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Phenomenological Description of the Evolution of a Geological Repository for Radioactive Waste in Opalinus Clay: Handling of FEPs in the Safety Assessment

September 2024

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KEYWORDS
Safety Case, Database, Audit, FEP, Safety assessment

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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 report "Handling of FEPs in the safety assessment" has been elaborated by a project team consisting of Tamara Baldwin[1], Olivier Leupin[2] and Paul Smith[3].

Many different authors (>30 Nagra staff) contributed their expertise to this report:

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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 supplements the phenomenological description of the evolution of a geological repository for radioactive waste in Opalinus Clay (Nagra 2024a) by developing a FEP database and auditing the phenomena included in the safety assessment against Nagra's FEP database.

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List of Acronyms

CRZ	Containment-providing rock zone
EDZ	Excavation damaged zone
ENSI	Swiss Federal Nuclear Safety Inspectorate
FEP	Features, events and processes
FHA	Future human action
HLW	High-level waste (spent fuel assemblies and vitrified high-level waste from reprocessing)
L/ILW	Low- and intermediate-level waste
MIRAM	Model Inventory for Radioactive Materials
MOX	Mixed oxide fuel
NEA	Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (OECD)
NWMO	Canada's Nuclear Waste Management Organization
PEGs	Potentially exposed groups
QA	Quality assurance
RD&D	Research, development & demonstration
RP-HLW	Vitrified high-level waste reprocessing product
SF	Spent fuel assemblies

1 Introduction

The present report supplements the phenomenological description of the evolution of a geological repository for radioactive waste in Opalinus Clay (Nagra 2024a) with the development of a FEP database and audit of the phenomena included in the safety assessment against Nagra's FEP database.

1.1 Background and aims of this report

Safety assessment is defined by Nagra as the process of gathering the evidence and arguments and carrying out analyses of the safety of the repository system during the post-closure phase and is the process by which a safety case is developed. Safety assessment consists of four main processes:

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

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

- features, events, and processes (FEPs) and their interactions that could affect post-closure safety have been thoroughly identified, and
- these FEPs have been adequately managed in the safety assessment.

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

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

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

These activities are described in the present report. As described in Section 1.2, Nagra's FEP database has been developed iteratively over many years, largely independently of the main safety assessment process[1]. Each version has been reviewed by internal Nagra experts and external third-

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

party experts and compared with other relevant FEP databases compiled by national organisations in other countries and by international bodies.

The FEP audit considers whether all the FEPs in the FEP database have been adequately treated in the safety assessment or that their omission is well justified. 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 FEPs are considered either in performance assessment, or directly in the analysis of radiological consequences. 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.

FEPs can be included in the safety assessment in different ways, for example:

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

Where FEPs are excluded, it must be shown that these are either outside the scope of, or irrelevant to, the safety assessment in support of the general licence application. This then helps to ensure that no relevant FEPs have been overlooked and that there is a sound justification for the exclusion of any FEPs.

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

1.2 The Nagra FEP database

The Nagra FEP database has been developed over many years. The FEP database for Project *Entsorgungsnachweis* (termed the OPA FEP List) was developed based on an earlier Nagra FEP list related to the disposal of the reprocessing product vitrified high-level waste (RP-HLW) in a crystalline host rock (Sumerling et al. 1999), as well as on several ancillary FEP lists compiled by Nagra and Nagra's consultants, which considered various aspects of the proposed repository system. The ancillary FEP lists focused on those aspects of the repository system and its assessment that differed from earlier Nagra safety assessments (i.e., FEPs related to disposal of spent fuel (SF) and intermediate-level waste (ILW), and FEPs related to the performance of the Opalinus Clay as a host rock and migration barrier).

The OPA FEP List was developed internally by Nagra through a process of accumulation, addition, organisation and rationalisation based mainly on the experience of Nagra staff. To promote comprehensiveness of the OPA FEP List, an audit was performed (Nagra 2003) where the OPA FEP List was compared with two independently derived FEP lists:

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

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

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

The FEP database was updated based on this completeness check, reviewed and, where necessary, modified. It is this version of the FEP database that is used in the safety assessment in support of the general licence application and is the subject of the present report.

The current Nagra FEP database only refers to the reference safety scenario and to FEPs that could perturb that safety scenario, such as future human actions. That is, the FEPs describe the features of the repository system and biosphere, and events and processes that act on, or occur within, the system, but do not attempt to cover in a comprehensive manner FEPs that may arise in extreme situations as a result of those events and processes, such as repository excavation by erosion. Any such FEPs are, however, expected to be identified and analysed in the course of the safety assessment.

The FEP database is organised into 17 categories, as presented in Tab. 1-1, which, when extracted, form smaller FEP catalogues (e.g., the Biosphere FEP catalogue). Each FEP in the database is recorded with a unique numerical identifier, a short title and a description. Developed as part of the FEP audit, the database also summarises the potential impact of each FEP on repository system performance and safety, and how the FEP has been handled in the safety assessment for the general licence application. The complete list of FEPs in each category is reproduced in App. A, which also identifies how each FEP has been handled in the safety assessment.

Tab. 1-1: FEP categories within the Nagra FEP database for the general licence application

	Category
1	FEPs outside assessment scope
2	Common FEPs
3	Siting, design and implementation
4	Vitrified RP-HLW
5	Spent fuel
6	L/ILW waste packages
7	HLW canister
8	HLW emplacement drift buffer and liner
9	L/ILW cavern backfill and liner
10	Access structures and closure system
11	Geological setting
12	Containment-providing rock zone (CRZ)
13	Repository-induced effects
14	Geological processes and events
15	Climatic processes and events
16	Biosphere
17	Future human actions

1.3 Information flow in the safety assessment

The information and workflow between each of the safety assessment processes outlined in Section 1.1 is described in Ch. 5 of (Nagra 2024c) and summarised graphically in Fig. 1-1. The FEP audit carried out in the present report forms part of the assessment basis shown in the box at the far right of the figure. The audit aims to ensure that the performance assessment and other processes in safety assessment, especially the analysis of radiological consequences, are comprehensive in the phenomena that they account for and that irrelevant FEPs and FEPs that are outside the scope of the safety assessment are identified and the rationale for their exclusion is explained.

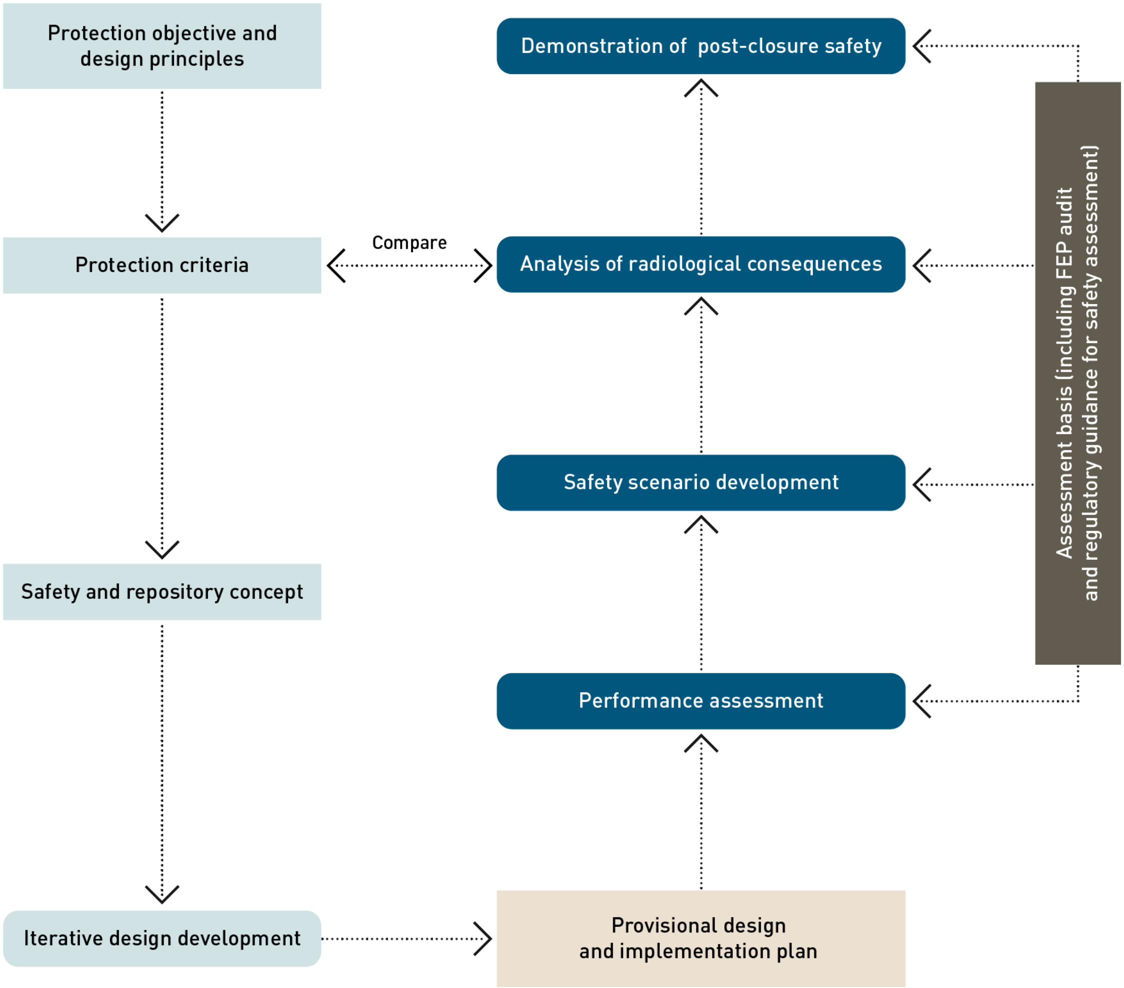

Fig. 1-1: Workflow for the post-closure safety case

Overview of the top-down procedure (left) for the development of a design and implementation plan for the current project milestone (bottom right) and the safety assessment of the repository system to demonstrate safety (right). Processes are illustrated with boxes with rounded corners and products/knowledge with boxes with square corners. The FEP audit presented in the present report forms part of the assessment basis (far-right box).

1.4 Methodology and organisation of this report

As discussed above, an evaluation of the phenomenological comprehensiveness of the safety assessment amounts to answering the following questions:

- Have all FEPs that could affect post-closure safety been identified?
- Have these FEPs been adequately managed in the safety assessment?

The first question is addressed through the systematic development of the FEP database, as described in Section 1.2. The second question is addressed by showing, by means of an audit, that every FEP in the FEP database is either included in the safety assessment, or that its omission is justified. More specifically, the audit approach adopted in the present report is to show that each FEP within the database can be assigned to one of the groups defined in Tab. 1-2.

Tab. 1-2: Grouping of FEPs according to their handling in, or exclusion from, the safety assessment for the general licence application

The table identifies the chapters and sections of this report where each group is described and whether they are included in the safety assessment or omitted on the grounds given in the respective sections of this report.

		Handling in the safety assessment	
		Included	Excluded
FEPs outside the assessment scope or not relevant to safety assessment		✗	Ch. 2
Features of the initial state or FEPs affecting the initial state of the repository system	Safety-relevant site and design features and planned implementation	**S. 3.1.1**	✗
	Other site and design features and deviations from design	**S. 3.1.2**	S. 3.2
FEPs occurring during the post-closure period	Geological and climatic	**S. 4.1.1**	S. 4.1.2
	Repository-related	**S. 4.2.1**	S. 4.2.2
	Future human actions and activities	**S. 4.3**	S. 4.3
Biosphere and surface/near-surface environment FEPs		**Ch. 5**	Ch. 5

The FEPs assigned to each group, and, where appropriate, the rationale for their assignment (and hence for their inclusion in, or exclusion from, the safety assessment) are described in the following chapters of this report:

- Chapter 2 describes those FEPs within the FEP database that are judged to be outside the scope of, or irrelevant to, the safety assessment in support of the general licence application.
- Chapter 3 includes FEPs that are either features of the initial state of the repository system at the time of closure or that affect this initial state in some way (e.g., FEPs related to repository construction and operation).
- Chapter 4 describes FEPs occurring during the post-closure period, but excluding biosphere and surface or near-surface environment FEPs, and
- Chapter 5 describes biosphere and surface or near-surface environment FEPs.

Finally, App. A provides a list of all the FEPs within the FEP database and identifies how they have been handled in the safety assessment.

2 FEPs outside the assessment scope or not relevant to safety assessment

2.1 FEPs outside the scope of the safety assessment

FEPs within the FEP database that are judged to be outside the scope of the safety assessment for the general licence application are listed in Tab. 2-1. The subsequent text in this section explains why each of the identified FEPs is outside the scope of the current safety assessment.

Tab. 2-1: FEPs outside the scope of the safety assessment for the general licence application

Number	FEP
1.2	Alternative designs for repository and engineered barriers
1.3	Chemically toxic contaminants
1.4	Unplanned events and remedial actions
1.5	Social, institutional and technological developments
1.6	Deliberate human intrusion
1.7	Explosions and crashes at the surface
1.8	Evolution of biota
1.9	Exposure of non-human biota

The provisional repository design considered in the safety assessment and safety case is the outcome of an ongoing and iterative design development process, as described, for example, in Nagra (2024c). Only one provisional design for the proposed siting region needs to be considered in the safety case for the general licence application. To support site comparison, this design is adapted as necessary to the other siting regions considered. It is expected that this design will be updated as part of the design optimisation foreseen for future licensing stages, in which alternative designs for the repository and engineered barriers (FEP 1.2) will be considered.

There are a number of chemically toxic materials (metals and organic compounds) present in the RP-HLW, SF and in some L/ILW waste. These could be considered contaminants (FEP 1.3) if these materials, or any toxic degradation products, were to be released from the repository. The consequences are currently not considered in the post-closure safety assessment. However, conformance of the repository with environmental protection laws is demonstrated in the "Umweltverträglichkeitsprüfung" (the environmental impact assessment) (Nagra 2025).

Unplanned events, such as accidents, mishaps, failure of quality control processes and intentional malicious acts could occur during repository construction, operation and closure, and could potentially impair the performance of the repository barriers. For example, unplanned events may include localised contamination from an oil spill or other stray material left in the repository, dropping the canisters and waste packages, faulty emplacement of waste packages and faulty installation of engineered components, fire events (including explosion of flammable natural gases), floods, collapse of tunnels, galleries or drifts, and theft or sabotage. Unplanned events are also conceivable during waste encapsulation and during the manufacture of other components at the surface. Operational/handling methods, equipment and processes will be designed to minimise the likelihood of unplanned events, and procedures will be developed to ensure, if necessary, that appropriate remedial measures are taken if such events were to occur. Although unplanned events and remedial actions (FEP 1.4) are considered to be outside the scope of the present safety assessment, certain deviations from the initial state assumed at the time of repository closure that could arise as a result of unplanned events, such as the presence of an initially damaged canister or poorly emplaced buffer, are considered as "what-if?" cases in the safety assessment (see FEP 3.3.11 in Chapter 3). In addition, in some cases, the effects of certain unplanned events on the results of the analysis of radiological consequences would be minor due to the conservatism in the handling of certain features. For example, no credit is taken for the integrity of the RP-HLW fabrication flasks and Zircaloy SF cladding after canister breaching, so the results of the analyses would be the same even if these components were to be damaged.

Social, institutional and technological developments (FEP 1.5) are generally not considered in the safety assessment. Although it is inevitable that human society, institutions and technology will change over the timescales of relevance for repository safety assessment, these changes are largely unpredictable. To limit speculation, it is assumed that human technological capabilities and societal patterns observed today, and in the past, provide a reasonable model to assess the safety of the repository in the future. Thus, for example, only future human actions that could be undertaken with present-day technology are considered and communities considered in the biosphere assessment are based on those of the present day. Note, however, that abandonment of the repository before it is fully backfilled and sealed, which could conceivably occur as a result of major societal changes (i.e., societal collapse; FEP 17.9.2), is included in the safety assessment as a future human actions safety scenario (FEP 17.9.3).

Deliberate human intrusion (FEP 1.6) is excluded from the safety assessment, as it is assumed that any society wishing to recover materials from the repository would have the technology to understand and manage the hazards. However, appropriate security actions will be taken to prevent malicious acts. Furthermore, it should be noted that the deep underground location of the repository and the backfilling and sealing of all access structures would make deliberate human intrusion a difficult, resource-intensive and highly visible process that could not easily be undertaken for secretive or malicious purposes.

