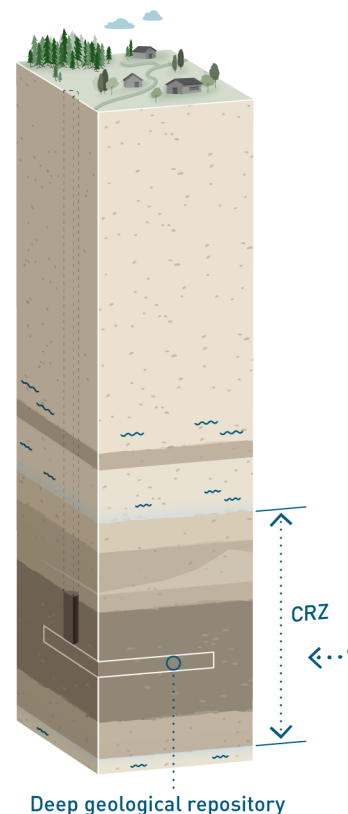


Fig. 2-9: Illustration of the barrier system for ATW and L/ILW, showing how the properties and/or processes of the individual barriers contribute to post-closure safety

This figure is not to scale. Only an L/ILW or ATW emplacement cavern is illustrated, the underground structures and the various seals of the repository are omitted in this figure.

The L/ILW waste matrices provide fixation of radionuclides and are likely to dissolve only slowly, although these favourable attributes are not taken into consideration in the current safety analyses.

The cementitious material also contributes to the retention and slow release of many radionuclides due to a suitable mineralogy. According to Nagra's current concept mentioned earlier, OPC with a high cement content is employed in the disposal containers, in the mortar used for backfilling of the caverns and in inner-shell tunnel support to maintain a pH value above 12.5 in the repository near-field. This high-pH level is sustained by the presence of portlandite ($\text{Ca}(\text{OH})_2$) within the

cement paste, which acts as a stable buffer mineral (see below). The primary purpose of the high-pH environment is to passivate iron and steel, which exist as reinforcement within concrete elements and are also present to a significant extent in the waste, waste drums, and disposal containers. Anoxic corrosion of iron and steel is primarily governed by kinetics and is strongly influenced by pH (Diomidis et al. 2023). The lower corrosion rates resulting from the high-pH environment help regulate the build-up of gas pressure. Additionally, the high-pH conditions inhibit microbial activities, promoting a slower degradation rate of organic materials and subsequently reducing the rate of gas pressure accumulation, and favour the retention by sorption of many radionuclides.

Once the lining degrades, the grains within the backfill mortar will take up the stress acting on the cavern, thereby limiting cavern convergence, while, at the same time, preserving a high porosity between the grains. The high permeability and porosity of this mortar serves to regulate the release of gas from the L/ILW emplacement caverns through the seals (formerly known as the engineered gas transport system or EGTS) into the VF1 backfill material.

2.4 Sealing system

The sealing system includes multiple individual seals, together with the backfilling of the access structures and all other underground openings. The current design for the geological repository foresees three different types of seals:

V1 seals, which will be placed at the entrances to HLW disposal drifts and L/ILW caverns in which the waste will be emplaced. As elaborated in the following paragraphs, the design of the V1 seals for the HLW drifts is somewhat different to those for the L/ILW caverns because of the requirement for the latter to be more gas-permeable. Therefore, the individual notations V1-HLW and V1-L/ILW were adopted.

V2 seals, which will close off the disposal areas for L/ILW and for HLW, as well as the pilot repositories for HLW and L/ILW, respectively, after the waste has been emplaced. Similar to the V1 seals, the notations V2-HLW and V2-L/ILW were adopted the latter being somewhat more gas permeable.

V3 seals, which will be placed in the access and ventilation shafts to seal the repository from the surface environment and protect it from external impacts, including the possibility of future human intrusion. No safety requirements are placed on components within the access shafts above the V3 seals¹².

Backfill material will be emplaced in the open tunnels and facilities between these different seals. The VF1 backfill material will be emplaced between the V1 and V2 seals, and the VF2 backfill material will be emplaced between the V2 and V3 seals. The arrangement of the V1, V2 and V3 seals and the VF1 and VF2 backfill materials is illustrated in Fig. 2-10.

The operations tunnel will be closed with a V3 seal immediately after the emplacement of all the V2 seals. The access and ventilation shafts will be closed later, again with V3 seals, after the end of the final monitoring phase. When this is done, the deep geological repository as a whole will have been transferred to a passive state.

¹² If a ramp were to be constructed, a seal would be installed with similar requirements as those applying to the V3 seal.

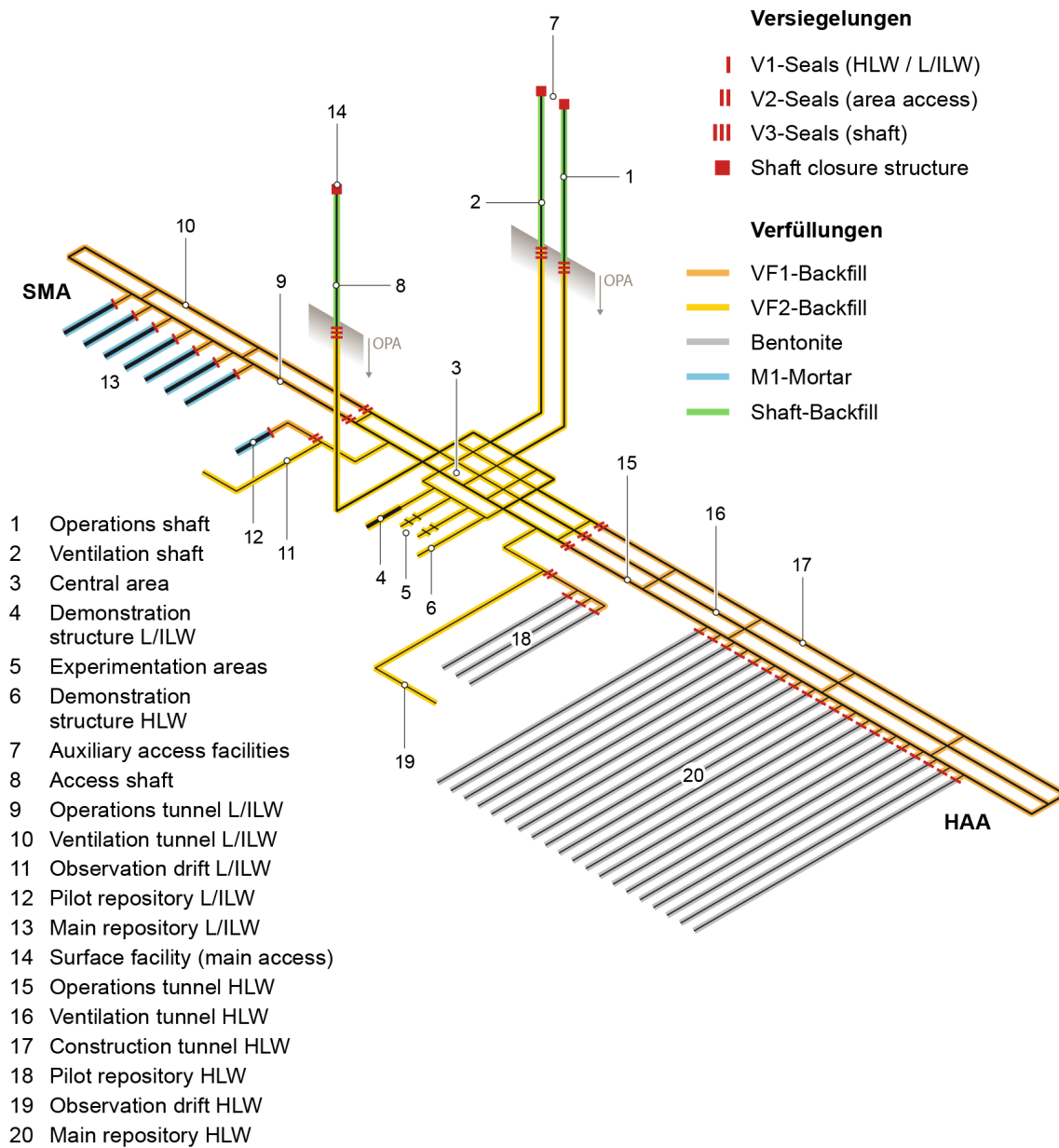


Fig. 2-10: Arrangement of the V1, V2 and V3 seals and the VF1 and VF2 backfill within a generic deep geological repository layout

The basic design concept is broadly similar for all types of seals and is illustrated in Fig. 2-10. The principal components of a seal comprise:

- one or more sealing elements composed of compacted bentonite clay or bentonite/sand,
- one or more concrete abutments to hold the sealing elements in place, absorbing mechanical stresses and bentonite swelling pressure from the adjacent sealing elements, and
- one or more transition layers for the purpose of structural design and to provide the physical separation between clay and concrete components.

Depending on the stability of the OPA, the entire tunnel support as well as the whole or part of the excavation-damaged zone (EDZ) will be removed to inhibit a preferential radionuclide transport pathway across the mechanically disturbed rock in the section of the sealing element.

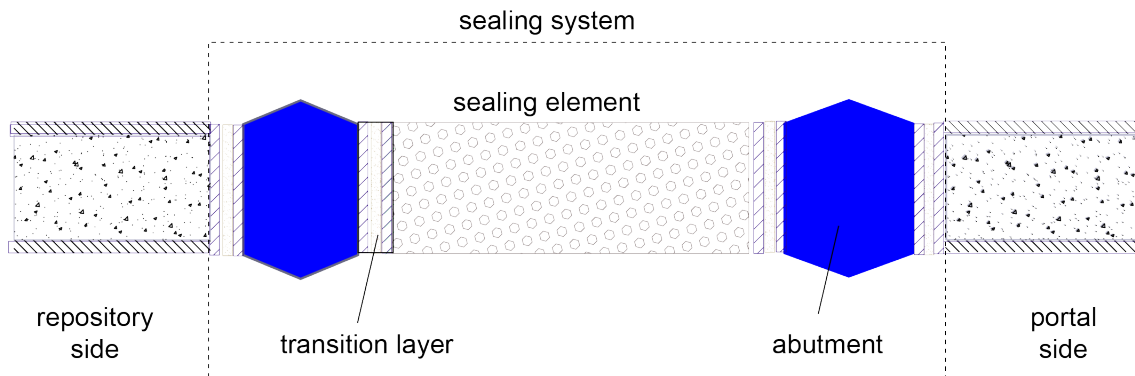


Fig. 2-11: Generic illustration of a seal, showing its principal components (not to scale)

In line with ENSI requirements (ENSI 2020b), the backfilling and sealing of the emplacement drifts and caverns must be coordinated with the requirements on post-closure safety. For the HLW repository section, the sealing system is designed to ensure minimum water fluxes at expected hydraulic pressure differences to prevent uneven, rapid saturation of the main disposal area. Flows result from the pressure differential associated with the permeability of the sealing system elements and their geometries (length and cross-section). Accordingly, V1-HLW and V2-HLW seals with sufficiently low hydraulic conductivities are necessary for the main disposal area; compacted bentonite is foreseen for the sealing elements of these seals.

In the case of the L/ILW repository section, the seals are also designed as a measure to reduce the gas pressure in the emplacement caverns (gas-permeable sealing). A gas-permeable V1-L/ILW seal with low hydraulic conductivity, a VF1 backfill with high gas storage capacity, and a somewhat gas-permeable V2-L/ILW seal with low hydraulic conductivity are thus required (Fig. 2-10). Because of the very low intrinsic permeability of compacted bentonite, bentonite/sand mixtures are foreseen for the sealing elements of these seals. The VF1 backfill material could be crushed clay material possibly mixed with sand (Nagra 2021c). Closure, which comprises the backfilling and sealing of all the remaining underground structures, is intended to prevent human access to the disposed waste and to ensure the continuing mechanical stability of the underground structures, thus providing controlled conditions compatible with the favourable conditions in the host rock, as well as strong retention and attenuated release of radionuclides to the environment (Nagra 2021c).

According to the Swiss Nuclear Energy Ordinance (KEV 2004), all open parts of a deep geological repository must be backfilled during closure, and the parts relevant to long-term safety and security must be sealed. The closure of a deep geological repository must in particular ensure that no inadmissible release of radionuclides occurs via the backfilled accesses, that the separation of the water-bearing rock strata existing prior to the construction of the repository is restored in the long term, and that the repository is permanently marked. Furthermore, the access structures or the sealing system must ensure that no rapid water ingress and thus not too rapid or uneven saturation of the disposal areas and the disposal area accesses will occur. Accordingly, a V3 seal must be provided as part of the access structures with low hydraulic permeability.

2.5 Staging of deep geological repository construction, operation and closure

The following timeline is taken from Nagra 2024k as an example of how the phases of repository construction and operation of an HLW repository (or the HLW section of the repository) might be staged (see Tab. 2-3)

Tab. 2-3: Staging of repository construction, operation and closure

Phase	Description
Operational phase 1a (0 – 21 years)	Construction and operation of the underground research laboratory: excavation and ventilation of access gallery, operations tunnel, test area and observation drift. Conditions defined by boundary layer suction (60% humidity) and regulated constant temperature (28 °C).
Operational phase 1b (21 – 36 years)	Construction of the main repository: ventilation of access tunnels, shafts, test area, observation drift as well as of construction, operations, ventilation tunnels and L/ILW emplacement caverns (including pilot caverns).
Operational phase 2a (34 – 36 years)	Construction and emplacement period for HLW: ventilation of 3 pilot HLW emplacement drifts.
Operational phase 2b (36 – 46 years)	Construction and emplacement period for SF: backfilling of the HLW emplacement drifts and L/ILW emplacement caverns, ventilation of L/ILW emplacement caverns and 3 pilot emplacement drifts.
Operational phase 3 (46 – 56 years)	First monitoring phase: backfilling of SF emplacement drifts and L/ILW caverns, ventilation of the shafts, accesses, and of the construction, operations and ventilation tunnels.
Operational phase 4 (56 – 96 years)	Second monitoring phase: backfilling of the construction, operations, ventilation and access tunnels. The test area, observation drift, shafts and accesses as well as the operations tunnels to the pilot drifts remain open and ventilated.
Post-closure phase (96 – 100,000 years)	After all components of the repository being backfilled the repository is being sealed off. The commencement of the post-closure phase initiates with the completion of the shaft seal.

2.6 Alternative repository concepts

Repository concepts other than those presented earlier in this chapter are being considered world-wide (Nagra 2024i). These differ from the current concepts proposed by Nagra in – among other aspects – the geological situation, the overall repository architecture, the type of underground access to the deep geological repository, the length and size of the emplacement drifts and caverns, the backfilling materials and the canister and container materials. Specific requirements and constraints inherent to the Swiss context, which include those of a geological nature (a very tight host rock with a limited thickness) and of a legal nature (such as the requirement that the canisters for SF and RP-HLW must provide complete containment for at least 1,000 years and the requirement for deep geological disposal of L/ILW waste) have led to the conclusion that the current concepts are advantageous for deep geological disposal in Switzerland compared with other concepts being considered elsewhere (e.g., Wildi et al. 2000). However, alternatives will continue to be evaluated in the future with the main objective of optimising safety (and also feasibility of construction; *cf.* Nagra 2021b). Repository architecture, engineered materials and layout are specified at the level of detail required at any given licensing step, following the staged approach defined in the Sectoral Plan for Deep Geological Repositories (SGT) and the legal framework.

3 Processes during the construction and pre-emplacement phase and related uncertainties

3.1 Baseline conditions at the site

Documentation of the undisturbed CRZ has been synthesised in Nagra 2024k. The collected and integrated information on the underground has been obtained through various field investigations including deep boreholes, seismic surveys, extensive sampling campaigns, and laboratory and field experiments. Safety-relevant parameters of the undisturbed system provide a baseline for evaluating all processes taking place in the host rock or all coupled processes in the host rock and near-field. A thorough baseline characterisation, i.e., a description of the initial state of the host rock and the wider geological setting, is instrumental for understanding the evolution of safety-relevant parameters and processes during subsequent phases.

3.2 Construction-induced processes and uncertainties

Only those activities impacting pre-emplacement conditions are discussed here. Issues specific to the construction of emplacement caverns and drifts are covered in Chapter 4, Section 4.2.

3.2.1 Evolution of regional hydrology and geochemistry

The excavation and presence of open underground structures can potentially affect groundwater flow in both the host rock and the confining units. Effects include:

- inflow to the shafts and ramp (if present);
- inflow to excavated structures at the disposal level;
- and creation of flowpaths along the EDZs of the shafts (and ramp) through low-permeability units, allowing crossflows between normally isolated permeable geological horizons.

Inflow to the shaft can be controlled through appropriate design measures, including freezing, pre-/post-grouting and injections of water-bearing units and features (cf. Nagra 2022). Reduction of the total inflow to the repository is desirable in terms of both a reduced hydrological impact and reduced pumping costs. In addition, it can inhibit the swelling of the OPA. Appropriate design measures to minimise crossflows between units through the EDZ can and will also be taken.

Inflows to deep geological repository underground structures at the disposal level directly from the host rock are expected to be very low and controlled by the low permeability of the OPA at the site (estimated at $\sim 10^{-21} \text{ m}^2$; Nagra 2024l).

Impacts on geochemical conditions arise largely through the creation of crossflows between units (although, as noted above, these will be minimised). Some very local impacts may occur due to cementing and injections. Exposure to air as a result of tunnel ventilation may also induce geochemical changes (development of fronts due to the progressive oxidation of pyrite and gypsum precipitation) at the exposed rock surfaces and within the associated EDZs (Bossart et al. 2004, Mayor & Velasco 2008, Vinsot et al. 2014).

Thermal impacts will be small due to the minor difference between operating temperatures in the repository structures and the ambient temperatures in the surrounding rock, except for short-term heat pulses due to cement hydration. The expected operating temperature in the repository is 28 °C, while, based on a mean surface temperature of 10 °C and a geothermal gradient of 0.045 °C/m. The expected ambient host rock temperature for a deep geological repository at 850 m depth is ~ 48 °C. A short-term cooling of the rock will result in a reduction in pore pressure due to the differential contraction of porewater and rock grains.

The presence of exploratory and monitoring boreholes may cause local perturbations to ground-water flow and composition, but effects can and will be minimised by ensuring the integrity of the borehole completions (casings, cement annulus and packer systems) until the boreholes are sealed.

3.2.2 Mechanical evolution of the host rock

Excavation of tunnels, drifts and caverns in the host rock leads to mechanical unloading and stress redistribution. The main mechanical impact will be the development of excavation-disturbed zones (EdZs) and EDZs¹³ around the underground structures, along with the possible occurrence of breakouts. In low-permeability rocks such as the OPA, these effects may have an impact on local flowpaths. EdZ and EDZ formation and the occurrence of breakouts are discussed in more detail in the context of the emplacement drifts and caverns in Chapter 6. Experience from the EDZ at the Mont Terri Rock Laboratory is summarised in Lanyon et al. (2014) and Lanyon (2019b).

Failure of the rock ahead of and around the excavation face results in yielding and macroscopic fracturing of the rock. Fracturing may be both tensile and shear, with formation of buckling zones, which in turn can lead to breakouts, increasing the surface roughness of the drift/cavern profile. The magnitude of this response depends on a number of factors, such as the time elapsed between excavation and emplacement of the tunnel support, stress field and drift/cavern orientation, rock strength and the excavation methods used. Volumetric strains induced by the excavation process (both compressive and dilational) result in pore pressure changes while, close to the excavation, drainage via induced fractures results in unsaturated conditions and drying of the rock.

These resulting pore pressure changes in the rock (both increases and decreases) away from the EDZ may take significant time to equilibrate and could – in case of porewater pressure increase – lead to local rock failure in critically stressed zones (e.g., within the EDZ of neighbouring excavations) if no appropriate measures are taken (e.g., rock support to limit deformation). The pattern of deformation is strongly influenced by stress and material anisotropy. The stress redistribution in response to the excavation process will cause convergence of the emplacement drifts, although this will be limited by the installation of rock support and later by the installation of buffer/backfill material.

Other potential rock-mechanical impacts of excavation include:

- reactivation of fractures and faults;
- and induced or triggered seismicity (unlikely).

Both effects would require that the rock mass around the excavation is highly pre-stressed, to the extent that the local stress perturbation caused by excavation could lead to reactivation or seismicity (Gibowicz & Kijko 1994).

¹³ In the past, various definitions of the disturbed and damaged zones have been used. This report uses those proposed by Tsang et al. (2005): The excavation-disturbed zone (EdZ) is a zone with hydromechanical and geochemical modifications, without major changes in flow and transport properties. Within the EdZ, state variables such as stress, water pressure, temperature, saturation, chemical composition of the porewater and related properties such as sonic velocity may be different from those of the undisturbed rock, but these changes are either temporary (e.g., saturation) or do not have a major influence on flow and transport properties (e.g., small changes in porosity due to changes in effective stresses). In contrast, the excavation-damaged zone, EDZ, refers to a zone in which the changes are both long-term and significant with respect to flow and transport.

At a larger scale, the presence of the repository itself would result in stress changes on nearby structures (fractures and faults). However, it is not expected that such structures would be in a highly pre-stressed state. Furthermore, pore pressure is likely to be reduced during excavation, resulting in an overall increase in effective stresses and stability. The development of thermally induced and gas-related pore pressure increases after closure and potential mechanical impacts are discussed in Chapter 7.

3.2.3 Other construction-induced effects

Other construction-induced effects include the desaturation of the rock mass around the excavated structures and various chemical processes. These effects are discussed in the context of the emplacement caverns and drifts in Chapters 4 and 6 but are expected to be qualitatively similar for other underground structures.

3.3 Waste- and packaging-related processes and uncertainties

There is significant uncertainty in the release and migration behaviour of activation and fission products initially adhering to the surfaces of SF rods (crud). However, the SF rods will stay in storage pools for decades before encapsulation, which means that the most easily leached part of the activity, including that associated with crud, will most likely be released during storage. If this is the case, that activity will then be bound (i) to the surfaces of the fuel pool and the water purification system and (ii) to the filters of the purification system and will ultimately form part of the L/ILW inventory.

3.3.1 SF-/HLW-related processes

Heat generation

The amount of radiogenic heat generated by SF is by its nature much higher than that generated by HLW. The variation with time of the average thermal power of each of the three generic SF disposal canister types (PWR-UO₂, PWR-MOX, and BWR¹⁴) has been calculated, starting from the reference year 2065 (approximate starting time for emplacement in the repository) up to 10⁷ years. The results for all three types are shown in Fig. 3-1 and correspond to the average thermal power in Watts per canister. The thermal power evolution with time shown in the figure is given on a double logarithmic scale and shows that the power output conforms, on average, to the safety requirement of 1,500 W per canister (maximum limit) at the time of emplacement.

¹⁴ The thermal power of the BWR disposal canister type corresponds to an average value for SF assemblies from boiling water reactors, whereas the PWR-UO₂ canister type is named after SF assemblies from pressurised water reactors containing up to 4 UO₂ assemblies, and PWR-MOX canisters are named for spent fuel assemblies from pressurised water reactor containing 1–2 MOX and up to 3 UO₂ assemblies (Nagra 2023b).

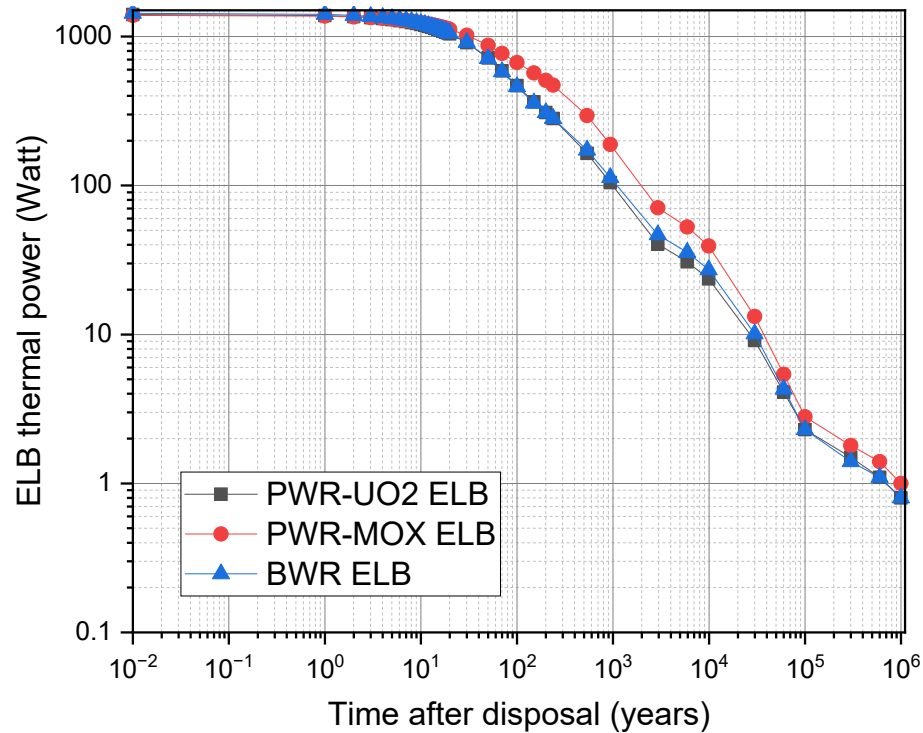


Fig. 3-1: Thermal power evolution per average final disposal canister (ELB) for the three canister types. The above-illustrated thermal power evolution was calculated on the basis of (Nagra 2023b)

The starting point 2065 is assumed to be the time of the start of emplacement.

The thermal power for the HLW is shown in Fig. 3-2. As stated above, it is lower than that for the SF. Note that the assumed starting time for emplacement is earlier for HLW since emplacement of the HLW inventory fraction is currently planned ahead of that for the SF fraction.

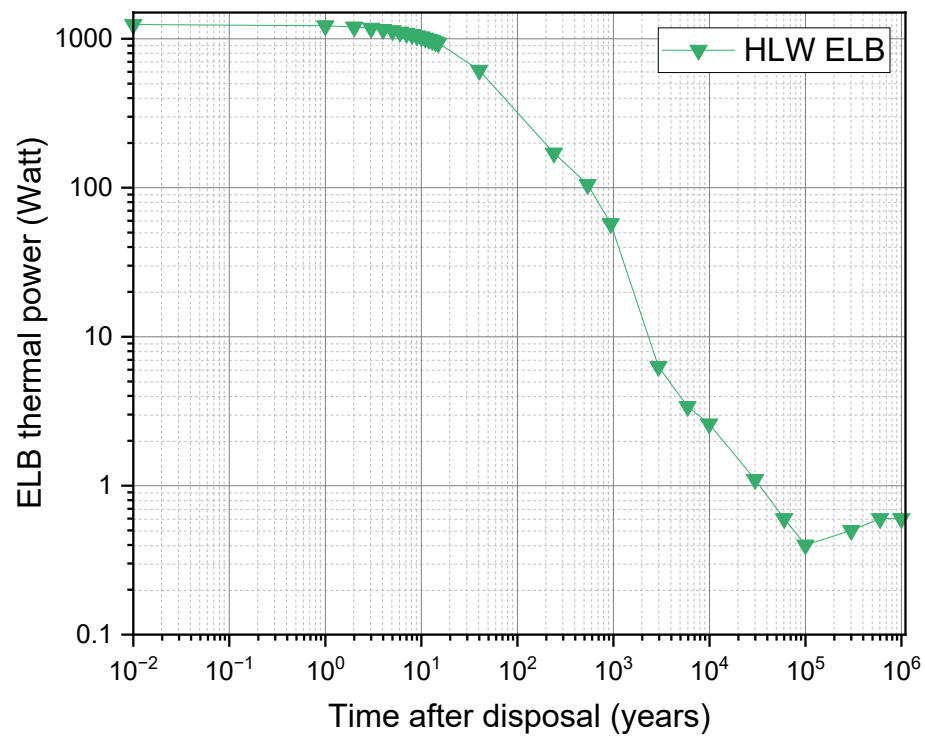


Fig. 3-2: Thermal power in Watt on double logarithmic scale as a function of time for HLW. The above-illustrated thermal power evolution was calculated on the basis of (Nagra 2023b)

The starting point is assumed to be the year 2060.

