nagra

# ARBEITSBERICHT NAB 24-09

## Radiological Consequences of Future Human Actions

October 2024

**Nagra | National Cooperative for the Disposal of Radioactive Waste**
Hardstrasse 73 | 5430 Wettingen | Switzerland
+41 56 437 11 11 | info@nagra.ch | nagra.ch

nagra.

# ARBEITSBERICHT NAB 24-09

## Radiological Consequences of Future Human Actions

October 2024

KEYWORDS
Future human actions, deep geological repository, scenario development, FEP, safety scenario, drilling, abandonment

**Nagra** | **National Cooperative for the Disposal of Radioactive Waste**
Hardstrasse 73 | 5430 Wettingen | Switzerland
+41 56 437 11 11 | info@nagra.ch | nagra.ch

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.

Core Team: R.A.J. Wüst[1], V. Bykov[1], G. Mayer[2], S. Diem[2]

[1] Nagra

[2] CSD Ingenieure AG, Schachenallee 29, 5000 Aarau, Switzerland

Numerous people have contributed to this report and are listed in alphabetical order:

E. Anderson, J. Andersson, M. Baldachin, T. Baldwin, N. Diomidis, R. Flückiger, T. Guillemot, B. Habermacher, I. Herwegh, H. Javanmard, O. Leupin, X. Li, K. Nikolaeva, A. Paulsen, M. Ruff, P. Smith, T. Spillmann, M. Storz, M. Unger, F. Vahlund, T. Vietor, S, Voinis, A. von der Dunk, J., Wolf, P. Zuidema

## Abstract

The Nuclear Energy Act (KEG) requires deep geological disposal of all of Switzerland's radioactive waste. Given the extensive timescales involved, safety assessments for radioactive waste disposal inherently involve uncertainties related to the activities of future generations around the repository site, such as those involving exploratory investigations. A key characteristic of the Swiss repository site is the lack of any significant underground resources specific to the region that could attract future human actions, including inadvertent intrusion into the repository. While the likelihood of disturbance of the deep geological repository by humans in the future is considered extremely low, even after knowledge of the site is lost, a consequence analysis of potential future human actions, confirming the post-closure safety of the repository, is a regulatory requirement. The radiological consequence analysis of future human actions is performed by assessing future events that could have the potential to affect the safety of the repository.

The employed methodology is a bottom-up approach involving an assessment of features, events and processes and the development of stylised future human actions safety scenarios for comprehensive radiological consequence analyses. In line with national and international guidelines, it outlines the potential consequences of future human actions. The future human actions safety scenarios conservatively account for the potential direct interaction with radioactive waste. This includes safety scenarios such as borehole penetration of a spent fuel disposal canister within a high-level waste emplacement drift, as well as the penetration of waste packages in a low- and intermediate-level waste emplacement cavern. Additionally, the safety scenarios consider the consequences of repository abandonment during the monitoring phase. The times considered for borehole penetration of the repository range between 500 and 50,000 years post-closure.

Analyses of dose consequences, based on conservative conceptual models and pessimistic parameter assumptions, indicate the following: The highest dose rate due to dissolved radionuclides for borehole penetration of a spent fuel canister is $3.7 \times 10^{-3}$ mSv/a, while gas release of volatile C-14 through boreholes results in a much smaller radiological impact with maximum dose rates of $2 \times 10^{-6}$ mSv/a. For borehole penetration of a low- and intermediate-level waste emplacement cavern, the highest short-term dose rate of 0.43 mSv/a occurs from the direct penetration of a single waste package after 500 years. The long-term release through the borehole with upward fluid flow produces a maximum dose rate of $6 \times 10^{-2}$ mSv/a. Gas and volatile C-14 release calculations result in a maximum dose rate of $6 \times 10^{-3}$ mSv/a. In the event of repository abandonment, the highest dose rate of $7 \times 10^{-4}$ mSv/a is associated with volatile C-14 released from the low- and intermediate-level waste repository section. The results show that all the considered future human actions safety scenarios result in dose rates well below the Swiss and international regulatory guidelines for future human actions of 1 mSv/a.