Explosions and crashes at the surface (FEP 1.7), including those due to a large meteorite, human space debris, acts of terrorism and war, are excluded due to the low probability of such events being large enough to disturb the repository. In addition, in the case of very large explosions/crashes (sufficient to damage the closed repository), consequences to local humans, biota and the environment will be dominated by effects not related to the presence of the repository.

Consideration of the evolution of biota (FEP 1.8) is excluded due to the impossibility of predicting future evolution over relevant timescales. Thus, the only biota considered in the biosphere assessment are those living in the present day.

According to Article 11, paragraph 2 of the Nuclear Energy Ordinance (KEV 2004), and as reproduced in ENSI's guideline ENSI-G03 (ENSI 2023), biodiversity may not be put at risk by geological disposal. Radiological exposure of non-human biota (FEP 1.9) is, however, not considered in the safety assessment. Rather, in accordance with ENSI's explanatory report for Guideline ENSI-G03 (ENSI 2020), it is assumed that, if exposure of humans is insufficient to cause harm, then the wider environment is also protected[2]. However, livestock and crops (including pasture) and other biota are taken into account in the safety assessment insofar as they may affect the transport and distribution of radionuclides in the biosphere (see biosphere FEPs in Chapter 5), and hence the dose rate to humans.

[2] Original text: *Die Richtlinie geht deshalb von der bisherigen Annahme aus, dass die Arten geschützt sind, wenn die nötigen Vorkehrungen zum Individualschutz des Menschen getroffen wurden.*

2.2 FEPs not relevant to the safety assessment

There are two further FEPs that are not relevant to the safety assessment, although they are relevant to repository design and implementation planning, since it is a regulatory requirement that they do not compromise post-closure safety. These are retrievability (FEP 3.3.8) and monitoring (FEP 3.3.9); see Tab. 2-2.

Tab. 2-2: FEPs not relevant to the safety assessment

Number	FEP
3.3.8	Retrievability
3.3.9	Monitoring

The repository is designed to facilitate retrieval of the waste if deemed necessary by future generations, but this is not expected to be required on safety grounds. According to ENSI's guideline G03 (ENSI 2023), necessary measures to ensure safety during the operating phase, including provisions for possible retrieval of the radioactive waste, must not compromise long-term safety[3].

An extensive monitoring period is foreseen prior to repository closure. ENSI's guideline G03 (ENSI 2023) states that the influence of the installations planned for monitoring of long-term safety must be demonstrated and minimised[4]. However, the underground monitoring programme is under development and its impact is assumed to be insignificant in the present safety assessment. The findings of underground monitoring will be taken into account in future iterations of the safety case, and the negligible impact of monitoring installations will be demonstrated.

[3] Original text: *Erforderliche Massnahmen zur Gewährleistung der Sicherheit während der Betriebsphase sowie Vorkehrungen für eine mögliche Rückholung der radioaktiven Abfälle oder den temporären Verschluss dürfen die Langzeitsicherheit nicht beeinträchtigen.*

[4] Original text: *Der Einfluss der für die Überwachung vorgesehenen Installationen auf die Langzeitsicherheit ist aufzuzeigen und zu minimieren.*

3 FEPs related to the initial state of the repository system

This chapter addresses FEPs that are either features of the initial state of the repository system at the time of closure or that affect this initial state in some way. Section 3.1 addresses FEPs that are included in the safety assessment and which either define the expected initial state of the repository system (Section 3.1.1) or that potentially give rise to significant deviations from the expected initial state (Section 3.1.2). Section 3.2 identifies FEPs related to the initial state that are excluded from detailed consideration in the safety assessment and, in each case, gives the rationale for their exclusion.

3.1 FEPs included in the safety assessment

3.1.1 FEPs that define the site, design and expected initial state of the repository system

FEPs that define the expected initial state of the repository system at the time of closure include those that concern:

- the repository site, geological setting and host rock (Tab. 3-1),
- the waste forms, inventory and packaging (Tab. 3-2), and
- the repository design and the materials and dimensions of the engineered components (Tab. 3-3).

These FEPs are included explicitly in many of the models and qualitative arguments used to evaluate the evolution and performance of the repository system in the safety assessment.

Tab. 3-1: FEPs that define the repository site, geological setting and host rock

Number	FEP
Site	
3.1.1	Repository site
Geological setting	
11.1.1	Host geology
11.1.2	Lithostratigraphy
11.1.3	Geological formation/history
11.1.4	Sedimentology, mineralogy etc. of the upper confining units
11.1.5	Sedimentology, mineralogy etc. of the lower confining units
11.1.6	Current regional stress regime
11.1.7	Local stress regime
11.1.8	Regional fault zones
11.1.9	Local faults
11.1.11	Mechanical properties
11.1.12	Groundwater and porewater composition

Number	FEP
11.1.13	Microbiological processes and conditions
11.1.14	Geothermal gradient
11.1.15	Natural resources
Hydrogeological characteristics	
11.2.1	Hydrogeological units
11.2.2	Effective hydraulic properties
11.2.3	Recharge and discharge
11.2.4	Regional hydraulic gradient
11.2.5	Local hydraulic gradient
11.2.6	Groundwater flow, flowpaths and discharge
Host rock and containment-providing rock zone (CRZ)	
12.1.1	CRZ rock matrix
12.1.2	CRZ discontinuities
12.2.1	CRZ hydraulic and gas permeability
12.2.2	CRZ porewater flow
12.2.3	CRZ anomalous pore pressures

Tab. 3-2: FEPs that define the waste forms, inventory and packaging

Number	FEP
General	
3.2.1	Waste forms and inventory
3.2.2	HLW inventory
3.2.3	L/ILW inventory
3.2.4	Waste emplacement in a geological repository
Vitrified RP-HLW	
4.1.1	RP-HLW vitrified waste form
4.1.2	RP-HLW stainless steel fabrication flask
4.1.3	RP-HLW glass cracking and surface area
Spent fuel	
5.1.1	Spent fuel assemblies
5.1.2	UO_2 fuel pellets and Mixed Oxide (MOX) fuel matrix
5.1.3	Fuel cladding and structural elements
5.1.4	SF disposal canister filling material and voids
5.1.6	Distribution of radionuclides in the SF

Number	FEP
5.1.8	Fuel cracking and surface area
L/ILW	
6.1.1	L/ILW disposal section waste types
6.1.2	L/ILW groups
6.1.3	Typical L/ILW disposal containers
6.1.4	L/ILW conditioning
6.1.5	L/ILW packages
6.1.7	L/ILW disposal section hydraulic and gas permeability
6.1.9	L/ILW organics

Tab. 3-3: FEPs that define the repository design and the materials and dimensions of the engineered barriers

Number	FEP
Repository design (general)	
3.3.1	Appropriate repository design and closure
3.3.2	Repository layout and layout constraints
3.3.3	HLW emplacement drifts
3.3.4	L/ILW emplacement caverns
HLW canister, emplacement drift, buffer and liner	
7.1.1	HLW carbon steel disposal canister
8.1.1	HLW drift liner
8.1.2	HLW buffer emplacement and composition
8.1.3	HLW bentonite buffer plasticity and self-sealing
8.1.4	HLW bentonite buffer hydraulic and gas permeability
8.1.5	HLW bentonite buffer inhomogeneities (properties and evolution)
L/ILW cavern backfill and liner	
9.1.1	L/ILW cavern liner
9.1.2	L/ILW cavern rock bolts
9.1.3	L/ILW cavern backfill material
9.1.4	L/ILW cement additives
9.1.5	L/ILW backfill emplacement
9.1.8	L/ILW near-field hydraulic and gas permeability
Access structures and closure system	
10.1.1	Underground openings and access to the disposal sections

Number	FEP
10.1.2	Repository seals
10.1.3	Tunnel backfill
10.1.4	Closure system hydraulic and gas permeability

FEPs that concern the implementation of the repository are presented in Tab. 3-4. These FEPs are also included, though in a more implicit manner, in many of the models used to evaluate the evolution and performance of the repository system in the safety assessment.

Site investigation boreholes (FEP 3.1.2) are generally assumed to be backfilled and sealed prior to repository closure and to have negligible impact on the performance of the geosphere. The safety-related consequences of investigation boreholes have been evaluated (Mayer et al. 2015).

Administrative control (FEP 3.3.5) during the pre-closure period is assumed to lead to well-defined conditions after closure, that is, administrative control is assumed to be effective in ensuring an initial state at the time of closure that accords with the repository design considered in the safety assessment. Nonetheless, some examples of possible initial state deviations are considered in scenario development within the safety assessment (see FEP 3.3.11). Administrative control is not foreseen after closure and is thus excluded from the long-term safety assessment. It is, however, assumed that human intrusion into the repository can be excluded for a limited period after closure due to the preservation of memory of the repository (e.g., records and markers; FEP 17.9.1; the preservation of records could be seen as a form of administrative control).

Construction and operation of disposal areas (FEP 3.3.6) and, specifically, their effects on the initial state and subsequent evolution of the repository (FEP 13.1.1) are considered. Such effects may include, for example, desaturation of the rock due to ventilation, perturbations to porewater composition in the host rock and the development of an excavation damaged zone (EDZ). Processes occurring as a result of exposure of the host rock to air are reversible and/or of limited extent and are not expected to have any significant impact on performance and safety. The only effect of the construction and operation phases propagated to the post-closure safety assessment is EDZ formation and evolution (see FEP 13.2.1).

Repository closure (sealing and backfilling) (FEP 3.3.7) is generally assumed to take place according to plan. The system of seals and backfill that will be installed to close the repository is a key feature accounted for in both the performance assessment, especially the assessment of the saturation behaviour of the repository and the fate of repository-generated gas, and in the analysis of radiological consequences. However, as noted above, abandonment of the repository before it is fully backfilled and sealed, which could conceivably occur as a result of societal collapse, is included in the safety assessment as a future human actions safety scenario (FEP 17.9.3).

Quality management in the pre-closure period (FEP 3.3.10) is implicitly assumed in the safety assessment modelling to be effective in ensuring that the repository is implemented in accordance with the requirements on the site, design and waste. The possibility of failure of quality management is implicitly considered in the safety assessment when evaluating initial state deviations (see Tab. 3-5).

Tab. 3-4: FEPs that concern the implementation of the repository

Number	FEP
3.1.2	Site investigation boreholes
3.3.5	Administrative control
3.3.6	Construction and operation of disposal areas
3.3.7	Repository closure (sealing and backfilling)
3.3.10	Quality management
13.1.1	Effect of the construction and operation phase (general)

3.1.2 FEPs potentially giving rise to significant deviations from the expected initial state

FEPs potentially giving rise to significant deviations from the expected initial state of the repository at the time of closure are listed in Tab. 3-5, which also summarises how these are included in the safety assessment.

Tab. 3-5: FEPs potentially giving rise to significant deviations from the expected initial state

Number	FEP	Inclusion in the safety assessment
Handling, design and implementation FEPs		
3.3.11	Initial-state deviations	Deviations from the initial state assumed at the time of repository closure arise if repository components are left in place that do not conform with design specifications. This could arise, for example, due to a failure of administrative control (FEP 3.3.5) and quality management (FEP 3.3.10), or due to unplanned events (FEP 1.4). Initial state deviations include, but are not limited to, a mis-sealed HLW canister (FEP 7.1.2), poor emplacement of liner and buffer in the HLW emplacement drifts (FEP 8.1.6), poor emplacement of the liner and backfill in the L/ILW emplacement caverns (FEP 9.1.10), and poor or incomplete emplacement of the backfill and seals in the repository closure system (FEP 10.1.5). These deviations are considered implicitly in the "what-if?" cases in the analysis of radiological consequences.
HLW canister		
7.1.2	Mis-sealed HLW disposal canister	It is possible that the welds used to seal the disposal canisters could be incomplete or faulty. The planned quality assurance (QA) procedures that would be applied in canister manufacture are designed to detect weld defects of critical size with high confidence, since this size is more than one order of magnitude larger than the detection limit. Nevertheless, manufacturing defects and irregularities could, if they were to escape detection, make the canister more prone to early mechanical failure following weakening by corrosion. The possibility of early canister breaching one thousand years after closure is considered as a "what-if?" case in the analysis of radiological consequences.

Number	FEP	Inclusion in the safety assessment
HLW emplacement drift, buffer and liner		
8.1.6	Poor emplacement of HLW bentonite buffer and liner	Poor emplacement of the bentonite or the liner could have a significant impact on the performance of the barriers. Deviation from the as-planned state could result, in extreme cases, in the collapse of the drift, hydraulic preferential flowpaths, microbial activity or canister movements all resulting in shortened lifetime of the canister. Given the planned QA procedures, poor emplacement of the buffer and liner to the extent that such effects arise is unlikely. Nonetheless, in the analysis of radiological consequences, a "what-if?" case is analysed in which the bentonite buffer is hypothetically assumed to be degraded, though without any specific cause.
L/ILW cavern backfill and liner		
9.1.7	Cavities in the L/ILW backfill/liner	Although backfilling methods will be used that should ensure uniformity in the cavern backfill, as well as filling of any voids between the two L/ILW cavern liner shells, it cannot currently be excluded that poor emplacement results in the presence of cavities that remain after emplacement of the mortar. Cavities could impact the mechanical support provided to the host rock and thus impact L/ILW cavern stability. Given the planned QA procedures, poor emplacement of the backfill to the extent that such effects arise is unlikely. Nonetheless, a "what-if?" case is analysed in which the cementitious backfill is hypothetically assumed to be not homogenously emplaced leaving cavities, though without any specific cause.
9.1.10	Poor emplacement of the L/ILW backfill and liner	
Access structures and closure system		
10.1.5	Poor or incomplete emplacement of backfill and seals	The performance of seals could be influenced by a poor or incomplete emplacement of sealing material: the sealing elements are designed to limit the water flow and maximise the gas permeability. Poor or incomplete emplacement may put this functionality at risk. Given the planned QA procedures, poor emplacement of the backfill and seals to the extent that such effects arise is unlikely. Nonetheless, in the analysis of radiological consequences, a "what-if?" case is analysed in which the closure system is hypothetically assumed to be degraded, though without any specific cause.
Geological setting		
11.1.10	Undetected features	The term "undetected features" here refers to non-mappable faults, that is, faults that cannot be detected in seismic surveys, or other natural or man-made features or heterogeneities that escape detection. Reactivation of non-mappable-scale faults may occur in the post-closure period, which could lead to a limited temporary increase in the permeability of these features. This could potentially lead to some disruption of the engineered barriers and new structural lineaments could also develop. Non-mappable faults and new structural lineaments are, however, expected to be limited in length and offset and are therefore unlikely to cut across the host rock as discrete connected elements. Nonetheless, the possibility of a non-mappable fault that intersects the repository underground openings, including the emplacement drifts and caverns, becoming re-activated by geological events and processes, such as erosion and seismic activity, or by repository-induced effects, such as heat- and gas-generation, is considered in safety scenario development and in the analysis of radiological consequences.

Number	FEP	Inclusion in the safety assessment
11.2.8	Natural groundwater colloids	Colloids are expected to be immobile in the fine pore structure of the host rock and other CRZ layers (FEP 12.1.5), but may be transported by diffusion and (if there is groundwater flow) advection within the overlying and underlying aquifers. They may facilitate radionuclide transport if radionuclides diffusing from the CRZ become attached to the colloids (see colloid-facilitated radionuclide transport; FEP 2.3.9). Conservatively, in the analysis of radiological consequences, radionuclides reaching the local and regional aquifers are assumed to be conveyed instantly and without attenuation to the discharge zones. Thus, the possibility of colloid-facilitated radionuclide transport within the aquifers is implicitly accounted for but is not modelled explicitly.

3.2 FEPs excluded from detailed consideration in the safety assessment

FEPs excluded from detailed consideration in the safety assessment, and the rationale for their exclusion, are presented in Tab. 3-6.

Tab. 3-6: FEPs excluded from detailed consideration in the safety assessment

Number	FEP	Rationale for exclusion
L/ILW and packages		
6.1.6	L/ILW disposal container cavities and voids	The space between waste packages (or directly around the waste) inside the concrete containers will be filled with a cement-based materials. Some voids may, however, remain between, and within, the waste packages inside the containers at the time of emplacement. However, these voids are expected to be small and few in number – the void space is accounted for in the inventory and on this basis is shown to be small. The voids may collapse over time but are unlikely to have any effect on the stability of the L/ILW emplacement caverns in the long term.
6.1.10	L/ILW disposal section extraneous materials (including microbes/biological materials)	The presence of extraneous (unintended) materials in large enough quantities to significantly influence degradation of organic materials in the waste is not expected due to the application of QA measures, and so this is not accounted for in the safety assessment. Microbial activity cannot be excluded in the L/ILW, although such activity will be limited by the high pH environment. The role of microbial activity in the evolution of near-field chemistry is analysed in the performance assessment (see FEP 6.2.8).
L/ILW cavern backfill and liner		
9.1.6	Joints and cracks in the L/ILW backfill/liner	Joints and cracks in the backfill and liner may affect repository saturation and the fate of repository-generated gas. In principle, they could also lead to enhanced groundwater flow after saturation of the near field. However, groundwater flow is expected to be limited due to the low hydraulic conductivity of the surrounding host rock and the additional porosity created by cracks or joints would, in any case, be negligible compared with the initial porosity of the backfill.