Partitioning of radionuclide inventory

The sintered SF pellets mostly consist of UO_2 with only a small fraction of other actinides and fission products. There are also mixed oxide fuel types that have been enriched with plutonium. The fuel pellets are stacked and packed into Zircaloy hulls (Fig. 3-3). Several rods are then bundled into an SF assembly.

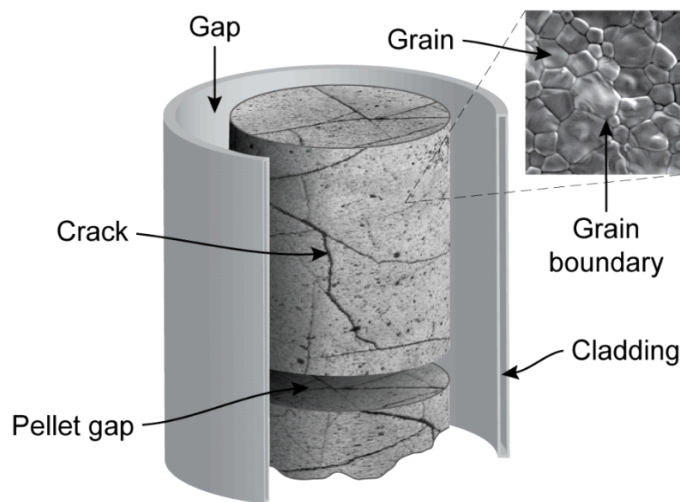


Fig. 3-3: The macro- and microstructures of a fuel pellet after its irradiation

See the cracks and the grain boundaries. The widths of the pellet-cladding and pellet-pellet gaps are purposely exaggerated for the sake of clarity (Fors et al. 2009).

During irradiation in the nuclear reactor, the Zircaloy is activated and may become brittle as a result. The temperatures within the UO_2 pellets range from 1,000 – 1,500 °C in the pellet centre to about 400 °C at the pellet rim. As a result of this thermal gradient, a fraction of the radionuclide inventory produced in the UO_2 matrix is segregated to grain boundaries, to cracks in the fuel and to the gap between the fuel and the cladding (see Fig. 3-4); for further details see Johnson et al. 2022). This part of the inventory (< 3%) will be released as part of the instant release fraction, when water enters the disposal canister after canister breaching (cf. Chapter 9). The Zircaloy cladding also becomes a source of radionuclides once the cladding starts to corrode after canister breaching. However, the majority (> 97%) of the radionuclide inventory resides in the UO_2 matrix, which mostly consists of uranium dioxide (UO_2).

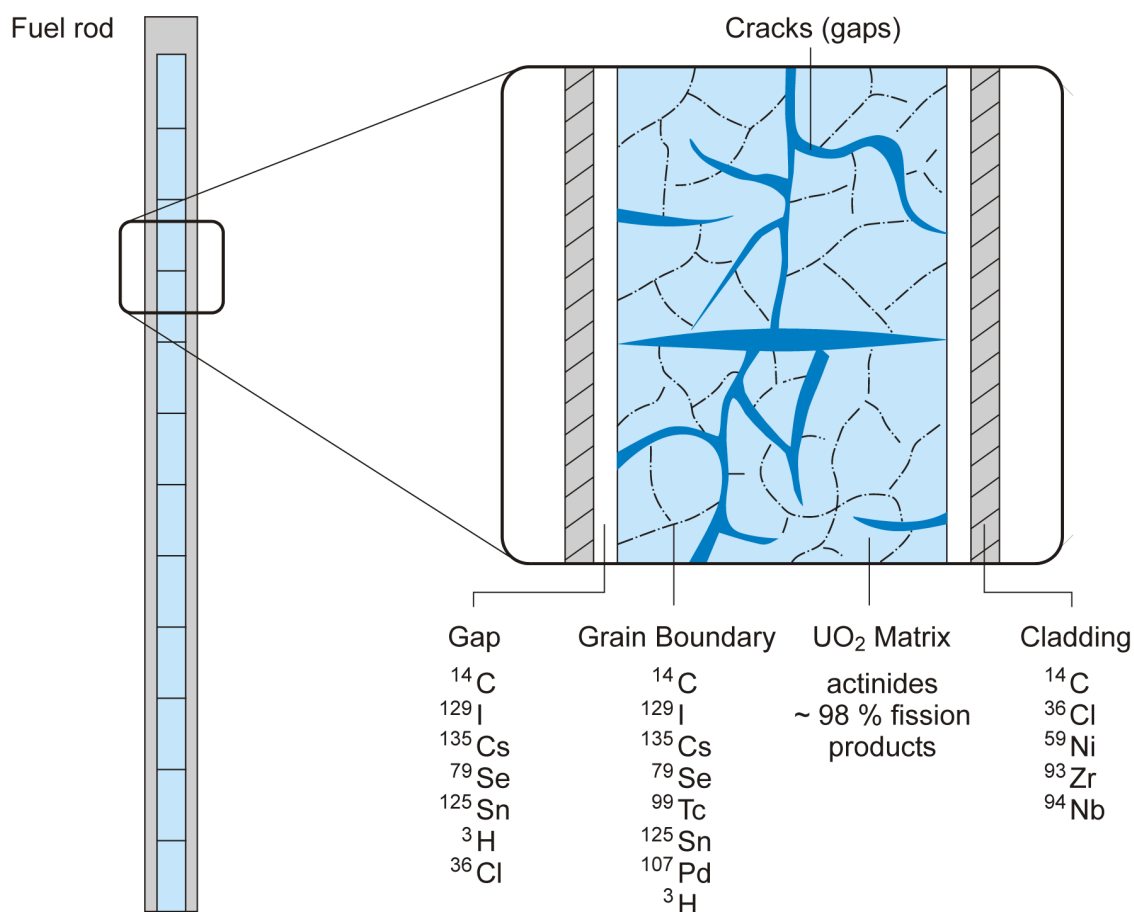


Fig. 3-4: Conceptual distribution of radionuclides in a spent fuel rod

Based on Johnson & Tait (1997)

For comparison, in vitrified HLW, the radionuclide inventory can be assumed to be distributed more homogeneously. Vitrified HLW is the product of the treatment and reprocessing of SF, aiming at extracting fissionable U and Pu for re-use in nuclear power plants. The waste from Switzerland has been vitrified in facilities in France and the United Kingdom. The used fuel is first dissolved and after a complex extraction procedure, the remaining solution is then evaporated, calcined and mixed at high temperatures with a borosilicate-glass-forming additive to produce a homogeneous molten glass. The melt is poured into stainless steel flasks of a few mm wall thickness and allowed to solidify before sealing by welding. During cooling, the glass monolith undergoes unavoidable thermal stress fragmentation, causing an increase of the geometric surface area. The waste in Switzerland is embedded in two types of borosilicate glass, related to the reprocessing by Orano (France) and Sellafield Ltd (UK). The major components of the glass are SiO₂ (45 – 46 wt.%), B₂O₃ (14 – 17 wt.%), Na₂O (8 – 10 wt.%) Al₂O₃ (5 wt.%) and Fe₂O₃ (2.5 – 3 wt.%). The major difference between the SON68 and the MW glass is the presence of 4 wt.% CaO and 2.5 wt.% ZnO in the SON68 glass. In contrast, the MW glass contains 6.9 wt.% MgO as a result of the fuel from the Magnox reactors in the UK, which operate with natural uranium rods inserted into an Mg-alloy cladding. This leads to a slightly different dissolution behaviour of these two glass types. The extensive miscibility of SiO₂ and B₂O₃ results in a flexible structure that then can accommodate a large amount and variety of network modifiers, including most dose-relevant actinides and fission products.

Detailed information is provided in Curti (2022). Therefore, in comparison to spent fuel, the radionuclide inventory in the HLW can be assumed to be more or less homogeneously mixed in each glass block.

Changes in the physical properties of HLW

As long as the HLW canisters remain unbreached, only solid-state mechanisms will lead to changes in the properties of the SF and RP-HLW.

The principal solid-state processes relevant to long-term SF behaviour are related to the generated thermal gradients by the irradiation history of the fuel and actinide decay, which may influence the diffusion of fission products in the UO_2 lattice. The cladding also has become activated during this irradiation process (for details see (Johnson et al. 2023)).

In the vitrified HLW, because of the thermal stress during post-production cooling, the HLW glass blocks will fragment. Glass fragmentation is important in relation to post-closure safety since it will increase the surface area of the glass, which affects how much glass dissolves and how many radionuclides are released in the event of canister breaching. Due to fragmentation, it is estimated that the surface effectively exposed to aqueous attack will be about 12.5 to 15 times larger than the area of the initial monolithic cylindrical block (Nagra 2022).

3.3.2 L/ILW-related processes

If, during interim storage, the water content and/or humidity inside the L/ILW drums are high enough (due the initial mixing water of cementitious matrices), corrosion and degradation processes will occur. Abiotic degradation of organic material will release CH_4 and CO_2 , where CO_2 leads to carbonation of the cementitious backfill materials, dissolving part of the portlandite present. As a result, the Ca/Si-ratio of the C-S-H phases in the cement decreases. The production and speed of diffusion of CO_2 limit the rate of the carbonation reaction. Metallic components of the waste will corrode anaerobically if the gas phase inside the waste drums is depleted of O_2 . If the O_2 level is higher, corrosion processes will be faster, leading to a decrease in the metallic inventory for disposal. If present, bacteria will also start to degrade organics and consume H_2 from the anaerobic corrosion processes. Internal concrete degradation will start due to the interaction of the alkaline pore solution in the cement. The very fine-grained siliceous fraction present in the cement formulation will cause a pH reduction. Overall, due to the large variety of waste types, there is significant uncertainty related to their mutual interactions and the consequences for gas pressure build-up and barrier integrity. However, as shown by Wieland et al. (2018), Kosakowski et al. (2020) and Martin et al. (Martin et al. 2023), degradation of cementitious material, organics substances and corrosion of metals is limited by the availability of water.

3.4 Potential impact of storage and transport on the waste packages

During the dry storage of L/ILW, the low availability of water limits the possibility of chemical reactions within the waste (Huang et al. 2018). Thus, the period of storage will have little impact on the physical and chemical properties of L/ILW.

Regarding the waste drums, apart from material ageing, dry oxidation of the steel surface prior to emplacement will result in the formation of a uniform oxide film that should not negatively affect their integrity.

In the interim storage facility at the Zwischenlager Würenlingen AG (ZWILAG), some of the 200 L drums for L/ILW are sealed with a rubber lid. The cement can thus interact with CO₂ in the atmosphere, and it is likely that, at the top surface, carbonation could affect the cementitious material.

Metallic and concrete blocks activated during the decommissioning of nuclear power plants (NPPs) will be placed within disposal containers and backfilled in accordance with the existing plan using a highly fluid cement suspension (Nagra 2023b). A significant amount of unbound water present in the cement formulation is expected to evaporate during the storage period due to the ambient conditions at ZWILAG. Moreover, carbonation of the top-surface of the concrete walls of the disposal container will occur (within a mm-range). Due to the presence of CO₂ in the atmosphere, the progression of the carbonation front is expected to be slow (the steel reinforcement is 25 mm beneath the concrete surface), as the concrete container has a very dense fabric. Moreover, the high cement content of the cement suspension envisaged to be used as container infill mortar has a very high resistance to carbonation. Thus, highly alkaline conditions can be maintained for a long period of time.

4 Processes during the pre-closure phase

4.1 Overview

The evolution of emplacement caverns and drifts up to the time that they are sealed is important with regard to post-closure safety, as several safety-relevant parameters are defined or can be modified during excavation, operations, waste emplacement and backfilling operations. In the case of the host rock, significant changes are expected to be restricted to within a few metres of the excavation.

The staging of deep geological repository construction and operations involves the successive excavation of emplacement caverns and/or drifts, waste emplacement, backfilling and sealing. Each emplacement cavern/drift is envisaged to remain open for approximately the same amount of time. Thus, the evolution of each emplacement cavern/drift from the start of its excavation until it is sealed is expected to be broadly similar and is the subject of the present chapter. There are, however, mutual interactions between sealed and unsealed deep geological repository structures that may differ to some extent between caverns and drifts according to the staging of construction and operations activities. These mutual interactions are also described. The evolution of HLW emplacement drifts and L/ILW emplacement caverns are described together in this chapter since they are, in many ways, broadly similar. Differences are highlighted as needed.

Alheid et al. (2005) compiled observations from experiments in various underground research laboratories (URLs), together with laboratory experiments on rock samples and the results of various numerical modelling activities. Valuable insight has been gained into the deformation behaviour of the rock during construction of the openings. This behaviour is associated with micro-cracking, fracturing and tunnel convergence in the vicinity of the excavations, together with a progressive mechanical loading of the engineered structures, particularly on the lining structures. The interaction between the corrosion of metallic components and the chemical evolution of the lining structures will impact the mechanical behaviour of the host rock, particularly through the carbonation of cement hydrates, and through the alkaline alteration and oxidation of interfaces and fracture-filling materials within the host rock. The account given in the following sections of this chapter, and in subsequent chapters, is based largely on these studies.

Accordingly, the influence diagram in Fig. 4-1 shows an overview of the events and processes occurring during the pre-closure phase of an HLW emplacement drift and the interactions between such drifts. Key events and processes are:

- excavation of underground openings and the consequent mechanical unloading of the OPA host rock;
- installation of rock support (including cementitious liner);
- ventilation and cooling;
- installation of canisters/containers (holding the waste) and backfill material;
- and heat generation (principally decay heat).

They especially lead to, or influence, numerous other processes that may directly or indirectly affect the long-term performance of the repository.

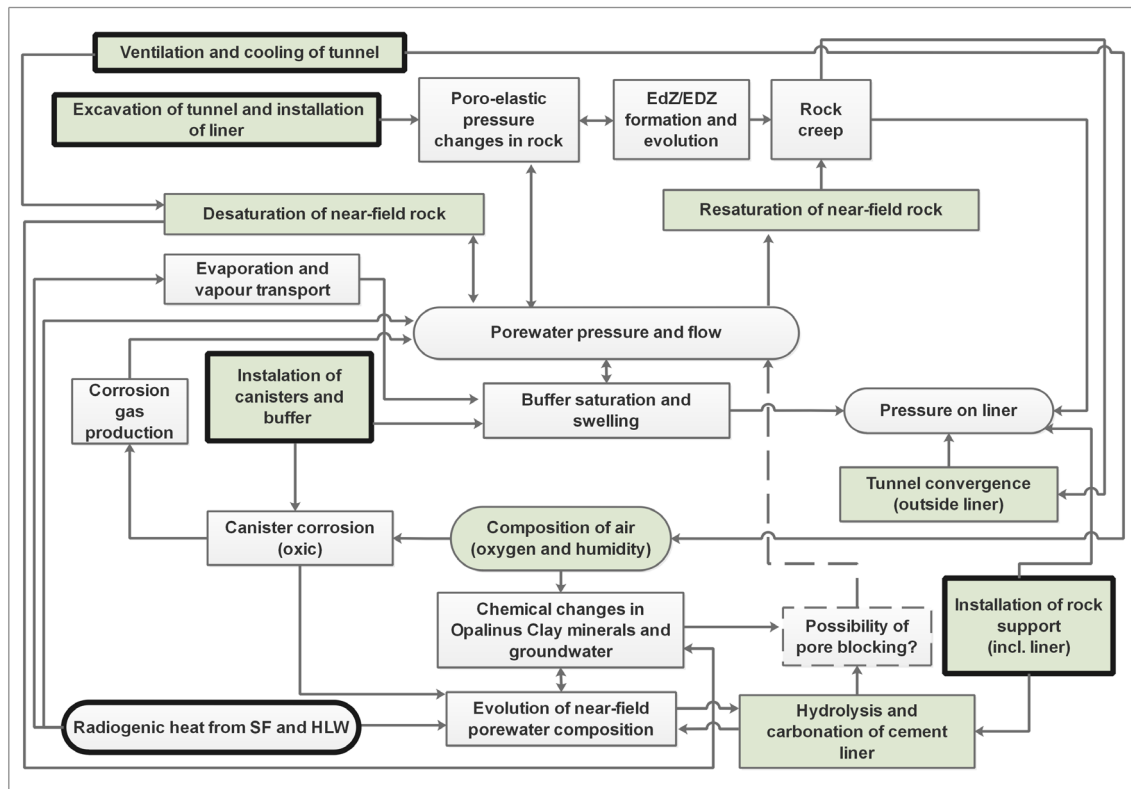


Fig. 4-1: Expected interdependencies of processes and phenomena during the construction and operational phases of an HLW emplacement drift

Boxes with thick black outlines indicate key events and processes. Green-filled boxes indicate events or processes that cease or become unimportant by the end of this period.

During this phase, and as discussed in the following sections, the main processes and phenomena affecting deep geological repository evolution are thermal, hydraulic and mechanical in nature while chemical processes have a relatively minor impact. Fig. 4-2 shows the main THM processes in an emplacement drift during excavation, ventilation and emplacement.

The events, processes and interactions occurring in L/ILW emplacement caverns are qualitatively similar in many respects to those occurring in HLW emplacement drifts, although the decay heat from L/ILW waste is significantly lower to almost non-existent. A major difference is the back-filling material and the tunnel support.

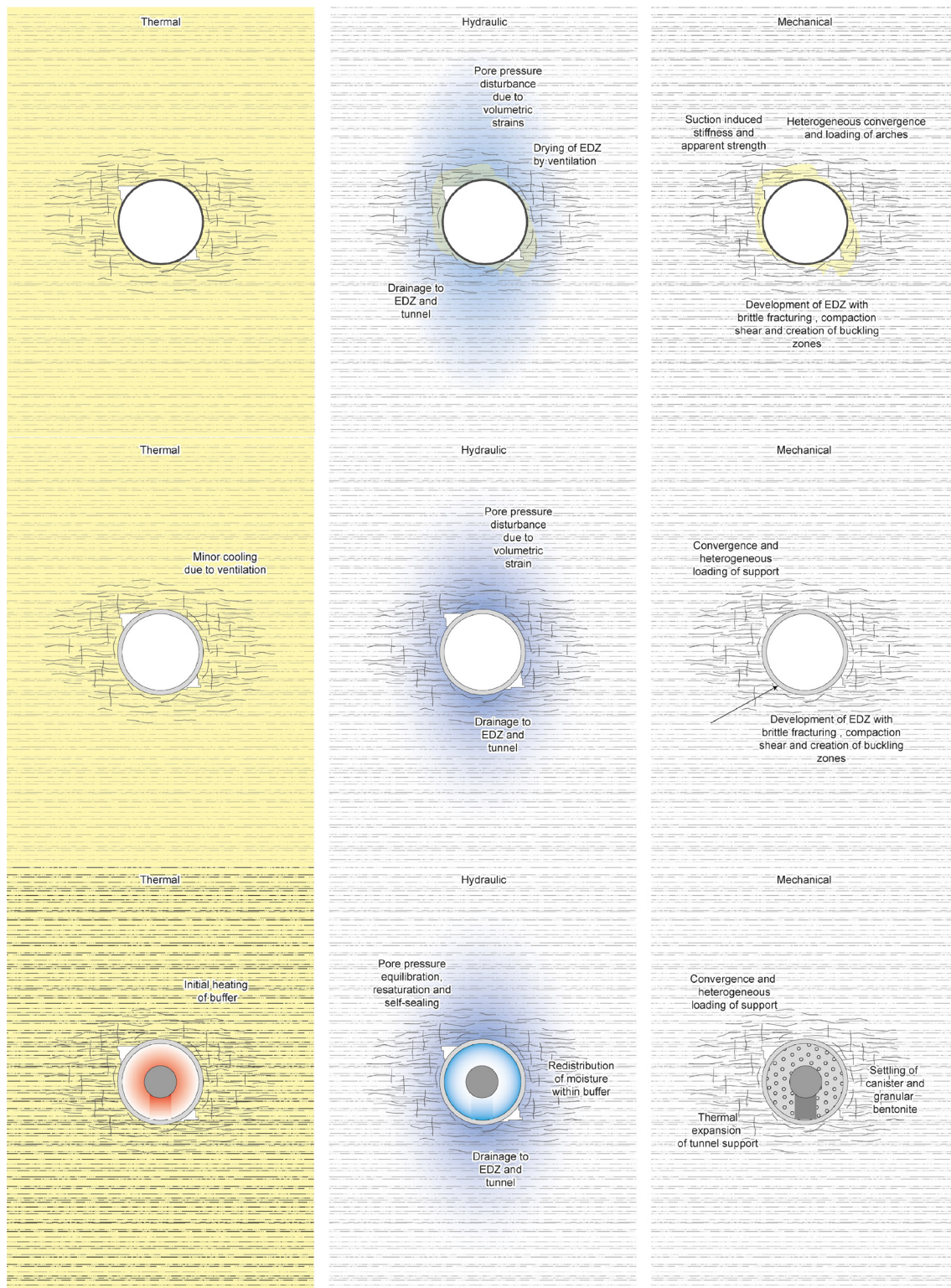


Fig. 4-2: Principal THM processes in an emplacement drift during excavation (top row), ventilation (centre row) and emplacement (bottom row)

4.2 Key events and processes and their consequences

4.2.1 Excavation and consequent mechanical unloading of the rock

The formation of the EDZ is associated with brittle fracturing and shear deformation with an increased porosity, thus leading to a higher hydraulic conductivity, higher gas permeability and (due to porosity increase, fracturing and temporary partial desaturation) lower thermal conductivity, as well as a lower gas entry pressure around the emplacement caverns and drifts, sealing zones and other underground structures (see Fig. 4-3). The HLW drifts are backfilled with compacted bentonite, and the annulus between the segmented lining and the rock is filled with a low-viscosity annulus grout.

Because of the large pores of the mortar used for backfilling the L/ILW emplacement caverns, the hydraulic conductivity of the EDZ is not expected to significantly affect overall transport pathways for gas, water or even radionuclides.

Excavation of the caverns and drifts will not take place under sterile conditions, and it is inevitable that microorganisms will be introduced. The microorganisms brought in are not necessarily adapted to thrive under deep geological repository conditions and their impact on the safety-relevant properties of the near-field is expected to be limited (Leupin et al. 2017a).

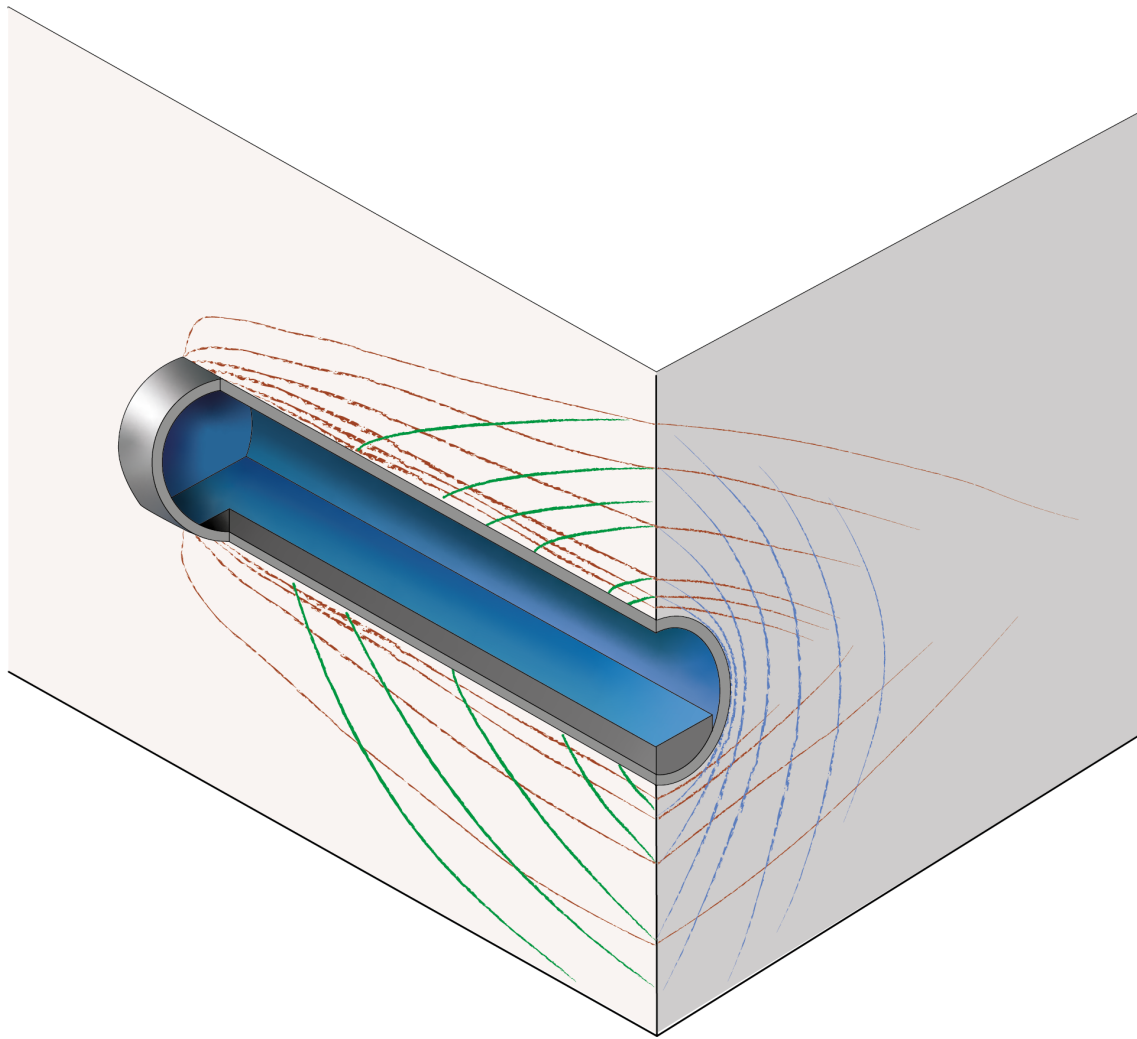


Fig. 4-3: Conceptual figure of the shape and extent of an EDZ around an emplacement drift

The extent and shape of the EDZ will, among other factors, highly depend on the local stress situation, the rock-mechanical properties of the rock and the type and timing of the tunnel support being emplaced. This figure is not to scale.

4.2.2 Installation of rock support

HLW emplacement drifts will be excavated with a shielded tunnel-boring machine (TBM) and supported by pre-cast concrete liner segments (Nagra 2023a).

L/ILW caverns will be supported by a grid of anchors and by a fibre-reinforced concrete lining (shotcrete). Dependent on the rock properties, gliding arches will be installed to take up the primary convergence of the L/ILW emplacement caverns. Rock support is assumed to be emplaced simultaneously with the excavation. After the primary convergence, an inner shell tunnel support made of in-situ concrete will be installed as the main rock support (Nagra 2023a).

In the case of the HLW emplacement drifts, larger voids (most likely above the tunnel crown) behind the concrete liner segments caused by breakouts before installation will be filled with a highly fluid injection grout (annular gap filling material).

Voids that are connected to the annular gap between rock and lining are filled during grouting of the annular gap. Voids enclosed in the surrounding rock may be grouted by means of short subvertical borings through the lining.