The findings further provide evidence that, although surface markers and robust record-keeping practices may help to reduce the potential of early future human actions and thus can support post-closure safety, the Swiss deep geological repository is located and designed to securely contain the radioactive waste purely by its system of passive barriers until the waste reaches radiotoxicity levels equivalent to natural rock. The stylised approach for the assessment of future human actions demonstrates that the system is robust even under the most conservative cases of inadvertent human intrusion. Since the highest dose rates are below the regulatory guideline for future human actions, no further efforts to reduce future human actions are warranted. Host rock properties, repository depth and repository design will therefore ensure long-term passive radiological safety for both humans and the environment throughout the full post-closure period of the repository, taking future human actions into account. These findings highlight that post-closure safety requirements are maintained even if memory of the repository is lost.

# Table of Contents

## List of Tables



## List of Figures

## List of Acronyms

| | |
|---|---|
| BFE | *Bundesamt für Energie* (Swiss Federal Office of Energy, SFOE) |
| BZL | Swiss Federal Interim Storage Facility (*Bundeszwischenlager,* for radioactive waste from medicine, industry and research) |
| CCS | Carbon capture and storage |
| CRP | Coordinated research project |
| CRZ | Containment-providing rock zone |
| DBD | Deep borehole disposal |
| DH | Direct hit |
| EBS | Engineered barrier systems |
| ENSI | Swiss Federal Nuclear Safety Inspectorate (*Eidgenössisches Nuklearsicherheitsinspektorat*) |
| FEP | Feature, event and process |
| FHA | Future human actions |
| HLW | High-level waste (spent fuel assemblies and HLW from reprocessing) |
| IAEA | International Atomic Energy Agency |
| ICRP | International Commission on Radiological Protection |
| IRF | Instant release fraction |
| JO | Jura Ost (siting region) |
| KEG | Nuclear Energy Act (*Kernenergiegesetz*) |
| KEV | Nuclear Energy Ordinance (*Kernenergieverordnung*) |
| L/ILW | Low- and intermediate-level waste |
| MCL | Minimum canister lifetime |
| MIR | (Radioactive waste from) medicine, industry and research |
| MIRAM | Model Inventory for Radioactive Materials |
| NAB | Nagra Work Report (*Nagra Arbeitsbericht*) |
| NEA | Nuclear Energy Agency of the OECD |
| NL | Nördlich Lägern (siting region) |
| NTB | Nagra Technical Report (*Nagra Technischer Bericht*) |
| OECD | Organisation for Economic Co-operation and Development |
| PDC (drill bit) | Polycrystalline diamond compact (drill bit) |
| PFP | Preferential flow path |
| PWR-MOX | Pressurised water reactor – mixed oxide fuel |

| | |
|---|---|
| RBG | General licence application (*Rahmenbewilligungsgesuch*) |
| RC | Reference case |
| RS | Reference scenario |
| SF | Spent fuel (assemblies) |
| SGT | Sectoral Plan for Deep Geological Repositories (*Sachplan geologische Tiefenlager*) |
| ZNO | Zürich Nordost (siting region) |

# 1 Introduction

## 1.1 Context

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

The Sectoral Plan for Deep Geological Repositories (SGT) regulates the search for suitable siting regions for deep geological repositories in Switzerland. This site selection process is conducted in three stages (BFE 2008). Stages 1 (SGT-E1) and 2 (SGT-E2) have already been completed, and Stage 3 (SGT-E3) is currently in progress. Clarifications on the safety-related specifications for this stage are provided in ENSI 33/649 (ENSI 2018), while ENSI Guideline G03 and the corresponding explanatory report (ENSI 2023, ENSI 2020) specify the protection objective, protection criteria and design principles for deep geological repositories.

Following a comparison of the three siting regions Jura Ost (JO), Nördlich Lägern (NL) and Zürich Nordost (ZNO) during SGT-E3, Nagra is applying for a general licence for a repository for both HLW and L/ILW in the NL siting region with surface facilities located at Haberstal. The justification for this selection and the safety demonstration for a repository at the site are submitted as part of the general licence application (RBG[2]). The overall safety-related argumentation, including post-closure and operational safety, is summarised in an overarching safety report ("*Sicherheitsbericht*") NTB 24-01 (Nagra 2025) (Fig. 1-1). The post-closure safety case for the repository at the site, including its synthesis in the post-closure safety report is documented in NTB 24-10 (Nagra 2024g), while the details of the safety and repository concept, including the provisional design, are found in the supporting documents that make up the assessment basis.