Number	FEP	Rationale for exclusion
9.1.9	Effects of initial (operating) conditions on L/ILW cavern materials	The operational phase of a cementitious repository (open and ventilated caverns) may influence safety relevant properties of some repository components. This is minimised by sealing the L/ILW caverns immediately after waste emplacement and so this FEP is excluded.

4 FEPs related to post-closure evolution of the waste and to the performance of the repository system

This chapter addresses FEPs related to post-closure evolution of the waste and to the performance of the repository system. Section 4.1 addresses geological and climate-related FEPs, Section 4.2 covers repository-related FEPs and Section 4.3 covers FEPs related to future human actions. In each of these sections, FEPs that are included in the safety assessment are identified, as are those FEPs that are excluded from detailed consideration, and, in each case, the manner of inclusion or rationale for exclusion is given.

4.1 Geological and climate-related FEPs

4.1.1 FEPs included in the safety assessment

The following tables list the geological and climate-related FEPs included in the safety assessment and summarise how they are included. Tab. 4-1 concerns the geological and climatic FEPs themselves, and Tab. 4-2 concerns the assumed impact of geological and climatic FEPs on the repository system.

Tab. 4-1: Geological and climatic FEPs included in the safety assessment

Number	FEP	Inclusion in safety assessment
Geological and environmental events and processes		
14.1	Regional vertical movements	Over a million-year time frame, none of these processes can be excluded; their potential impacts on the repository system are considered in the performance assessment, scenario development and in the analysis of radiological consequences, as appropriate. • The effects of climate and climate change on the characteristics of the CRZ and geological setting are considered. Uncertainties in the vertical hydraulic gradient in the geosphere associated with climate change are also considered. • The possible impacts of erosion (including decompaction due to extreme erosion) are considered, although the extent of erosion over the next million years and the depths of incisions are expected to be much more shallow than planned repository depths. Self-sealing capacity (FEP 12.1.3) is considered robust for an overburden of > 200 m. • Subsidence in the Northern Upper Rhinegraben is considered in the assessment of future erosion. However, the effect in the siting regions is limited, as most of the space arising from this process will be infilled by fluvial sediments. • It is assumed that respect distances to local, seismic-scale faults ensure that such features generally have no direct impact on the repository. However, the possibility of a local fault that intersects the closure system becoming re-activated by geological events and processes, such as a large
14.2	Regional horizontal movements	
14.3	Effects of climate change (general)	
14.4	Erosion and geomorphological changes	
14.5	Fluvial erosion/sedimentation	
14.6	Glacial erosion/sedimentation	
14.7	Glacial-fluvial erosion/sedimentation	
14.8	Subsidence	
14.10	Neotectonic activity	
14.11	Seismic activity	
14.12	Creep	
14.19	Evolution of regional stress regime	

Number	FEP	Inclusion in safety assessment
14.20	Fault re-activation and formation of new faults	earthquake, or by repository-induced effects, such as heat- and gas-generation, is considered. The possibility of a sub-seismic scale fault that intersects the emplacement drifts and caverns becoming re-activated is also considered.
14.21	Compaction and decompaction	
Present and potential future climatic conditions		
15.1	Climate	The safety assessment explicitly considers climatic conditions and the potential for different conditions to occur over time. Climatic conditions also represent an important component in describing and parameterising the biosphere, including the definition of feasible human habits.
15.2	Present-day climatic conditions	Present-day interglacial climate conditions in Northern Switzerland are mild in comparison with the full glacial-interglacial cycle and support a wide range of types of agriculture. Basing reference biosphere modelling on present-day conditions, therefore, allows a broad range of potential exposure pathways to be evaluated. It provides confidence that the biosphere system being modelled is internally consistent because parameterisation can be supported with reference to present-day observations and familiar environmental conditions.
15.3	Future climatic conditions	The potential for different climate characteristics to be prevalent when radionuclide releases might occur in the far future is considered in the biosphere modelling. The radiological consequence analysis seeks to envelope the reference conditions, which are based on present-day climate, by considering bounding warmer and colder climate conditions that still support potential human presence in the area local to radionuclide releases to the biosphere.
15.4	Human-induced climate change and greenhouse effect	Human influences on climate are accounted for through consideration of long-term climate change. The potential for geoengineering is not directly considered, because the assessment is based on consideration of technologies and capabilities available today.
15.5	Glacial climate	The on-going effects of ice sheets and valley glaciers in shaping the landscape of Northern Switzerland in the future (FEPs 14.6 and 14.7) are assumed to not result in a landscape that differs significantly from that of the present day. People are unlikely to be present during glacial periods. Nonetheless, biosphere dose factors for reference conditions (based on present-day climate) are used throughout to provide a measure of potential impact, even if such exposures are implausible.
15.6	Permafrost	Cold climatic conditions where people may still be present in the area local to radionuclide releases to the biosphere are explicitly considered as an alternative climate scenario. There is potential for people to be present in the local area when temperatures are low enough for permafrost, such that discontinuous permafrost and taliks are included in the cold climate biosphere model. The assessment accounts for differing human behaviour under such conditions (e.g., limited potential for agricultural exploitation) as well as differing biosphere
15.7	Tundra climate	

Number	FEP	Inclusion in safety assessment
		characteristics (including precipitation, evapotranspiration, surface run-off, and different soil properties).
15.8	Dry climate	Warmer-drier climate conditions are explicitly considered as an alternative in biosphere modelling. This includes the effect on human habits (e.g., increased irrigation demand) as well as differing biosphere characteristics (including precipitation, evapotranspiration, surface run-off).
15.9	Warm seasonal humid climate	Higher surface and groundwater flow during warm-humid periods mean that potential dose consequences have previously been shown to be lower than those for present-day and warmer-drier conditions. Therefore, although the conditions may occur, they are not explicitly evaluated within the radiological consequence analyses.

Tab. 4-2: FEPs describing the assumed impact of geological and climatic FEPs on the repository system

Number	FEP	Inclusion in safety assessment
7.2.13	Impact of geological events and processes on the HLW disposal canisters	Potentially significant impacts of the FEPs identified in Tab. 4-1 on the HLW canisters and emplacement drifts are considered as "what-if?" cases in the analysis of radiological consequences – early HLW canister breaching due to a large earthquake, and extreme erosion leading to the decompaction and eventual loss of the buffer. The impact of erosion on the performance of the closure system is analysed in the performance assessment.
8.2.15	Impact of geological events and processes on the HLW buffer and liner	
10.2.10	Impact of geological events and processes on the access structures and closure system	

4.1.2 FEPs excluded from detailed consideration in the safety assessment

Geological and climate-related FEPs excluded from detailed consideration in the safety assessment, and the rationale for their exclusion, are presented in Tab. 4-3. Some of these FEPs concern the impact of geological events and processes identified in Tab. 4-1 on the L/ILW near-field. These are covered in the top part of the table. The remainder of the table addresses geological events and processes and climatic conditions that are judged not to be of concern for a repository sited in northern Switzerland.

Tab. 4-3: Geological and climatic FEPs excluded from detailed consideration in the safety assessment

Number	FEP	Rationale for exclusion
Impact of geological events and processes identified in Tab. 4-1 on the L/ILW near-field		
6.2.12	Impact of geological events and processes on the L/ILW and packages	No credit is taken in the analysis of radiological consequences for the physical containment of radionuclides by the waste packages or by the L/ILW disposal containers, and so the possibility of damage to these components by seismic activity is, in effect, handled conservatively.
9.2.12	Impact of geological events and processes on the L/ILW backfill and liner	Most potential geological events and processes that could perturb the L/ILW near-field would only occur long after most radionuclides have been released from the L/ILW. Seismic activity cannot be excluded in the shorter term and could crack or weaken the L/ILW backfill and liner if, for example, a fault intersecting the L/ILW caverns were to be re-activated and undergo slip. Although this could lead to the formation of connected paths through these materials, their mass transport properties are not expected to be significantly affected due to their initially high permeabilities and diffusivities.
Other geological events and processes		
14.9	Folding	The past evolution shows that deformation preferentially localises in the area of existing fault zones. Large-scale folding has generally taken place in the area of regional fault zones. Significant regional fault zones are avoided by repository siting. Consequently, no relevant fold-related uplift or subsidence is expected in the repository area and this FEP is excluded. The effects of small-scale folding and associated sub-seismic faulting are covered in FEPs 14.11 and 14.20 (see Tab. 4-1).
14.13	Magmatic activity (volcanism and plutonism)	There has been no magmatic activity in the area of northern Switzerland for at least the last 5 million years (volcanic activity in the neighbouring Hegau ceased in the Early Pliocene times). Considering the current tectonic setting of the region, a direct intrusion or extrusion of magma is very unlikely in northern Switzerland during the next one million years. Magmatic activity is therefore not considered further.
14.14	Hydrothermal activity and effects	Significant geothermal anomalies (e.g., regional fault zones) are avoided by repository siting. The temperature measurements during the deep drilling campaign have not delivered any indications of relevant thermal anomalies in the area of the repository (temperatures in the host rock do not exceed 50 °C). The host rock has seen considerably higher temperatures in the course of its geological history. During the period of consideration, the natural temperature in the host rock at repository level is rather expected to decrease as a result of overburden reduction by erosion (see also FEP 17.2.2, Tab. 4-14, on geothermal exploitation).
14.15	Metamorphism	The rocks of the CRZ have not seen the high pressures or temperatures that are necessary for rock metamorphosis.

Number	FEP	Rationale for exclusion
14.16	Diagenesis	Opalinus Clay is a slightly over-consolidated clay rock. Over the period of concern, the site will be affected by uplift and erosion (FEP 14.4, Tab. 4-1). Further diagenetic processes (e.g., water-rock interactions and microbial activity) are not of concern during this period. Beyond the period of concern, Opalinus Clay rock properties may be altered as the rock comes into the shallow decompaction zone.
14.17	Dissolution/karstification	The Opalinus Clay contains only small amounts of minerals that are susceptible to dissolution. It is therefore considered to be a rock unit that is not susceptible to dissolution processes. Some beds of the confining rock units have higher carbonate contents. The development of highly transmissive water pathways by dissolution processes is not expected due to hydraulic considerations (e.g., very low hydraulic gradient and lack of larger fault zones in the repository area). It is not expected that this situation will change during the period under consideration. For the same reasons, it is not expected that, below the repository zone, relevant volumes of rock will be dissolved during the period of consideration leading to faulting and increased permeability in the overlying CRZ.
14.18	Diapirism	Salt thickness in the area of the siting regions is limited. There is no indication for salt diapirism during the multistage burial and erosion history.
14.22	Hydrogeochemical evolution	Influx of oxidising water, significant salinity changes and other relevant changes in groundwater composition are ruled out based on the regional hydrogeological and hydrochemical situation, including the low hydraulic conductivity of the CRZ. Furthermore, the over- and underlying aquifers contain oxygen-free, reducing groundwater and, even if this were to change, the strong buffering by pyrite, siderite and organic matter would prevent oxidising water from penetrating far into the CRZ.

4.2 Repository-related FEPs

4.2.1 FEPs included in the safety assessment

The following tables show the repository-related FEPs that affect, or have the potential to affect, evolution and performance of the repository system and so are considered in detail in the safety assessment. The following tables summarise how these FEPs are included in the safety assessment: Tab. 4-4 concerns heat-related FEPs, Tab. 4-5 concerns mechanical FEPs, Tab. 4-6 concerns chemical, microbiological and radiation-related FEPs, Tab. 4-7 concerns flow, transport and retention-related FEPs, and finally Tab. 4-8 concerns other FEPs related to radionuclide release and radionuclide migration pathways.

Tab. 4-4: Heat-related FEPs included in the safety assessment

Number	FEP	Inclusion in safety assessment
2.2.1	Heat sources, heat transfer and thermal evolution	The thermal evolution of the repository, including all significant heat sources and heat transfer processes (conduction, convection and radiation), is evaluated in detail in the performance assessment. Significant heat sources are the RP-HLW (FEP 4.1.4) and the SF (FEP 5.1.5). The heat output from the RP-HLW and the SF is considered in developing the repository layout, in assessing the evolution and performance of engineered and geological barriers.
4.1.4	RP-HLW heat generation	
5.1.5	SF heat generation	
2.2.4	Pore pressure	The temperature will affect the physical and chemical properties of the engineered materials and rock. The heat generated by HLW is considered in performance assessment in terms of its wider effects on the engineered barrier system and surrounding rock, and is also considered in the repository design in order to ensure that thermal criteria, especially for bentonite, are met. The coupled thermal and hydraulic evolution of the bentonite buffer is modelled in the performance assessment. Temperature gradients that may affect radionuclide transport are assumed to have dissipated by the time of canister breaching in the analysis of radiological consequences. The prevailing temperature is, however, taken into account in the evaluation of transport and retention parameter values, including diffusion coefficients. The HLW heat output is also taken into account when assessing the possibility of thermally-induced degradation of clay. Thermally-induced pore pressure gradients are taken into account when modelling the advective transport of solutes and gas both in the performance assessment and in the analysis of radiological consequences. The evolution of pore pressures due to both heat and gas generation, and the potential for this to cause mechanical damage, is evaluated in the performance assessment.
4.2.14	Effects of RP-HLW temperature and temperature gradients	
5.2.15	Effects of SF temperature and temperature gradients	
7.2.2	HLW canister temperature evolution	
8.2.12	Effects of HLW near-field temperature and temperature gradients	
13.3.1	Thermally-induced degradation of clay	
13.3.3	Thermally-induced pore pressure increase	

Tab. 4-5: Mechanical FEPs included in the safety assessment

Number	FEP	Inclusion in safety assessment
2.2.11	Mechanical evolution (general)	The mechanical evolution of the repository, and especially EDZ formation, the development of swelling pressure in bentonite-based repository components, HLW canister breaching and the mechanical impact of climatic and geological phenomena, such as seismicity and glacial loading and unloading, are evaluated in the performance assessment. In the analysis of radiological consequences, the EDZ is handled primarily by assigning it conservative transport parameters and canister breaching is handled by assuming a canister breaching time that is conservative, based on the results of performance assessment.
7.2.6	Solid HLW canister corrosion products and volume expansion	HLW canister breaching due to mechanical loading following weakening by corrosion leads to the release of radionuclides, as accounted for in the analysis of radiological consequences. The mechanisms and timing of canister breaching are analysed in the performance assessment. Formation of magnetite from iron oxidation can lead to an increased volume, which has the effect of potentially increasing the compaction of the bentonite.
7.2.8	HLW canister breaching	
8.2.2	HLW bentonite buffer swelling, homogenisation and swelling pressure	Bentonite swelling, homogenisation and the development of swelling pressure are considered in the performance assessment, for example, in assessing the mechanical forces acting on the HLW canister. In the analysis of radiological consequences, it is assumed that initial inhomogeneities have reduced by the time of canister breaching to the extent that they do not affect the transport of radionuclides released from the breached canister. Convergence of the underground openings due to host rock creep is evaluated in the performance assessment, as well as convergence-induced fluid flow. Self-sealing of fractures and small, re-activated faults resulting from repository-induced effects and from geological events and processes is also assumed in scenario development and in the analysis of radiological consequences, although any such features are assumed to remain open for long enough to allow the escape of any repository-generated gas that has accumulated under pressure in the near-field, allowing for gas-facilitated radionuclide transport. The potential loss of self-sealing in the event of substantial erosion of the overburden is also considered as a "what-if?" case in scenario development.
8.2.13	HLW buffer and liner mechanical evolution and bentonite creep	
10.2.1	Saturation of the closure system	
12.1.3	CRZ swelling and self-sealing	
13.1.3	Host-rock creep and convergence	
13.2.1	Excavation-damaged zone (EDZ) formation and evolution	EDZ formation and its subsequent evolution are analysed in the performance assessment, accounting for the self-sealing properties of the rock, as is the role of the EDZ in the fate of repository-generated gas. The EDZ is treated conservatively in the analysis of radiological consequences when considering the radial transport of dissolved radionuclides released from the emplacement drifts and caverns. The possibility that compaction and decompaction due to long-term geological processes could displace porewater axially along the EDZ is considered in the performance assessment.