Overbreaks behind the concrete segments lining the HLW drifts (reference design) will be filled with low-viscosity grout during construction (see Section 2.2.1). It is, however, conceivable that some overbreaks will remain undetected and will therefore not be completely backfilled. Fig. 4-4 shows activities and conditions of the ground and rock support for relevant phases during construction of the HLW emplacement drifts. Dissipation of excavation-induced excess porewater pressures will occur, and loading of the lining reaches its peak around 100 years after excavation. The mechanical lifetime of the lining is designed to last until the HLW drifts have been backfilled. After backfilling, the lining will gradually lose its support capacity, deform and find a new static equilibrium with the bentonite buffer and host rock.

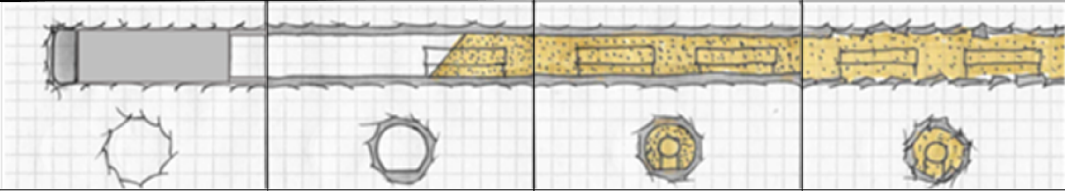
Time	Excavation	Operation	Retrieval	Resaturation
	0 a	< 2 a	< 100 a	>100 a
Ground & rock support conditions				
	• Short-term, undrained ground conditions • Unsupported sections (2-3 tunnel diameters) • Initial (short-term) loading of rock support	• Transient seepage conditions (dissipation of excess porewater caused by excavation) • Ground deformation and loading of rock support due to consolidation processes		• Transient seepage conditions with ongoing saturation of granular bentonite material • Swelling of bentonite • Rock support loses its support capacity
Work activities	• Full face excavation • Support installation	• Remotely handled emplacement of canisters and granular bentonite material	• Remotely handled removal of granular bentonite material and recovery of disposal canisters	• None

Fig. 4-4: Activities, ground and support conditions for the construction of HLW emplacement drifts

Retrieval of waste is not part of the normal operations but is shown here to illustrate the expected conditions in case the decision to retrieve is made within about one hundred years.

4.2.3 Ventilation and cooling

The caverns and drifts can remain open or partially open after excavation and installation of rock support and prior to waste emplacement to allow further rock characterisation, as well as the phasing of emplacement operations. During this period, they will be ventilated and cooled to 28 °C at a relative humidity (RH) of 60% (Papafotiou et al. 2018) to maintain the legally defined ambient working conditions for underground mining activities.

In this period:

- The pre-cast concrete lining may dry out due to the ventilation. At the surface, carbonation will occur. The grout behind the lining will cure after emplacement. Some water loss from the grout to the pre-cast liner elements and the EDZ is expected.
- If sections are left unlined, ventilation will dry the rock, leading to the precipitation of salt and potentially to the creation of desiccation cracks. In desaturated parts of the rock, any significant suction developed will result in increased stiffness and apparent strength.

Ventilation and cooling will also give rise to some hydraulic gradients which were attenuated by the cementitious lining. At the Full-Scale Experiment (FE) in Mont Terri, almost no changes in volumetric water content could be measured in the OPA behind the shotcrete (Lanyon 2019b).

Unstable ventilation conditions could create cyclic deformations, which could lead to the weakening of the rock (Wild et al. 2017) and cause additional convergence. Good operational procedures and tunnel support structures are expected to prevent the phenomenon of cyclic creep.

Evidence was found in the Ventilation Experiment (VE) at Mont Terri that evaporation and cooling during an extended operational phase could lead to salt precipitation in the unsaturated zone and potentially, after buffer emplacement and during buffer saturation, increase the salinity of the porewater in the buffer close to the waste canisters (Bossart & Nussbaum 2007). It has been assumed that most of the near-field chloride and sulphate enrichment occurred while the VE microtunnel was open for approximately 4 years prior to the Ventilation Experiment and that it was not accelerated by additional desaturation periods during the experiment. Salt precipitation can be reduced by minimising rock desaturation.

During excavation and emplacement, the caverns or drifts are ventilated and aerobic conditions will prevail, resulting in some oxidation of the immediately surrounding OPA. Estimates of the extent of oxidation in OPA have previously been derived from various field studies (Nagra 2002). Results indicate that gypsum formation by the oxidation of pyrite in the EDZ is limited to open fracture surfaces. Calculations based on field studies of tunnels open from a few years (Mont Terri) to over 100 years (Hauenstein railway tunnel) permit bounds to be placed on the extent of oxidation. In HLW emplacement drifts, only about 1% of the pyrite originally present in the EDZ will be altered. Thus, long-term impacts are expected to be insignificant (Mäder & Mazurek 1998, Wersin et al. 2020).

4.2.4 Installation of canisters/containers and backfill material

The HLW disposal canisters will be emplaced co-axially at intervals along the drifts and supported by pedestals of compacted bentonite blocks. Immediately after emplacement of an HLW disposal canister, the respective section of the emplacement drift will be backfilled with highly compacted granular bentonite. Trials conducted as part of the FE Experiment have demonstrated that the bentonite block pedestal can support the weight of a filled HLW canister, with a sufficient margin of safety (Müller et al. 2017).

The initial water content in the emplaced granular bentonite adjacent to the canister surface is up to 5 wt.% and up to 18 wt.% in the blocks used for the pedestal on which the canister is placed.

The HLW emplacement drifts may be inclined so the evolution at one end might be slightly different from that at the other. Based on the current geological knowledge of the potential siting regions, it is possible that the drifts or caverns will have a downward inclination of up to 10%. Emplacement of the waste will start at the lower end of the drifts and then proceed upslope. This could potentially result in a lower emplaced density of bentonite in the upper parts of each drift if there is settlement of the dry buffer pellets, creating heterogeneity in the emplaced dry density. The low permeability of the OPA limits any possible water flow down the drifts, but it is possible that thermal gradients from emplaced HLW in the lower part of the emplacement drifts could result in convective air flow through the unsaturated buffer.

In the case of the HLW, some atmospheric corrosion of the canisters will occur before, during and immediately after emplacement. Aerobic corrosion of tunnel support materials in general, such as (if present) anchors, nets or steel fibres, is to be expected. However, given the short duration of this phase and the alkalinity of the cement (responsible for low corrosion rates (Diomidis et al. 2023)), no long-term safety-relevant effect is expected.

In both the HLW and L/ILW repository sections, following backfilling, partially saturated regions of the near-field rock will slowly resaturate due to flow from the rock, and pore pressures will equilibrate. Resaturation of the near-field rock will be driven by movement of water from the undisturbed host rock, which is controlled by its permeability and pore compressibility, as well as by the thermally affected pore pressure around the HLW repository section. Resaturation of the EDZ will be associated with swelling and self-sealing of EDZ features (Lanyon 2019a, Lanyon 2019b, Alcolea et al. 2014). At the same time, the EDZ may develop further, as ongoing failure is driven by pore pressure recovery and/or equilibration with increasing pore pressure as well as by potential ongoing compaction and crack growth.

Loads on the lining will increase; these are likely to be anisotropic and heterogeneous. The time required for resaturation of the near-field rock, and also for full saturation of the initially partly saturated HLW buffer, is dependent on e.g., the initially unsaturated pore volume, the ability of the undisturbed OPA to provide water (permeability and pore compressibility), the permeability of the lining and the thermal gradients. Given the short period that the drifts are open prior to waste emplacement, as well as the low EDZ pore volume and the limited extent of desaturation due to ventilation, it is possible that the near-field rock will have substantially resaturated by the time a drift is sealed. As the EDZ resaturates, any fractures or voids are expected to seal over time due to swelling of the host rock and creep. Near-field saturation is described in more detail in Chapter 6.

The grout and waste within the L/ILW containers are expected to be partially saturated due to excess water. Any excess water present in the pores will dynamically equilibrate with the relative humidity in the cavern atmosphere.

In contrast, the HLW buffer will require a significant period of time to become fully saturated (see Section 5.1.3) due to the expected low flow from the OPA.

4.2.5 Heat generation

Especially in the case of SF emplacement drifts, but also to some extent in those for HLW (more about the heat evolution in HLW emplacement drifts in Sections 6.1.1 and 7.1.1), radiogenic heat will increase the temperature of the buffer and, later, the surrounding rock. In the case of SF emplacement drifts, the temperature in the EDZ will start to increase around the first canisters that are emplaced at the end of the drift by the time this drift is closed.

There will be no heat output associated with the prefabricated concrete liner segments, as the exothermal curing of the cement will take place prior to emplacement. Only minimal heat is expected from curing of the grout behind the lining as this will occur during the ventilation period immediately after excavation. Similarly, heat output from cement hydration following the emplacement of any shotcrete liner (alternative support concept) will be minimal as the curing of the cement will coincide with the ventilation period.

Regarding the curing temperature of the backfill in the L/ILW repository, Darcis et al. (2014) modelled the temperature evolution in the L/ILW repository, and the results show that the maximum temperatures reached in the caverns and in the adjacent host rock are predominantly caused by the short-term release of hydration heat following the backfilling with mortar¹⁵. In most cases considered, the temperature in the backfilled cavern increases by around 50 °C during hydration and thus remains below 80 °C, and significantly below 100 °C. In these cases, the temperatures in the emplacement containers remain below 60 °C. In the first metre of host rock around the caverns, the temperature increases by less than 10 °C above the in-situ temperature. Darcis et al. (2014) concluded that the temperature peaks occur within a few months after mortar application. Temperatures then fall for a period ranging from a few years to decades until they approximately reach the ambient temperature in the surrounding rock. The authors assumed that the cavern would be backfilled in one step.

Temperature will affect the rates of many processes, including desaturation/resaturation of the near-field rock and buffer, and the evolution of buffer/backfill porewater composition. In addition, thermal expansion of porewater in the rock will result in an increase in porewater pressure (also discussed in Chapter 7).

¹⁵ The heat release calculated by Darcis et al. (2014) for the backfill mortar M1 turned out to be very conservative with respect to the maximum temperature that can be reached. Hydration heat measurements of the backfill mortar M1 preheated to 40 °C resulted in an increase of around 12 – 14 °C for the first hours (Martin et al. *in prep.*, Chapter 6 of this report).

5 Interactions between sealed and unsealed deep geological repository structures

The low hydraulic and low thermal diffusivity of the intact OPA means that interactions between sealed and unsealed emplacement drifts and caverns, as well as between these and other deep geological repository structures, will be limited to coupled mechanical effects due to changes in stress and strain. The diameter of the HLW emplacement drifts relative to their spacing should result in only very minor interactions due to excavation and subsequent emplacement and thermal expansion of the buffer and near-field rock (see Fig. 5-1). Vibrations or ground movements due to excavation will be small due to the use of an appropriate excavation technique. The same applies to the L/ILW caverns.

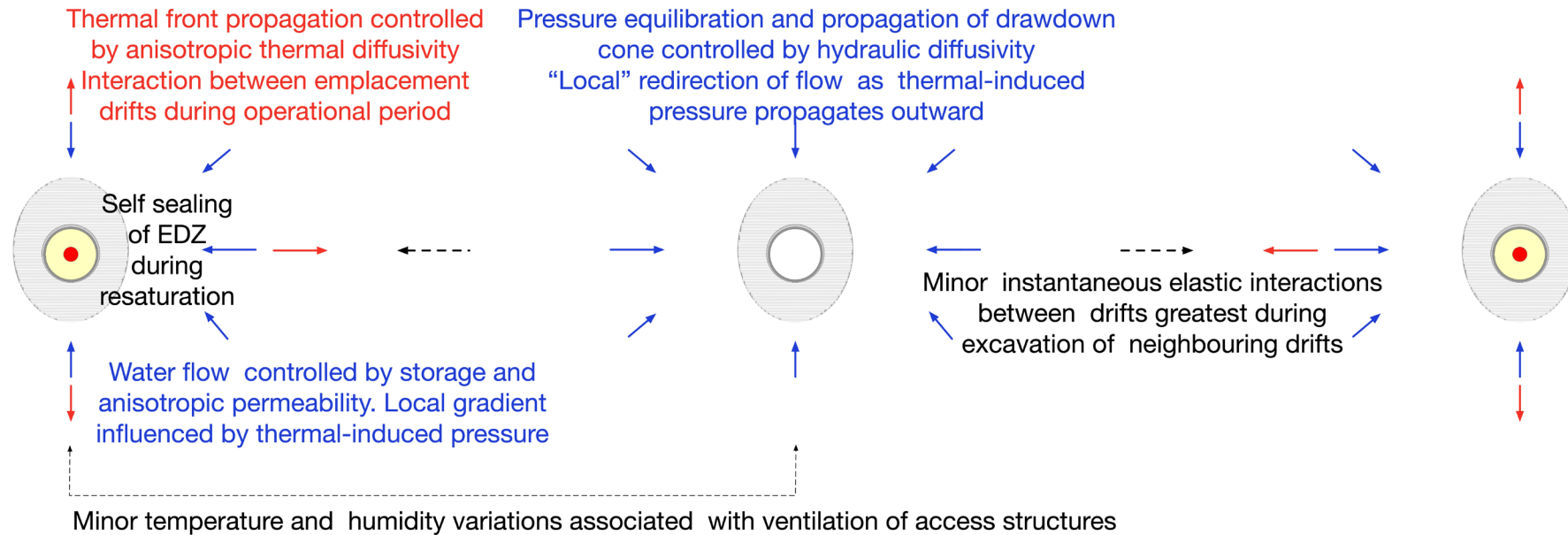


Fig. 5-1: Interactions between HLW drifts during the operational phase of the repository

The figure shows the dominant THM couplings during the operational phase. Because disposal canisters will first be emplaced in every other drift, the temperature front and the humidity gradients towards the open drift will result in a drawdown cone.

5.1 Potential impact of imperfect¹⁶ manufacture and installation of emplacement drift and cavern components

5.1.1 HLW bentonite buffer emplacement

The HLW bentonite buffer is emplaced as blocks (pedestals) and in granular form (pellets). Experience from emplacement tests run in the framework of the FE experiment at the Mont Terri URL has shown that the bentonite pellets might segregate during emplacement. This can reduce the buffer density at some locations, especially at its interfaces with the lining and canister, partly depending on the roughness of the inner surface of the lining (which will likely be lower for the pre-fabricated concrete liner segments foreseen in the reference concept than for the potential alternative, shotcrete (Müller et al. 2017)). Heterogeneity in buffer density could potentially reduce the capacity of the buffer to maintain low microbial activity, provide self-sealing and resist tunnel convergence once the lining degrades. It could also lead to uneven loads on the tunnel walls (including the lining) and on the canister. The outcome of the Bosch et al. (2023) project has shown that for the Nagra near-field design, a sufficiently homogeneous dry density distribution of the bentonite can be expected upon saturation.

5.1.2 HLW voids behind the segmented lining (reference design)

In line with the current concept, the annular space and overbreaks from the construction process between the segmented lining and the host rock will be filled with a very fluid, low-viscosity, two-compound mortar (see Section 4.2.1) as part of the TBM excavation sequence. It is, however, possible that some voids remain open either between the lining and the rock, in the rock and/or within the grout. The resaturation process and convergence of the rock are expected to seal most of the remaining voids in or close to the rock surface. If the annulus grout breaks due to convergence, this may provide preferential axial parallel flowpaths along the drifts similar to those in the EDZ, but they will be less likely to self-seal than the EDZ.

5.1.3 L/ILW cementitious backfill

In the case of the L/ILW cementitious backfill, potential deviations from the design basis can arise if voids remain despite comprehensive backfilling operations or if compaction through the emplacement procedure results in an excessive degree of compaction.

5.2 Summary of main processes and key factors that influence them

As noted at the start of this chapter, prior to the closure of an emplacement cavern or drift, the main processes and phenomena affecting evolution are thermal (T), hydraulic (H) and mechanical (M) in nature, with chemical processes having a relatively minor impact.

Tab. 5-1 summarises major and less important THM processes occurring during this phase, as well as key factors that influence the rate or extent of these processes.

¹⁶ The term “imperfect” refers to deviations from the original plans in the actual construction of a project. These deviations may be caused by operational issues, changes in materials, or natural factors, but do not affect the safety or integrity of the engineered or geological barriers in the project.

Tab. 5-1: Processes during cavern excavation, ventilation and emplacement

Major processes	Excavation: • Brittle fracturing, shear failure and reactivation of pre-existing features in the drift and cavern near-field (EDZ formation); • Unloading of the rock and consequent changes in volumetric strain and pore pressure. Ventilation period: • Desaturation of the EDZ during active ventilation and cooling of the drifts and caverns; • EDZ development due to pore pressure recovery as soon as tunnel support is emplaced; and • Loading of the lining and convergence of the rock external to the lining as soon as the pore pressure recovers. Emplacement: • Initial heating of the buffer and redistribution of moisture due to heating (local drying close to canister, and diffusive and convective transport of water vapour possible); and • Resaturation of the EDZ and self-sealing: self-sealing as water reaches any open fractures but also development of (or changes in) the EDZ due to loading, pressure recovery and resaturation (loss of apparent cohesion).
Less important processes	Excavation and ventilation period: • Pore pressure equilibration – likely to be slow relative to excavation advance; • Drying of the rock and chemical alteration of fracture surfaces due to ventilation during excavation; and • Thermal stresses due to excavation and ventilation. Emplacement: • Loading of the pedestals and granular bentonite. Internal loading of lining (weight of buffer and canister); • Minor displacements of the canister and buffer due to compaction and moisture redistribution and thermal strains (not explicitly mentioned in the text); • Stress and strain changes due to excavation of neighbouring drifts and caverns; • Establishment of anoxic conditions after closure; and • Minor gas generation due to corrosion of the tunnel support (rock bolts, mesh).
Key factors	• Excavation geometry and method; • Rock strength and stiffness; • <i>In-situ</i> stress magnitude and anisotropy; • Cavern/drift orientation with respect to stress, bedding and tectonic features; • Extent of tunnel support (pre-cast concrete liner segments or alternative concept of shotcrete and bolts) and timing of installation; and • Limitation (grouting) of inflows to shafts (and, if present, ramps) in the overlying rocks.
Supporting dataset	• Excavations at Mont Terri (e.g., ED-B, MB, HG-A – see Marschall et al. (2017), Lanyon et al. (2014)). • Heater experiments (FE and HE-E) at Mont Terri (Müller et al. 2017). • HotBENT at the Grimsel Test Site (URL) (Nagra 2021b).

6 Early post-closure processes

Once the first emplacement drifts and caverns are backfilled and sealed, some decades are expected to elapse before the final closure of the repository. During this period, the remaining emplacement drifts and caverns will be constructed, operated and sealed. This is followed by a monitoring period, which is expected to last for about 40 years prior to the final closure. The pre-closure evolution of the sealed HLW emplacement drifts and L/ILW emplacement caverns is described separately in this chapter as the different nature of the backfill materials (compacted bentonite vs. cementitious mortar) strongly affects how evolution proceeds. The evolution of the access structures is also described separately, since these will remain open significantly longer than the emplacement rooms. The evolution of the access structures of both repositories will be similar in this period, and these are thus described together.

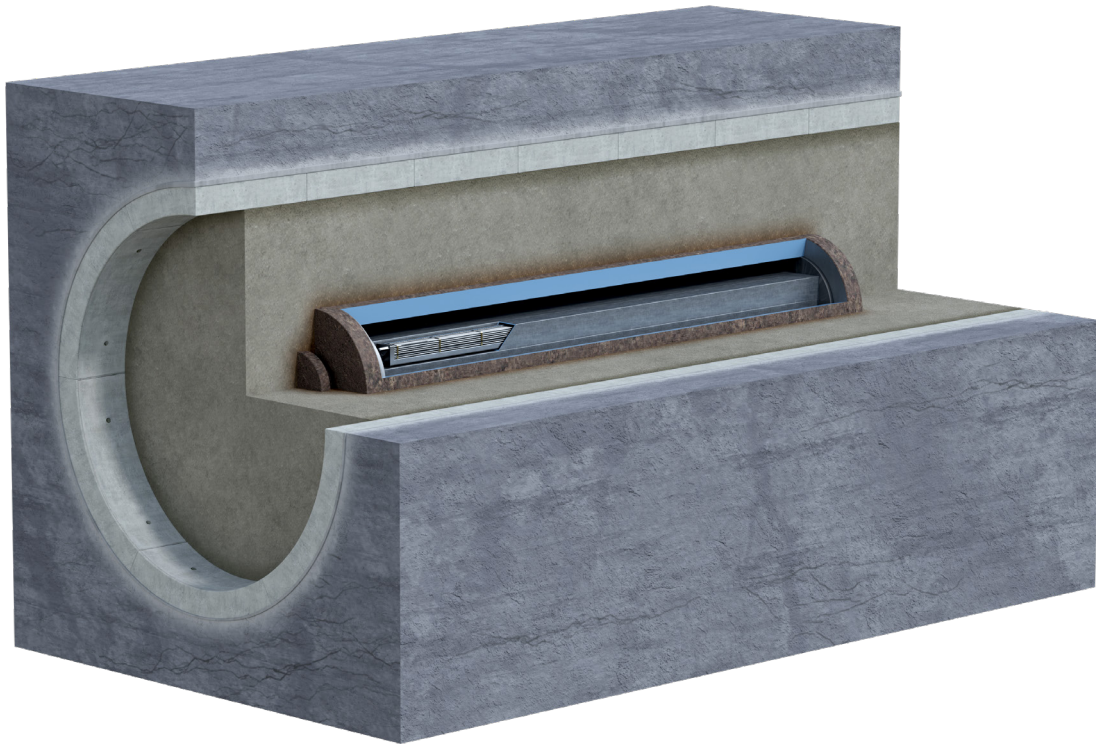


Fig. 6-1: An illustrative representation of a fully saturated HLW drift hundreds of years after deep geological repository closure

6.1 HLW emplacement drifts

Fig. 6-1 to Fig. 6-3 give an overview of the events and processes occurring in the HLW emplacement drifts in the period up to deep geological repository closure and the interactions between them. After closure of an HLW drift, the redistribution of moisture and water inflow from the rock will have led to the saturation of the bentonite, the development of swelling pressure and the sealing of the EDZ.

The cementitious lining will have started to chemically degrade and interact with the OPA and bentonite within a range of 1 – 2 mm at the interface but this will not impair its safety-relevant properties.

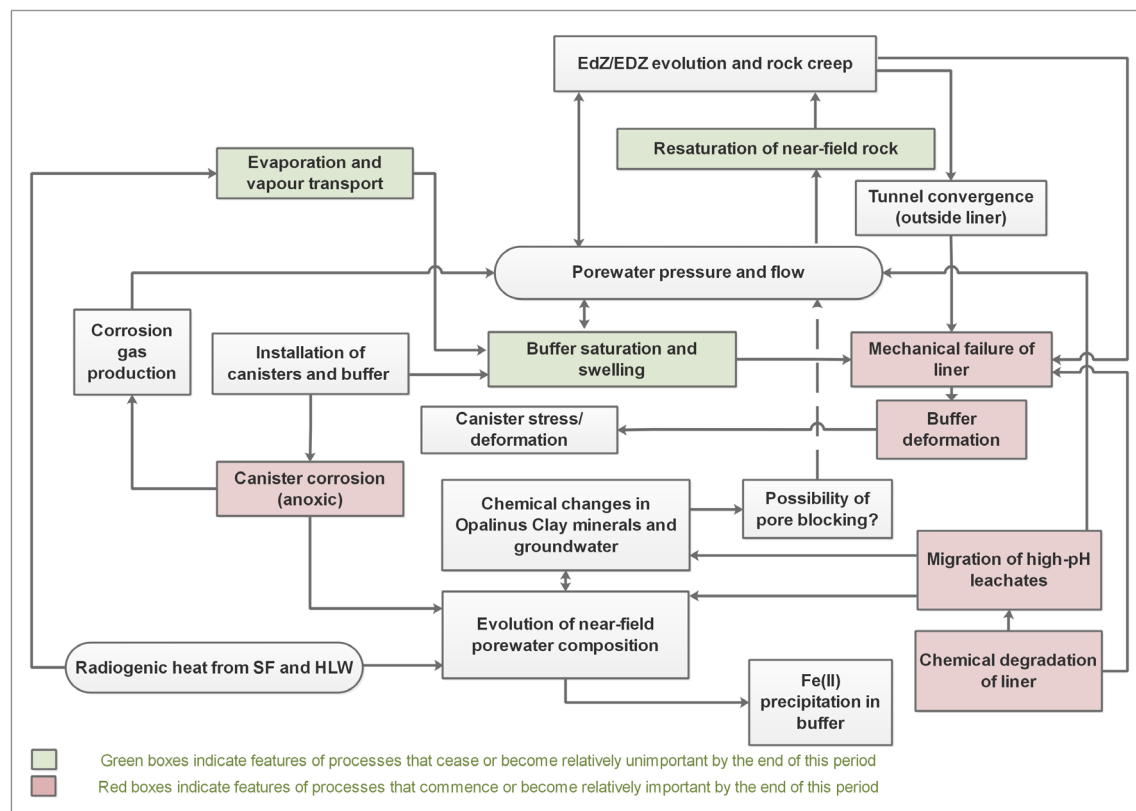


Fig. 6-2: Expected interdependencies of processes and phenomena in a sealed SF emplacement drift prior to deep geological repository closure

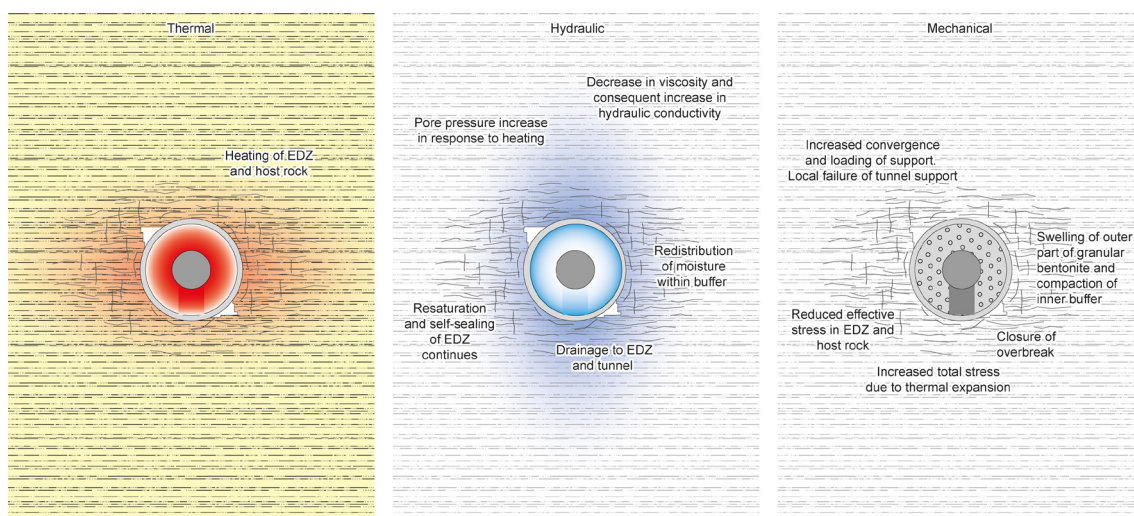


Fig. 6-3: Expected THM processes during the first 100 years after closure of an HLW emplacement drift

Key THM processes described in the following sections are:

- heat generation and its effects;
- buffer saturation;
- swelling pressure, tunnel convergence and evolution of the EDZ.

As metal corrosion, gas generation and the development of redox conditions are intrinsically coupled to the THM processes and safety-relevant processes, they are also described in this section.