The overarching post-closure safety objective of a deep geological repository is *"the long-term protection of humans and the environment from the effects of ionising radiation, without imposing undue burdens and obligations on future generations"* (ENSI 2020). The iterative design development process incorporates the radioactive waste inventory, protection objective, design principles, protection criteria and the safety and repository concepts. This comprehensive approach resulted in an implementation plan for a deep geological repository with surface facilities at Haberstal forming the foundation for the post-closure safety case and underlying safety assessment (see Fig. 1-1). The description of the post-closure safety case workflow (i.e. methodology) is found in the safety assessment methodology report NTB 24-19 (Nagra 2024k) (Fig. 1-1). The general description of safety scenario development is provided in NTB 24-21 (Nagra 2024c), which draws on the findings of the performance assessment (Nagra 2024l). The radiological consequences for all safety scenarios other than those for future human actions (FHA) are described in Part B of NTB 24-18 (Nagra 2024i).

---

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

[2] From the German *Rahmenbewilligungsgesuch.*

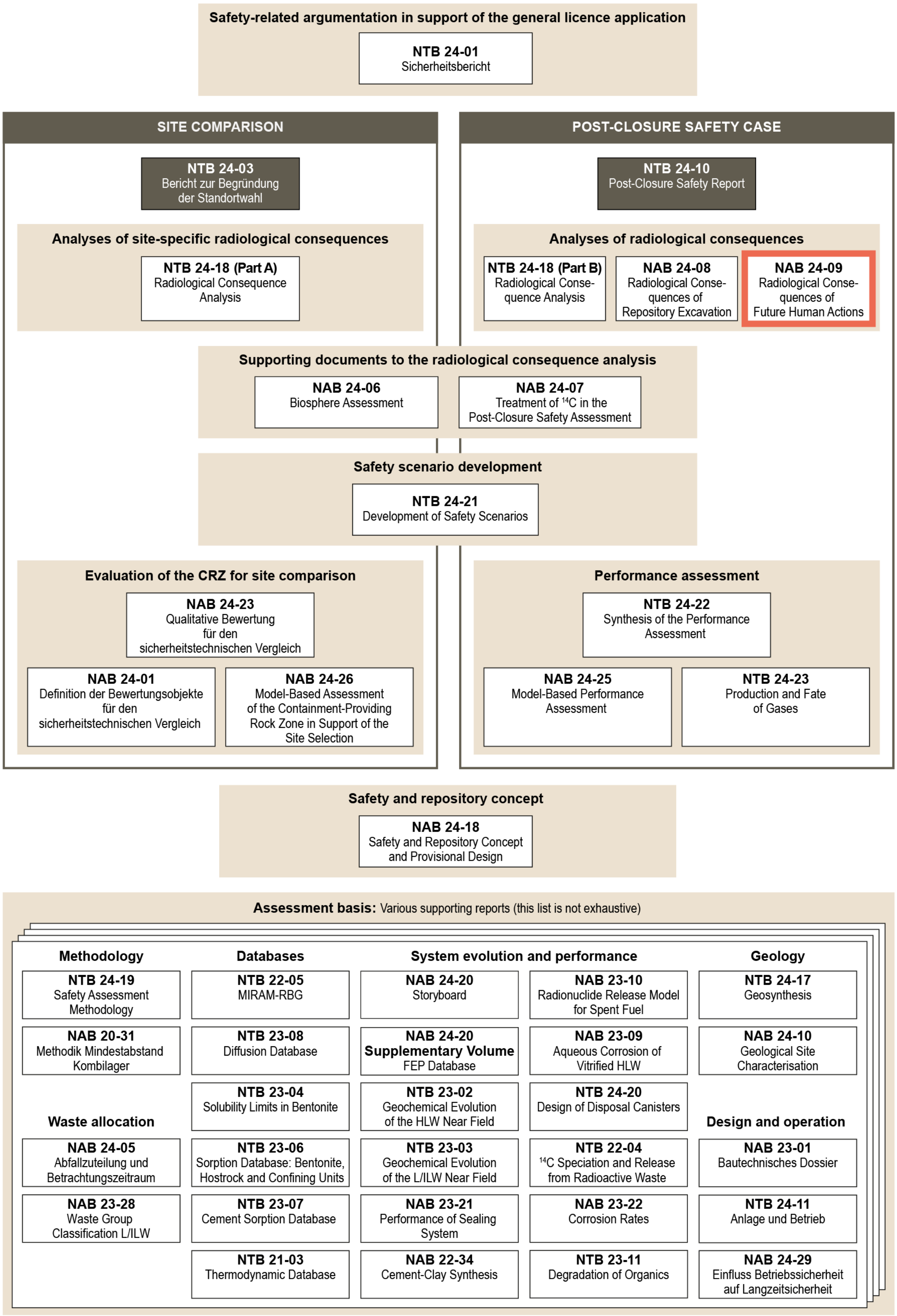


Fig. 1-1: Structure of reports covering post-closure safety aspects of the site comparison and the post-closure safety case

A key safety function of a deep geological repository with respect to FHA is the isolation of radioactive waste from humans and the environment which is achieved by placing it deep underground, minimising the likelihood of intrusions by future generations (Nagra 2024j). This aligns with the recommendations of the International Atomic Energy Agency (IAEA) as outlined in IAEA SSG-23 Par. 6.52 – 6.65 (IAEA 2012).

For the safety case, the approach used to develop FHA safety scenarios is somewhat different from the approach used for other safety scenarios. Specifically, a stylised approach for selected safety scenarios is applied using assumptions derived from current societal practices following a loss of control of the repository or the eventual loss of knowledge about the repository. This separate treatment of FHA from all other safety scenarios stems from the unpredictable nature of future social behaviour and development, in contrast to other types of safety scenarios, which can be developed systematically, transparently and traceably based on deviations from expected evolution, as identified in the performance assessment (Nagra 2024l). A detailed description of the safety assessment methodology used for performance assessment, for the