Number	FEP	Inclusion in safety assessment
10.2.5	Pore-pressure-induced damage to the closure system	The evolution of pore pressures due to both heat (Tab. 4-4) and gas (Tab. 4-7) generation, and the potential for this to cause mechanical damage to the closure system and host rock, is evaluated in the performance assessment and, if the possibility for damage cannot be excluded, it is considered in the analysis of radiological consequences.
13.3.4	Induced seismicity	
13.3.6	Pore-pressure-induced stress changes, fracturing and fault reactivation	

Tab. 4-6: Chemical, microbiological and radiation-related FEPs included in the safety assessment

Number	FEP	Inclusion in safety assessment
2.2.5	Chemical evolution and microbiological processes	A wide range of chemical evolution and microbiological processes is considered in the performance assessment in order to evaluate their influence on the performance of the barriers. The chemical evolution of the porewater is assessed in the L/ILW near-field (FEP 6.2.2) and HLW near-field (FEP 8.2.5), and closure system (FEP 10.2.3) and within the near-field rock (FEP 13.4.3), for example, because of its impact on the retention of radionuclides and the evolution of buffer swelling pressure. In the analysis of radiological consequences, the chemical composition of the porewater is assumed to have reached an equilibrium state by the time of HLW canister breaching, and this porewater composition is accounted for in evaluating, for example, the rates of radionuclide release, and the degree to which radionuclides released from the breached canisters sorb on the buffer. In general, microbially-induced processes are taken into account explicitly in the performance assessment when they can be shown to have a potentially detrimental effect on safety. Microbiological activity in the L/ILW near-field (FEPs 6.2.8 and 9.2.7) is assessed (e.g., because of its effect on gas production) and is also assessed in the EDZs (FEP 13.2.1), for example, due to the potential production of corrosive agents.
6.2.2	Chemical evolution of the L/ILW near-field porewater	
6.2.8	Microbial activity in L/ILW	
8.2.5	Chemical evolution of HLW near-field porewater	
9.2.7	Microbial activity in L/ILW caverns	
10.2.3	Chemical impact of inflowing water on the closure system	
13.4.3	Repository-induced changes in host rock pore water composition	
2.2.6	Corrosion of metals	A wide range of corrosion mechanisms is accounted for in the performance assessment when assessing the corrosion of metals within the repository system (FEPs 2.2.6). Corrosion and corrosion products are important because of their long-term impact on HLW canister integrity (FEPs 7.2.3), on porewater composition in the canister interior (FEPs 5.2.11 and 7.2.12) and as a source of gas in the L/ILW near-field and HLW near-field (see Tab. 4-7), including after canister breaching (FEP 7.2.9). In the case of SF, corrosion of the cladding and other metals following canister breaching will release radionuclides embedded in these features (FEP 5.2.5). A gas phase around the canisters is accounted for in the assessment of
5.2.5	Corrosion of SF cladding and other metal parts	
5.2.11	SF disposal canister corrosion products	
6.2.4	Corrosion of L/ILW metallic components	
7.2.3	Corrosion prior to HLW canister breaching	

Number	FEP	Inclusion in safety assessment
7.2.5	Gas around the HLW canister and impact on corrosion	canister corrosion, gas generation and canister breaching in the performance assessment (FEP 7.2.5). The presence of hydrogen is also accounted for in the SF dissolution rates assumed in the analysis of radiological consequences. Effects of porewater composition on corrosion are accounted for when selecting several parameter values for the analysis of radiological consequences, including the dissolution rate of SF and RP-HLW.
7.2.9	Corrosion after HLW canister breaching	
7.2.12	Effects of water composition on HLW canister corrosion	
4.2.6	RP-HLW glass dissolution	The dissolution rate of vitrified RP-HLW glass (FEP 4.2.6) is a key parameter in the near-field modelling, since it controls the rate of release of radionuclides from this waste form in the analysis of radiological consequences. A cement-buffered environment is not expected to arise in the HLW near-field, and so is not considered in the context of RP-HLW glass dissolution. The precipitation of silicates (the formation of a passivating gel layer on the surface of the dissolving glass) is implicitly accounted for when determining the glass dissolution rate (FEP 4.2.9), as is the presence of iron corrosion products and clay minerals (FEP 4.2.8).
4.2.8	Iron corrosion products/clay minerals and glass dissolution	
4.2.9	Precipitation of silicates/silica gel and RP-HLW glass dissolution	
5.2.4	Fuel pellet dissolution	The SF pellet dissolution rate is a key parameter in the near-field modelling carried out in the analysis of radiological consequences, since it determines the release rate of radionuclides incorporated in the pellets. The rate of the fuel pellet dissolution is determined by the low solubility of U(IV). Fast dissolution of UO_2 SF due to radiolytic oxidants is prevented by hydrogen produced by the anaerobic corrosion of the canister and the Zircaloy cladding, which is catalytically activated by metallic fission product particles in the fuel. After hydrogen gas production ceases, alpha radiolysis will be too weak to induce oxidative fuel dissolution.
8.2.3	HLW bentonite buffer mineralogical alteration	The potential for the alteration of bentonite minerals (FEP 8.2.3), including bentonite-iron interactions (FEP 8.2.4), leading to a reduction in bentonite swelling properties and/or plasticity is considered in the performance assessment. In general, these processes either have no effect on the safety-relevant properties of the buffer or affect its properties only within a zone of limited spatial extent. An altered layer of bentonite around the canister is accounted in the radiological consequence analysis.
8.2.4	HLW bentonite buffer - iron disposal canister interactions	
2.2.7	Cement degradation and carbonation	The chemical evolution of cementitious materials, including the waste conditioning materials, backfill and liner in the L/ILW near-field (FEPs 2.2.7, 6.2.1 and 9.2.4), is considered in the performance assessment as it affects retention of the nuclides, pore structure (FEP 9.2.6) - and hence gas permeability and hydraulic conductivity - and corrosion rates of metals. The evolution of pH and other chemical parameters is taken into account when defining retention parameter values for near-field modelling in the analysis of radiological consequences. The effects of cement degradation are accounted for in the analysis of radiological consequences and, in the performance
6.2.1	Degradation of L/ILW cementitious conditioning material	
9.2.4	Chemical degradation of L/ILW cementitious materials and porewater evolution	

Number	FEP	Inclusion in safety assessment
9.2.6	Cementitious near-field evolving pore-structure	assessment, it is accounted for in the assessment of gas pressure evolution (FEP 2.2.2).
2.2.8	Cement-clay interactions	Contact between concrete materials and clay materials occurs around the emplacement drifts and caverns and within the closure system (FEPs 2.2.8, 8.2.6 and 10.2.8). Interactions at the zone of contact between concrete materials and clay materials in the repository can affect the pore structure (FEP 8.2.7) and can potentially lead to pore clogging and hence affect the gas permeability and hydraulic conductivity of these materials (FEP 13.4.2). Geochemical reactions at the interface can lead to local changes in the porewater and mineral composition (dissolution and secondary minerals). The organic content of the L/ILW waste is in combination with the cement backfill too small to lead to any significant migration of organic chemical species into the surroundings (FEP 10.2.9 and 13.4.4). Some waste types contain nitrate. However, due to kinetic and thermodynamic considerations, redox reactions with nitrate are expected to be spatially limited in the Opalinus Clay with the current design for the technical barrier. Cement-clay interfaces, including the extent of chemical reactions and the potential for precipitation and pore clogging, are investigated as part of the performance assessment.
8.2.6	HLW liner cement - bentonite buffer clay interactions	
8.2.7	HLW buffer and liner evolving pore structure	
10.2.8	Cement-clay interactions in the access structures and closure system	
10.2.9	Migration of chemical species from the L/ILW near-field into the closure system	
13.4.2	Pore clogging	
13.4.4	Migration of chemical species from L/ILW	

Tab. 4-7: Flow, transport and retention-related FEPs included in the safety assessment (solutes and gas)

Number	FEP	Inclusion in safety assessment
2.3.1	Fluid flow	Fluid flow (FEP 2.3.1), including two-phase flow of water and gas (FEP 2.3.2), is considered in multiple safety assessment models, including those used in the performance assessment and in the analysis of radiological consequences. Two-phase flow is one of the processes accounted for in the integrated modelling of repository saturation (FEP 2.2.3) and of the fate of repository-generated gas (FEP 2.2.2) in the performance assessment, and is accounted for in the evaluation of gas-mediated radionuclide transport in the analysis of radiological consequences.
2.3.2	Two-phase flow	
2.2.2	Gas sources, gas transfer and gas sinks	Gas sources, gas transfer and gas sinks (FEP 2.2.2) are modelled quantitatively in the performance assessment. Major sources of gas included in modelling are gas generation due to corrosion of the HLW canisters (FEP 7.2.4), construction materials, cladding and due to corrosion and microbial activity in the L/ILW (FEPs 6.2.7 and 6.2.8). The SF represents a more minor source of gas, but is important because these include gaseous radionuclides (FEP 5.2.2). Modelling of gas migration includes gas transfer through the bentonite buffer (FEP 8.2.10) and through the L/ILW caverns (FEP 9.2.2), gas transport and storage within the closure system (FEP 10.2.4), gas transport in
2.2.3	Saturation of the repository	
2.3.3	Gas dissolution	
5.2.2	SF gas generation	
6.2.7	L/ILW gas generation and migration	
6.2.8	Microbial activity in L/ILW	

Number	FEP	Inclusion in safety assessment
7.2.4	Gas generation due to HLW canister corrosion	the rock and gas dissolution (FEPs 2.3.3 and 11.2.7). The advective transport of radionuclides as gaseous species with repository-generated gases is evaluated in the performance assessment and, if found to be potentially significant, in the analysis of radiological consequences. The evolution of gas pressure in the repository is closely coupled to, and hence modelled together with, saturation (FEPs 2.2.2 and 2.2.3).
8.2.10	HLW bentonite buffer gas pathways	
9.2.2	L/ILW cavern gas migration and storage	
10.2.4	Gas migration and storage in the closure system	
11.2.7	Host rock gas pathways	
2.2.4	Pore pressure	Pore pressure gradients are taken into account when modelling the advective transport of solutes and gas both in the performance assessment and in the analysis of radiological consequences. The effects of gas on pore pressures within and around the repository (FEPs 2.2.4 and 13.3.5), and the potential for this to cause mechanical damage, are modelled quantitatively in the performance assessment.
13.3.5	Gas-induced pore-pressure increase	
2.2.3	Saturation of the repository	Post-closure saturation of the repository (FEP 2.2.3) is modelled in detail in the safety assessment as part of the evaluation of the coupled thermal and hydraulic evolution, including saturation of the HLW near-field (FEP 8.2.1) and L/ILW near-field (FEP 9.2.3), and the EDZ (FEP 13.2.1).
8.2.1	HLW bentonite buffer saturation	
9.2.3	L/ILW cavern saturation/hydraulic evolution	
13.2.1	EDZ formation and evolution	
10.2.6	Axial water flow through the saturated closure system	The possibility of preferential paths for water movement in the saturated repository system is modelled quantitatively in the performance assessment, including axial water flow through the closure system (FEP 10.2.6) and through the EDZs (FEPs 13.2.1).
13.2.1	EDZ formation and evolution	
2.3.4	Advection and dispersion	Solute transport and retention are modelled quantitatively in the safety assessment when assessing the chemical evolution of the repository system and when assessing the fate of released radionuclides in the analysis of radiological consequences. The solute transport processes included are advection and dispersion (FEP 2.3.4) and diffusion, including matrix diffusion and accounting for anion exclusion and surface diffusion (FEPs 2.3.5 and 2.3.6). Matrix diffusion is considered in the analysis of radiological consequences in any scenarios in which transmissive features in the CRZ are relevant. Anion exclusion and surface diffusion are considered where diffusion in porous media is considered. The retention processes of sorption (and desorption) (FEP 2.3.7), and immobilisation by precipitation and co-precipitation of solids (FEP 2.3.8), are considered. Gas-mediated radionuclide transport (FEP 2.3.10) is also modelled.
2.3.5	Diffusion and matrix diffusion	
2.3.6	Anion exclusion and surface diffusion	
2.3.7	Sorption and desorption	
2.3.8	Immobilisation by precipitation and co-precipitation of solids	
2.3.10	Gas-mediated transport	

Number	FEP	Inclusion in safety assessment
7.2.1	HLW canister radiation shielding	Relative to the interior of the canister, the radiation field at the canister outer surface is greatly reduced by the shielding that the canister provides. Radiation shielding is accounted for implicitly in the performance assessment via the assumption that there is no radiation damage and radiolysis in the materials outside the canister (see Tab. 4-11).

Tab. 4-8: Other FEPs related to radionuclide release and radionuclide migration pathways included in the safety assessment

Number	FEP	Inclusion in safety assessment
2.1	Radioactive decay and ingrowth	Radioactive decay and ingrowth are accounted for in all models used in the analysis of radiological consequences and as a source of heat in the analysis of repository-induced effects in the performance assessment.
2.4.1	Radionuclide speciation and complexation	Radionuclide speciation and complexation are assessed and accounted for in all models of radionuclide migration used in the analysis of radiological consequences. Due to the trace concentrations of radionuclides released from the waste forms, it is assumed that all radionuclides behave as individual components. Most radionuclides are considered to be in inorganic form. For some radionuclides, however, organic species may also be relevant and hence are considered explicitly (notably C-14).
4.2.3	Contact of RP-HLW with water	Contact of vitrified RP-HLW (FEP 4.2.3) and SF (FEP 5.2.1) with water is conservatively assumed to occur immediately upon canister breaching. Radionuclide release due to contact with water and subsequent dissolution is explicitly modelled in the analysis of radiological consequences.
5.2.1	Contact of SF with water	
4.3.1	Radionuclide release from RP-HLW	Radionuclide release from the waste forms is the source term for modelling of radionuclide transport in the near-field in the analysis of radiological consequences. Radionuclides embedded in RP-HLW glass (FEP 4.3.1), the SF pellets (FEP 5.3.1) and the bulk of the SF cladding (FEP 5.3.2) are assumed to be released congruently with their dissolution or corrosion following canister breaching. Radionuclides that are partially segregated to the fuel-sheath gap and grain boundaries are assumed to be released instantaneously upon canister breaching, as are radionuclides enriched in the oxide film formed on the cladding surfaces during reactor irradiation. Radionuclides in L/ILW, including the instant release fraction, are assumed to be released rapidly following repository closure (FEPs 6.3.1 and 6.3.2).
5.3.1	Radionuclide release from spent fuel	
5.3.2	Radionuclide release from SF cladding and structural materials	
6.3.1	Radionuclide release through L/ILW degradation	
6.3.2	L/ILW instant release fraction	
5.3.4	SF radionuclides in gaseous or volatile form	Gaseous and volatile radionuclides, including C-14, may be released from the SF (FEP 5.3.4), and L/ILW (FEP 6.3.3).