6.1.1 Heat generation and its effects

For SF canisters, the initial heat output is assumed to be 1,500 W per canister, which will result in a temperature at the interface between the SF canister and the buffer of up to 150 °C within about ten years after the drift has been backfilled and sealed (Senger et al. 2014). For HLW canisters, which have a lower thermal loading than the SF canisters, the surface temperature reaches a maximum of around 130 °C a few years after repository closure, followed by a gradual decay. The temperature of the rock at the drift boundary will reach its maximum ($\delta T = 50$ °C at the drift boundary of the rock and $\delta T = 40$ °C at 20 m above the rock) after about 100 years. Heat transport to the far-field rock, which will become more effective once the buffer has been saturated, will increase the temperature to a maximum value of ~ 75 °C at a distance of 20 m around the drifts.

The thermal conductivity of bentonite has a significant impact on peak temperatures in the buffer and is particularly strongly coupled to buffer saturation (see Section 6.1.2, below). In contrast, the evolution of the thermal conductivity of the buffer has little impact on the temperatures in the surrounding OPA. By limiting the thermal load from the canisters such that temperatures in the rock remain below the reconstructed maximum paleotemperature of the OPA, any detrimental chemical or mineralogical effects on the safety-relevant properties of the host rock can be excluded (Nagra 2008b).

There are several types of chemical processes that can degrade the swelling capacity and reduce the plasticity of the bentonite buffer over time, all of which show temperature dependency. However, as discussed in Sellin & Leupin (2013), measurements on bentonites from short-term thermal studies and natural analogue studies show relatively minor changes of hydraulic properties (about 1 order of magnitude) below about 130 °C, regardless of the experimental conditions. At temperatures of 150 °C and above, the swelling pressure can be somewhat reduced and the hydraulic conductivity increases. Exposure of compacted bentonite to temperatures of 150 °C and above may alter the plastic properties due to cementation effects (Johnson et al. 2014). Nonetheless, these hydrothermally altered bentonites are still characterised by very low hydraulic conductivities as well as reasonable plasticity and sorption capacity, even in cases where the content of expandable clays is low (Kaufhold et al. 2021, Kale & Ravi 2018, Fox et al. 2019, Zheng et al. 2015).

The THM behaviour of the saturated buffer material has been characterised (Seiphoori 2015) and the dependence of hydraulic conductivity on temperature and hydraulic gradients determined. Changes in water-retention behaviour were linked to microstructural modifications occurring during saturation. The microstructural analysis demonstrated that, upon saturation, a clear transition from a double-structured (in the compacted state) to a single-structured porosity network (after full saturation) occurs with permanent features that affect water retention, which, in turn, increases the retention capacity of the material. Analysis of the available information on the hydration of smectite clay at the particle level indicated the evolution of an active porosity within the microstructure, which consequently affects the macroscopic hydromechanical response of the bentonite. Thus, from experiments and a literature review reported in Leupin et al. (2014), it can be concluded that, for the expected evolution of the repository temperature, performance indicators such as swelling pressure and hydraulic conductivity are not adversely affected in the long term by heat generated during the thermal transient.

Increasing temperature in the near-field rock will result in thermal stresses, rock heave and some increase in hydraulic conductivity due to reduced viscosity. Differential thermal expansion between porewater and matrix in the rock and in the (saturated) buffer, coupled with their low hydraulic conductivity, will also result in an increase in porewater pressure. Within about 20 m of the drifts, the pressure has been calculated to increase to as much as 70% of the lithostatic pressure after about 100 years. The potential mechanical impacts of porewater pressure increases are, however, expected to be minor, as described later. Thermally induced pressures in the host rock around the EDZ will also drive increased water flow into the EDZ and buffer, promoting saturation and consequent self-sealing of the EDZ (Lanyon 2019a, Lanyon 2019b) and increased saturation of the buffer. Buffer saturation is discussed further in the following section.

6.1.2 Buffer saturation

As noted in Section 4.2, it is possible that the near-field rock may have become substantially saturated by the time an HLW emplacement drift is sealed. In contrast, the HLW buffer will require a significantly longer period to saturate. Flow of water from the near-field rock to the buffer through the lining will occur in only a few places at first, most likely through joints between the concrete liner segments, and will also be affected by heterogeneity in EDZ development (effective permeability and pore volumes) along and around the repository drifts.

The block pedestal undergoes significant drying near the canister, which is also evident from RH measurements. Initially emplaced with a saturation degree (Sr) of 0.8, the blocks dry up to values below $Sr = 0.2$ in the first few years. However, this drying is limited to the initial period, before the temperature peak is reached, after which the buffer becomes globally hydrated. Although the saturation rate rapidly increases at external points of the buffer during the first few years, it

gradually decreases thereafter. Full saturation throughout the barrier is reached at roughly the same time. This is due to the coupled hydro-mechanical behaviour, where the external bentonite hydrates and the void ratio increases, causing the rate of saturation to evolve more slowly.

Conversely, at internal points, the saturation rate increases not only due to hydration but also due to compression from the external bentonite. The buffer is predicted to reach complete saturation after 80 years of operation (Bosch et al. 2023).

During the early post-emplacement period, a saturation front will develop due to the steep pressure gradient into high-suction bentonite material which drives vapour diffusion and/or liquid flow, resulting in early saturated conditions near the drift perimeter. Non-isothermal conditions will affect the further saturation behaviour of the bentonite buffer. In particular, porewater in the buffer will be evaporated and transported away from the canister by vapour diffusion into cooler regions, where the vapour will condense, creating a counter flow of liquid water towards the canister. These processes are illustrated in Fig. 6-4 and Fig. 6-5 and show the thermo-hydraulic (TH) conceptualisation at different stages of saturation of the HLW drifts. Swelling of the outer parts of the bentonite buffer may result in additional compaction and increased density close to the canister.

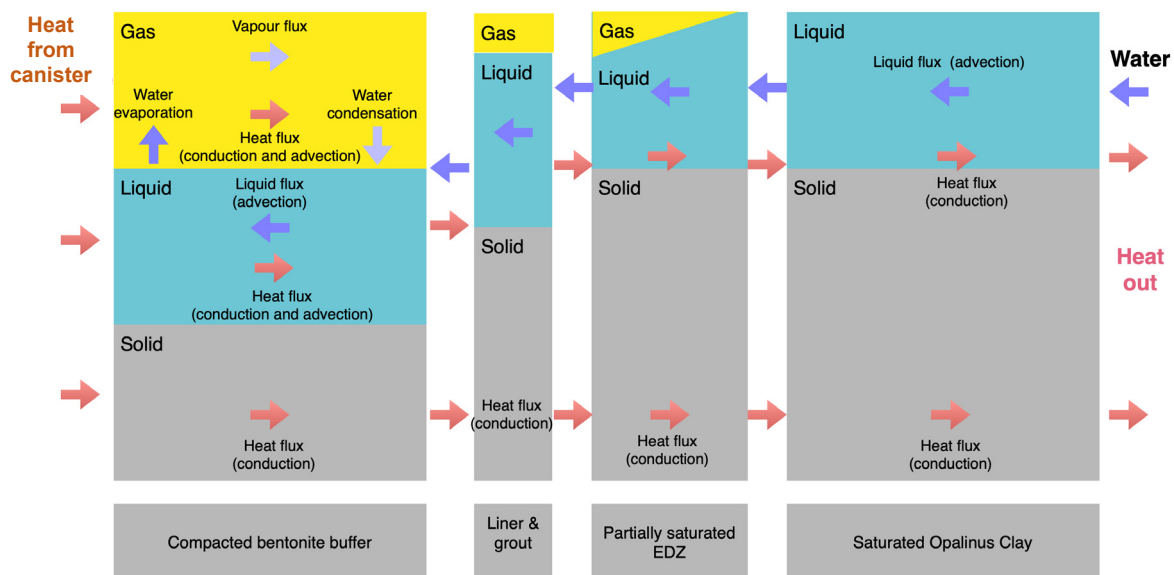


Fig. 6-4: Schematic illustration of coupled processes associated with vapour transport
Adapted from Gens et al. (2004). The schematic is simplified and shows the initial state.

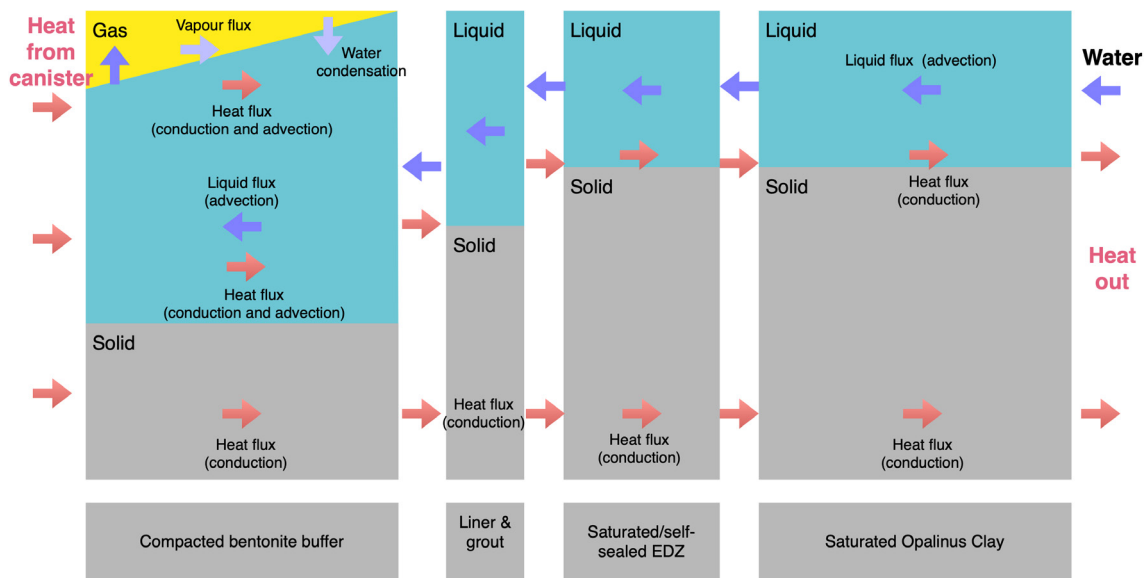


Fig. 6-5: Schematic illustration of coupled processes associated with vapour transport

Adapted from Gens et al. (2004). The schematic is simplified and shows how the saturation progresses.

Saturation of the buffer has been estimated to take about 200 years (Nagra 2024d). This resaturation may be significantly slower in the case of very low permeability of the OPA. No adverse effects are expected from a slower resaturation process. As defined here, the saturation phase ends with the close-to-full saturation of the buffer (a residual gas predominantly trapped at an air saturation of 1 – 2% is expected in the buffer at the end of the resaturation phase as the trapped gas will eventually and largely dissolve into the porewater and diffuse into the geosphere).

By then, it is likely that all construction and operations tunnels will have been backfilled and sealed, although the shafts will remain open to allow monitoring. The monitoring period will allow the saturation process to be followed in detail in the pilot repository, and any deviation from the expected evolution to be identified.

Initially, upon saturation, porewater pressures within the buffer will be much lower than those in the surrounding host rock but will increase thereafter.

6.1.3 Corrosion, gas generation and redox conditions

As noted in Section 4.2.4, most of the metallic materials will be covered with a film of corrosion products on their surface at their time of installation. It is assumed that this film of corrosion products will not protect the metals below from further corrosion. For components, especially the canister, which have a post-closure safety function, the aerobic corrosion phase is considered in the overall design. For the components contributing to the relatively short-term tunnel support, no corrosion allowance¹⁷ is included in the design and it is not taken into consideration for the tunnel support in the safety case.

¹⁷ For the metallic components of the tunnel support that do not require long-term safety considerations, “no-corrosion allowance” means that there is no additional margin included in the design to account for potential corrosion while still maintaining functionality.

Eventually, anaerobic and reducing conditions will be established throughout the near-field within and around the emplacement drifts. The transition to reducing conditions is an important change in the geochemical conditions in the near-field, affecting, among other factors, the type of corrosion and the corrosion rate of the canister. Reducing conditions are more favourable than oxidising conditions from the point of view of safety.

Based on recent findings (Tomonaga et al. 2019, Müller et al. 2017), the transition to anaerobic conditions might be shorter than previously assumed. In the FE drift, the gas composition revealed very low concentrations of residual oxygen only few weeks after backfilling¹⁸. Ongoing research is now investigating the mechanisms responsible for O₂ consumption. At the same time, gaseous H₂ has been observed, indicating the occurrence of anaerobic corrosion; however, after an initial peak, the concentrations are declining suggesting the presence of H₂ sinks.

Gas is expected to be generated in the HLW emplacement drifts principally as a result of anaerobic corrosion of metals, which produces H₂. Gas generation through anaerobic corrosion of the steel used in the tunnel support and of the canisters takes place following the establishment of anaerobic conditions throughout the pre-closure period and beyond. Most of the gas produced by corrosion in the first 200 years will dissolve in porewater (Papafotiou & Senger 2014). However, the remaining undissolved gas (mix of trapped air and a small amount of corrosion gas) may cause some delay to the full saturation of the buffer. H₂ gas pressure build-up in the near-field could increase H₂ absorption in the metal of the canister, leading to reduced fracture toughness. However, this effect can be considerably reduced by an appropriate choice of alloy and welding techniques (Turnbull 2009). Gas generated by corrosion of the canister will dissolve in the bentonite porewater and diffuse. If the gas production rate exceeds the rate at which the dissolved gas can diffuse, a discrete gas phase will form in the macropores and then accumulate until the gas pressure becomes sufficient to exceed the entry pressure, allowing advective flow to occur. Recent studies (e.g., Harrington & Horseman 2003, Harrington et al. 2017, Harrington et al. 2019) indicate that advective gas flow through compacted bentonite occurs via transient dilatant pathways. Gas may also temporarily accumulate in partially saturated regions of the buffer, potentially delaying saturation of these regions (Levasseur et al. 2020).

Corrosion of the steel canister and metal in the tunnel support will produce solid corrosion products and mobile iron species that will migrate through the buffer (as noted above). About half the oxidised iron species are expected to diffuse into the bentonite matrix while the other half will be incorporated into the corrosion product layer (Schlegel et al. 2014). The mobile Fe(II) species will eventually precipitate around the corroding components as Fe(III)-hydroxides. It is expected that, due to the precipitates, porosity will be reduced. The extent of these corrosion-affected zones will grow with time. Based on process-based models, the growth rate of such corrosion-affected zones in the buffer follows an asymptotic behaviour. This is because the reduction of porosity lowers the diffusion rate of corrosion products (Leupin et al. 2021). The precipitation is mainly due to redox reaction of the Fe(II) from the corrosion reaction with oxidation agents such as entrapped O₂ in the bentonite. Fig. 6-6 illustrates the current understanding of the interaction between steel corrosion and bentonite.

¹⁸ Similar observations have been made in the HotBENT experiment at the Grimsel Test Site and confirm the trend of O₂ disappearing rapidly from the gas phase.

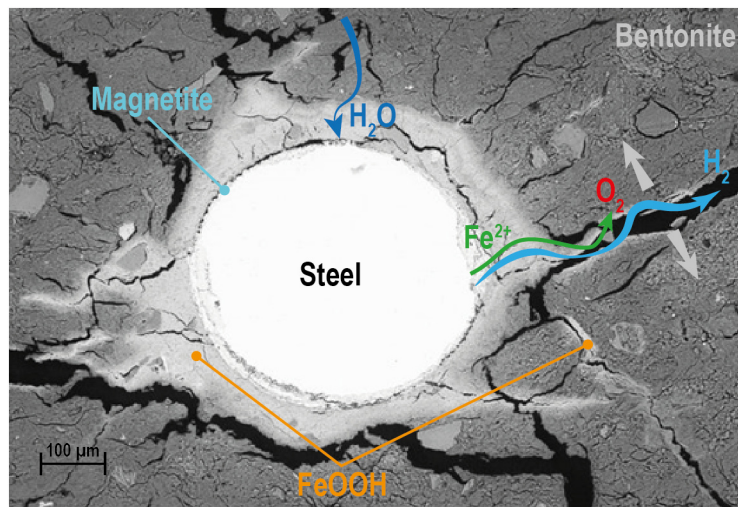


Fig. 6-6: Current understanding of the processes occurring at the canister-bentonite interface

Steel is corroded by the reduction of water that diffuses through the bentonite. At the steel surface, a magnetite layer forms. Unbound Fe^{2+} diffuses into the bentonite matrixes where it precipitates when oxidised by sorbed O_2 . Dessication cracks form due to a slow water transport in the bentonite, fast consumption by the corrosion at the metal surface and formation of H_2 gas. Smectite minerals are not expected to be altered by the precipitation of iron oxyhydroxides.

6.1.4 Swelling pressure development, tunnel convergence and evolution of the EDZ

The effective permeability of the EDZ is expected to undergo an initially rapid drop, followed by a slower, long-term reduction, as seen in experiments at the Mont Terri URL (Lanyon et al. 2014, Lanyon 2019a, Lanyon 2019b). Furthermore, the development of swelling pressure in the buffer will seal and potentially recompact the EDZ once the tunnel support degrades and loses its mechanical strength (see below). The full restoration of the initial mechanical properties of the rock is, however, not expected.

In the EDZ, self-sealing and filling of any ungrouted overbreaks by rock fragments and swelling of the OPA will continue. The EDZ will also be affected by the non-isothermal conditions, resulting in an accelerated recompaction due to thermal expansion of the host rock.

6.2 L/ILW emplacement caverns

6.2.1 Saturation conditions and initial gas generation

In the early monitoring phase of the repository, i.e., after emplacement and sealing of the L/ILW caverns and prior to deep geological repository closure, the hydraulic pressure gradient will be directed towards the cavern. As a result, the partially saturated EDZ will begin to resaturate (Fig. 6-7). It is expected that within a short time after deep geological repository closure (i.e., within decades following L/ILW emplacement in the caverns), the L/ILW emplacement caverns will have a very high relative humidity, whereas the availability of free water will depend on the chosen emplacement saturation of the cavern materials. Due to their different capillary suctions

(i.e., shotcrete, concrete disposal containers, container infill mortar, waste packages, concrete of inner-shell tunnel support), the high relative humidity in the cavern will lead to the redistribution of water within the capillary pores for the emplaced construction materials.

The high relative humidity is also sufficient to initiate anaerobic corrosion, which will generate H_2 at metal-type specific rates (cf. Diomidis et al. 2023).

After the excavation and ventilation period, the rock adjacent to the tunnel will have dried out (Fig. 6-7) as water will have been taken up by capillary suction into the OPA. By the time of deep geological repository closure, it is expected that the emplacement caverns might only be partially, i.e. locally, saturated, as hardly any water passes through the V1-L/ILW seal. It will take several hundred years until the EDZ reaches full saturation and several thousand years until the partial saturation degree of the bottom of the cavern increases. Nonetheless, anaerobic conditions will have rapidly developed during this phase due to the consumption of O_2 by aerobic corrosion and other processes.

Model calculations estimate that the net water inflow between the cavern and the EDZ in the early post-closure phase is very low (i.e., well below $1 \text{ dl/m}^2/\text{a}$ based on data extracted from repository-scale simulations from Papafotiou & Senger 2016a).

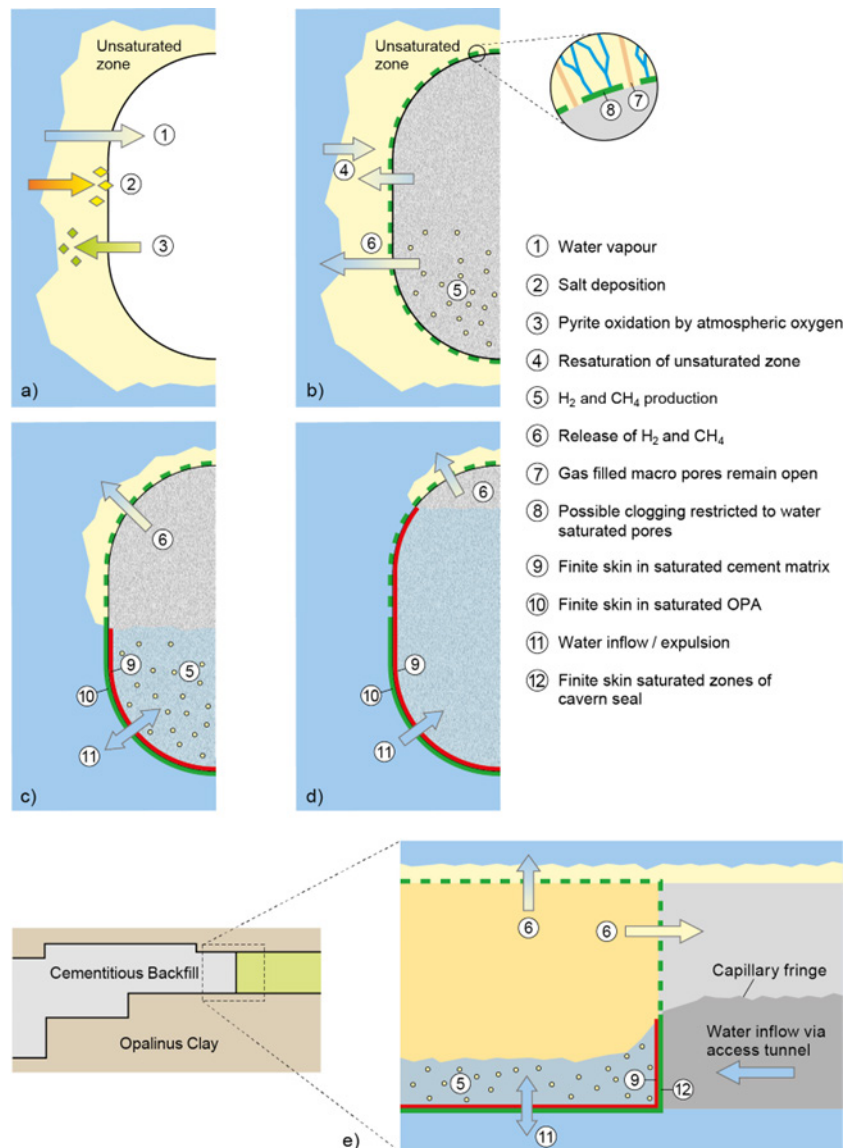


Fig. 6-7: Schematic sketch showing the evolution of the cavern near-field during the operational phase and after closure

a) Development of an unsaturated zone during the operational phase;

b) – d) Mass transfer processes in the early, middle and late post-closure periods (beyond 100 ka). A cement skin layer mostly only forms at the bottom of the cavern, allowing for gas to escape from the upper part of the cavern;

e) Mass transfer processes around the cavern plug after closure.

6.2.2 Near-field evolution: cement degradation stages and processes

The cement used in the L/ILW repository plays an important role in creating the desired chemical pH environment in the near-field of the L/ILW repository section.

Over the entire assessment period, the composition of the cementitious near-field is expected to evolve. For the scope of the safety analysis, the degradation of the cementitious material has been discretised into four cement degradation stages. In a simplified manner, these stages of cement degradation can be described as follows (Fig. 6-8; Wieland & Kosakowski 2020):

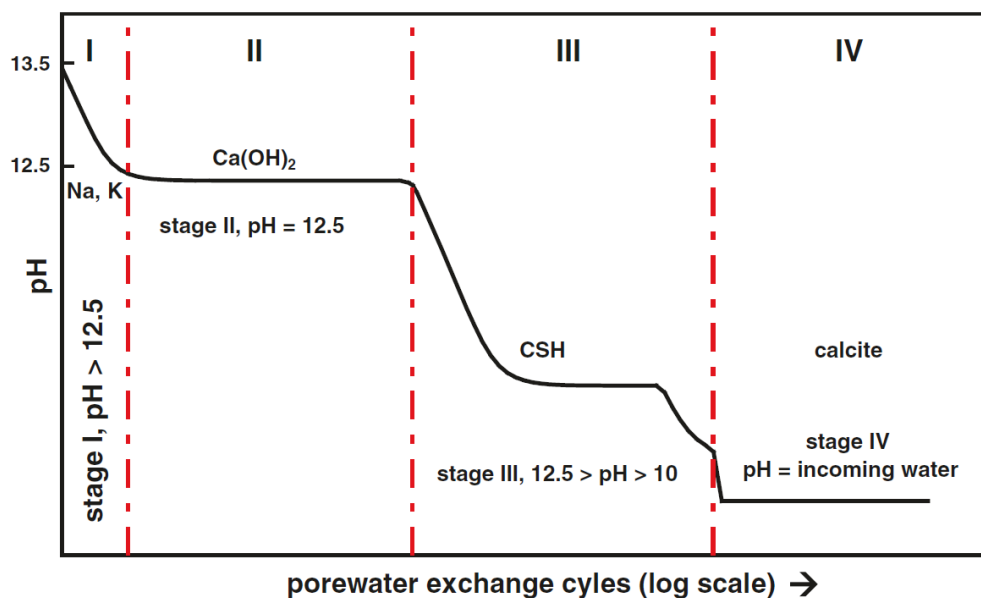


Fig. 6-8: Schematic representation of the generic degradation stages of cement
(after Ochs et al. 2016)

Stage I: This stage accounts for freshly hydrated cement with a pH of the porewater between 12.5 and 13.5 at 25 °C. The solution composition is dominated by high concentrations of free alkali metal ions, which are released from the clinker minerals during cement hydration. Equivalent OH⁻ concentrations are generated to fulfil charge balance.

Stage II: The porewater pH is buffered by portlandite solubility, which also fixes the total Ca concentration $[Ca]_{tot}$ at $\sim 2 \times 10^{-2}$ M and the pH at ~ 12.5 . However, its significance for radionuclide sorption is negligible. In the presence of portlandite, C-S-H phases with a high Ca/Si-ratio form. These C-S-H phases are key to the retention of metal cations. The initially amorphous C-S-H gel can gradually convert to a more crystalline phase to become a thermodynamically more stable mineral phase (e.g., Atkinson et al. 1989).

Stage III: This stage follows once portlandite is dissolved due to uptake of Ca by secondary precipitates (e.g., CaCO₃ in the case of CO₂ formation), exchange of Ca with the solutes of the porewater or the dissolution of fine-grained siliceous components, providing silica to the system. The pH drops continuously to reach values between 10 and 12.5, controlled by incongruent dissolution of the C-S-H phases. The Ca/Si ratios of the C-S-H phases change from initially ~ 1.65 at pH ~ 12.5 to ~ 0.8 at pH ~ 10 as a consequence of the incongruent dissolution of the C-S-H phases (Tits et al. 2014, Atkins & Glasser 1992). Congruent dissolution of the C-S-H phases

occurs at the end of Stage III, buffering the pH at ~ 10 (Ochs et al. 2016). With the degradation from Stage II to Stage III (as defined by Wieland & Kosakowski 2020), a reduction of the sorption is expected.

Stage IV: This stage is reached when all cement mineral phases are transformed into calcite, zeolites and clays. This stage is only reached in theory as it reflects a situation at full thermodynamical equilibrium.

An additional degradation process is the so-called alkali-silica reaction: alkali elements from the aggregate react with the cement paste, forming voluminous alkali-silica reaction products resulting in cracks (see Section 7.2.3).

6.2.2.1 Initiation of cement-clay interaction

Interactions between cement and clay occur where they are in close contact, especially in the OPA below the massive volume of concrete at the floor of the cavern.

A typical phenomenon related to cement-clay interaction is that, either in the clay or in the cement, a zone with altered porosity is formed at the interface due to ion exchange and the pH gradient. This leads to local mineral dissolution and precipitation (cf. Prasianakis et al. 2022). As demonstrated in the Cement-Clay Interaction (CI) Experiment at the Mont Terri Rock Laboratory (e.g., Maeder et al. 2017, Bernard et al. 2020), ten years of interaction between OPA and Portland cement have resulted in portlandite dissolution in the cement up to ~ 0.2 mm from the interface, ~ 1 mm for ettringite and in the partial depletion of C-S-H up to around a millimetre (Bernard et al. 2020). Dissolution of clay minerals remained below detection. As discussed in Prasianakis et al. (2022), reaction kinetics at the interface slow down with time. Luraschi et al. (2020) demonstrated that skin zones with a low porosity limit the diffusive transport of HTO and $^{36}\text{Cl}^-$ across the interface. After around 3.5 to 6 years of reaction, very limited diffusion of HTO and $^{36}\text{Cl}^-$ through the alteration front was observed in the experimental setup. With respect to the repository scale, it is not expected that a fully continuous impermeable skin will form around the caverns. Zones of reduced porosity might be expected in the floor region of the cavern, where full saturation is expected to occur first. Furthermore, clogging of fully saturated nanopores (e.g., interlayer pores of clay mineral or C-S-H phases) do not provide sufficient volume for the precipitation of solids and therefore cannot be clogged (Prasianakis et al. 2022, Martin et al. 2023). As a result, release of dissolved H_2 will always be possible across a cement-clay interface.