development of other safety scenarios and for the analysis of radiological consequences, including the concepts of safety indicators, radionuclide screening, modelling of the radionuclide release, retention and transport, biosphere modelling and dose conversation factors, is provided elsewhere (Nagra 2024g). In addition, details of the provisional design concept, safety features, general methodologies, and modelling information are found in the documents that form the assessment basis (Fig. 1-1) and thus are not repeated here. This also includes details of the evaluation of the future surface and near-surface features, events and processes (FEPs) (Nagra 2024e), which have no impact on the barrier integrity of the deep geological repository, and are thus excluded here.

The geological setting of the repository, including repository depth and environment and rock strata, along with the selection of the Opalinus Clay as host rock, significantly reduce the potential for FHA and limits their consequences.

## 1.2 Regulatory guidance and requirements related to FHA

As FHA that could affect the deep geological repository cannot be fully excluded, they are assessed primarily with a view to addressing inadvertent intrusions that may compromise the integrity of the disposal facility and lead to potential radiological consequences. The Sectoral Plan for deep geological repositories and regulatory guidance given in ENSI Guideline G03 (ENSI 2023) require the asssessment of FHA as part of the safety case argumentation. ENSI Guideline G03 (ENSI 2023) and its corresponding explanatory report (ENSI 2020) explicitly outline how FHA should be evaluated and assessed:

---

ENSI Guideline G03, Section 4.3.2 Post-closure phase

*b. During the assessment period, the radiological consequences of* ***inadvertent human intrusion*** *into the deep geological repository have to be assessed on the basis of criteria (c) and (e) as set out in paragraph 2.15 of IAEA Safety Standard SSR-5 (IAEA 2011a), s*pecifically: c) efforts to reduce the probability of intrusion or limit its consequences are not warranted if inadvertent human intrusion is expected to lead to an annual dose of <1 mSv to those living around the site; and e) if annual doses range between 1-20 mSv, then reasonable efforts to reduce the probability of intrusion or limit its consequences are warranted.

---

Authorised activities deliberately disturbing the disposal facility, including its natural and engineered barriers and the waste, are considered planned activities and are not taken into consideration (ENSI Guideline G03, Section 9.3.4). Intentional human intrusion is thus excluded from the safety assessment of the FHA report.