Number	FEP	Inclusion in safety assessment
6.3.3	L/ILW gaseous and volatile radionuclides	Their advective transport with repository-generated gas is evaluated in the performance assessment and, if found to be potentially significant, in the analysis of radiological consequences.
7.2.7	Other HLW canister degradation processes	Other processes that could potentially degrade the canister include chemical reaction with radiolysis products, high-temperature creep and hydrogen embrittlement. The canister is designed to provide sufficient radiation shielding to limit radiation damage and radiolysis around the canister. Hydrogen embrittlement is considered in evaluating canister performance and breaching time.
2.4.2	Radionuclide migration pathways and processes	A range of radionuclide migration pathways and processes (FEP 2.4.2) are accounted for in the analysis of radiological consequences. Radionuclide migration from the RP-HLW glass and SF, cladding and other structural materials and into the water- and gas-filled volume inside the canister is handled implicitly in the near-field radionuclide transport modelling carried out in analysis of radiological consequences by assuming that these radionuclides are well mixed in both the aqueous and gas phases in this volume (FEPs 4.3.2 and 5.3.3). Transport within the HLW canister interiors (FEP 7.3.1) is accounted for implicitly and conservatively by assuming rapid and complete mixing of radionuclides within the canister void space. No credit is taken for sorption in the canister interior or for the transport resistance of the breached canisters. Radionuclide transport in the HLW bentonite buffer (FEP 8.3.1) is assumed to take place by diffusion; advective/dispersive transport is not modelled in the buffer due to its low permeability. Radionuclide retention by sorption on buffer pore surfaces is modelled, as is immobilisation by precipitation if any element in solution exceeds its solubility limit. Radionuclide migration from the L/ILW containers into the water- and gas-filled volume inside the surrounding cementitious backfill is handled implicitly in the L/ILW near-field radionuclide transport modelling by assuming that these radionuclides are well mixed in both the aqueous and gas phases in this volume. Sorption of dissolved L/ILW radionuclides is accounted for, but immobilisation by precipitation and co-precipitation is conservatively omitted from the modelling (FEPs 6.3.4 and 9.3.1). Radionuclide migration in solution from the HLW and L/ILW repository sections through the closure system and access structures is expected to be unimportant, since most RNs will diffuse directly from the HLW emplacement drifts and L/ILW caverns into the rock. However, gas-mediated radionuclide transport through the closure system and access structures is modelled explicitly (FEP 10.3.1). Transport pathways and processes are modelled explicitly though the EDZ (FEP 13.2.1) and in the CRZ (FEPs 11.3.1 and 12.3.1). Radionuclide transport by diffusion is considered, and
4.3.2	RP-HLW radionuclide migration and pathways	
5.3.3	SF radionuclide migration and pathways	
6.3.4	L/ILW radionuclide migration and pathways	
7.3.1	Radionuclide migration and pathways for breached HLW canisters	
8.3.1	HLW buffer radionuclide migration and pathways	
9.3.1	L/ILW near-field radionuclide migration and pathways	
10.3.1	Closure system radionuclide migration processes and pathways	

Number	FEP	Inclusion in safety assessment
11.3.1	Geosphere migration processes and pathways	also transport by advection and dispersion, although these are relatively insignificant due to the low permeability. Radionuclide retention by sorption on pore surfaces is modelled. The possibility of gas-mediated radionuclide transport is considered in the performance assessment and modelled in the analysis of radiological consequences if found to be necessary. Transport from the CRZ to the surface environment is accounted for implicitly and conservatively by assuming instantaneous transport of radionuclides in solution or in gaseous form to the biosphere, without attenuation.
12.3.1	CRZ radionuclide migration processes and pathways	
13.2.1	EDZ formation and evolution	

4.2.2 FEPs excluded from detailed consideration in the safety assessment

Repository-related FEPs excluded from detailed consideration in the safety assessment, and the rationale for their exclusion, are presented in the following tables. Tab. 4-9 concerns heat-related FEPs, Tab. 4-10 concerns mechanical FEPs, Tab. 4-11 concerns chemical, microbiological and radiation-related FEPs, Tab. 4-12 concerns flow, transport and retention-related FEPs, and Tab. 4-13 concerns other FEPs related to radionuclide release and radionuclide migration pathways.

Tab. 4-9: Heat-related FEPs excluded from detailed consideration in the safety assessment

Number	FEP	Rationale for exclusion
General		
13.3.2	Thermally-induced flow	Thermal gradients, in principle, influence porewater flow and solute transport in the HLW near-field and in the host geology. However, due to the very low hydraulic conductivity of the bentonite and host rock, thermally-induced flow effects are considered to be negligible.
L/ILW and waste packages, caverns, backfill and liner		
6.1.8	L/ILW disposal section heat generation	Heat generation inside the L/ILW waste packages due to radioactive decay and cement hydration in the L/ILW caverns is limited and is not expected to perturb the temperatures and temperature gradients to the extent that their safety-relevant properties would be affected. Temperature-induced pore-pressure increases are also expected to be low.
6.2.11	Effects of L/ILW temperature and temperature gradients	
9.2.1	L/ILW cement hydration and heat generation	
9.2.10	Effects of L/ILW near-field temperature and temperature gradients	

Tab. 4-10: Mechanical FEPs excluded from detailed consideration in the safety assessment

Number	FEP	Rationale for exclusion
Spent fuel (SF)		
5.2.3	Cracking of fuel pellets by helium build-up	Cracking because of helium build-up from alpha decay, if it were to occur, would change the surface area of the SF matrix, influencing its dissolution rate. However, this is not expected, as pressures in fission gas bubbles in fuel are already extremely high and do not cause cracking.
5.2.6	Hydrogen-induced cracking of the SF cladding	This FEP is omitted, as no credit is taken for the physical intactness of the cladding in the safety assessment.
5.2.12	SF structural materials corrosion product volume expansion	Even if SF structural material corrosion products of greater volume are formed, the void volume inside the canisters is sufficiently large that complete filling of the voids and the build-up of stresses inside the canister are not considered likely. In addition, in the near-field model for the analysis of radiological consequences, the residual transport resistance of the breached canister is conservatively disregarded. Thus, the build-up of stresses inside the breached canister due to the volume expansion caused by corrosion of metals (including the corrosion of the inside surfaces of the breached canister), which could potentially cause deformation and a reduction in transport resistance where the canister is breached, is irrelevant given the model assumptions made.
L/ILW and waste packages		
6.2.5	L/ILW galvanic effects	Galvanic coupling of different metals may occur in the L/ILW waste containers, affecting the corrosion rates. As the overall effect is considered insignificant it is not considered in performance assessment.
6.2.6	L/ILW volume expansion	Volume expansion of the waste and/or the packaging material is expected to occur and may lead to deformation, cracking and porosity decrease in the surrounding materials. Volume changes will be too small to affect the backfill around the containers to a significant degree, but corrosion of rebar could, over time, lead to mechanical damage of the containers themselves. No credit is taken in the analysis of radiological consequences for the physical containment of radionuclides by the L/ILW containers, and so their degradation due to corrosion of rebar is handled conservatively.
6.2.10	L/ILW mechanical evolution	In the long-term, steel drums may corrode and concrete containers may be damaged by rebar corrosion and volume expansion (FEPs 6.2.4 and 6.2.6), giving rise to cracks. No credit is taken in the analysis of radiological consequences for the physical containment of radionuclides by the waste packages or by the L/ILW disposal containers, and so the possibility of mechanical damage to these components is handled conservatively.

Number	FEP	Rationale for exclusion
HLW emplacement drift, buffer and liner		
8.2.11	HLW bentonite buffer erosion	The bentonite buffer could, in principle, be eroded mechanically by flowing water. Buffer material could also, in principle, be lost to fractures intersecting the drifts due to swelling into the fractures and the production of a bentonite sol in the presence of sufficiently dilute water ("chemical erosion"). In the context of a repository in Opalinus Clay, the only situation in which flowing water could affect the buffer mechanically would be in the event of flooding, prior to the installation of seals at the end of the HLW emplacement drifts. Flooding is among the accidents and unplanned events (FEP 1.4) that are excluded from the scope of the present safety assessment. The conditions necessary for chemical erosion cannot arise in the context of a repository in Opalinus Clay.
L/ILW cavern, backfill and liner		
9.2.5	Reaction with metals and inorganic materials in L/ILW caverns	The only metals in the L/ILW caverns outside the waste containers would be all the metallic parts (FEP 9.1.2), which may be used to support the emplacement rooms, together with shotcrete. These will corrode over time, although the cement-based L/ILW near-field contributes to the passivation of metals, keeping corrosion rates low. Some Fe-incorporation in the cement may occur. Interactions with other inorganic materials, such as ceramics and asbestos, will not cause any chemical degradation of the cement and in any case would occur inside the containers. Therefore, this FEP is excluded.
9.2.9	L/ILW backfill and liner mechanical evolution	Although cracking of the liner and backfill is likely and could lead to the formation of connected paths through these materials, their mass transport properties are not expected to be significantly affected due to their initially high permeabilities and diffusivities. These are expected to remain high, despite any limited tunnel convergence.
Access structures and closure system		
10.2.2	Closure system erosion by inflowing water	Hydraulic erosion of bentonite-based sealing elements could potentially be caused by water flowing through the closure system prior to saturation. Flooding is among the accidents and unplanned events (FEP 1.4) that are excluded from the scope of the present safety assessment. However, the extent of buffer or backfill erosion in case of accidental flooding of the repository during operation is minimised by the emplacement of abutments designed to withstand the expected water column and by the availability of remedial actions if needed. After closure, no advective water movements sufficient to cause erosion are expected as the underground structures will be backfilled and sealed. Therefore, this FEP is excluded.

Tab. 4-11: Chemical, microbiological and radiation-related FEPs excluded from detailed consideration in the safety assessment

Number	FEP	Rationale for exclusion
General		
2.2.9	Sulphate/chloride attack	Concrete structures may be disrupted by volume increases associated with sulphate and chloride attack, and cracking may occur. These cracks may lead to minor changes in the hydraulic and mechanical properties of the concrete structures, but, since these properties have no safety role in the post-closure period, such changes are of no safety relevance.
4.2.11	Microbial activity impact on RP-HLW glass	The level of microbial activity is expected to be low in the nutrient deficient conditions within the engineered barriers of the HLW disposal area, including around the vitrified RP-HLW (FEP 4.2.11), around the SF (FEP 5.2.13), the bentonite buffer (FEP 8.2.9), and within the CRZ (FEP 12.1.4). Microbes are considered non-viable in the bentonite buffer due to the limited physical space available in this material. Furthermore, in the early stages of repository evolution, many microbes will be unable to survive due to radiation and heat. Although microbes may survive under the alkaline conditions present in the liner as it degrades, their activity can be assumed to be low. In the case of a poorly emplaced bentonite buffer, microbial activity remains limited by the nutrients available in the porewater from the Opalinus Clay.
5.2.13	Microbial activity impact on SF	
8.2.9	HLW near-field microbial activity	
12.1.4	Microbial activity in the CRZ	
2.2.12	Radiolysis and radiation damage	Irradiation of the bentonite buffer (FEP 8.2.14), while the activities of SF and vitrified RP-HLW are high, is not expected to affect its mineralogy due to the shielding of the canister (FEP 7.2.1). Radiolysis of buffer porewater is also not expected due to shielding. Radiolysis of water (FEP 2.2.12) may occur in the interior of HLW canisters following canister breaching. In the case of vitrified RP-HLW and L/ILW, the radiation is too low to cause significant radiolysis (FEPs 4.2.4, 6.2.3 and 9.2.11) or radiation damage (FEPs 4.2.5 and 6.2.13). In the case of SF (FEP 5.2.7), fast oxidative dissolution of UO_2 in spent fuel is expected to be prevented by the presence of hydrogen gas, for example, from canister corrosion and catalytic effects on the SF pellet surface. Radiation damage to the SF (FEP 5.2.9) is expected to be minor. Production of additional oxidising species by the bromide effect on radiolysis in highly saline water is not expected for the porewater composition within and around the repository (FEP 5.2.8). No radiation effects are expected in the host rock (FEP 13.5).
4.2.4	RP-HLW radiolysis	
4.2.5	RP-HLW matrix radiation damage	
5.2.7	SF radiolysis	
5.2.8	Bromide effect on SF radiolysis in highly saline water	
5.2.9	SF radiation damage	
6.2.3	L/ILW radiolysis	
6.2.13	L/ILW radiation damage	
8.2.14	HLW buffer and liner radiolysis/irradiation	
9.2.11	L/ILW near-field radiolysis	
13.5	Radiation effects	

Number	FEP	Rationale for exclusion
2.2.13	Criticality safety	Criticality safety is excluded from detailed consideration in the general licence application since it will be a design requirement of the repository, specifically, for the HLW final disposal canister and for the HLW canister loading plans. Technical and administrative measures are being developed and will be implemented to ensure criticality safety of the deep geological repository system.
Vitrified RP-HLW		
4.2.1	RP-HLW glass recrystallisation	Glass recrystallisation is a slow process that is unlikely to occur below 400 °C and is therefore assumed not to occur during encapsulation or under repository conditions.
4.2.2	RP-HLW phase separation	Improper heat treatment during production of the RP-HLW could produce macroscopic phase separation, which could lead to a reduction of the resistance of the glass to chemical alteration. In the safety assessment, the process of phase separation is assumed to be avoided by application of suitable quality control procedures during RP-HLW vitrification.
4.2.7	Selective leaching of RP-HLW radionuclides	Selective leaching of specific alkali and alkali-earth ions from the glass is a short-term effect which is only significant before alteration layers build up on the wetted glass surfaces. Forward glass dissolution (i.e., dissolution before the formation of a protective layer) is accounted for in the safety assessment calculations by employing pessimistic glass dissolution rates.
4.2.10	RP-HLW gas generation	Helium will be produced from alpha decay of vitrified RP-HLW but, following canister breaching and ingress of water, will either dissolve or mix with the larger volumes of gas produced by canister corrosion, and is thus assumed in the safety assessment to be insignificant compared with other sources of gas.
4.2.13	RP-HLW glass dissolution and borate release	Scoping calculations indicate that complexation with borate released during the dissolution of HLW glass will have only limited effects on the solubility of specific radionuclides (trivalent actinides) in bentonite porewaters and is therefore disregarded in the safety assessment.
Spent fuel (SF)		
5.2.10	Fuel alteration product formation	Dissolution rates are so low that within the period of consideration this process is not expected to happen.

Tab. 4-12: Flow, transport and retention-related FEPs excluded from detailed consideration in the safety assessment

Number	FEP	Rationale for exclusion
General		
2.2.10	Colloids	Colloids (FEP 2.2.10) are expected to be present or to develop in water-filled pore space throughout the repository system. They may, for example, be produced during the degradation of L/ILW (FEP 6.2.9). Colloids from RP-HLW and SF are due to the slow dissolution kinetics of glass and SF highly unlikely to form. However, colloid-facilitated transport (FEP 2.3.9) of solutes, including radionuclides, is excluded. This is firstly because, in cementitious environments, dissolved colloids will coagulate and become immobilised (FEP 9.2.8). Secondly, colloids present elsewhere are also likely to be immobilised in the fine pore structure of the bentonite buffer (FEP 8.2.8) and other compacted bentonite structures in the closure system (FEP 10.2.7) and in the undisturbed CRZ, which also lacks any open fractures (FEP 12.1.5). In the cement sorption database, a sorption reduction factor for the presence of colloids has been implemented for radiological consequence analysis.
2.3.9	Colloid facilitated transport	
4.2.12	RP-HLW dissolution colloids	
5.2.14	SF colloids	
6.2.9	L/ILW colloids	
8.2.8	HLW colloids	
9.2.8	L/ILW backfill and liner colloids	
10.2.7	Access structures and closure system colloids	
12.1.5	Colloids in the CRZ	
2.3.11	Onsager coupled processes	Solute transport processes driven by gradients other than concentration gradients (i.e., other than diffusion; FEP 2.3.5) are referred to as coupled ("off-diagonal") transport processes and consist of thermal diffusion or the Soret effect (driven by the thermal gradient), hyperfiltration (driven by a hydraulic gradient), and electrophoresis (driven by an electrical gradient). Note that, in this scheme, advection (FEP 2.3.4) is a diagonal fluid process for fluid (rather than solute) transport, driven by a hydraulic gradient. Coupled diagonal Onsager processes are implicitly taken into account when assessing the performance of the repository. The off-diagonal Onsager processes have been shown in previous Nagra safety assessments to be negligible.
HLW canisters		
7.2.10	Residual HLW canister crack/hole effects	The flow in/out and transport resistance of a breached canister will evolve with time in a way that cannot be reliably modelled. Therefore, in the analysis of radiological consequences, once a canister is breached, it is conservatively assumed to offer no further resistance either to porewater ingress or to the release of radionuclides.
7.2.11	Gas pressure build-up inside breached HLW canister	The generation of gas inside a breached canister may reduce or prevent the further ingress of water and the release of dissolved radionuclides. The effect cannot be reliably modelled and is therefore cautiously disregarded in the safety assessment. However, gas pressure build-up within and/or around the canisters is considered in the performance assessment when evaluating gas transport and the possibility of gas-mediated radionuclide transport through the bentonite buffer.

Tab. 4-13: Other FEPs related to radionuclide release and radionuclide migration pathways excluded from detailed consideration in the safety assessment

Number	FEP	Rationale for exclusion
10.3.2	Dilution of radionuclides in the closure system	Dilution of radionuclides will occur during transport through the repository system, including within the CRZ, the geological setting (FEP 11.3.2) and the access structures and closure system (FEP 10.3.2). This dilution is, however, expected to be small compared with that occurring in the surface and near-surface environment, and therefore is not considered in detail in the analysis of radiological consequences.
11.3.2	Dilution of radionuclides in the geosphere	

4.3 FEPs related to future human actions

Tab. 4-14 lists the FEPs related to future human actions included in the safety assessment, but the handling of these is discussed in detail in Becker & Marnat (2024, Nagra (2024b) and is not described further in the present report. Future human action FEPs excluded from detailed consideration in the safety assessment, and the rationale for their exclusion, are presented in Tab. 4-15.