Chemical evolution in a waste drum

Waste with metallic and/or organic constituents may be highly heterogeneous and often embedded¹⁹ in a cementitious matrix. In many cases, the operational waste may have been conditioned decades before it is emplaced in the repository and therefore its internal degradation will have begun long before emplacement. The extent of this degradation is dependent on the components of the waste, the exposed surface areas, the chemical environment within the waste drum, the degradability of the materials and the overall presence of water, e.g., waste that contains large amounts of readily degradable organics will degrade faster than waste consisting of slowly reactive material.

Kosakowski et al. (2020) modelled the chemical evolution of a single waste drum, mainly containing readily degradable cellulose, slowly degradable organic materials (plastic, PVC, rubber), cement paste, quartz sand and steel.

¹⁹ Note that in other waste drums, ion-exchange resins could also be conditioned in nitrate-free bitumen and polystyrene, both assumed to be only weakly soluble. Vitrified slags, incineration products from L/ILW, are directly placed in coquilles, themselves placed in disposal containers, and backfilled with cementitious grout.

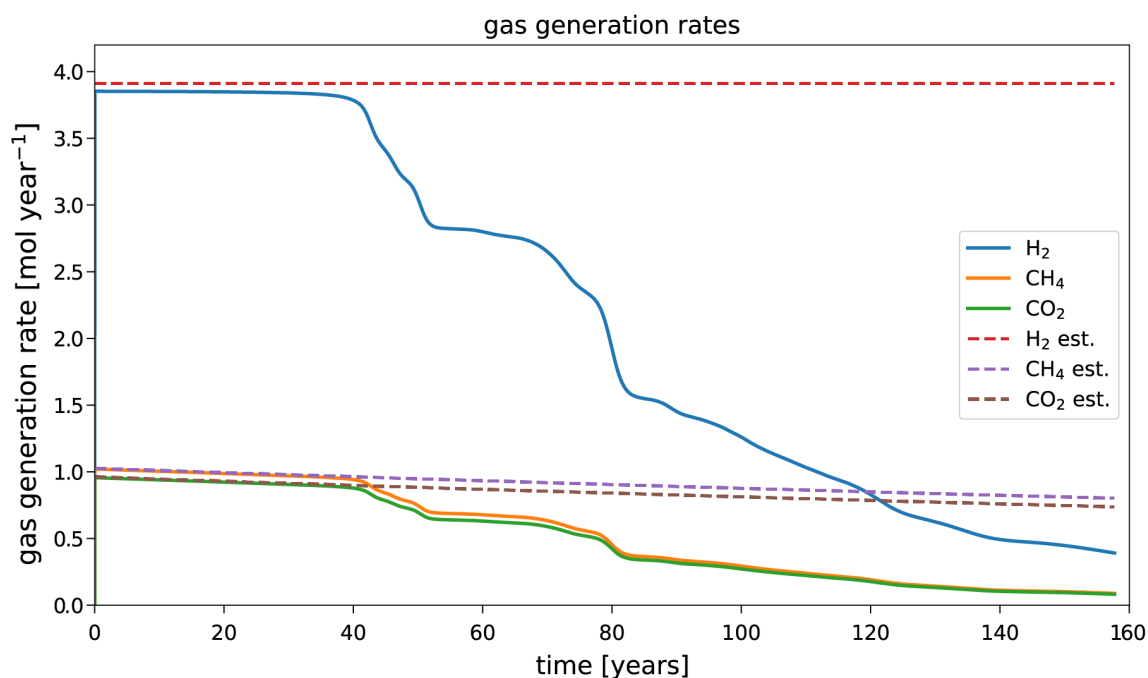


Fig. 6-9: Gas generation rates as a function of time for a model waste package (Kosakowski et al. 2020)

Solid lines are results accounting for the limited availability of water and dotted lines are results assuming unlimited availability of water.

Fig. 6-9 illustrates the modelled gas generation of a sample waste drum during the first 100 years. The model highlights the importance of the availability of water with regard to the degradation processes. Whereas the mortar is almost fully water-saturated at the time it is emplaced, water is continuously consumed. Water consumption occurs due to metal corrosion, generating H₂ in the early phase, and dissolution of siliceous aggregates resulting from interaction with the high pH of the cement by means of a pozzolanic reaction. Once water is consumed, gas generation rates decrease (solid lines Fig. 6-9). If the amount of water is unlimited, continuous gas generation at the initial high rates occurs (Fig. 6-9 dashed lines). The limited availability of water significantly slows down waste degradation and gas generation (Kosakowski et al. 2023). In contrast, the limited availability of water in the L/ILW cavern helps to maintain an alkaline cementitious near-field with favourable sorption conditions over extended periods of time. Additionally, this scarcity of water also serves to restrict gas generation caused by waste degradation.

6.2.2.2 Evolution of the waste drums

As described earlier in Section 4.2.4, the strongly reinforced disposal containers are manufactured using high-pH alkaline Portland cement to ensure the passivation of the steel and to contribute to the integrity of the waste drums. The same applies for the activated steel emplaced in a cement suspension. Water is not expected to seep through the host rock and the tunnel lining into the cavern in the early post-closure phase. However, given that water would be present, it will be taken up by capillary suction from the concrete elements. Therefore, for the early post-closure phase, the integrity of the container, waste drums and the concrete segments can be assumed, and no free water will be available.

6.3 Access tunnels, plugs and auxiliary underground facilities

Following the completion of waste emplacement, a monitoring period is foreseen that will comprise two phases.

During the first monitoring phase, construction and operations tunnels remain open. The evolution of the access structures and the surrounding near-field rock is expected to be qualitatively similar to (i.e., involve broadly the same processes as) the pre-emplacement evolution of the emplacement drifts and caverns during this phase. However, the repository access structures will remain open significantly longer than the emplacement drifts and caverns and the influence of this open period, e.g., the extent of desaturation of the rock around the structures, is thus expected to be greater.

In a second phase, the operations tunnel will be backfilled with a sand/clay mixture or crushed OPA, with only the test area and pilot repository remaining accessible. Inflow from the OPA will saturate the backfill over time in a qualitatively similar manner to the saturation of the emplacement drifts and caverns described in Sections 6.1 and 6.2, although the access structures are expected to remain mostly partially saturated for several tens of thousands of years after closure of the deep geological repository (Martin et al. 2023).

6.4 Potential impact of imperfect manufacturing and emplacement of closure components

A key challenge is to avoid improper backfilling of access structures as this could result in the segregation of the material and, in turn, lead to heterogeneous material properties (“nests”). Over time, the concrete lining’s support resistance will deteriorate, and as the backfill material compresses, the tunnels and drifts will begin to deform and converge. This gradual deformation can ultimately contribute to the expansion of the EDZ.

6.5 Summary of main THM processes and key factors influencing these

Tab. 6-1 and Tab. 6-2 summarise major and less important THM processes occurring, respectively, in the HLW emplacement drifts and L/ILW emplacement caverns prior to deep geological repository closure, as well as key factors that influence the rate or extent of these processes.

Tab. 6-1: Processes occurring in the HLW emplacement drifts prior to deep geological repository closure

Most important processes	Onset of EDZ and buffer saturation; Self-sealing of EDZ due to saturation; Temperature increase in buffer, EDZ and host rock due to thermal output from canister.
Less important processes	Onset of the degradation of rock support and local failure of the segmental lining (concrete liner segments); Extension of the EDZ due to resaturation, tunnel convergence, thermal stress and thermally driven pore pressure increase; Saturation of seals.
Key factors	Ability of OPA to provide water to saturate EDZ and buffer; Water volumes required for saturation (porosity and initial saturation of buffer); Thermal loading of deep geological repository (canister output and spacing); Stiffness of host rock and long-term strength response to thermal overpressure.
Supporting dataset	FE and HotBENT experiments post-closure.

Tab. 6-2: Processes occurring in the L/ILW emplacement cavern prior to deep geological repository closure

Most important processes	Onset of EDZ resaturation; Partial decrease in O ₂ pressure; Cement-clay interactions and loss of anion-accessible porosity and thus permeability at the interfaces (in the area of the tunnel sole; note that the interlayer porosity will remain available for the transport of dissolved gases and neutral species); Gas generation and pressure build-up due to anaerobic corrosion of metals.
Less important processes	Onset of gas production from degradation of organics; Onset of rock support degradation and local failure of the lining.
Key factors	Gas transport through the EDZ; Relative rates of occurrence of different processes over this period, including internal cement degradation by aggregate-cement interaction, carbonation of the cementitious phases, O ₂ consumption, water inflow and (partial) saturation, passive corrosion, and precipitation of corrosion products (giving rise to potential loss of pore volume to accommodate water inflow and gas distribution, most cement in degradation Stage II and locally Stage III (see Fig. 8-2).
Supporting dataset	Modelling exercise(s), e.g., Kosakowski et al. (2020), Wieland et al. (2018), Diomidis et al. (2016).

7 Processes during the post-closure period

Closure of the repository involves the stepwise backfilling of all remaining underground structures, the installation of seals within the access structures to plug the individual disposal areas and within the underground access structures (which also serve to re-establish the permanent hydraulic separation of aquifers) as well as the installation of durable deep geological repository markers. The total length of the access tunnels of the disposal areas will be backfilled with appropriate materials such as sand/bentonite or sand/crushed clay mixtures that ensure a diffusive transport regime, but also allow for a low gas entry pressure to avoid the build-up of potentially damaging gas pressures. A favourable property of clay-based backfill materials are the generally good retention properties for various radionuclides.

Closure also involves all activities that are required for the nuclear and conventional decommissioning of the surface infrastructure, including the disposal of small amounts of radioactive waste that may arise. Technology and procedures for these activities are readily available.

This chapter describes the continuing evolution of the deep geological repository after closure. The HLW and L/ILW repository sections are described separately. This includes their access structures, which evolve differently, mainly due to the higher rates of gas generation as the access structures for the L/ILW underground facilities are designed to act as conduits for gas release.

7.1 HLW underground facilities

Fig. 7-1 gives an overview of the long-term, post-closure events and processes occurring in the HLW emplacement drifts of the HLW repository section and of the interactions between the drifts.

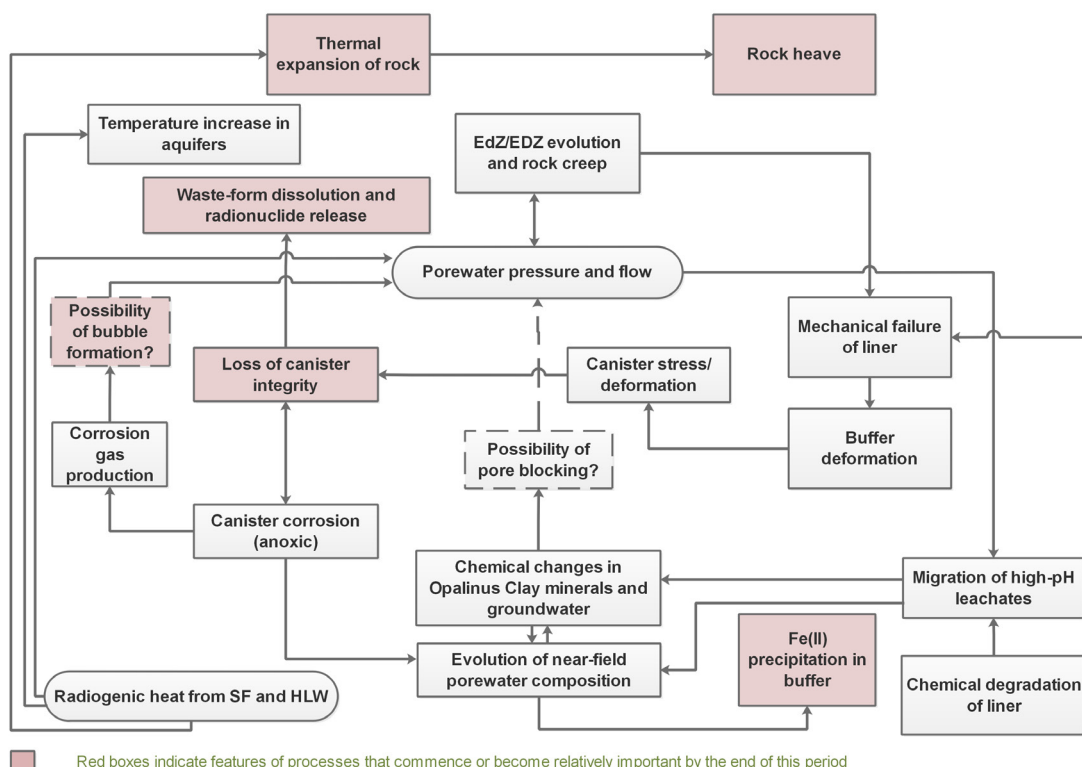


Fig. 7-1: Expected interdependencies of processes and phenomena in the HLW repository section after closure

7.1.1 Evolution while significant radiogenic heat is produced

In the case of the SF emplacement drifts, in the period up to around 1,000 years after closure, the canister surface temperature will decline from around 130 °C to around 60 – 80 °C. During this period, the near-field rock temperature will also decline. Anaerobic corrosion of metallic deep geological repository components will continue to generate gas. Fig. 7-2 illustrates the main THM processes occurring during this period.

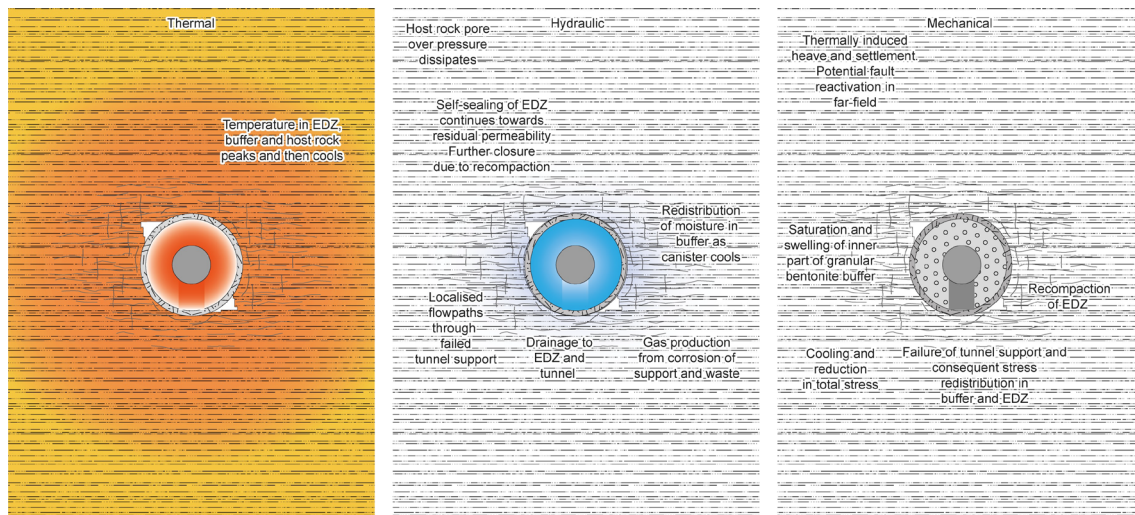


Fig. 7-2: Expected THM processes during the period of 100 – 1,000 years after deep geological repository closure for an SF emplacement drift

Porewater and groundwater pressure will be affected by heat generation and, to a lesser extent, gas generation throughout this period. Within the EDZ, the magnitude and evolution of the increase in porewater pressure will depend on the evolution of saturation and permeability (Lanyon 2019b). Pressures will remain low while the buffer is not fully saturated and the EDZ has not sealed. Porewater pressures immediately around the emplacement drifts have been calculated to reach a maximum of about 5 MPa above the initial formation pressure between 500 and 1,000 years after sealing off the drift. At a greater distance from the drifts (20 m from drift axes and beyond), the porewater pressure will increase for about 500 years and then begin to decline. The increased pressure due to the thermal evolution is not expected to be strong enough to cause any significant mechanical effects in the intact host rock (fracturing) or the reactivation of faults. Furthermore, several studies have illustrated the rapid sealing of fractures in OPA to self-seal (Lanyon 2019b, Nagra 2002, Nagra 2024c), so that, even if fracture creation were to occur, no significant long-term increase in the hydraulic conductivity of the host rock is expected. However, increasing pore pressure in the EDZ and reduced effective stresses could lead to some further development of existing EDZ fractures. In the confining units, groundwater pressures will experience only minor increases. No significant mechanical effects on the rock in the confining units due to these pressure increases are expected.

The thermal expansion of the rock sequences above the HLW repository section will result in a heave of the ground surface. By assuming a thermal dilation coefficient of about 2.0×10^{-5} per °C for OPA, Te Kamp (2008) calculated a maximum vertical displacement of about 4 cm at the level of the HLW underground facilities (after 300 years) and about 10 cm at the ground surface after 10,000 years. Complementary thermo-hydraulic simulations by Senger et al. (2014) confirmed the order of magnitude of these calculated heaves.

The limited magnitude of the strains resulting from these thermally induced heaves means that faults are not expected to be reactivated by this process. Induced pore pressure gradients in the confining units could potentially lead to flow disturbances along faults (López & Smith 1995) and within other permeable features (Bjørlykke et al. 1988).

The cementitious tunnel support will continue to slowly degrade, and an alteration zone due to the pH gradient between the clay materials and cementitious material is expected to affect a few centimetres of the host rock and bentonite on either side of the tunnel support (Savage 2013, Savage & Cloet 2018, Prasianakis et al. 2022, Curti et al. 2023). Partial dissolution of the smectites in the outermost few centimetres of the bentonite might occur (Savage & Cloet 2018) and precipitates can form in the pore spaces of these materials, leading to the possibility of some pore clogging (skin formation). As learned from the investigation of cement-bentonite interfaces in the scope of the CI experiment, the main alteration of up to 10 – 15 mm took place within the first 5 years but hardly progressed up to 10 years. Further, no montmorillonite dissolution was detected, and no significant cation exchange, no change in the mean-layer charge and no illitisation or beidelitisation have been observed (Yokoyama et al. 2021). This implies that the safety-relevant properties of the bentonite are not affected by interaction with cement (Prasianakis et al. 2022).

Tab. 7-1 summarises both major and less important THM processes occurring in the HLW emplacement drifts after closure in the period during which significant radiogenic heat is produced, as well as key factors that influence the rate or extent of these processes.

Tab. 7-1: Long-term post-closure processes occurring when significant radiogenic heat is produced

Most important processes	Ongoing saturation of the EDZ and buffer. Self-sealing of EDZ due to resaturation; Swelling of buffer and possible recompaction of EDZ (after degradation of rock support); Temperature peaks in EDZ and host rock due to reducing power output from canister. Cooling of buffer and EDZ with reduction in thermal stresses; Thermal heave and subsequent settlement.
Less important processes	Degradation of rock support; Gas production around canisters and, to a limited extent, from metallic tunnel support (sealing sections) in parallel with significant buffer saturation; Potential reactivation of faults as well as failure of intact host rock between emplacement drifts due to thermally induced effective stress changes.
Key factors	Thermal loading of deep geological repository (canister output and spacing); Water volume needed for saturation of EDZ and buffer, together with the limited rate at which the OPA can provide water; Stiffness (storativity) of host rock and long-term strength response to thermal overpressure and then cooling stress path.

7.1.2 Evolution after the non-isothermal period

Temperatures within and around the repository will continue to decline. In the case of the SF emplacement drifts, the buffer temperature will fall from about 60 °C to about 50 °C in the period from 1,000 to 10,000 years after closure and, in the host rock around the drifts, the temperature will decrease to around 10 °C above geothermal gradients ambient. Gas production rates in both the SF and the HLW emplacement drifts will reach a steady state, although gas generation from corrosion of the thick-walled disposal canisters will continue. Fig. 7-3 and Fig. 7-4 show illustrative representations of the HLW near-field.



Fig. 7-3: An illustrative representation of an HLW emplacement drift in the period following deep geological repository closure

The artistic rendering shows the status after the canister have breached. The now mostly isothermal conditions have led to a completely saturated buffer. The radionuclides from the HLW dissolve in porewater that enters through the breached canister and start to diffuse into the buffer. The cementitious lining is not expected to have any structural functionality at this stage. The interfaces reach a thermodynamical equilibrium.



Fig. 7-4: An illustrative representation of the drift when no metal remains

After more than 60,000 years after deep geological repository closure, the canister has collapsed and has lost its structural integrity. Ongoing out-diffusion of radionuclides is the dominant safety-relevant process occurring at this stage.

Due to reduced thermal and gas-related effects, groundwater/porewater pressures within and around the drifts will fall by several MPa. Thermal contraction of the rock and porewater may result in some compaction, but this will be limited due to the slow rate of temperature reduction. Based on current understanding, no compaction of the bentonite around the canister is expected to occur as the adjacent rock reconsolidates. The EDZ is expected to have largely self-sealed by this period, although increased gas pressures may keep some pathways open.

Beyond 10,000 years after deep geological repository closure, the temperatures will further decrease towards ambient values. Corrosion and gas production will continue for tens of thousands of years. As described in a dedicated report (Nagra 2024b), the carbon steel canisters engineered to contain the high-level waste are designed to ensure complete isolation for a minimum of 1,000 years. With time corrosion may result in canister breaching. Stress intensification at pre-existing weld flaws, coupled with metal embrittlement due to hydrogen uptake, could lead to localised openings in the canisters. This poses a risk by creating potential pathways for water from the buffer to access the fuel assemblies, ultimately contributing to canister breach. The main processes associated with canister breach are detailed in Tab. 7-2.

Once such pathways are formed and intersect the full or remaining thickness of the canister, porewater from the saturated bentonite can enter the cavities inside the canister. This will then initiate corrosion of the waste package and the previously intact internal surfaces of the canister. Consequently, anaerobic iron corrosion and gas production may likely increase after the failure of the canisters. Entering porewater will come into contact with various materials, including Zircaloy cladding, other structural materials (mainly Ni-Cr alloys), and the SF pellets or the vitrified waste (Curti et al. 2023).

The interaction of these will start reactions among these materials and may lead to the partial diffusion of radionuclides from the breached containment. Porewater in contact with the Zircaloy SF cladding, the SF pellets (when the cladding has failed), the HLW stainless steel flasks and the HLW matrix when the flask has failed will equilibrate. It is not expected that large quantities of bentonite will enter the canister along with the porewater (Curti et al. 2023).

After water enters the canister interior and corrodes the Zircaloy cladding, the instant release fraction (IRF) is released and fractions of the radionuclide inventory of Cs^{137} , ^{129}I , ^{36}Cl , ^{79}Se , ^{14}C , ^{126}Sn , ^{90}Sr , ^{107}Pd and ^{99}Tc (Johnson et al. 2023) diffuse into the solution, through the saturated buffer and degraded lining, and into the host rock. The majority of the radionuclide inventory (around 97%) will be slowly released by fractional dissolution with a reference rate of 10^{-7} a^{-1} (Johnson et al. 2023).

The corrosion products formed during the evolution of the near-field are likely to contribute to the attenuation of radionuclide release when the canisters eventually breach.

Canister breaching will expose internal metal surfaces to water and consequent corrosion, increasing gas production rates locally. As a result, the porewater pressure in the rock surrounding the drifts will increase again slightly, before gradually declining until corrosion is complete after about 50,000 – 100,000 years (Fig. 7-4).

As a result of the corrosion processes, H_2 will continuously form and be transported, in dissolved form and/or as a gas phase, through the buffer into the EDZ. At that point, the lining and the annular gap filling material will have lost any mechanical integrity and will have chemically degraded.

In general, potential interactions of engineered components (e.g., canister metals, cementitious tunnel support) with the bentonite buffer will lead to precipitation of secondary minerals and thus reduce buffer macroporosity with time. In the long term, this will lead to the partial occlusion of the buffer macropores, thus limiting the scale of transformation through mass transport considerations. The slow, time-dependent nature of mineral transformation processes means that not all can be readily studied by conventional laboratory experimental procedures. Consequently, the results of published reaction and transport simulations have been important in defining the scale of mineral transformation and the key properties that affect it over timescales relevant to post-closure safety.

Nonetheless, several interactions with bentonite have been assessed experimentally at different scales or have been investigated with natural analogues. These include:

- Effects of the thermal output of the waste;
- Interactions with the concrete tunnel support;
- Interactions with the corrosion products of various metallic engineering components.

Despite the differing nature of the chemical interactions of bentonite with concrete and with corrosion products, the timescales of bentonite alteration are considered to be similar in both cases due to the similar rates of key processes, such as montmorillonite dissolution and the growth of zeolite and sheet silicate minerals at alkaline pH. However, it should be noted that:

- Alteration of the bentonite by concrete moves in the same direction as the saturation front;
- Alteration of the bentonite by steel corrosion moves in the opposite direction to the saturation front and occurs somewhat delayed to provide conditions needed for corrosion to occur.

As reported by Jenni et al. (2019), the expected evolution of the bentonite in the HLW near-field does not result in a failure at fulfilling the long-term safety requirements.

Tab. 7-2: Processes relevant to canister breach and corrosion of spent fuel baskets

Canister breaching	The carbon steel will slowly react with water to create magnetite and H₂. Porewater will eventually enter the canister as vapour through microcracks formed at the welded lid. The surfaces of the microcracks are quickly transformed into magnetite which reduces the aperture. The inert gas inside the canister will start to diffuse through the bentonite.
Bentonite porewater enters the canister	Once the RH of the canister has reached a threshold value and water condensates at the inner part of the wall, a continuous water film can be built up. Anaerobic corrosion transforms steel into magnetite, covering the surface and thus resulting in a passive film that reduces the corrosion rate. The ongoing corrosion of the inner wall of the canister results in an increasing H₂ partial pressure. Inert gas continuously diffuses from the canister.
Release of radionuclides	Once the RH is high enough, the Zircaloy tubes will start to slowly corrode (< 10 nm/yr). When the Zircaloy tubes lose their integrity, an instant release of fission gas is to be expected. Once the degree of saturation allows the radionuclides to dissolve in the porewater within the canister and diffuse through the microcracks of the canister, it will come into contact with the bentonite. Inside the canister, a high partial H₂ pressure is maintained by the ongoing corrosion of the canister inside, creating highly reducing conditions.

7.2 L/ILW underground facilities

7.2.1 Saturation scenarios for the L/ILW underground facilities

Several scenarios were modelled using different gas generation rates, different permeabilities and lengths of seals for an L/ILW repository at 750 m b.g.l. (Papafotiou & Senger 2016a). According to model results, the repository will saturate with water in less than 10,000 years, if reference corrosion rates and highly gas-permeable seals are considered. In contrast, by assuming impermeable and longer seals, full saturation can take over 100,000 years.

At the end of the gas generation phase, i.e., after more than 100,000 years, the unsaturated zones in the host rock and in the emplacement cavern backfill will decrease in size, and the gas pressure in the emplacement caverns will equilibrate to hydrostatic pressure. Some isolated zones with a free gas phase will remain (i.e., trapped gas, most likely at the top of the emplacement caverns), but these will eventually disappear as a result of dissolution and diffusion processes.