The radiological consequences of inadvertent disturbance for the local population and environment are based on safety scenarios for the assessment of FHA. Regarding these safety scenarios, ENSI Guideline G03 (ENSI 2023) states:

---

ENSI Guideline G03, Section 9.3.3

*b. When calculating the radiation dose, assumptions have to be based on a representative individual from the population group most affected by the potential impact of a deep geological repository, with realistic living habits based on a present-day perspective. The analysis has to assume the following:*

*[...]*

2. *The effect of ionising radiation on humans is based on current knowledge.*
3. *Scenarios in which the safety of the deep geological repository is influenced by human actions have to be handled in a way that appears credible from the perspective of present-day society* (for example, in the construction of reservoirs, tunnel or well structures, and exploratory drilling)

---

ENSI Guideline G03, Section 9.3.1

*c: For the scenario analysis and details of the calculation cases referred to under letter a number 7 [*i.e. scenario analysis and details of the calculation cases used to examine the anticipated evolution of the deep geological repository*], safety FEP (features, events and processes) have to be covered by the calculation cases. The radiological effects of future developments have to be assessed by using envelope variants or estimated by using conservative assumptions.*

---

Importantly, although the dose rates for individuals in the vicinity of the site under FHA safety scenarios are assessed, any dose received by drilling team members involved in waste penetration is considered a result of an accidental workplace scenario and is excluded from FHA assessment.

Given the time period of one million years considered in Nagra's safety assessment, any assumptions about the nature of FHA, including the nature (or existence) of future human society and technology, are speculative at best. To avoid undue speculation about future human society and technology, a stylised approach to handling FHA is applied, based on current practices and technological know-how, as recommended in BFE (2008), IAEA (2011b), and IAEA (2012). Specifically, a small number of illustrative, stylised FHA scenarios are developed and analysed within relevant geological and geographical settings. These are not intended to forecast the future, but rather to explore and clarify potential outcomes that may or may not occur, and to quantify their consequences.

Considering deep drilling as an FHA scenario, such an approach also takes into account current practices and recommendations of handling drilling waste in accordance with existing environmental protection laws. Therefore, it dismisses the speculative notion that future drill cuttings and core materials may be scattered randomly across agricultural fields, assuming instead that any drilling waste will be disposed of properly and in accordance with current Swiss practices and regulations. Hence, requirements for handling drilling fluids and solid waste material, such as the Federal Act on the Protection of Waters (Waters Protection Act, WPA 1991), the Water Protection Ordinance (WPO 1998) or the Ordinance for Transportation of Waste Material (VeVA 2005), are assumed to apply.

Regulatory guidelines for radiological consequences permit higher dose rates for stylised FHA safety scenarios than for other types of safety scenarios. Guidance regarding the limits of radiation dose rates and associated risks to the public in terms of predetermined dose criteria are provided by both international bodies (IAEA 2011a) and federal authorities (ENSI 2023). For FHA scenarios, an annual dose of up to 1 mSv for residents living near the site is deemed acceptable before it needs to be shown that the probability of intrusion and its consequences has been reduced as far as reasonably achievable (IAEA 2011a). This differs from the 0.1 mSv per year dose criterion for other safety scenarios given in ENSI Guideline G03 (ENSI 2020, ENSI 2023), reflecting the expected low likelihood of intrusion into the deep geological repository. It should be noted that IAEA SSR-5 also recognises that "[...] *radiation doses to people in the future can only be estimated and that uncertainties associated with these estimates will increase for periods farther into the future. Caution needs to be exercised in applying criteria for periods far into the future. Beyond such timescales, the uncertainties associated with dose estimates become so large that the criteria might no longer serve as a reasonable basis for decision making*."