Tab. 4-14: Future human action FEPs included in scenario development

Number	FEP
Deep geological resources	
17.1.1	Resource exploitation through boreholes
17.1.2	Mining activities
Deep groundwater management	
17.2.1	Deep groundwater extraction
17.2.2	Geothermal exploitation
Deep infrastructure and waste management	
17.3.1	Infrastructure projects
17.3.2	Liquid waste and gas injection
17.3.3	Deep geological waste disposal through boreholes
17.3.4	Waste disposal in a geological repository
Societal activities	
17.9.1	Repository records and markers
17.9.2	Societal changes
17.9.3	Abandonment

Tab. 4-15: Future human action FEPs excluded from detailed consideration in the safety assessment

Number	FEP	Rationale for exclusion
Exploitation of near-surface resources		
17.4.1	Surface/shallow subsurface exploitation of resources	Future exploration and exploitation of surface and shallow subsurface resources will have no impact on a deep geological repository within the Opalinus Clay as such exploitation activities are well above any confining aquifer and thus have no impact on the far- or near-field barrier system of the repository.
17.4.2	Near-surface geothermal exploitation	
Surface and near-surface water management		
17.5.1	Shallow groundwater extraction	Shallow groundwater systems in Switzerland are located typically within the uppermost 50 m (up to max 120 m) of the Earth's surface. Because of the significant difference in depth between shallow aquifers and the planned deep geological repository, these near-surface processes are considered to have no impact on the safety functions of the repository barriers. Similarly, surface water management activities are considered to have no impact on the safety barriers and the long-term performance of the repository.
17.5.2	Surface water management	
Surface and near-surface infrastructure and waste management		
17.6.1	Geotechnical work and construction in the shallow subsurface	The planned deep geological repository will be located at such significant depth, that the impact of shallow engineering or geotechnical construction projects on the barrier safety functions of the repository can generally be excluded. The only exception to this is the potential disturbance of the uppermost part of the access shaft. However, this uppermost portion of the access shaft/ramp does not play a significant role in ensuring post-closure safety as multiple barriers isolate it from the main repository system. Surface waste disposal activities will also have no impact on the deep geological repository due to its substantial distance.
17.6.2	Infrastructure projects	
17.6.3	Tunnelling	
17.6.4	Surface or near-surface waste disposal	
Surface and near-surface pollution		
17.7.1	Surface pollution	The impact of surface/near-surface and groundwater pollution on the long-term safety and integrity of the repository is considered insignificant. In the context of the repository, the radioactive waste is emplaced deep underground within the tight and low permeability Opalinus Clay, isolating it from any potential effects of surface waters or shallow groundwater. Thus, this FEP is not considered in scenario development due to the significant distance between the repository and the surface.
17.7.2	Groundwater pollution	
Archaeology		
17.8.1	Archaeological investigation	Archaeological investigations use a variety of techniques, including geophysical surveys, drilling, and excavation. In northern Switzerland, archaeological activities are limited to tens of metres to a maximum of 50 m below the surface, where historical and cultural heritage items, including evidence of prehistoric settlements, Roman military installations, and medieval fortifications, have been found. Because of the significant distance between the archaeological activities and the deep geological repository, impacts on the safety barriers due to future archaeological activities can be excluded.

5 Biosphere and surface/near-surface environment FEPs

This chapter addresses biosphere FEPs, including FEPs related to the surface and near-surface environment. Tab. 5-1 shows those FEPs which are included in biosphere modelling for safety assessment and summarises how they are included. No FEPs related to the biosphere have been excluded from the safety assessment.

Tab. 5-1: FEPs included in the biosphere modelling for the safety assessment

Number	FEP	Inclusion in safety assessment
Environmental features and characteristics		
16.1.1	Variability in surface conditions over time	Although significant changes in surface conditions will occur during the period under consideration (e.g., different climate states), those changes will typically be slow (i) relative to the timescale of processes that determine the fate of contaminants in the biosphere, and (ii) relative to the timescale of potential exposure (i.e., human lifetimes). Although differing surface conditions are explicitly represented, gradual changes between different biosphere states need not be explicitly modelled. Seasonal variations are very short in comparison with the timescales for potential contaminant releases to the biosphere and to the timescale of human lifetimes over which potential dose rates and risks are assessed. Short-term seasonal changes are relevant to description of surface conditions and are represented in the parameterisation of processes (e.g., irrigation).
16.1.2	Geographical location and extension	The geographical location and extent of the biosphere area(s) that may receive repository-derived contaminants, the potential extent of the local area affected and the resource area needed to sustain potentially exposed groups (PEGs), are explicitly considered in biosphere modelling.
16.1.3	Topography and geomorphology	It is judged that the current morphology of Northern Switzerland, with hills and gravel-filled valleys, is sufficiently representative of future topography/morphology within the area of interest over the period under consideration. Consideration is given to different morphologies, including valley sections with rivers, wetland areas and lakes. The relatively impermeable strata beneath lakes and the degree of dispersion within lakes typical of Northern Switzerland mean that the assessment focuses on river sections and lakes are not explicitly represented. Explicit consideration is given to wetland areas that may have been drained for agricultural use.
16.1.4	Atmosphere	The atmosphere forms an explicit part of the biosphere systems represented in the radiological consequence analyses. Its characteristics are described as part of the biosphere systems and it is explicitly represented within biosphere modelling.
16.1.5	Soils	Soils are explicitly represented in biosphere modelling, including explicit representation of different soil horizons (surface soil and deep soil) and the ability to represent soil areas with differing characteristics within the same biosphere system. Different soil characteristics are represented for different morphologies and climates.
16.1.6	Unsaturated zone	An unsaturated zone between the local aquifer and surface soils is explicitly included in reference biosphere modelling.

Number	FEP	Inclusion in safety assessment
16.1.7	Surface waters	Rivers form part of the reference biosphere system considered in the radiological consequence analysis. Lakes are excluded on the basis that the relatively impermeable strata beneath lakes and the degree of dispersion within lakes typical of Northern Switzerland mean that potential dose consequences would be lower in comparison to rivers. There is no pathway for contamination of springs, so they are not explicitly represented. Potential direct and indirect exposure pathways associated with surface water are explicitly considered, including drinking water, ingestion of fish and use of surface water for irrigation and as drinking water for livestock.
16.1.8	Bed sediments	Bed sediments are explicitly represented in the biosphere modelling.
16.1.9	Aquifers	Near-surface aquifers local to areas of potential contaminant discharge from depth are explicitly represented in biosphere modelling, along with associated direct and indirect exposure pathways. A permafrost layer at the top of the local aquifer is explicitly represented in an alternative case representative of cold climate conditions.
16.1.10	Plants, algae and fungi	Crops and pasture are explicitly represented, including potential root uptake and interception of irrigation water. Fungi are not explicitly represented, given their relatively small contribution to diets and given that a wide range of potential exposure pathways is considered through self-sufficient lifestyle assumptions and given that uptake by crops is included. Aquatic plants and algae are not explicitly represented, although they can be considered to be implicitly represented in assumptions regarding uptake of contaminants from surface water by fish. Uptake by berries and other wild gathered foods are explicitly represented in cold climate conditions.
16.1.11	Animals	Livestock (cattle and chickens) are explicitly represented in biosphere modelling along with ingestion of associated animal products. The potential for fish to take-up contamination from surface water and to form part of the diet of the local group is also explicitly represented. During cold climate conditions, the potential for grazing animals over semi-natural areas is also represented.
16.1.12	Human communities	It is impossible to predict the evolution of human communities over timescales relevant to deep geological disposal of radioactive waste. Rather, PEGs are defined that are representative of local communities that may be present should contaminants reach the near-surface during the period under consideration. Under present-day and warm climate conditions, it is feasible for a PEG to derive most of its resource needs (food and water) from the local area, maximising potential exposure rates. Thus, current lifestyles in Northern Switzerland are assumed, in combination with sustainable self-sufficient farming (so far as is practicable given the biosphere conditions). Under cold climate conditions, a proportion of the group's food is obtained from outside the local area.
16.1.13	Chemical and physical fronts	Materials with different geochemical and physical characteristics are represented separately within the safety assessment. They are characterised by porosity, tortuosity, density, saturation, infiltration/flow rates and sorption (retention) characteristics. Examples include explicit distinction between topsoil, deep soil, variably saturated gravels and the local aquifer.

Number	FEP	Inclusion in safety assessment
16.1.14	Geosphere-biosphere interface	Groundwater from depth is taken to discharge to a local shallow aquifer. The local aquifer comprises unconsolidated porous Quaternary sediments of glaciofluvial origin, such as gravel. The flow rate and geochemical conditions of the local aquifer are dominated by shallow groundwater conditions.
Environmental processes		
16.2.1	Discharge of deep groundwater	The contribution of deep groundwater to near-surface groundwater flows and surface water flows is explicitly taken into account within the water-balance model for the biosphere. The model includes the potential for influx of both uncontaminated and contaminated water sources, including from depth. Deep groundwater discharge to river and wetland areas is explicitly represented. Discharge to lakes is not explicitly represented (see FEP 16.1.7). Potential for permafrost and taliks under cold climate conditions is given explicit consideration (see FEP 15.6). Thermal groundwater discharging to the near-surface would arise at depths significantly greater than the repository and so are not considered further. The potential for radionuclide release with deep groundwater is covered separately within FEP 16.3.1.
16.2.2	Precipitation	Precipitation over land is explicitly represented and parameterised in the biosphere modelling as a component of the water balance. Precipitation on surface waters is neglected because the modelling focuses on discharge to rivers where the surface water area is much smaller than the area of the catchment that they drain.
16.2.3	Infiltration and surface run-off	Surface run-off is an explicit input to the water balance model for the biosphere. Infiltration is calculated as precipitation and irrigation/flooding minus surface run-off. Lateral flow from the valley bottom discharges to the river in the reference biosphere modelling.
16.2.4	Evapotranspiration	Evapotranspiration is an explicit input to the water balance model for the biosphere. Evaporation from surface waters is neglected, because modelling focuses on discharge to rivers where the surface water area is much smaller than the area of the catchment that they drain.
16.2.5	Percolation, groundwater recharge and capillary rise	Capillary rise is an explicit input to the water balance for the biosphere model. Percolation and groundwater recharge are calculated as part of the water balance.
16.2.6	Surface water flow	The potential for uncontaminated inflow to surface water from up-gradient and contaminated discharge from deep groundwater to surface water form explicit inputs to the water balance model. The model includes additional contributions to surface water flow from the biosphere area modelled, including contribution from surface run-off (overland flow), lateral flow from soils and discharge from the local aquifer. The potential for surface water to be used for irrigation is also explicitly included. Reduction in surface water flow due to uses other than irrigation (e.g., drinking water for people and livestock, other domestic uses) are neglected on the basis that they would represent a small perturbation in the overall flow rates. Lakes are not explicitly represented for the reasons discussed in FEPs 16.1.3 and 16.1.7.

Number	FEP	Inclusion in safety assessment
16.2.7	Flooding	The potential for sediment transfer from surface water to soils as a result of flooding forms an explicit input to the sediment balance in the biosphere modelling. The potential for water to overlie soils during flooding events forms an explicit input to the water balance calculations in the biosphere modelling.
16.2.8	Groundwater flow	The groundwater flow rate in the local aquifer is calculated as part of the water balance in the biosphere model. No groundwater flow is modelled within permafrost under cold climate conditions. However, the potential for groundwater flow below the permafrost layer is represented.
16.2.9	Erosion/deposition	Erosion and deposition form an integral part of the mass balance calculations within the biosphere modelling. For radionuclide releases in groundwater to valley bottoms, landslides contribute to the definition of deposition over the valley floor.
16.2.10	Soil formation (podogenesis)	The potential for weathering of mineral material to contribute to soil formation is explicitly included within the mass balance modelling. Cycling of material between plants/animals and soils is implicitly represented in equilibrium assumptions (losses from soils due to plant uptake and ingestion by animals are taken to be compensated by return to the soil via dead organic matter and decomposition). Biosphere modelling for C-14 includes explicit representation of soil organic matter and release to soil water and soil gas via degradation and gas exchange.
16.2.11	Sediment transport	Suspended sediment is explicitly represented and parameterised for the surface water in the biosphere modelling. Transport of suspended sediment is also explicitly represented alongside surface water flow.
16.2.12	Sedimentation/re-suspension	Sedimentation and resuspension are explicitly represented in the biosphere modelling. Resuspension is defined by a turnover rate for the bed sediment and sedimentation is determined via mass balance.
16.2.13	Biosphere transport processes	Bioturbation between soil layers is explicitly represented and parameterised in the biosphere model. Plant uptake from the soil and transfer to animal produce are both represented with equilibrium assumptions. In this way, material removed from the soil by plant uptake and animal ingestion are effectively taken to be recycled back to the soil via dead organic matter (see also FEP 16.2.10). The potential for losses via migration and removal of crops and animal produce are neglected to conserve radionuclides within the local area.
16.2.14	Gas-related processes	Free gases released from the repository are expected to dissolve in groundwater before reaching the biosphere. A special biosphere model is used to support representation of C-14, including the processes described. C-14-labelled carbon dioxide is more radiologically significant than C-14-labelled methane because it can be taken-up and incorporated into plant organic matter via photosynthesis. C-14-labelled methane reaching the soil is conservatively taken to be fully oxidised to C-14-labelled carbon dioxide. Volatilisation losses for elements other than carbon are conservatively ignored. Air flow/wind is explicitly represented in both calculation of atmospheric concentrations and as a loss-term from the biosphere area.

Number	FEP	Inclusion in safety assessment
16.2.15	Water management	The potential for use of shallow local aquifers is explicitly represented in the biosphere modelling. Modelled water uses include irrigation, drinking and animal watering, with the potential for these to be drawn from the surface water or local aquifer. Sewage treatment is not taken to result in a significant movement of material (water or solids). The potential for water treatment prior to drinking is included with a filtration fraction, although this is conservatively neglected via parameterisation in the modelling itself. The biosphere modelling allows for potential channel irrigation from surface water by analogy to flooding/spray irrigation.
16.2.16	Earthworks	The biosphere system is represented as being static; this reflects the assumption that people would seek to maintain the environment. The biosphere modelling includes the potential for dredging of riverbed sediments onto land. The modelling also allows for uncontaminated mass to be introduced to the topsoil and riverbed sediment, which can be used to reflect human actions in maintaining the configuration of the biosphere.
16.2.17	Agriculture	Biosphere modelling focuses on self-sufficient agriculture within relatively small communities, as conditions under which potential exposures may reasonably be maximised. For present-day and warmer climates, the biosphere is taken to be maintained to optimise agricultural productivity, allowing for a broad range of crops. The assessment includes consideration of cold climate conditions that are not optimal for agriculture. In that context, a small area of horticulture under greenhouses/polytunnels is represented distinct from a broader semi-natural area used for grazing.
16.2.18	Other human activities	Activities that maintain biosphere conditions, including use of manure and composting to maintain soil quality, are implicitly represented in equilibrium assumptions and in assuming that conditions remain constant. Construction activities (e.g., buildings, roads) are not explicitly considered on the basis that relatively small volumes of material would be involved and because a human community is already taken to be present when potential releases to the biosphere occur. Gathering of wild foods is explicitly considered under cold climate conditions. Forestry and peat production do not represent an intensive land use and are not explicitly represented within the biosphere modelling. Leisure activities are assumed not to significantly affect the movement of material within the biosphere.
Radionuclide migration		
16.3.1	Radionuclide source term	For Northern Switzerland, discharge of deep groundwater that carries radionuclides originating from the repository into a surface aquifer may be considered the most likely situation for release into the biosphere (see FEP 16.2.1). This situation forms the basis of the reference biosphere modelling. Direct use of deep groundwater is not assessed based on plausibility grounds, given the ready availability of surface water and shallow groundwater. Any gases released from the repository are expected to dissolve in deep groundwater, such that release to the biosphere accompanies the groundwater pathway. The potential for human intrusion (e.g., via drilling) is dealt with separately.