The following simulations are based on a report (Martin et al. 2023) aiming at understanding the evolution of the sealing performance. The data underlying these simulations were extracted from (Papafotiou & Senger 2016a) and are based on corrosion and degradation rates reflecting the state of knowledge of that time. Newer corrosion and degradation rates are generally lower, thus delaying the peak of gas pressure to around 20,000 years after closure (Nagra 2024g). The overall saturation behaviour of the L/ILW underground facility, however, remains the same.

L/ILW emplacement caverns

Degradation of organic materials can be triggered by free water phases and microorganisms (e.g., due to the presence of the initial unbound water within the waste packages as a result of manufacturing processes). The rates of gas production (such as CH₄ and CO₂) depend on the different degradation kinetics of the organic materials considered (cf. Guillemot et al. 2023). Gas generated by the anaerobic corrosion and degradation of organics in the L/ILW emplacement caverns will first dissolve into the cement porewater in intimate contact with the degrading material and then, once the solubility limit is reached, eventually form a gas phase. Because of the high solubility of CO₂ gas in cement porewater, the formation of a free CO₂ gas phase is not to be expected.

Over time, due to gas accumulation and resulting gas pressure buildup, large capillary pores will desaturate with water and become saturated with gas if not blocked by precipitates that would result from chemical interaction at interfaces. The blocking of these pores can somewhat reduce the inflow of water. In capillary pores, where water is bound (e.g., nanopores such as interlayer pores), neutral species or gas can dissolve and be released to the OPA (cf. Prasianakis et al. 2022, Martin et al. 2023).

Water exchange between the caverns and the surrounding EDZs during this period may take place in both directions, depending on the interplay of capillary, viscous, and gravity forces at different elevations of the cavern wall. At later periods of the post-closure phase (around 1,000 to 10,000 years), the increase of gas pressure in the cavern will result in water expulsion into the surrounding rock. Thereafter, in the late post-closure phase when gas pressures decrease and the EDZ becomes fully resaturated, the flow direction will once again reverse and will be directed from the EDZ into the cavern. However, water fluxes during this long resaturation phase will remain low (cf. Martin et al. 2023). Therefore, water accumulation in the caverns will happen very slowly and will be confined to the bottom parts of the caverns, while highly desaturated conditions, with pore space occupied by remaining gas, will remain stable in the upper parts for several tens of thousands to hundreds of thousands of years.

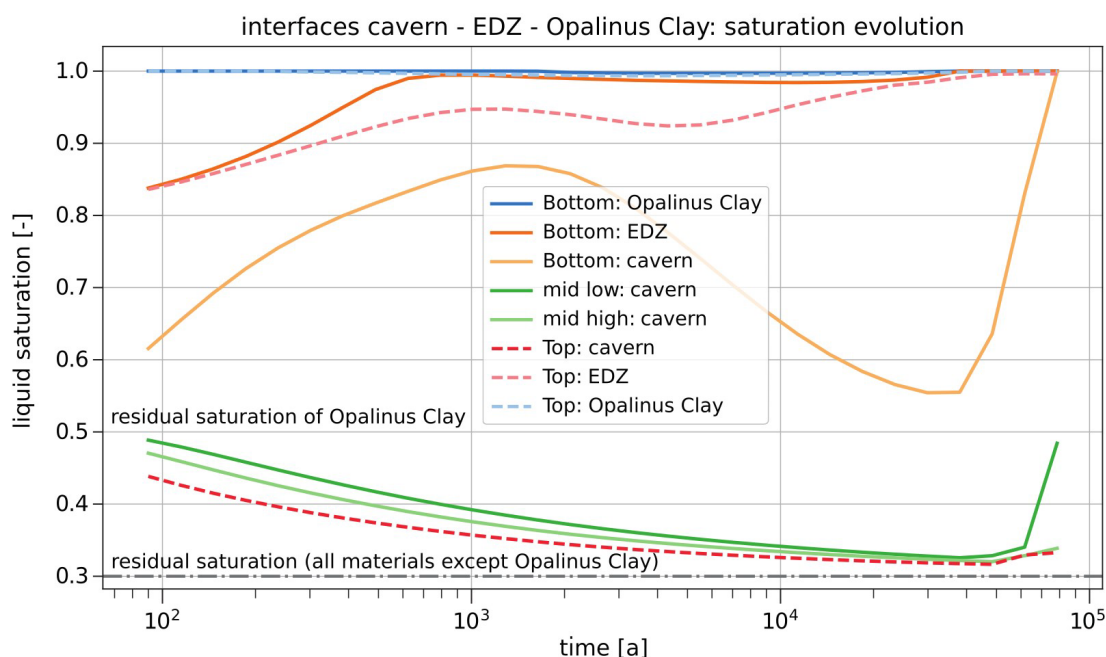


Fig. 7-5: Temporal evolution of liquid saturation of an L/ILW emplacement cavern and neighbouring materials extracted from the base-case model in Papafotiou & Senger (2016a)

7.2.2 Internal degradation of cement-based elements

The long-term chemical evolution of the L/ILW near-field depends on the degradation of the cement-based elements in combination with the degradation of the steel in the waste and cavern reinforcement, as well as the organic material present within the waste. Internal degradation of cement may occur through the carbonation process, the pozzolanic reaction, alkali-aggregate reaction or cement-aggregate interaction.

In the early post-closure phase, the cement can be expected to still be either in cement degradation stages I or II (see Section 6.2.2) except for some cement formulations where a low-pH cement was used, i.e., where all portlandite has reacted by design and the composition will be at the onset of degradation Stage III. Cement porewater present within the cement paste will still be highly alkaline, which will passivate the steel reinforcement and the activated metals embedded in a cement and inhibit microbial activities.

With respect to the degradation of cement, all the reactions above are controlled by the availability of water, CO_2 and, more generally, the chemical conditions in the repository. As indicated above, no free water is expected at this stage in the repository evolution, but partially saturated conditions occur.

Whereas O_2 will already have been consumed (see Section 6.2.1), CO_2 and CH_4 will have been generated by degradation of organics present in the waste. The presence of CO_2 will slowly lead to the carbonation of the surfaces of various cement-based elements. The rate-limiting factors for carbonation are the generation and speed of diffusion of CO_2 . The extent of carbonation depends on the local availability of CO_2 and the amount of cement paste in contact with CO_2 -containing porewater. Therefore, no massive carbonation is expected in this phase of evolution.

Degradation of disposal containers and impact of different types of container infill mortars

The disposal container and the disposal infill mortar will, for a certain period, contribute to the integrity of the waste drums and contribute to the slow release of radionuclides. However, an actual prediction of container failure is difficult given the spatially heterogeneous evolution of the cavern and progression of cement degradation. For the analysis of the radiological consequences, it is therefore assumed that all waste constituents and components are homogeneously mixed in a fully saturated emplacement cavern and the disposal container and its nuclide retention properties are not taken into consideration.

Wieland et al. (2018) calculated the long-term evolution of a low-pH cement with siliceous aggregates for the conditioning of metallic decommissioning waste. Small concentrations of readily degradable organic material with low molecular weights, such as diethanolamine, formaldehyde, gluconic acid, methanol, melamine resin, etc., are present in this waste type, as well as, to some extent, in the cement used for its conditioning (Wieland et al. 2018, Kosakowski et al. 2020). The degradation of the concrete in the model is caused by (i) degradation of organic materials producing CO_2 , which leads to carbonation and (ii) degradation of the cement by its interaction first with the silica fume and then with the siliceous aggregates.

Wieland et al. (2018) (see Section 6.2.4.1 of their report) showed that in a low-pH cement, portlandite is completely converted to C-S-H phases due to the addition of the microsilica upon curation. This implies that this mortar is already in degradation Stage III when it is emplaced in the deep geological repository.

Modelling results show that after around 1,300 years, the pH decreases to < 10.5 in the cement porewater. After 1,500 years and given the presence of zeolites, all water in the waste is expected to have been consumed, bringing the reaction to a halt. In the absence of zeolites, the chemical evolution of this waste type is slower, extending to around 5,000 years. This is because zeolites take up alkali elements, which contribute to maintaining higher pH conditions for longer and thereby slowing corrosion and water consumption (Kosakowski et al. 2020).

If the aggregates are made of pure limestone (i.e., CaCO_3 without SiO_2 present, as in siliceous limestone), this would result in the long-term durability of the cement-based materials from a chemical point of view. In particular, a $\text{pH} > 12.5$ could be preserved for a much longer period (Wieland et al. 2018, Wieland & Kosakowski 2020, Kosakowski et al. 2020), see Fig. 7-6.

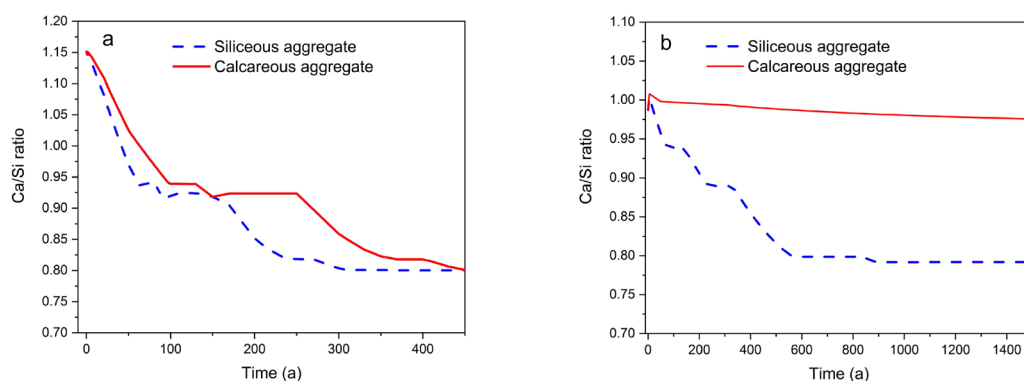


Fig. 7-6: Time dependence of the Ca/Si ratio of C-S-H phases for two different waste types (a) BA-PH-PF and (b) SA-L-MX, using siliceous or calcareous aggregates

Degradation of the waste drum within the disposal container

Loss of integrity of the waste drums within the disposal container may occur as a result of gas overpressure, corrosion-induced cracking or other mechanical damage, bringing the waste within the containers in an exchange with the infill mortar of the disposal container. If the waste includes large amounts of organics, CO₂ will lead to carbonation of the container infill mortar. Carbonation reaction will release some water, which may further accelerate chemical reactions. This can result in the further degradation of organic material, cement carbonation and steel corrosion until all organic material in the waste has been consumed, or the reactions come to a halt because of the limited availability of water.

7.2.3 External degradation of concrete elements: presence of water under partially saturated conditions

Processes mainly occurring under partially saturated conditions are discussed below covering the period of 10,000 to 100,000 years after deep geological repository closure (Fig. 8-2). Overall, lateral water movement is expected to be limited but, as previously indicated, water can accumulate in the lower parts of the caverns over long timescales, while the upper parts are still saturated with gas.

Disintegration of the disposal containers

The caverns will resaturate from the bottom up. As a result, the lower rows of concrete containers will lose their mechanical integrity earlier than the upper container rows. Different processes will contribute to or accelerate this disintegration: tunnel convergence, corrosion of the rebars, weight of the overlying containers, alkali-silica reactions, aggregate-cement interaction, carbonation, etc.

Fig. 7-7 shows the dissolution of the aggregates due to the alkaline cement porewater reaction (pozzolanic reaction) at a pH > 10, which can last for several tens of thousands of years (Kosakowski et al. 2023).

Volume increase by corrosion processes will induce mechanical stresses on the container walls, leading to their further disintegration. The surface area increase of the resulting pieces will further accelerate the disintegration of the concrete container. The same applies to the massive concrete structures within the cavern (inner-shell tunnel support, compartment walls, infrastructural elements, etc.).

As the cavern has no open spaces, no major mechanical displacement is expected. Nevertheless, the possibility of asymmetric tunnel convergence due to the disintegration of the concrete containers within the cavern cannot be discounted.

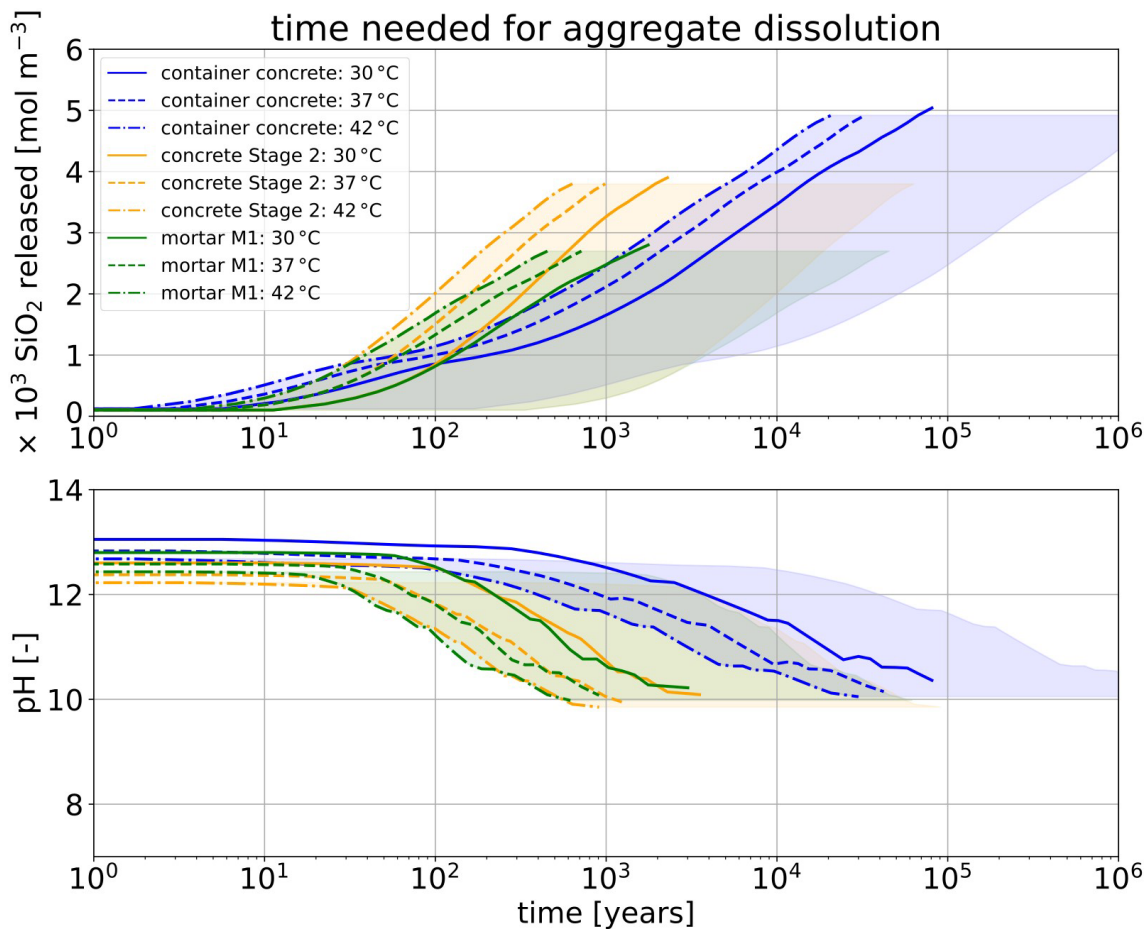


Fig. 7-7: Estimates of aggregate dissolution with time (upper figure) and pH evolution with time due to aggregate dissolution only (lower figure)

The vertical lines indicate the completion of aggregate dissolution, i.e. quartz is in thermodynamic equilibrium with the other mineral phases. The shaded areas show slowdown of aggregate dissolution rates of up to two orders of magnitude for the materials at 42 °C due to lower reactive aggregate surface area and desaturation. In principle, for a certain slowdown, curves are shifted to the right, i.e. for 100 times slower dissolution rates the curves are shifted from the left boundary of the shaded area to the right boundary. In reality, in highly desaturated (“dry”) materials aggregate dissolution rates are probably close to zero. (Kosakowski et al. 2023)

Degradation of the backfill mortar

Backfill mortar will carbonate at a rate that depends on the activity of CO_2 . In the case of siliceous aggregates, degradation Stage III might be reached after less than 1,000 years due to internal degradation (pozzolanic cement-aggregate reaction) (Kosakowski et al. 2020). Calcareous aggregates will significantly delay the degradation of the cement mineralogy in the backfill mortar.

Where the backfill mortar is in contact with water (initially in the lower part of the caverns), chemical leaching will result in the transformation of the cement minerals.

Chemical evolution of the water

The slow resaturation rate of the cavern preserves high-pH conditions because it limits the degradation rate of the waste, the concrete and the cement. By the time the disposal container has completely disintegrated, the porewater inside is equilibrated at a pH of < 10 . C-S-H phases are presumably still present but with a low Ca/Si ratio.

7.2.4 Corrosion of steel waste disposed of in MOSAIK containers

Corrosion of activated metals releases ^{14}C , mainly as volatile radionuclides. Some important sources of ^{14}C , e.g., activated reactor internals, are packaged and disposed of in MOSAIK containers (Nagra 2023b). The evolution of the environmental conditions inside a MOSAIK container is relevant in order to derive meaningful corrosion rates and associated ^{14}C release rates.

Evolving conditions inside MOSAIK containers

Apart from a comparatively rapid degradation of the seal, the rest of the container is expected to degrade very slowly. The alkaline anoxic environment of the emplacement cavern will lead to very low corrosion rates of the container walls and its lid (cf. (Diomidis et al. 2023)). The massive design and vertical positioning of the MOSAIK-II in the cavern reduces the probability for important mechanical deformation that could lead to early structural damage. This means that no porewater is expected to enter the container until the repository has saturated enough that the water level in the cavern reaches the height of the container lid and can flow inside. When this happens, the composition of the porewater will define any reactions occurring inside the container.

If the saturation of the cavern slowly proceeds from the floor of the cavern to the upper part towards the ridging of the cavern, the MOSAIK containers emplaced higher up would saturate later and thus impact the release of ^{14}C .

7.3 Access tunnels and auxiliary underground facilities

Waste-generated gas will accumulate within the backfilled operations tunnels and other deep geological repository structures. Partially saturated regions of the tunnel backfill will provide preferential pathways for gas transport. As gas pressure develops, water from the structures will be expelled into the EDZ. Gas will also accumulate in the EDZ around the structures and potentially migrate along it. The gas can then migrate from these structures and the surrounding EDZ into the host rock.

In the case of the HLW repository section, the access tunnels will remain partially saturated for some time after closure, and pressure gradients from the emplacement drifts towards the partially saturated (or under-pressured) excavations will drive water flow towards them, while gas is largely released from the HLW emplacement drifts directly to the host rock (Papafotiou & Senger 2016b). At a later point in time, pressure in the access tunnels can increase above the hydrostatic pressure due to resaturation and the influence of gas generation, but the pressure in the access tunnels will remain significantly below that in the emplacement drifts.

Waste-generated gas will migrate into the L/ILW disposal area and accumulate within the backfilled operations tunnels. As gas saturation and pressure develop in the tunnels, gas and porewater will be expelled into the EDZ.

V1-L/ILW seals and VF1 backfill

The saturation evolution of the V1-L/ILW seal is tied to that of the emplacement cavern. Similarly, to the emplacement caverns, porewater initially present in the V1-L/ILW seals will begin to redistribute within the seals through the interaction of capillary and buoyancy forces, while some water mass will be drawn into the surrounding unsaturated EDZ (Fig. 7-8). The gradual increase of gas and liquid pressures in the L/ILW emplacement caverns will result in water expulsion from the caverns into the V1-L/ILW seals (and subsequently into the VF1 backfill). Saturation in the lower part of the less permeable sealing elements will increase slightly until it exceeds hydrostatic pressure in the L/ILW emplacement caverns (corresponding to the peak liquid saturation in Papafotiou & Senger (2016a) at the cavern top after around 2,000 years), and water displacement to the surrounding rock increases. The upper part of the seals will remain unsaturated for several tens of thousands of years, forming the predominant pathway for gas release from the L/ILW caverns to the VF1 backfill (Fig. 7-9). The transport of gas through the upper part of the seal above the capillary fringe will sustain a continuous gas pathway for as long as the gas phase is supplied by the emplacement caverns across the seal to the VF1 backfill.

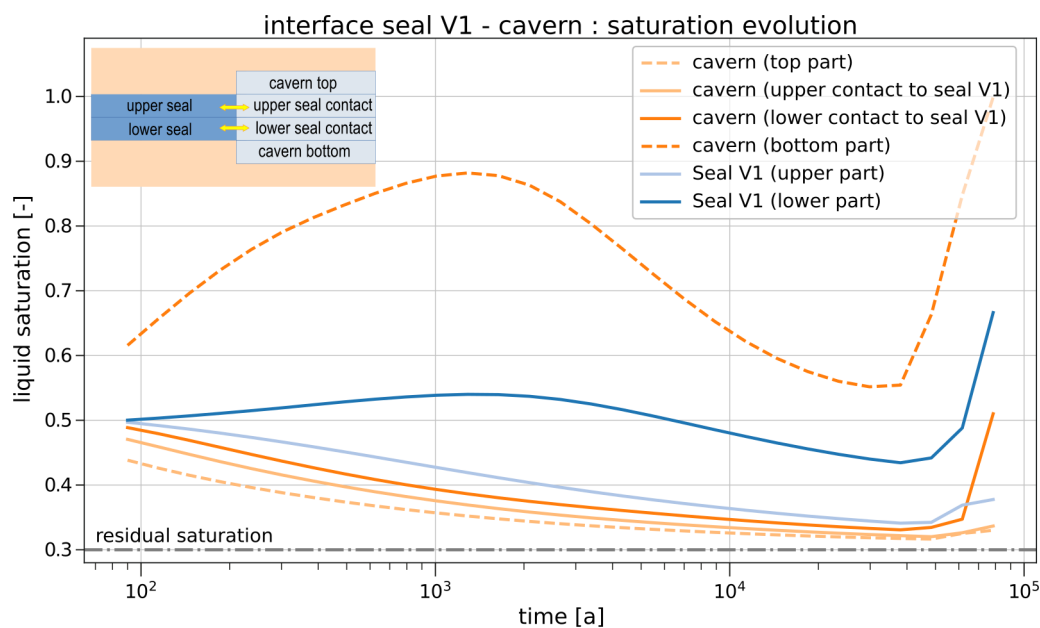


Fig. 7-8: Temporal evolution of liquid saturation for a V1-L/ILW seal and adjacent cavern
Extracted from the base-case model in Papafotiou & Senger (2016a)

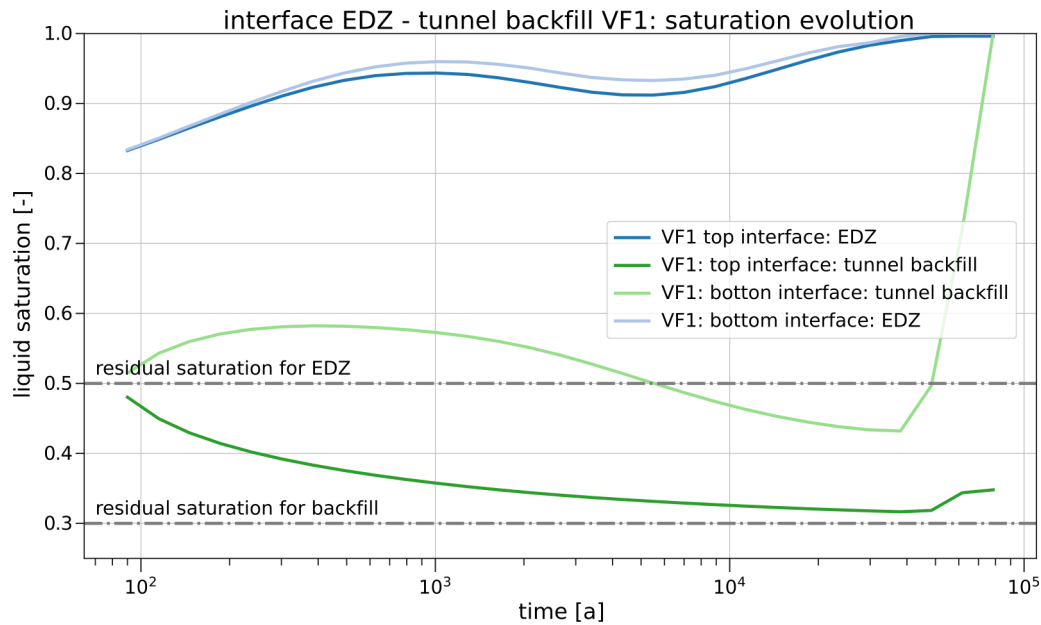


Fig. 7-9: Temporal evolution of liquid saturation at the top and bottom interfaces between tunnel backfill/EDZ halfway between the V1-L/ILW seals and the V2 seals

Extracted from the base-case model in Papafotiou & Senger (2016a).

In the late post-closure phase ($> 50,000$ years), gas generation in the L/ILW caverns will decrease significantly and the V1-L/ILW seals and the lower part of the VF1 backfill will begin to saturate with porewater from the surrounding rock. However, the volume for gas storage will still be maintained in the upper part of the caverns and the VF1 backfill for a period $> 100,000$ years, as shown in Fig. 7-8 and Fig. 7-9 (data from Papafotiou & Senger 2016a). The VF1 backfill next to the V1-HLW seals will resaturate earlier as the V1-HLW seals are not required to provide gas transport to the VF1 backfill (Section 7.2.3). However, this is not relevant to the gas issue.

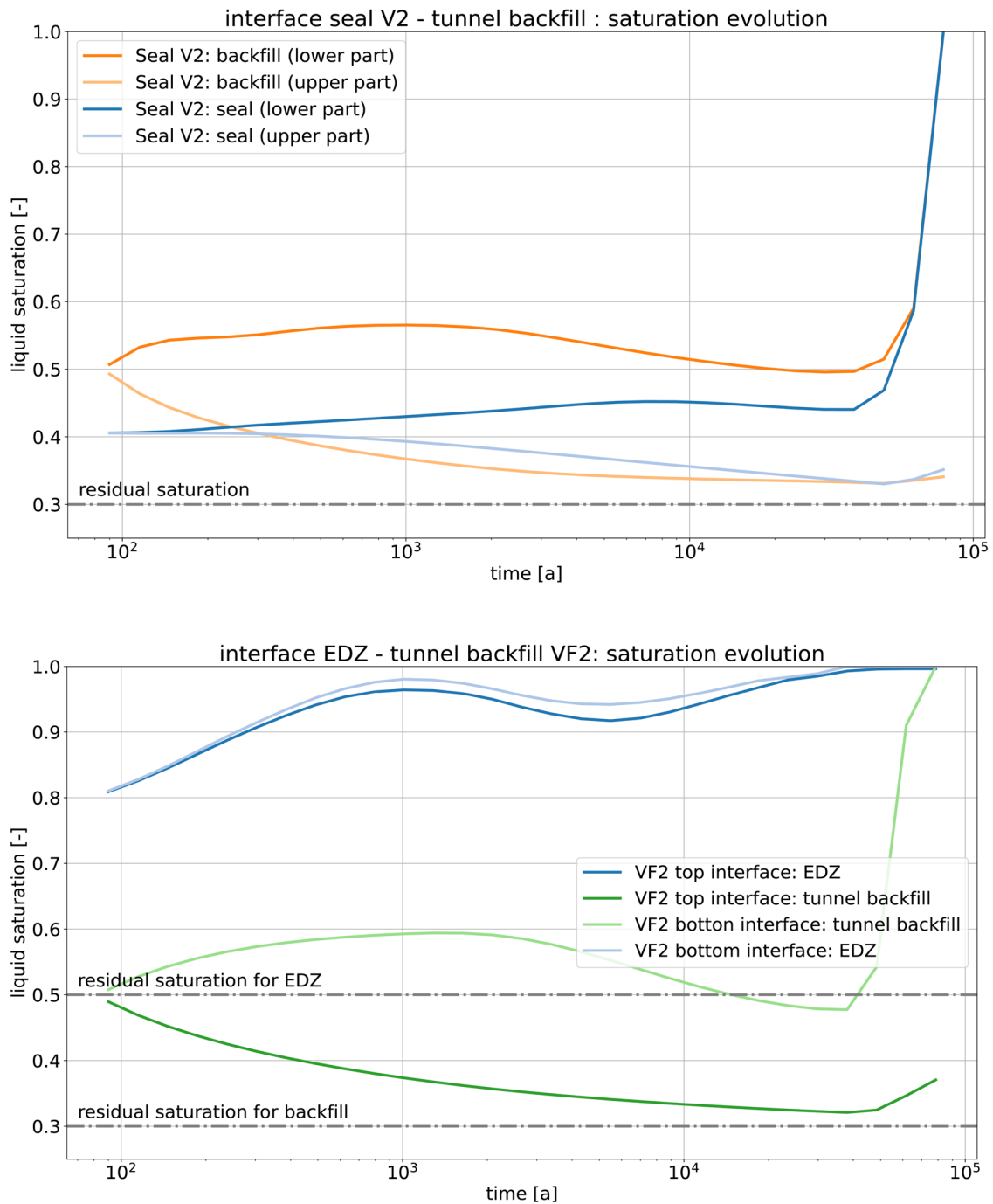


Fig. 7-10: Top: temporal evolution of liquid saturation for a V2-L/ILW seal and adjacent backfill material. Bottom: temporal evolution of liquid saturation at the top and bottom interfaces halfway between the V2 and V3 seals

Extracted from the base-case model in Papafotiou & Senger (2016a).

V2-L/ILW seals and VF2 backfill

Saturation in the V2-L/ILW seals will evolve in a similar way to that of the V1-L/ILW seals, albeit with a somewhat lower magnitude of saturation changes over time, as shown in Fig. 7-10. Saturation in the lower parts of the V2-L/ILW seals will slowly increase, whereas gas coming from the VF1 backfill of the L/ILW disposal area will result in lower saturations in the upper parts. Overall, saturation of the VF2 backfill will occur in a very similar manner to that of the VF1 backfill in the L/ILW disposal area and provide a continuous pathway for gas over tens of thousands of years.

Overall, transport of repository-generated gas through the sand-bentonite V1-L/ILW and V2-L/ILW sealing elements will tend to maintain a gas pathway in sand-bentonite mixture above the capillary fringe, thus further supporting the maintenance of a continuous gas storage volume. As discussed in earlier chapters, as long as there is a connected gas phase along the underground openings, pore blocking will be limited and continuous gas transport will remain unperturbed, as assumed in the model calculations. In contrast, the vertical shaft seal V3 will saturate considerably faster (within the first thousand years) and, given its high bentonite content, will effectively separate the deep geological repository from the aquifers above and minimise gas transport through the shaft (Nagra 2024g).

Microbial gas consumption

Since the period for assessment will be characterised by anoxic and reducing conditions, anaerobic microorganisms will constitute the bulk of the microbial population in the repository. Under these conditions, H_2 produced by the anoxic corrosion of metals may be used by the microbial populations present in the backfilled operations and ventilation tunnels.

Many microbiological processes can consume H_2 in a deep geological repository. Which of these processes will take place depends on the availability of nutrients (electron donors and electron acceptors). At low H_2 partial pressures, the thermodynamic sequence will dictate the sequence of electron acceptor depletion. A heterogeneous distribution of the community can be expected in the backfill material, with, for instance, zones of local sulphate depletion, providing conditions that will then favour the activity of methanogens. However, when H_2 is not the limiting substrate, several metabolic processes with varying thermodynamic favourability, e.g., sulphate reduction and methanogenesis, may co-occur at the same location.

The microbially-induced reduction of sulphate is the most probable reaction pathway for H_2 oxidation due to the abundance of sulphate in the Opalinus Clay porewater and its energy yield. Sulphate is an important electron acceptor in anaerobic respiration, and sulphate-reducing microorganisms are widespread in nature. Sulphate can be provided by the backfill material itself (e.g., dissolution of sulphate minerals such as gypsum) or by the host rock, since the Opalinus Clay porewater is rich in dissolved sulphate (Mäder & Wersin 2023). All sulphate-reducing bacteria are capable of using H_2 as an electron donor. The presence and viability of sulphate-reducing bacteria have been confirmed in dedicated experiments at the Mont Terri underground rock laboratory (Bagnoud et al. 2016, Leupin et al. 2017a), and thus these bacteria are also expected to be present and viable in both the HLW and L/ILW sections of the deep geological repository.

In addition to sulphate-reducing bacteria, iron-reducing bacteria can consume H_2 using Fe(III) as the electron acceptor. However, the amount of Fe(III) present in the repository is not well constrained; therefore, it is not yet possible to quantitatively assess the magnitude of this H_2 sink. Clay minerals in the backfill may contain some bioavailable Fe(III), but its overall contribution to H_2 consumption is unknown. Indeed, the generation of ferrous iron has been observed in experiments investigating hydrogen consumption by native microorganisms in OPA porewater, with and without the presence of a sand-bentonite matrix (Bagnoud et al. 2016) and (Rolland

et al. *pre-print*). These data indicate the activity of Fe(III)-reducing organisms and are corroborated by genetic analyses. However, under these conditions, sulphate-reducing conditions rapidly prevail, indicating that it is the predominant sink for H₂ in these systems.

Methanogens and acetogens can also both use CO₂ as an electron acceptor and H₂ as an electron donor in their energy metabolism. During methanogenesis, methanogens (e.g., members of the *Methanosarcina* genus) carry out the conversion of H₂ to CH₄, while during acetogenesis acetogens (e.g., members of the *Acetobacterium* genus) carry out the conversion of CO₂ to acetate. Compared to methanogenesis, it should be noted that the latter metabolism releases slightly less free energy (ΔG^0) and is thus less thermodynamically favourable to microbial gas consumption.

Based on today's understanding, bacteria have the potential to significantly reduce the gas pressure buildup in a deep geological repository. Technical and natural analogues (Leupin et al. 2016) show that microbial activity with respect to hydrogen oxidation can differ in scale and last for extended periods of time.

8 Robustness of the barriers

The repository barriers are required to be robust, in the sense that they are highly likely to provide their safety roles, irrespective of any detrimental phenomena that may occur over the course of time, including their attendant uncertainty. Phenomena of particular relevance to the present phenomenological description are potentially detrimental repository-induced thermal, rock mechanical, gas-related and chemical effects. The evolution of some of these phenomena is illustrated in Fig. 8-1 and Fig. 8-2 for the HLW and for the L/ILW repository sections, respectively. The barriers can continue to perform their safety roles provided that:

- The increased temperatures and pore pressures due to heat generated by the waste and cement hydration are insufficient to adversely affect the transport and retention properties of the host rock and engineered barrier system.
- The EDZ formed around underground openings does not lead to a significant alteration of the pattern of transport pathways for radionuclides.
- Gas is able to migrate without permanently damaging the transport and retention properties of the host rock and the engineered barrier system. And
- The effects of canister corrosion products, the high-pH plume from cementitious materials and trapped O₂ on the host rock and engineered barrier system are insignificant, and the materials used to stabilise underground openings are not used in amounts that could compromise the safety roles of the barriers.

The capacity of disposal systems to fulfil these conditions will be evaluated in performance assessments, which will be based on the present phenomenological description or future iterations thereof.

It should also be noted that, if needed, design options are available to reduce peak temperatures (although these may require considerable design or operational effort), to reduce the impact of the EDZ and to reduce the gas-pressure buildup in the repository tunnel system.

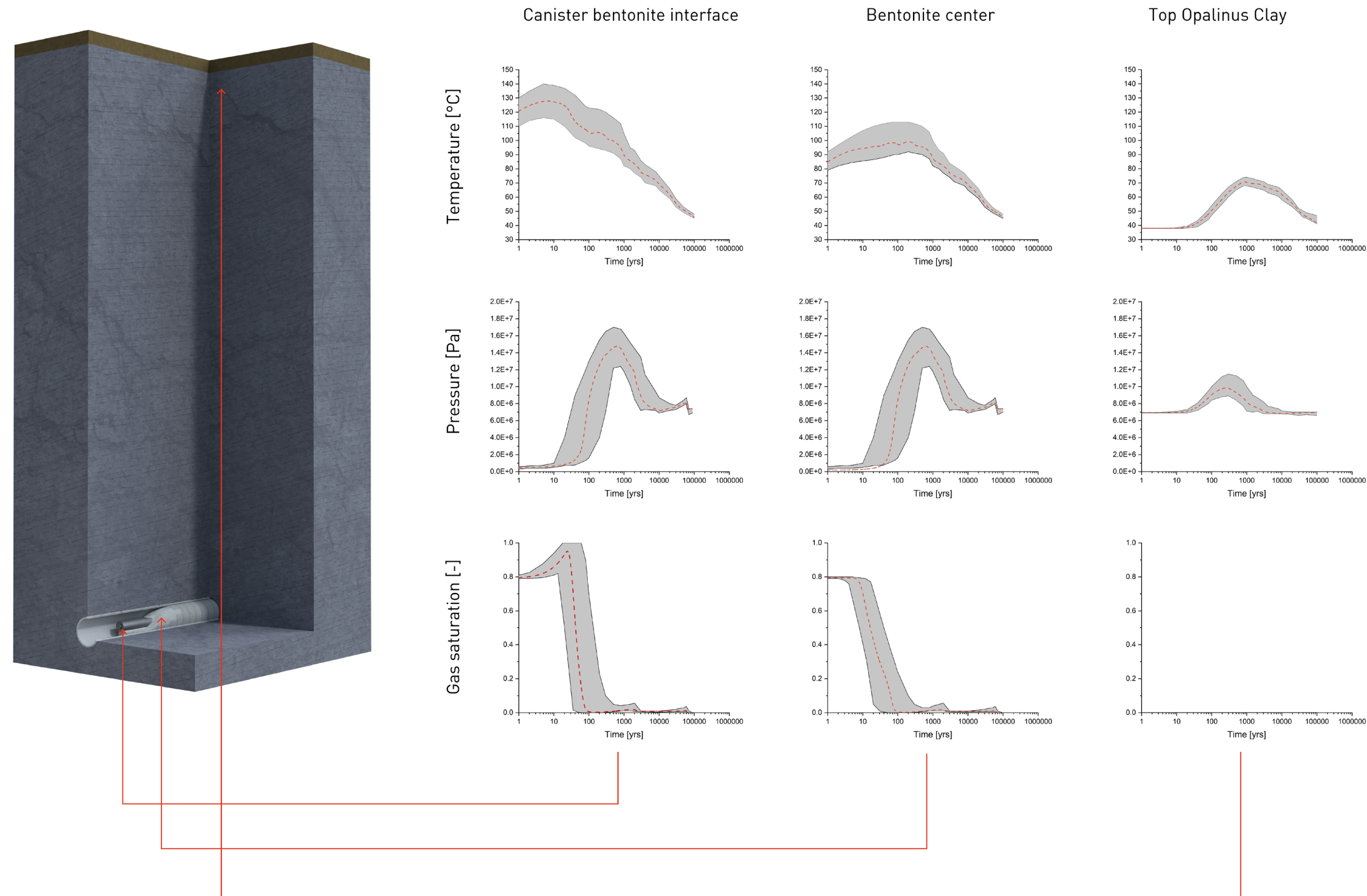


Fig. 8-1: Overview of the expected evolution of the main processes in the HLW section of a combined repository, based on a compilation of modelling reports and experimental data

The red line indicates the approximate closure time of an HLW repository. Note that the gas pressure is calculated based on a best estimate corrosion rate of $0.3 \mu\text{m}/\text{year}$. Canisters are assumed to breach simultaneously, which results in a gas pressure peak around 10,000 years after deep geological repository closure as it has to be assumed that water can penetrate the canister and start to corrode the metal from the inside.

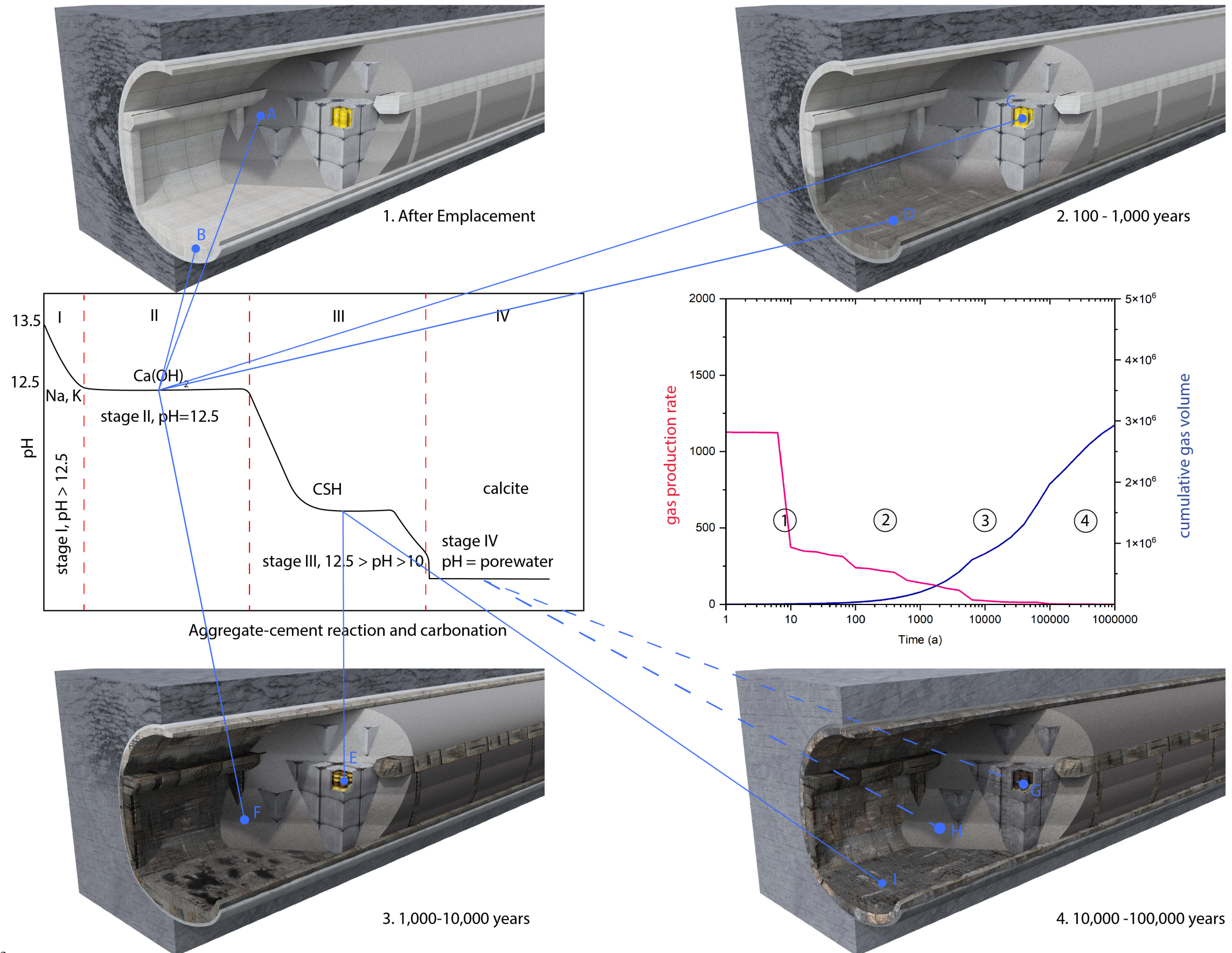


Fig. 8-2: see next page

Fig. 8-2: Overview of the expected evolution of the main processes in the L/ILW section of a combined repository

The artistic representation aims at being as realistic as possible. A cut through the near-field allows for the visualisation of the different deep geological repository elements. See also Fig. 7-8 for details regarding the resaturation of the L/ILW emplacement cavern. The evolution of the cementitious built-ins in the L/ILW repository is shown in four stages. The cement properties mainly evolve through internal cement degradation processes (carbonation and alkali aggregate reaction) and with the exchange of porewater at different speeds depending on the cement composition and properties and the influx/availability of water. The degradation stages are described in detail in Chapter 6.

A: Most of the cementitious material used in the cavern cures rapidly and evolves to Stage II within days to weeks. The backfill mortar is portlandite-buffered and contributes to a high-pH chemical near-field. Between the aggregates, the mortar provides interconnected gas storage space. B: The high pH of the in-situ concrete used for the sole and tunnel support is expected to remain stable for up to thousands of years because of the concrete's low porosity; it will thus degrade slowly. C: Metallic decommissioning waste will be embedded in a high-pH and low-viscosity cement within the disposal containers. This infill mortar in the disposal container is designed such that the pH is portlandite-buffered. The high pH of the cement results in lower corrosion rates for up to about 1,000 years. D: In-situ concrete for the tunnel support reaches the end of the lifetime it has been designed for, i.e., the structural support of the cavern. Towards the end of that period, portlandite will disappear, the pH will drop and Stage III will be reached. E: Most of the disposal containers in the lower rows will now reach Stage III due to the porewater exchange and carbonation. F: Backfill mortar may remain in Stage II for up to thousands of years if calcareous aggregates are admixed and availability of CO₂ gas is limited. If siliceous aggregates are used, it will rapidly (< 1,000 years) reach Stage III. G: Total degradation of the container infill mortar might now be reached depending on leaching rates and carbonation. H: Total degradation of the backfill mortar might now be reached by leaching of the cement depending on porewater exchange volumes. I: Due to the initially high portlandite content and the low porosity, the in-situ concrete for the tunnel support might remain at Stage III longer. Stage IV is reached when all the cement minerals are in a thermodynamic equilibrium and transformed to zeolites, clay and calcite.

In the context of safety and performance assessment, it is conservatively assumed that the onset of gas production starts when the cavern is sealed off (assuming immediate full saturation and anoxic conditions of the cavern). In reality, it may take tens of thousands of years for the cavern to become fully saturated. Another simplification is that the continuous ventilation of the operations and construction tunnels that lasts for about hundred years is disregarded. As a result, the gas produced during the first one hundred years is erroneously added up in the total cumulative gas volume. A more realistic appreciation of the saturation process must be based on the assumption that the pores of the concrete will be initially partially filled with gas. With progressing water saturation, corrosion gas will dissolve in the porewater and not contribute to a gas pressure buildup. Once the solubility limit is reached, a gas phase is formed and the gas pressure increases. However, until the repository has been sealed, gas can escape, and no gas pressure will build up. The highest rates are given by the readily corrodible metals (e.g., aluminium) with high surfaces. Full water saturation of the cavern is only expected toward the end of the time period under consideration.

9 Migration of radionuclides

9.1 Transport in the near-field

When the canister is breached and sufficient porewater enters, the breached inner containment allows water to come into contact with the waste matrix. This interaction initiates the dissolution and diffusion of radionuclides from their initial containment. Some of the nuclides, located in cracks in the UO_2 matrix or in the annular gap between fuel pellets and rods, may be instantly released as fission gas or as dissolved nuclides (IRF). However, the majority of nuclides will be released upon the dissolution of the UO_2 matrix.

Fission gas release (FGR)

The quantification of FGR from SF rods is relevant to short-term as well as to post-closure safety and safety assessment. In the short term, it is relevant to the safe handling and encapsulation of damaged fuel assemblies in the final disposal canisters. In the context of post-closure safety, FGR from SF is known to correlate with the IRF for ^{129}I and ^{137}Cs , which make up a fraction of the inventory of safety-relevant radionuclides that may be rapidly released mainly from the fuel shortly after canister breaching. Trapped fission gas also contributes to gas pressure buildup that can affect the integrity of the cladding. Thus, campaigns to calculate the FGR for all Swiss reactor fuel assemblies, except for Mühleberg, have been carried out in order to obtain reliable average FGR data. These data (Nagra 2010, AREVA 2012, Oldberg 2009), combined with measurements of radionuclide release from SF carried out by Nagra in collaboration with PSI, SKB and Studsvik for fuel with burnups from 45 to 65 GWD/tHM, have provided the basis for a radionuclide release model. This question is being further investigated within the framework of an international effort that includes modelling and analogue studies, as well as sampling campaigns of fuel in hot cells. The derivation of the IRF for the Swiss NPPs relevant for the calculation for the consequence analysis is documented in (Johnson et al. 2023).

Dissolution of radionuclides

Once the porewater level is high enough inside the SF canister, radionuclides can start to dissolve and diffuse through microcracks in the Zircaloy's hulls and later through the breached canister shell into the bentonite. Most of the radionuclides present in the Swiss waste inventory are expected to be released in solution (Nagra 2024h).

Upon contact with porewater, vitrified glass will dissolve extremely slowly. The released radionuclides will diffuse along microcracks in the glass, first through the breached inner stainless-steel coquille and then through the breached canister shell into the bentonite (Curti 2022).

Most of the radionuclides will decay within the bentonite and before they reach the OPA (Nagra 2024h). A few of the released radionuclides will decay within the host rock. Negatively charged, non-sorbing and long-lived radionuclides (such as ^{129}I and ^{36}Cl) may eventually reach the biosphere.

In the L/ILW repository, resaturation of the L/ILW cavern is a slow process. When gas pressure increases, it limits the inflow of water from the host rock into the cavern. This, in turn, will limit gas production. Once the L/ILW caverns are sufficiently saturated, radionuclides may dissolve in the porewater and start to diffuse (Curti et al. 2023). Within the L/ILW cavern, sorption processes will be mainly controlled by secondary minerals formed from the degraded cementitious backfill in the emplacement caverns (Tits & Wieland 2023, Marinich et al. 2024).

Volatile radionuclides

The most relevant radionuclide released as volatile is the very short-lived ^{14}C , predominantly in the form of methane. Transport mechanisms for $^{14}\text{CH}_4$ within the repository structures will vary with time, the degree of saturation and the disposal area (i.e., HLW vs. L/ILW). While the HLW near-field will saturate with water within a few hundred years, the L/ILW near-field is expected to remain merely partially saturated for a much longer period. Moreover, the HLW bentonite near-field exhibits relatively homogenous and isotropic porous media properties relevant to transport, whereas the cementitious near-field of the L/ILW part is more heterogeneous. Volatile radionuclides will migrate along the repository structures through advection and diffusion in the gas phase (Nagra 2024m).

9.2 Transport to the host rock and CRZ

When radionuclides move away from the source and into the OPA, concentration of most radionuclides will sharply decrease with distance and remain significantly below their solubility limits (Hummel et al. 2023). The OPA matrix provides an ideal environment for diffusion-dominated transport, that, combined with retardation (sorption) and anion-exclusion facilitated by the abundance of negatively charged surfaces of clay minerals, will efficiently contain the radionuclides. The ability of the OPA to efficiently immobilise radionuclides is further enhanced by the incorporation (absorption) of some radionuclides into minerals, as supported by the findings of Bradbury et al. (2017). This process reduces their mobility and contributes to long-term immobilisation.

Transport of dissolved radionuclides

Based on evidence from studies on OPA and compacted and saturated bentonite (Glaus et al. 2024), alongside observations from natural clay analogues, it is expected that the long-term transport of radionuclides in the host rock will primarily be dominated by diffusion-related processes. Diffusion experiments have been carried out for many anionic, cationic and neutral species (Glaus et al. 2024). In addition, studies on the diffusivity of tracers in OPA have allowed for an estimation of the diffusion rates of radionuclides (Nagra 2024l). Diffusion studies in the laboratory and field experiments give consistent values for different spatial and temporal scales (Leupin et al. 2017b). In the OPA and clay-rich rocks from the over- and underlying rock units, the phenomenon of anion exclusion has been experimentally observed and corresponding diffusivities determined (Van Loon et al. 2024, Glaus et al. 2024).

Temperature is an important parameter that influences diffusion processes. The relationship between temperature and diffusion constants follows an Arrhenius-type behaviour (Van Loon 2014). When extrapolating these data to the conditions of the expected host rock (approximate $T \approx 45 - 50\text{ }^{\circ}\text{C}$ at 900 m depth), the expected effective diffusivities for neutral species are approximately $10^{-11}\text{ m}^2\text{ s}^{-1}$, while for anions, they are approximately $10^{-12}\text{ m}^2\text{ s}^{-1}$. The experimentally determined low D_e values indicate the presence of anion-exclusion effects. This phenomenon implies that certain anions experience restricted diffusion in the host rock compared to neutral species, further impacting the overall radionuclide transport behaviour. The understanding of these diffusion characteristics and temperature dependence is essential for accurately assessing and predicting radionuclide migration in geological repositories under realistic conditions.

Besides the diffusion-dominated transport process, sorption is a critical factor controlling radionuclide transport in both near- and far-fields (i.e., bentonite, host rock, clay-rich rock units) (Marques Fernandes et al. 2024). The scientific understanding of radionuclide retardation has been demonstrated through numerous experimental studies in laboratory and field studies and is also applicable for bentonite.

The potential influence of complexing organic molecules naturally occurring in OPA on the sorption of radionuclides has been investigated by Glaus et al. (2001). Their study examined whether the presence of organic matter affected the sorption behaviour of specific radionuclides, namely Ni, Eu, and Th, on OPA. The findings of the study revealed that the complexing organic molecules in OPA had no significant impact on the sorption of Ni, Eu, and Th. In other words, the sorption behaviour of these radionuclides on OPA remained largely unaffected by the naturally present organic matter.

Colloids can exist in OPA porewater, but their mobility is expected to be extremely limited due to specific properties of the clay material. The small pore size, typically ranging from 2 – 15 nm with limits of 2 to 100 nm, and the presence of charged surfaces of clay platelets contribute to the immobilisation of the colloids. In addition, the moderate ionic strength of the OPA porewater further limits colloid movement (Mäder & Wersin 2023).

Considering these factors, it is expected that colloid transport through OPA can be ruled out (Kosakowski et al. 2023).

Transport of dissolved radionuclides by diffusion through the shafts is limited due to the redundant properties of the engineered barriers that will be put in place: (i) the operations and construction tunnels will be backfilled with a clay or a clay/sand mixture that has a hydraulic conductivity that limits water movement to diffusion; (ii) the operations and construction tunnels will be sealed at various locations using highly compacted bentonite with very low hydraulic conductivity to further limit radionuclide transport. Finally (iii), the shaft seal will also be filled using highly compacted bentonite (Martin et al. 2023, Nagra 2021c) with transport properties comparable to undisturbed OPA.

Advection in the clay matrix or within the clay-rich rock zones is expected to have a minimal role in radionuclide transport. Occurrences of preferential flow through fractures in OPA at depths within the repository zone are not expected. The presence of fractures in the OPA has been observed, but under deep geological repository depth conditions, i.e., the prevailing compressive tectonic influence and lithostatic pressure, the natural self-sealing mechanism prevents enhancement of any fluid flow. Experimental studies conducted 300 m underground at Mont Terri confirmed that artificially created pathways formed in the OPA did not lead to substantial changes in permeability (Nagra 2024l). Despite these findings, there are certain existing uncertainties that need to be considered, and minor increases in transmissivity cannot be completely ruled out. Hence, some advective transport with matrix diffusion perpendicular to the direction of flow may be possible. Nevertheless, modified or enhanced transmissivities under such circumstances are expected to be limited, i.e. mostly fall below $< 10^{-10} \text{ m}^2 \text{ s}^{-1}$ (Nagra 2024l).

Volatile radionuclides

Repository-generated gases could penetrate the CRZ as a separate gas phase but, because of the slow gas production rate, they mostly dissolve in porewater. Dissolved gas (mainly H_2) will therefore be transported through the host rock predominantly via diffusion and to some extent by water displaced due to the gas pressure buildup in the underground structures. Some dissolved gas may reach the over- and underlying confining units, depending on the amount of gas generated in the repository and the transport properties of the barriers. A continuous gas phase across the host rock and its confining units is considered as highly unlikely (Nagra 2024g). The slow migration associated with the relatively fast decay of ^{14}C ensures no significant release dose into the biosphere (Nagra 2024h).