Number	FEP	Inclusion in safety assessment
16.3.2	Advective/dispersive transport in the aqueous phase	The potential for radionuclide transport with water flows, including those dissolved in the water and those associated with mobile solid particles, is explicitly modelled. Biosphere modelling is founded upon both water and mass balance calculations. The distribution/dispersion of radionuclides within the biosphere is considered, including the dimensions of the local discharge area/valley section, coupled with consideration of the resource use area for PEGs.
16.3.3	Advective/dispersive transport in the gaseous phase	The biosphere modelling includes the potential for radionuclides to volatilise from the soil. This includes the potential for volatile species incorporating radionuclides to be lost from the biosphere via air flow and their contribution to potential inhalation exposures (see FEP 16.4.3). The potential for radionuclides to be attached or incorporated onto solid particles resuspended in the air (dust) is explicitly included in the exposure calculations. The potential for loss from the biosphere region due to wind-blown dust is conservatively neglected.
16.3.4	Exsolution / volatilisation	The biosphere modelling includes the potential for volatilisation from soil to atmosphere. A special biosphere model is used for C-14, given its unique behaviour, to support its representation in assessments. That model explicitly distinguishes soil water, soil gas and exchanges with the plant canopy and free atmosphere, along with associated transfers. Rn-222 and Rn-220 are included as short-lived daughters of Ra-226 and Th-228, respectively. Exposure to radon and thorium emanating from the soil is neglected, given the degree of atmospheric dispersion outdoors and given that buildings are less likely to be constructed directly over areas that might be affected by repository-derived radionuclides (areas irrigated or with groundwater close to surface).
16.3.5	Diffusive transport in the aqueous phase	Diffusive transport in the aqueous phase is explicitly represented in the biosphere modelling, including the potential for diffusion through the sediment column and for diffusive exchange between a local shallow aquifer in contact with surface water bed sediment. The potential for volatile species containing radionuclides to be lost from the soil to the atmosphere is explicitly represented; this encompasses diffusive transport. A special biosphere model is used for C-14, given its unique behaviour, to support its representation in assessments (see above). Losses of other radionuclides by volatilisation (e.g., Se-79) are conservatively ignored in parameterising the model.
16.3.6	Diffusive transport in the gaseous phase	The potential for radionuclides as volatile species to be lost from the soil to the atmosphere is explicitly represented in the biosphere modelling; this encompasses diffusive transport. A special biosphere model is used for C-14, given its unique behaviour, to support its representation in assessments (see above).
16.3.7	Sedimentation / resuspension in the aqueous phase	Sedimentation and resuspension are explicitly represented in the biosphere modelling. Resuspension is defined by a turnover rate for the bed sediment and sedimentation is determined via mass balance.

Number	FEP	Inclusion in safety assessment
16.3.8	Sedimentation / resuspension in the gaseous phase	Resuspension of soil dust is explicitly represented in biosphere modelling, contributing to radionuclide concentrations in the atmosphere. Conservatively, resuspension to the atmosphere is assumed to not result in radionuclides being lost from the biosphere. The settlement of radioactive aerosols on surface waters is considered negligible for river systems due to their relatively small area, but may be important for lakes.
16.3.9	Transport through bulk movement	The biosphere modelling includes a mass balance model that explicitly represents radionuclide transfer via processes including erosion, dredging and ploughing.
16.3.10	Chemical and physical alterations	Materials with different physicochemical properties are represented separately in the biosphere modelling and the properties are distinguished in parameterisation, especially in terms of radionuclide sorption (see FEP 16.3.11). The effect of organisms on radionuclide mobility is assumed to be an inherent property of the associated material in the biosphere. For example, the effect of root exudates, fungi and microorganisms on radionuclide mobility in soil is taken into account when parameterising soil properties, including sorption (see FEP 16.3.11).
16.3.11	Sorption/desorption	Partitioning between solid and liquid phases is represented with sorption/distribution coefficients (Kd). Sorption/desorption processes are assumed to be rapid and non-saturated, such that a steady-state equilibrium is assumed to be achieved between concentrations in the solid and liquid phases.
16.3.12	Precipitation, complexation, dissolution and leaching	Concentrations are assumed to be below solubility limits in assessment of radionuclide releases to the biosphere via groundwater (including as dissolved gases).
16.3.13	Uptake by crops and wild terrestrial plants	Radionuclide uptake by crops and wild terrestrial plants is explicitly represented, including external contamination, uptake from intercepted irrigation water and soil-to-plant uptake. The uptake processes are considered fast, such that empirical transfer coefficients are used. The biosphere modelling focuses on agricultural use of areas local to radionuclide releases to the biosphere. Forestry is taken to be limited/insignificant in this context.
16.3.14	Uptake by livestock and wild terrestrial animals	Radionuclide uptake into animal produce is explicitly represented, including via ingestion of water, feed and soil. The uptake processes are considered fast, such that empirical transfer coefficients that reflect equilibrium conditions are used. Uptake by animals following inhalation of aerosols is taken to be negligible in comparison to other pathways. Similarly, potential exposures arising from other uses of animal produce are taken to be relatively insignificant.

Number	FEP	Inclusion in safety assessment
16.3.15	Uptake by aquatic organisms	The potential for radionuclide uptake by fish and ingestion by humans is explicitly represented in the biosphere modelling. The uptake process is fast relative to other biosphere processes, such that empirical transfer coefficients are used. Ingestion of aquatic plants and invertebrates is not explicitly considered on the basis that these represent a small contribution to diets and that ingestion of fish is sufficiently representative of aquatic food exposure pathways. Fish are assumed to be obtained from surface water. Aquaculture making sole and direct use of groundwater is not represented on the basis that it is atypical in the local area.
16.3.16	Enrichment or depletion through processing	The biosphere modelling includes processing factors for crops and filtration factors for drinking water. Processing factors for animal produce are conservatively neglected and it is noted that ingestion rates are defined for whole foods (e.g., the ingestion rate of milk effectively represents ingestion of milk and milk produce). Potential exposures arising from non-ingestion uses of crops and animal produce are taken to be relatively insignificant (including use of straw, wool and leather).
16.3.17	Removal mechanisms	Removal mechanisms via surface water flow, groundwater flow and atmospheric dispersion are explicitly represented in the biosphere modelling. Removal of produce from the local area (e.g., cropping losses) are conservatively ignored. Given that the assessment focuses on communities with self-sufficient lifestyles, rather than large-scale, intensive agricultural practices, ignoring such losses is not a significant conservatism.
Radionuclide exposure		
16.4.1	Potentially exposed groups	PEGs are defined that spend all of their time in the area local to radionuclide releases to the biosphere and make reasonable maximal use of local resources (water, crops, animal produce, fish). The assessment focuses on relatively small agricultural communities, whereby the range of potential exposure pathways is maximised. A range of behaviours is explored, consistent with the range of alternative biosphere conditions (climate and morphology) that are assessed. For long-term, post-closure assessments associated with radioactive waste disposal, doses and risks to adults are considered to adequately represent the PEGs as a whole. Gender-averaged dosimetry is used to account for metabolic differences. Habit data are generally based on the present-day Swiss population.
16.4.2	Exposure and radiation dose	Radiation exposure is explicitly evaluated along with resulting effective doses in the safety assessment. The radionuclide kinetics and radiation absorption processes are relatively fast; hence, these processes are not modelled explicitly but transfer coefficients (called dose coefficients) that relate effective dose rates to exposure rates are used. Dose coefficients are defined such that the uncertainty about the underlying processes (including synergistic effects) is reflected in a conservative manner. A linear-no-threshold model is assumed for the relation of health detriments to the effective dose.

Number	FEP	Inclusion in safety assessment
16.4.3	Main exposure pathways	Potential exposure pathways represented in the assessment include external irradiation from soil, ingestion of drinking water (from groundwater or surface water), ingestion of plant produce (including the potential for associated soil contamination), ingestion of animal produce, ingestion of fish, and inhalation of particulates and gases.
16.4.4	Other exposure pathways	Inadvertent ingestion of soil and river sediment is not included, on the basis that these will be a relatively small. Ingestion of soil contamination on plant produce is explicitly included. Dermal uptake is not represented in biosphere modelling for groundwater or gas scenarios. It is more typically assessed in human intrusion calculations, where there is direct exposure to waste and other potential exposure pathways are relatively limited. Potential exposures arising from bathing/showering (immersion, inadvertent ingestion of water, inhalation of spray) are excluded. They are expected to be small compared to other pathways (especially drinking water and external irradiation from soil irrigated with the same water). Uses of plant and animal produce other than for food are neglected on the basis that potential exposures would be small in comparison. Peat and timber production is excluded because biosphere modelling focuses on environments where people can make wider use of local resources in comparison to peat and forestry areas. Potential exposures arising from use of soil/sediment/gravel in construction are excluded. External irradiation to soil is included with 100% occupancy. Rn-222 is included as a short-lived daughter of Ra-226. Exposure to radon emanating from soil is not included on the basis that outdoor concentrations would be low, and buildings would not be constructed over irrigated soil nor where groundwater is close to the soil (irrigation and groundwater being important pathways for bringing Ra-226 to the soil).

6 Conclusions

Concluding remarks are made below on the FEP management process and its contribution to the overall confidence in the safety assessment. As discussed in Section 1.1, the objectives of the FEP management process outlined in this report include:

- Compiling a comprehensive set of information in the format of FEPs. As detailed in Section 1.2, the FEP database has been continually updated and cross-referenced with international FEP databases. This has resulted in the creation of a thorough FEP database containing information relevant to the safety assessment.

  As stated earlier, a key focus in safety assessment revolves around achieving phenomenological comprehensiveness. While it is impossible to definitively prove the completeness of an assessment, efforts can be made to facilitate the identification of all potentially relevant phenomena. Equally important is ensuring that once identified, safety-relevant phenomena are accurately represented in the assessment.

- Conducting an audit of the phenomena included in the safety assessment against the FEP database through a process termed FEP management.

  The Nagra FEP database's iterative and long-term development, as discussed in Chapter 1, involved auditing FEPs against other national and international databases. Phenomena included in the safety assessment have been thoroughly audited against the FEP database. It has been demonstrated that every FEP in the database is either included in the safety assessment, or its omission is justified.

The development of the FEP database is a highly iterative process, with the FEPs and their descriptions presented in this report undergoing multiple cycles before reaching their current form. Confidence in the completeness of the Nagra FEP database, the appropriate treatment of information, and the thorough analysis of a broad range of assessment cases with adequate tools is believed to be at a level that is robust for the present safety case as a result of this process. This qualitative aspect complements the quantitative results of the safety assessment, providing an additional layer of support for the overall findings.

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App. A Classification of FEPs

This appendix provides a list of all FEPs within the FEP database, along with a summary of their handling in the safety assessment[5]. In the main report, each FEP within the database is assigned to one of the groups defined in Tab. 1-2, according to its scope and its inclusion in, or exclusion from, the safety assessment. For the purposes of this appendix, each group is assigned a number, from 0 to 7, as defined in Tab. A-1.

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

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

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

As noted in Section 1.2, the FEP database is organised into 17 different categories, as presented in Tab. 1-1. The first category, "FEPs outside the assessment scope", are not reproduced in this appendix; they are described in Section 2.1 of the main report (FEPs 1.2 to 1.9). FEPs in the second category, "common FEPs", are listed in Tab. A-2. These concern rather general phenomena that may occur or be found in multiple locations in the repository, often for extended periods of time. Tab. A-3 to Tab. A-12 list FEPs related to specific system components (including the host rock and geological setting). Finally, Tab. A-13 to Tab. A-17 list FEPs related to repository-induced effects, geological process and events, climatic processes and events, biosphere and future human actions, respectively.

[5] All FEPs in the current Nagra FEP database are listed in this appendix. Gaps in the numbering of the FEPs correspond to FEPs that have been deleted (specifically, numbers 1.1, 5.1.7, 13.1.2 and 13.4.1).

Tab. A-2: Handling of common FEPs

Each FEP is assigned a code and colour according to the scheme shown in Tab. A-1.

Number	FEP	
2.1	Radioactive decay and ingrowth	4
Evolution processes		
2.2.1	Heat sources, heat transfer and thermal evolution	4
2.2.2	Gas sources, gas transfer and gas sinks	4
2.2.3	Saturation of the repository	4
2.2.4	Pore pressure	4
2.2.5	Chemical evolution and microbiological processes	4
2.2.6	Corrosion of metals	4
2.2.7	Cement degradation and carbonation	4
2.2.8	Cement-clay interactions	4
2.2.9	Sulphate/chloride attack	5
2.2.10	Colloids	5
2.2.11	Mechanical evolution	4
2.2.12	Radiolysis and radiation damage	5
2.2.13	Criticality safety	5
Flow, transport and retention processes		
2.3.1	Fluid flow	4
2.3.2	Two-phase flow	4
2.3.3	Gas dissolution	4
2.3.4	Advection and dispersion	4
2.3.5	Diffusion and matrix diffusion	4
2.3.6	Anion exclusion and surface diffusion	4
2.3.7	Sorption and desorption	4
2.3.8	Immobilisation by precipitation and co-precipitation of solids	4
2.3.9	Colloid-facilitated transport	5
2.3.10	Gas-mediated transport	4
2.3.11	Onsager coupled processes	5
Radionuclide migration processes		
2.4.1	Radionuclide speciation and complexation	4
2.4.2	Radionuclide migration pathways and processes	4

Tab. A-3: Handling of siting, design and implementation FEPs

Each FEP is assigned a code and colour according to the scheme shown in Tab. A-1.

Number	FEP	
Siting		
3.1.1	Repository site	1
3.1.2	Site investigation boreholes	1
Waste		
3.2.1	Waste forms and inventory	1
3.2.2	HLW inventory	1
3.2.3	L/ILW inventory	1
3.2.4	Waste emplacement in a geological repository	1
Facility, design and operation		
3.3.1	Appropriate repository design and closure	1
3.3.2	Repository layout and layout constraints	1
3.3.3	HLW emplacement drifts	1
3.3.4	L/ILW emplacement caverns	1
3.3.5	Administrative control	1
3.3.6	Construction and operation of disposal areas	1
3.3.7	Repository closure (sealing and backfilling)	1
3.3.8	Retrievability	3
3.3.9	Monitoring	3
3.3.10	Quality management	1
3.3.11	Initial-state deviations	2

Tab. A-4: Handling of vitrified RP-HLW FEPs

Each FEP is assigned a code and colour according to the scheme shown in Tab. A-1.

Number	FEP	
Facility, design and operation		
4.1.1	RP-HLW vitrified waste form	1
4.1.2	RP-HLW stainless steel fabrication flask	1
4.1.3	RP-HLW glass cracking and surface area	1
4.1.4	RP-HLW heat generation	4
Evolution processes		
4.2.1	RP-HLW glass recrystallisation	5
4.2.2	RP-HLW phase separation	5
4.2.3	Contact of RP-HLW with water	4
4.2.4	RP-HLW radiolysis	5
4.2.5	RP-HLW matrix radiation damage	5
4.2.6	RP-HLW glass alteration/dissolution	4
4.2.7	RP-HLW glass selective leaching	5
4.2.8	Iron corrosion products/clay minerals and glass dissolution	4
4.2.9	Precipitation of silicates/silica gel and RP-HLW glass dissolution	4
4.2.10	RP-HLW gas generation	5
4.2.11	Microbial activity impact on RP-HLW glass	5
4.2.12	RP-HLW dissolution colloids	5
4.2.13	RP-HLW glass dissolution borate release	5
4.2.14	Effects of RP-HLW temperature and temperature gradients	4
Radionuclide migration		
4.3.1	Radionuclide release from RP-HLW	4
4.3.2	RP-HLW radionuclide migration and pathways	4

Tab. A-5: Handling of SF FEPs

Each FEP is assigned a code and colour according to the scheme shown in Tab. A-1.

Number	FEP	
Facility, design and operation		
5.1.1	Fuel assemblies	1
5.1.2	UO_2 and MOX fuel	1
5.1.3	Fuel cladding and structural elements	1
5.1.4	SF disposal canister filling material and voids	1
5.1.5	SF heat generation	4
5.1.6	Distribution of radionuclides in the SF	1
5.1.8	Fuel cracking and surface area	1
Evolution processes		
5.2.1	Contact of SF with water	4
5.2.2	SF gas generation	4
5.2.3	Cracking of fuel pellets by helium build-up	5
5.2.4	Fuel pellet dissolution	4
5.2.5	Corrosion of SF cladding and other metal parts	4
5.2.6	Hydrogen-induced cracking of the SF cladding	5
5.2.7	SF radiolysis	5
5.2.8	Bromide effect on SF radiolysis in highly saline water	5
5.2.9	SF radiation damage	5
5.2.10	Fuel alteration product formation	5
5.2.11	SF disposal canister corrosion products	4
5.2.12	SF structural materials corrosion product volume expansion	5
5.2.13	Microbial activity impact on SF	5
5.2.14	SF colloids	5
5.2.15	Effects of SF temperature and temperature gradients	4
Radionuclide migration		
5.3.1	Radionuclide release from spent fuel	4
5.3.2	Radionuclide release from SF cladding and structural materials	4
5.3.3	SF radionuclide migration and pathways	4
5.3.4	SF radionuclides in gaseous or volatile form	4

Tab. A-6: Handling of L/ILW and packages FEPs

Each FEP is assigned a code and colour according to the scheme shown in Tab. A-1.