9.3 Assessing the radionuclide release in the biosphere

Biosphere modelling for post-closure safety assessment is undertaken within the framework of the broader post-closure safety assessment, which, in turn, supports the safety case for deep geological disposal.

The purpose of Nagra (2024e) on biosphere modelling is to provide the capability to evaluate the potential radiological significance of calculated radionuclide release from the deep geological repository over a very long period. The objective is to provide means of demonstrating that deep geological disposal can sufficiently protect humans and the environment.

Consistent with ENSI guideline ENSI (2020b), radiological significance is evaluated by assessing potential doses to people. The calculation of the radiological consequences for a given radionuclide release is performed by means of a model referred to as the biosphere model which (i) represents the behaviour of the released radionuclides in the human habitat, and (ii) determines the potential radiation exposure for a representative individual of the most affected population based on major exposure pathways.

Given uncertainty in making projections about biosphere conditions in the very long term, the assessment is made on a generally pessimistic basis, i.e., by assessing the exposure of a representative individual from the population group most affected by the potential impact of a deep geological repository. This is defined as a population group making reasonable maximum use of local resources through a self-sufficient lifestyle. To help avoid undue pessimism, the behaviours of the population group(s) aim to be realistic and credible, based on present-day behaviours relevant to the assumed local and climatic conditions.

10 Summary of the geological long-term evolution of Northern Switzerland

The following summary of the geological long-term evolution of Northern Switzerland is based on Nagra (2024I) and references therein.

10.1 Tectonic evolution of Northern Switzerland

- Tectonic deformation rates in Northern Switzerland are small.
- The spatial pattern of rock uplift over the next million years will continue to be dominated by a ceasing Alpine uplift, regardless of whether it is caused by tectonic shortening or isostatic compensatory movements. Uplift rates (mean of all sites) are expected to be between 0.02 and 0.36 mm/a (median 0.16 mm/a) with relatively small differences between the Nördlich Lägern siting region (NL) and Zürich Nordost (ZNO) siting regions and slightly lower rates near the Jura Ost (JO) siting region.
- The main driver of the tectonic evolution and the fault inventory in the siting region are known. Fault reactivation preferentially localises on existing zones of weakness (regional fault zones). These are avoided during placement of the deep geological repository.
- If new faults develop in the host rock, these will be evenly distributed and small in length and offset.

10.1.1 Climate evolution in Northern Switzerland

- According to different anthropogenic CO₂ scenarios, 3 – 5 large glaciations (LGM-sized or larger) are expected that could reach the Alpine foreland in the next one million years. The climate conditions during a glacial are expected to be similar to those during past cycles.
- Considering the present conditions and the longevity of the carbon dioxide gases within the atmosphere, the next glacial inception will be significantly delayed, and the next large glaciation will only occur after the following ~ 200,000 or even 350,000 years. Accordingly, we only expect an initially extended interglacial period and a swing to the overarching one-hundred-thousand-year cycle around 500,000 years into the future.
- Each glacial period is expected to be associated with permafrost conditions during the coldest phases. Permafrost is expected to reach maximum depths of 100 – 200 metres.
- Due to the different distance to the Alps and different topography, ice thicknesses and the duration of the ice cover at the sites varied during past glacial cycles (ZNO > NL > JO). The same pattern will most likely also be seen during future glaciations.
- It is likely that the future climate in the lowlands of Switzerland will pass from a polar climate (glaciation and permafrost) to a continental climate followed by a temperate climate (warmer than continental climates with more distinct seasonal changes). Depending on the duration of the interglacial (and prevalent states of climate drivers), lowland Switzerland might even, at one point, see dry climates (very little precipitation and very high average temperatures throughout the year).

10.1.2 Erosion in Northern Switzerland

- Future erosive processes (glacial and non-glacial) are expected to be comparable to the Quaternary (but at lower rates: no major drainage reorganisation, smaller glaciers, delay in glacial inception, and harder-to-erode rocks below the Molasse assemblage).
- The main river system affecting erosion in the siting regions over the next one million years remains the Aare – Rhine River system. The Rhine continues to grow at the expense of the Danube but with a very limited impact on the incision potential.
- Fluvial incision by itself does not pose any threat to Zürich Nordost and even less to Nördlich Lägern siting region. The host rock remains below the local erosion base (LEB) at these sites. For Jura Ost, a range of scenarios exists where this is not the case after one million years. This site thus depends on the preservation of the local topography.
- With erosion progressing the morphology around the deep geological repository will evolve with regard to infiltration and exfiltration areas. Malm will outcrop closer to the repository sites and the length of exfiltration pathways in the deep aquifers will decrease accordingly. A residual cover of 200 m is deemed sufficient for self-sealing and can be shown for the most likely scenarios in all siting regions for the period under consideration. Using the 5 – 95% range as reference, the Jura Ost siting region showcases less robustness regarding the 200 m criterium.
- Excavation of the deep geological repository within the next one million years is extremely unlikely in all three siting regions. Due to the large deep geological repository depth and the expected rates of erosive processes, the Nördlich Lägern siting region is the most robust in this regard.

10.1.3 Hydrogeology and hydrochemistry of Northern Switzerland

- Aquifer dynamics and exfiltration are expected to change over time. Changes are more probable in relation with future glaciations: glaciers can change infiltration and exfiltration areas and hydraulic gradients, and permafrost can clog the exfiltration pathways.
- Future erosion and deposition may change the morphology and, consequently, the infiltration and exfiltration areas. This can shorten the release pathways in the deep aquifers and/or lead to more active flow systems.
- Faults in the repository areas are small and deformation tends to be distributed (preventing continuous flowpaths). In combination with the high self-sealing capacity of the host rock, this implies that there are no relevant or only very small and short-lived increases of transmissivities after fault reactivation.
- In the host rock, diffusion-dominated transport will prevail owing to the low hydraulic conductivities and the high self-sealing capacity.
- Ice loading and unloading induce overpressures and underpressures, respectively, in the host rock. Owing to the overconsolidation of the host rock, the resulting porosity changes are of minor importance.
- Diffusion processes only result in a relevant increase when deep geological repository overburden becomes very shallow and the porosity significantly increases. Such a reduction of overburden is not expected at the repository sites during the next one million years.

- Changes in the porewater composition of the host rock are expected to be small over the next one million years.
- Dissolution processes are very unlikely in the host rock due to the lack of dissolvable rocks. The «Herrenwis Unit» in the upper confining units of Nördlich Lägern siting region could be karstified, if uplifted above the local base level. This is not expected during the next one million years. Dissolution processes below the host rock are very unlikely due to the lack of driving forces and/or pathways (larger faults are avoided at all sites).

10.2 Expected geological long-term evolution at the Nördlich Lägern siting region

Long-term rock uplift, fluvial incision and remaining overburden

The Rhine will grow at the expense of the Danube, with headward erosion rather than through major river capture events as seen in the pre-Quaternary and Quaternary periods. Instead, the evolution of the river profile is largely controlled by rock uplift and sediment input. The erodibility of the subsoil is only of secondary importance for vertical fluvial incision but might have an influence on lateral erosion.

The spatial pattern of rock uplift in Northern Switzerland over the next one million years will continue to be dominated by Alpine uplift, regardless of whether as tectonic uplift or as isostatic compensatory movements. In simplified terms, the main gradient can be assumed to become steeper from the foothills towards the Alps along a direction that is roughly perpendicular to the Alpine chain. The long-term rates are low. Total uplift between ~ 25 m and a maximum of ~ 360 m (5 – 95%) over a million years is assumed for the Nördlich Lägern siting region. Short phases of higher rates might be expected in correlation with, and postdating, deglaciation of large glaciation events.

Significantly higher incision can only be achieved by additionally lowering the base level. Two intermediate base levels will be important in the future: as long as the Rhenish Massif continues to be uplifted (roughly near Bingen, Germany), it decouples the upstream part of the Rhine River from the sea. Furthermore, the sedimentary basin of the Upper Rhine south of Bingen (*Oberrhein*) is controlled by tectonic subsidence and transitions to the *Hochrhein* near the city of Basel. Today, there is no disturbance of the river profile at this point; the subsidence is compensated by sediment accumulation. Potential elevation gain by oversupply in sediment is compensated by vertical incision into these sediments. Averaged over the next one million years, however, it cannot be ruled out that the base level at Basel could fluctuate by up to ± 70 m.

Under these boundary conditions, a vertical fluvial incision²⁰ of between 80 and 390 m (most likely ~ 170 m) at the confluence of the Aare and Rhine rivers, i.e., near Nördlich Lägern siting region, can be expected. This corresponds well with Quaternary incision on a timescale over one million years, which were estimated to be between 30 and 300 m in the area around Nördlich Lägern siting region but includes uncertainties. Given the provided incision estimates, a remaining overburden of 370 – 670 m (5 – 95%) can be expected.

²⁰ Rounded to the nearest 10 m.

It is therefore possible that after one million years, the Malm limestones will be incised fluvially in the area of the siting region or that the future exfiltration area will be located progressively closer to the siting region and to the site of the disposal area. This however is not expected to negatively impact the self-sealing capacity or result in a decompaction of the CRZ.

Short-term modulation of fluvial incision by glacial/interglacial cycles

The long-term incision will be modulated by phases of sediment accumulation without net vertical incision. These sediment dynamics are largely controlled by glacial/interglacial cycles. During the interglacial warm period, we expect a relatively high precipitation rate and consequently a relatively high water-discharge. In contrast, the sediment flux will probably be limited by a weak coupling between the glacially conditioned sediment sources and the active transport pathways that can be observed today. We therefore expect the lowest sediment flux during the interglacial. During the regrowth of the Alpine ice cap, the reworking of periglacial deposits by advancing glaciers and an increase in the area subject to subglacial abrasion should lead to a peak in sediment flux. During the main glacial phase, sediment flux is assumed to be larger than the interglacial rate because of increased glacial activity and higher climate variability. For the termination, we infer a peak in water discharge that is due to the warming-induced increase in atmospheric moisture and a pulse of meltwater from the decaying ice. The high water availability induces faster glacial sliding and hence an increase in glacial abrasion. In combination with the paraglacial adjustment of the landscape, this should result in a maximum contribution of sediment to the fluvial system. After glacial retreat, however, in many places, the sediment is trapped in perialpine lakes and overdeepened basins for up to several tens of thousands of years, thus reaching into the interglacial period.

The expected glacial scenario and deep glacial erosion

In accordance with various anthropogenic CO₂ scenarios, the onset of the next glacial period is anticipated to be significantly postponed, with the occurrence of a substantial glaciation not expected for approximately 200,000 to 350,000 years. In the event of extensive future foreland glaciations, profound glacial erosion can be expected in the eastern section of the Nördlich Lägern siting region, where the current topography is characterized by low relief. This specific area may undergo recurrent glaciation if the forthcoming glacier matches or surpasses the extent and erosive efficacy observed in the penultimate glaciation (Beringen).

Under such circumstances, the cumulative depth of glacial erosion is projected to extend below the local erosion base (LEB). Given that the base level has already lowered, it is conceivable for deep glacial erosion to penetrate the Malm limestone. On average, the Malm limestone is estimated to be only half as susceptible to erosion as Molasse-type rocks. Consequently, it is not anticipated that glacial overdeepenings will reach the host rock. This likelihood is further mitigated by avoiding the most probable areas for the future development of glacial overdeepenings, specifically the present-day locations, when selecting the disposal area.

Occurrence of deep permafrost

Each glacial period is expected to be associated with permafrost conditions during the coldest phases. This timing does not necessarily correspond to the timing of the glacial maximum but might pre- or postdate this peak. Permafrost can also be expected beyond the glacial extent. Depending on the glacial scenario, such behaviour can be expected initially after 200,000 or 350,000 years. During the coldest period, the deep permafrost might block the aquifer and increase the hydraulic head accordingly. Permafrost is expected to reach maximum depths of 100 – 200 m.

Earthquakes and faulting

The Nördlich Lägern siting region is located within a low-seismicity intraplate region. Faulting is primarily related to the shortening of the Alpine and Jura mountains as well as to transtensional deformation within the Upper Rhine Graben, which is linked to the plate motion between the European plate and the Adriatic microplate. These plate-dynamic forces define the stress field that is not expected to vary significantly from the present direction. Rates of strain accumulation are expected to be low in the next one million years. As typical for intraplate areas, the location of faulting is expected to change over time, and areas that are currently rather inactive from a seismic perspective might become the focus of future seismic activity. Earthquakes and fault ruptures are thus possible in the vicinity of the siting regions. Earthquake faulting might happen in the long term, as it must be assumed that faults are critically loaded. Accordingly, changes in local stress conditions might trigger faulting. Such changes might result from vertical glacial loading or unloading, large erosion events, or from loading through interaction with neighbouring faults. Importantly, irrespective of timing and trigger, it is expected that earthquakes will occur along preexisting faults. Some of these regional fault systems bound the sites and are accordingly avoided when deciding where to place the repository infrastructure.

10.3 Impacts of the long-term geological evolution on exposure to radiation

The calculation of the radiological consequences for a given radionuclide release is performed by means of a model referred to as the biosphere model (Nagra 2024e).

In the biosphere model, it is assumed that the transport of radionuclides after their release from the confining rock zone of a deep geological repository into the human habitat is caused by deep groundwater exfiltration into the local aquifers. Therefore, the biosphere model areas are located where the groundwater flux of the deep aquifers from the siting regions reaches local aquifers (exfiltration), because that is where the highest radionuclide concentrations are to be expected in the environment.

The reference biosphere model is based on the present-day climate. Potential evolution scenarios of the climate, and their safety significance, are explored through alternative biospheres. This includes a consideration of both warmer climate and colder (periglacial) climate.

The long-term evolution of the geology and landscape can affect the transport properties of the confining geological units (e.g., by decompaction) and impact the transport length through the different units (e.g., by erosion). A complete exhumation of the deep geological repository within the period under consideration by glacial processes is not expected and not further considered here.

The long-term evolution of the geology and landscape results from many slow and interrelated processes. The uncertainty in predicting the magnitude of the influences of these processes on the barrier properties cannot be further reduced. Regarding the rates at which geology and landscape might change to the extent that they could impact the performance of the repository, it can be safely assumed that the engineered barriers of the high-level waste deep geological repository would be fully saturated and operational. The L/ILW repository is not affected as these processes are expected to occur after the period under consideration for an L/ILW repository.

The potential impact of the long-term geological evolution of the siting region on the exposure to radiation from near-surface groundwater or surface waters (exfiltration) sites is thus considered to be low.

11 Conclusions

The present report describes the expected phenomenological evolution of a repository for both HLW and L/ILW in Opalinus Clay with surface facilities at the Haberstal site. The focus is on processes occurring during construction, operation and closure of the repository sections, as well as the post-closure period. This includes the safety-related impact of repository-induced effects on the geological barrier (e.g., thermal effects, the formation of an excavation-damaged zone, the effects of any high-pH plume and the effects of gas generation and gas pressure build-up).

The phenomenological description constitutes an important part of the assessment basis that will be used in future safety assessment, including performance assessment and the analysis of radiological consequences. In particular, it will support the identification of detrimental effects that must be accounted for when establishing or updating the expected performance and performance targets for the repository barriers, as well as requirements on the site, the engineered components and the waste to be disposed of. It will also provide a foundation for the identification of scenarios to be analysed in safety assessment.

The information contained within the phenomenological description comes from a range of sources, including:

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

This information is brought together and synthesised to form a unified, high-level account of the deep geological repository and its evolution, including associated uncertainty. As further information is gathered, the overall level of uncertainty in the phenomenological description and in the wider assessment basis is expected to decrease, although there may be unexpected findings that increase uncertainty on certain issues (at least until they are further investigated). This increase in information and associated decrease in uncertainty will be reflected in the future iterations of the phenomenological description that are planned over the next few years.

The evolution of the waste and of the repository barriers begins before waste emplacement, and thus pre-emplacement processes and uncertainty fall within the scope of phenomenology. Initially, the evolution of the deep geological repository is relatively complex, due to the presence of significant repository-induced thermal, mechanical, hydraulic, and chemical gradients. Over time, these gradients decline, the corresponding processes become less significant, and the repository evolves towards an equilibrated system. Associated with the relatively complex early evolution of the repository are significant uncertainty in the rates, spatial extent and sequences of the processes that occur, although the processes themselves are reasonably well known. The final, pseudo-steady state is expected to be unaffected by this uncertainty, provided it can be shown that the processes do not lead to significant and irreversible damage to the barriers. This issue is addressed by the performance assessment and supported by the phenomenological description.

Much of the uncertainty in the early evolution of the repository up to the point that a pseudo-steady-state is attained has its roots in the complexity of the resaturation process. Uncertainty in the resaturation process leads to uncertainty in the time of occurrence, rate or spatial extent of many repository-induced effects, including the development of overpressures in the host rock, the development and evolution of excavation damage and various chemical interactions between the host rock and the engineered materials. In the case of the HLW repository section, complexity arises mainly from the coupling of resaturation with the heat production from the waste. In the case of the L/ILW repository section, it arises mainly from the coupling with gas production in the emplacement rooms.

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App. A Section break (Odd page) in the following line: do not delete section break.Expected evolution as input for the performance assessment

In the context of the general licence application, a single reference evolutionary scenario is formulated for the selected site. The reference evolutionary scenario is a broad-brush description of how Nagra expects the repository system and its environment at the site to evolve and behave over time. This reference evolutionary scenario belongs to the assessment basis and informs the performance assessment on the most likely evolution of the deep geological repository.

The description in this chapter is based on current scientific understanding documented in this report, including uncertainty. As a broad-brush description, “parameter uncertainty” is an inherent part of the reference scenario. The reference scenario can be seen as an envelope around the most likely path or development of the deep geological repository and its components and includes multiple lines of evolution where, e.g., the rates of processes, the timing of events and the location of features, can vary from one line of evolution to another, but the overall description of these lines of evolution is qualitatively similar. Model abstraction and its attendant “model uncertainty” are not explicitly part of the reference scenario, i.e., the way in which the evolution of the system is simplified for modelling purposes is not part of the description of the reference scenario. However, the current scientific understanding on which this description is based is, in part, the result of modelling. Therefore, model uncertainty is implicitly present, generally in the form of uncertainty in those parameters that are obtained as the result of modelling. A third category of uncertainty, “scenario uncertainty”, is reflected in the existence of alternative scenarios, the description of which is not part of this document.

A.1 Waste inventory and acceptance

In the reference scenario, all waste conforms to the acceptance criteria. The effective waste inventory is identical to that of the modelled reference assumptions in the MIRAM (Model Inventory of Radioactive Materials) database for the general licence application (Nagra 2023b).

A.2 Location, construction, operation, and closure of the underground facilities

The repository is constructed at about 850 m b.g.l. in the middle of the OPA host rock layer, with separate disposal areas for the emplacement of SF/HLW (the HLW repository section) and L/ILW and ATW (the L/ILW repository section). Regional fault zones and zones of high tectonic complexity and seismically detectable local tectonic fault are avoided with a sufficiently respectful distance (Nagra 2024l).

The construction of all underground structures is carried out using state-of-the-art technologies and best engineering practices and complies with all relevant requirements and specifications. A respectful distance to exploration boreholes is observed (> 50 m from the disposal areas).

All the engineering deep geological repository components are also manufactured, handled, and emplaced with state-of-the-art technologies and best engineering practices in compliance with all relevant design requirements and specifications. Measures are undertaken to ensure that any accidents and incidents occurring in the pre-closure period have no impact on long-term safety.

The emplacement drifts for SF and HLW are continuously backfilled with bentonite buffer during emplacement of the disposal canisters. As soon as an emplacement drift has been filled with disposal canisters, it is closed with a V1 seal. The emplacement caverns for L/ILW and ATW are divided into compartments. Each compartment is backfilled with cementitious mortar within a few days after emplacement of the L/ILW disposal containers. After all compartments in a cavern have been filled, the cavern is closed with a V1 seal.

A monitoring phase starts once all waste has been emplaced. Early in this phase, the accesses to the HLW and L/ILW repository sections are backfilled and sealed at the repository level with V2 seals. At the end of the monitoring phase, i.e., after a few decades, test areas and all other open underground structures that are still in use, including the accesses that are still open, are backfilled and the access structures are sealed with V3 seals. The closure of the repository is again carried out with state-of-the-art technologies and best engineering practices and is assumed to comply with all relevant requirements and specifications.

A.3 Evolution of underground openings prior to backfilling

The excavation, cooling and ventilation of the underground openings results in the gradual desaturation and depressurisation of the surrounding rock, which eventually resaturates when ventilation ceases. Transient processes associated with ventilation that are assumed to have no long-term impact on the safety-relevant properties of the rock in the reference scenario include, for example:

- drying out of tunnel support materials;
- creation of desiccation cracks in the surrounding rock;
- precipitation of salts in these cracks due to evaporation of porewater;
- an increase in the salinity of the porewater and
- carbonation of cementitious materials due to reaction with CO₂ in the air.

An EDZ also forms around the underground openings. The EDZ, however, reseals in the post-closure period as it resaturates. Consequently, the EDZ has a limited impact on the radionuclide retention and transport properties of the CRZ, i.e., the host rock and the upper and lower confining units that act as barriers.

A.4 Saturation of the access structures

After closure, the V3 seals that are placed in the access shafts to seal the repository from the surface environment saturate relatively rapidly, i.e., within a few hundred years of installation, due to their high suction and the flow from more permeable rock formations above the repository down the shafts and into the seals. Once saturated, the sealing elements have a low permeability to both water and gas (permeability to water of 10^{-19} to 10^{-18} m²). This largely prevents further water flow down the shafts into the unsaturated underground structures of the repository. It also largely prevents the migration of repository-generated gas from the underground structures of the repository towards the surface environment. This is relevant to radiological safety, as repository-generated gas may convey gaseous and volatile radioactive species, such as ¹⁴C, mainly under the form of ¹⁴CH₄. Seals are built such that pore-clogging is unlikely to alter the gas transport properties.

A.5 Evolution of the L/ILW disposal area and connected underground structures after backfilling

After the emplacement of L/ILW and ATW and the backfilling and sealing of the emplacement caverns, the partially saturated EDZ and rock support around the caverns largely resaturate with water, although some gas-filled pores may remain because of repository-generated gas (see below). Some water may also enter the caverns and accumulate under gravity above the cavern floor. Anaerobic and reducing conditions develop due to the consumption of O₂ in trapped air and, in the porewater within and around the caverns, hyperalkaline conditions develop due to the presence of cementitious materials.

Gas generation takes place due to corrosion and degradation of organic materials in the caverns. Some of this gas dissolves in porewater within and around the caverns, with the remainder accumulating within the caverns, increasing the gas pressure and limiting further inflow of water. The partially saturated EDZ around other underground openings also resaturates with water. The V1 seals that close the L/ILW caverns and the V2 seals that isolate the L/ILW disposal area from the rest of the repository also start to saturate, but full saturation is prevented by gas from the caverns. This gas migrates through the seals and accumulates in the backfill of the adjoining underground structures, providing a storage volume for the gas in addition to that provided by the caverns themselves. Desaturated conditions persist in the upper parts of the L/ILW caverns and in the backfill of the connected underground structures for several tens of thousands to hundreds of thousands of years, until gas generation ceases. Some gas may enter the rock but will migrate through it without causing damage. Pore-clogging due to cement-clay interactions within the V1 and V2 seals that might impact overall seal permeability is not expected as long as the seals remain only partially saturated.

Transient heat initially produced by cement hydration and, in the longer term, radiogenic heat from the L/ILW, and especially from ATW, lead to a transient short-term increase in temperature within and around the L/ILW disposal area. This heat, in combination with gas penetration, also leads to elevated pore pressures. These elevated temperatures and pore pressures, however, have no long-term impact on the performance of the barriers.

The disposal containers will provide an initial resistance to water ingress, but they degrade over time, and, after a few hundred years, water will come into contact with the waste matrices in at least some of the containers, and the radionuclides embedded within them will start to be released. Some radionuclides are gaseous or can form volatile species, and these radionuclides become mixed with the repository-generated gas in the emplacement caverns and sealing system.

The tunnel support system around the emplacement drifts degrades and loses its mechanical strength over time, but the resulting stress redistribution has no impact on the safety-relevant properties of the barriers. In particular, the presence of backfill material prevents rock fall and limits cavern convergence to the extent that no previously sealed EDZ fractures are reactivated.

The cementitious near-field evolves over time due to the mineralogical evolution of cement phases. A high pH is expected to be maintained throughout the L/ILW assessment period of 100,000 years, but there are changes in the radionuclide retention properties of the backfill. Interactions between the cementitious near-field and the surrounding rock are of limited spatial extent and do not affect the safety-relevant properties of either barrier. In particular, any pore clogging that occurs due to precipitation does not reduce the overall permeability to gas.

A.6 Evolution of the HLW disposal area after backfilling

After emplacement of SF and HLW canisters, as well as buffer and seals of the emplacement drifts, the partially saturated EDZ and rock support around the tunnels resaturate with water, followed by saturation of the buffer and seals. The compacted clay structures saturate relatively quickly due to their high capillary pressure (suction), though the rate of saturation is limited by the low permeability of the rock and by decay heat generated by the waste. Full saturation is expected to occur some hundreds of years after emplacement. Saturation is sufficiently even to avoid potentially damaging stresses being exerted on the canisters. Any initial inhomogeneities in the buffer density are largely reduced over time. The buffer density around the canister is sufficiently high to prevent, when saturated, microbial activity that might otherwise increase the rate of canister corrosion.

Anaerobic and reducing conditions develop due to the consumption of O₂, e.g., by canister corrosion. Radiation shielding provided by the disposal containers is sufficient to protect the barriers from radiation-induced effects. Gas generation takes place due to the gradual anaerobic corrosion of the disposal canisters. Much of this gas dissolves in the porewater of the saturated bentonite buffer surrounding the canisters and diffuses through the rock support into the OPA porewater. However, some gas also migrates in the gas phase through the buffer and into the rock, where it dissolves. Gas migration causes no irreversible changes to either the buffer or the rock.

In the first few thousands of years following deep geological repository closure, repository-generated heat, primarily decay heat from the waste forms, leads to a transient increase in temperature and pore pressure within and around the HLW disposal area, including within the CRZ. However, these elevated temperatures and pore pressures have no long-term impact on the performance of the barriers. The tunnel support system around the emplacement drifts degrades and loses its mechanical strength, but the resulting stress redistribution has no impact on the safety-relevant properties of the barriers (any reactivation of EDZ fractures will be temporary, as the fractures will reseal).

Porewater composition in the buffer gradually equilibrates with that in the rock. Chemical interactions, including interaction of canister corrosion products with the clay barriers and between the cementitious lining and the surrounding rock, are of limited spatial extent and do not affect the safety-relevant properties of the repository barriers.

In the post-closure period from ten thousand years onwards, increasing numbers of disposal canisters become locally breached due to mechanical failure following weakening by corrosion or local flaws in the welding. The exposure of internal metal surfaces to water results in corrosion of these surfaces and locally increased gas production rates. The evolution of the waste packages following canister breaching is described in the context of radionuclide release, retention and transport in Chapter 9.

A.7 Evolution driven by climatic and geological processes

The long-term geological and climatic evolution, including glacial and fluvial erosion and uplift, geomorphological effects and activation or re-activation of fault zones, do not negatively impact the safety-relevant properties of the repository barrier system over a time period of one million years. Nonetheless, over a period of hundreds of thousands of years, erosion processes, in combination with uplift, gradually result in a partial loss of overburden. An exhumation of any part of the disposal areas, or any decompaction of the CRZ that would affect safety-relevant properties (especially its porosity, hydraulic conductivity and self-sealing capacity) can be ruled out for the chosen site and for the period under consideration.