Number	FEP	
Facility, design and operation		
6.1.1	L/ILW disposal section waste types	1
6.1.2	L/ILW groups	1
6.1.3	Typical L/ILW disposal containers	1
6.1.4	L/ILW conditioning materials	1
6.1.5	L/ILW packages	1
6.1.6	L/ILW disposal container cavities and voids	3
6.1.7	L/ILW disposal section hydraulic and gas permeability	1
6.1.8	L/ILW disposal section heat generation	5
6.1.9	L/ILW organics	1
6.1.10	L/ILW disposal section extraneous materials (including microbes/biological materials)	3
Evolution processes		
6.2.1	Degradation of L/ILW cementitious conditioning material	4
6.2.2	Chemical evolution of the L/ILW near-field porewater	4
6.2.3	L/ILW radiolysis	5
6.2.4	Corrosion of L/ILW metallic components	4
6.2.5	L/ILW galvanic effects	5
6.2.6	L/ILW volume expansion	5
6.2.7	L/ILW gas generation and migration	4
6.2.8	Microbial activity in L/ILW	4
6.2.9	L/ILW colloids	5
6.2.10	L/ILW mechanical evolution	5
6.2.11	Effects of L/ILW temperature and temperature gradients	5
6.2.12	Impact of geological events and processes on the L/ILW near-field	5
6.2.13	L/ILW radiation damage	5
Radionuclide migration		
6.3.1	Radionuclide release through L/ILW degradation	4
6.3.2	L/ILW instant release fraction	4
6.3.3	L/ILW gaseous and volatile radionuclides	4
6.3.4	L/ILW radionuclide migration and pathways	4

Tab. A-7: HLW disposal canister FEPs

Each FEP is assigned a code and colour according to the scheme shown in Tab. A-1.

Number	FEP	
Facility, design and operation		
7.1.1	HLW carbon steel disposal canister	1
7.1.2	Mis-sealed HLW disposal canister	2
Evolution processes		
7.2.1	HLW canister radiation shielding	4
7.2.2	HLW canister temperature evolution	4
7.2.3	Corrosion prior to HLW canister breaching	4
7.2.4	Gas generation due to HLW canister corrosion	4
7.2.5	Gas around the HLW canister and impact on corrosion	4
7.2.6	Solid HLW canister corrosion products and volume expansion	4
7.2.7	Other HLW canister degradation processes	4
7.2.8	HLW canister breaching	4
7.2.9	Corrosion after HLW canister breaching	4
7.2.10	Residual HLW canister crack/hole effects	5
7.2.11	Gas pressure build-up inside breached HLW canister	5
7.2.12	Effects on water composition on HLW canister corrosion	4
7.2.13	Impact of geological events and processes on the HLW disposal canisters	4
Radionuclide migration		
7.3.1	Radionuclide migration and pathways for breached HLW canisters	4

Tab. A-8: HLW emplacement drift, buffer and liner FEPs

Each FEP is assigned a code and colour according to the scheme shown in Tab. A-1.

Number	FEP	
Facility, design and operation		
8.1.1	HLW drift liner	1
8.1.2	HLW buffer emplacement and composition	1
8.1.3	HLW bentonite buffer plasticity and self-sealing	1
8.1.4	HLW bentonite buffer hydraulic and gas permeability	1
8.1.5	HLW bentonite buffer inhomogeneities (properties and evolution)	1
8.1.6	Poor emplacement of HLW bentonite buffer and liner	2
Evolution processes		
8.2.1	HLW bentonite buffer saturation	4
8.2.2	HLW bentonite buffer swelling, homogenisation and swelling pressure	4
8.2.3	HLW bentonite buffer mineralogical alteration	4
8.2.4	HLW bentonite buffer - iron disposal canister interactions	4
8.2.5	Chemical evolution of HLW near-field porewater	4
8.2.6	HLW liner cement - bentonite buffer clay interactions	4
8.2.7	HLW buffer and liner evolving pore structure	4
8.2.8	HLW colloids	5
8.2.9	HLW near-field microbial activity	5
8.2.10	HLW bentonite buffer gas pathways	4
8.2.11	HLW bentonite buffer erosion	5
8.2.12	Effects of HLW near-field temperature and temperature gradients	4
8.2.13	HLW buffer and liner mechanical evolution and bentonite creep	4
8.2.14	HLW bentonite buffer and liner radiolysis/irradiation	5
8.2.15	Impact of geological events and processes on the HLW buffer and liner	4
Radionuclide migration		
8.3.1	HLW radionuclide migration and pathways	4

Tab. A-9: L/ILW cavern, backfill and liner FEPs

Each FEP is assigned a code and colour according to the scheme shown in Tab. A-1.

Number	FEP	
Facility, design and operation		
9.1.1	L/ILW cavern liner	1
9.1.2	L/ILW cavern rock bolts	1
9.1.3	L/ILW cavern backfill material	1
9.1.4	L/ILW cement additives	1
9.1.5	L/ILW backfill emplacement	1
9.1.6	Joints and cracks in the L/ILW backfill/liner	3
9.1.7	Cavities in the L/ILW backfill/liner	2
9.1.8	L/ILW near-field hydraulic and gas permeability	1
9.1.9	Effects of initial (operating) conditions on L/ILW cavern materials	3
9.1.10	Poor emplacement of L/ILW backfill and liner	2
Evolution processes		
9.2.1	L/ILW cement hydration and heat generation	5
9.2.2	L/ILW cavern gas migration and storage	4
9.2.3	L/ILW cavern saturation/hydraulic evolution	4
9.2.4	Chemical degradation of L/ILW cementitious materials and porewater evolution	4
9.2.5	Reaction with metals and inorganic materials in L/ILW caverns	5
9.2.6	Cementitious near-field evolving pore-structure	4
9.2.7	Microbial activity in L/ILW caverns	4
9.2.8	L/ILW backfill and liner colloids	5
9.2.9	L/ILW backfill and liner mechanical evolution	5
9.2.10	Effects of L/ILW near-field temperature and temperature gradients	5
9.2.11	L/ILW near-field radiolysis	5
9.2.12	Impact of geological events and processes on the L/ILW backfill and liner	5
Radionuclide migration		
9.3.1	L/ILW near-field radionuclide migration and pathways	4

Tab. A-10: Access structures and closure system FEPs

Each FEP is assigned a code and colour according to the scheme shown in Tab. A-1.

Number	FEP	
Facility, design and operation		
10.1.1	Underground openings and access to the disposal sections	1
10.1.2	Repository seals	1
10.1.3	Tunnel backfill	1
10.1.4	Closure system hydraulic and gas permeability	1
10.1.5	Poor or incomplete emplacement of backfill and seals	2
Evolution processes		
10.2.1	Saturation of the closure system	4
10.2.2	Closure system erosion by inflowing water	5
10.2.3	Chemical impact of inflowing water on the closure system	4
10.2.4	Gas migration and storage in the closure system	4
10.2.5	Pore-pressure-induced damage to the closure system	4
10.2.6	Axial water flow through the saturated closure system	4
10.2.7	Access structures and closure system colloids	5
10.2.8	Cement-clay interactions in the access structures and closure system	4
10.2.9	Migration of chemical species from the L/ILW near-field into the closure system	4
10.2.10	Impact of geological events and processes on the access structures and closure system	4
Radionuclide migration		
10.3.1	Closure system radionuclide migration processes and pathways	4
10.3.2	Dilution of radionuclides in the closure system	5

Tab. A-11: Geological setting FEPs

Each FEP is assigned a code and colour according to the scheme shown in Tab. A-1.

Number	FEP	
Geological features		
11.1.1	Host geology	1
11.1.2	Lithostratigraphy	1
11.1.3	Geological formation/history	1
11.1.4	Sedimentology, mineralogy etc. of the upper confining units	1
11.1.5	Sedimentology, mineralogy etc. of the lower confining units	1
11.1.6	Current regional stress regime	1
11.1.7	Local stress regime	1
11.1.8	Regional fault zones	1
11.1.9	Local faults	1
11.1.10	Undetected features	2
11.1.11	Mechanical properties	1
11.1.12	Groundwater and porewater composition	1
11.1.13	Biological processes and conditions	1
11.1.14	Geothermal gradient	1
11.1.15	Natural resources	1
Hydrogeological characteristics		
11.2.1	Hydrogeological units	1
11.2.2	Effective hydraulic properties	1
11.2.3	Recharge/discharge zones	1
11.2.4	Regional hydraulic gradient	1
11.2.5	Local hydraulic gradient	1
11.2.6	Groundwater flow, flowpaths and discharge	1
11.2.7	Host rock gas pathways	4
11.2.8	Natural groundwater colloids	2
Radionuclide migration		
11.3.1	Geosphere radionuclide migration processes and pathways	4
11.3.2	Dilution of radionuclides in the geosphere	5

Tab. A-12: Containment-proving rock zone (CRZ) FEPs

Each FEP is assigned a code and colour according to the scheme shown in Tab. A-1.

Number	FEP	
Geological features		
12.1.1	Containing Rock Zone (CRZ) rock matrix	1
12.1.2	CRZ discontinuities	1
12.1.3	CRZ swelling and self-sealing	4
12.1.4	Microbial activity in the CRZ	3
12.1.5	Colloids in the CRZ	3
Hydrogeological characteristics		
12.2.1	CRZ hydraulic and gas permeability	1
12.2.2	CRZ porewater flow	1
12.2.3	CRZ anomalous pore pressures	1
Radionuclide migration		
12.3.1	CRZ radionuclide migration processes and pathways	4

Tab. A-13: FEPs related to repository-induced effects

Each FEP is assigned a code and colour according to the scheme shown in Tab. A-1.

Number	FEP	
Facility, design and operations		
13.1.1	Effect of construction and operation phase (general)	1
13.1.3	Host-rock creep and convergence	4
EDZ		
13.2.1	EDZ formation and evolution	4
Thermal- and gas-related effects		
13.3.1	Thermally-induced degradation of clay	4
13.3.2	Thermally-induced flow	5
13.3.3	Thermally-induced pore pressure increase	4
13.3.4	Induced seismicity	4
13.3.5	Gas-induced pore pressure increase	4
13.3.6	Pore-pressure-induced stress changes, fracturing and fault reactivation	4
Chemical interactions		
13.4.2	Pore clogging	4
13.4.3	Repository-induced changes in host rock porewater composition	4
13.4.4	Migration of chemical species from L/ILW	4
Radiation		
13.5	Radiation effects	5

Tab. A-14: FEPs related to geological processes and events

Each FEP is assigned a code and colour according to the scheme shown in Tab. A-1.

Number	FEP	
14.1	Regional vertical movements	4
14.2	Regional horizontal movements	4
14.3	Effects of climate change (general)	4
14.4	Erosion and geomorphological changes	4
14.5	Fluvial erosion/sedimentation	4
14.6	Glacial erosion/sedimentation	4
14.7	Glacial-fluvial erosion/sedimentation	4
14.8	Subsidence	4
14.9	Folding	5
14.10	Neotectonic activity	4
14.11	Seismic activity	4
14.12	Creep	4
14.13	Magmatic activity (volcanism and plutonism)	5
14.14	Hydrothermal activity and effects	5
14.15	Metamorphism	5
14.16	Diagenesis	5
14.17	Dissolution/karstification	5
14.18	Diapirism	5
14.19	Evolution of regional stress regime	4
14.20	Fault reactivation and formation of new faults	4
14.21	Compaction and decompaction	4
14.22	Hydrogeochemical evolution	5

Tab. A-15: FEPs related to climatic processes and events

Each FEP is assigned a code and colour according to the scheme shown in Tab. A-1.

Number	FEP	
Environmental features and characteristics		
15.1	Climate	4
15.2	Present-day climatic conditions	4
15.3	Future climatic conditions	4
15.4	Human-induced climate change and greenhouse effect	4
15.5	Glacial climate	4
15.6	Permafrost	4
15.7	Tundra climate	4
15.8	Dry climate	4
15.9	Warm seasonal humid climate	4

Tab. A-16: Biosphere FEPs

Each FEP is assigned a code and colour according to the scheme shown in Tab. A-1.

Number	FEP	
Environmental features and characteristics		
16.1.1	Variability in surface conditions over time	6
16.1.2	Geographical location and extension	6
16.1.3	Topography and geomorphology	6
16.1.4	Atmosphere	6
16.1.5	Soils	6
16.1.6	Unsaturated zone	6
16.1.7	Surface waters	6
16.1.8	Bed sediments	6
16.1.9	Aquifers	6
16.1.10	Plants, algae and fungi	6
16.1.11	Animals	6
16.1.12	Human communities	6
16.1.13	Chemical and physical fronts	6
16.1.14	Geosphere-biosphere interface	6
Environmental processes		
16.2.1	Discharge of deep groundwater	6

Number	FEP	
16.2.2	Precipitation	6
16.2.3	Infiltration and surface run-off	6
16.2.4	Evapotranspiration	6
16.2.5	Percolation, groundwater recharge and capillary rise	6
16.2.6	Surface water flow	6
16.2.7	Flooding	6
16.2.8	Groundwater flow	6
16.2.9	Erosion/deposition	6
16.2.10	Soil formation (podogenesis)	6
16.2.11	Sediment transport	6
16.2.12	Sedimentation/resuspension	6
16.2.13	Biosphere transport processes	6
16.2.14	Gas-related processes	6
16.2.15	Water management	6
16.2.16	Earthworks	6
16.2.17	Agriculture	6
16.2.18	Other human activities	6
Radionuclide migration		
16.3.1	Radionuclide source term	6
16.3.2	Advective/dispersive transport in the aqueous phase	6
16.3.3	Advective/dispersive transport in the gaseous phase	6
16.3.4	Exsolution/volatilisation	6
16.3.5	Diffusive transport in the aqueous phase	6
16.3.6	Diffusive transport in the gaseous phase	6
16.3.7	Sedimentation/resuspension in the aqueous phase	6
16.3.8	Sedimentation/resuspension in the gaseous phase	6
16.3.9	Transport through bulk movement	6
16.3.10	Chemical and physical alterations	6
16.3.11	Sorption/desorption	6
16.3.12	Precipitation, complexation, dissolution and leaching	6
16.3.13	Uptake by crops and wild terrestrial plants	6
16.3.14	Uptake by livestock and wild terrestrial animals	6
16.3.15	Uptake by aquatic organisms	6
16.3.16	Enrichment or depletion through processing	6
16.3.17	Removal mechanisms	6

Number	FEP	
Radionuclide exposure		
16.4.1	Potentially exposed groups	6
16.4.2	Exposure and radiation dose	6
16.4.3	Main exposure pathways	6
16.4.4	Other exposure pathways	6

Tab. A-17: FEPs related to future human actions

Each FEP is assigned a code and colour according to the scheme shown in Tab. A-1.

Number	FEP	
Deep geological resources		
17.1.1	Resource exploitation through boreholes	4
17.1.2	Mining activities	4
Deep groundwater management		
17.2.1	Deep groundwater extraction	4
17.2.2	Geothermal exploitation	4
Deep infrastructure and waste management		
17.3.1	Infrastructure projects	4
17.3.2	Liquid waste and gas injection	4
17.3.3	Deep geological waste disposal through boreholes	4
17.3.4	Waste disposal in a geological repository	4
Exploitation of near-surface resources		
17.4.1	Surface/shallow subsurface exploitation of resources	5
17.4.2	Near-surface geothermal exploitation	5
Surface and near-surface water management		
17.5.1	Shallow groundwater extraction	5
17.5.2	Surface water management	5
Surface and near-surface infrastructure and waste management		
17.6.1	Geotechnical work and construction in the shallow subsurface	5
17.6.2	Infrastructure projects	5
17.6.3	Tunnelling	5
17.6.4	Surface or near-surface waste disposal	5
Surface and near-surface pollution		
17.7.1	Surface pollution	5

Number	FEP	
17.7.2	Groundwater pollution	5
Archaeology		
17.8.1	Archaeological investigation	5
Societal activities		
17.9.1	Repository records and markers	4
17.9.2	Societal changes	4
17.9.3	Abandonment	4