The closure, sealing and documentation of the repository are also imperative to diminish the risk and consequences of human intrusion. These measures ensure: a) that there are no direct releases of radionuclides through the construction and access systems; b) the long-term separation of pre-existing water-bearing rock layers from the Opalinus Clay aquiclude hosting the repository; and c) the permanent marking of the geological deep repository (Art. 69 "Closure" of KEV 2004 2004). The presence of passive features, such as surface markers at the repository site, may play a role in deterring, or at least delaying, inadvertent human intrusion (Seitz et al. 2014). According to Swiss regulations (Section 6.3 of ENSI 2020):

*The Federal Council stipulates that the repository be permanently marked (Article 40 paragraph 7 of the KEG 2003). IAEA Safety Standard SSR-5 describes permanent marking as a possible measure (in addition to information preservation, documentation and archiving)* ***to reduce the risk of unintentional human intrusion into the repository.*** *According to Article 69 paragraph 3 letter c of the KEV 2004, permanent marking relates to the post-closure phase, in which a deep geological repository is no longer subject to nuclear energy legislation. […]*

The Swiss regulations and guidelines are in line with international requirements, recommendations, and guidelines from key organisations such as the IAEA, ICRP, and NEA (OECD) (e.g. IAEA 2017, IAEA 2011a, ICRP 1998, OECD/NEA 2019, ICRP 2013) (see App. A). Switzerland has adopted many of these internationally coordinated recommendations / guidelines and combined them with specific recommendations as guidelines for the RBG, considering local settings, waste characteristics and technological capabilities, which play a significant role in planning, approval, construction and emplacement of radioactive waste. This report also considers input from the international community including findings from the PAMINA (EU) (Bailey et al. 2011) and the HIDRA (IAEA 2017) projects.

## 1.3 Aims and approach

This report describes safety scenario development, the qualitative assessments of these safety scenarios and the quantitative analysis of their radiological consequences in the specific context of FHA. The stylised FHA safety scenarios are based on present-day human behaviour and technological knowledge and are, in this respect, similar to the biosphere modelling approach applied in the safety assessment (Nagra 2024f). This approach is viable because, despite the uncertainties about future behaviours and the probability of intrusion, the impact of FHA on the repository is predictable and can be assessed.

The objective of this report is to document:

- FHA related regulatory requirements and recommendations;
- FHA assessment methodology (FEPs, safety scenario development, radiological consequence analysis); and
- complementary arguments for the post-closure safety of the repository regarding FHA.

Nagra's methodology for addressing FHA in this report is a further evolution of that applied in Nagra's 2002 *Entsorgungsnachweis* (i.e. the demonstration of disposal feasibility for Project Opalinus Clay) (Nagra 2002). That report included an assessment of the consequences of FHA and their implications for repository integrity. Scenarios of deep drilling and abandonment of the repository during the monitoring period were assessed and radiological consequences determined. Since that time and throughout the SGT process initiated in 2008, the methodology has evolved and benefited from the work carried out as part of the site selection process and supporting safety assessments, including NTB 08-05 (Nagra 2008) and NTB 14-03 (Nagra 2014b). The current methodology is part of the assessment basis, which comprises the evidence, knowledge, assessment tools and methodologies (Nagra 2024k) developed or acquired by Nagra in support of the safety assessment (Nagra 2024i) for the RBG for a deep geological repository in Switzerland.

## 1.4 Structure of this report

The remainder of this report is structured as follows:

Chapter 2 presents the methodology applied in the report and details the procedures, tools and models used to assess the potential effects of FHA on deep geological repositories.

Chapter 3 identifies and describes FEPs relevant to FHA and their role in defining scenarios, variants and calculation cases.

Chapter 4 presents the results of the calculation cases and potential consequences for human health and the environment.

Chapter 5 provides a summary and discussion of key findings, with overarching conclusions.

# 2 Assessment methodology

## 2.1 Overview of the methodology

Fig. 2-1 shows the workflow for the post-closure safety case in support of the general licence application. The left-hand side depicts the process leading to a provisional design and implementation plan, for which a safety assessment is then carried out that provides the arguments and evidence for the safety case. The right-hand side depicts the four main processes within safety assessment. These are:

**Performance assessment**, whereby arguments are developed and evidence presented to show that the safety functions of the repository are upheld, and that the system will evolve as expected in most reasonably foreseeable situations. It also identifies uncertain and potentially detrimental phenomena and other uncertainties that could degrade the functionality of the components of the disposal system or of the overall disposal system.

S**afety scenario development**, which defines a set of safety scenarios that capture the broad ways in which the repository system could fulfil its safety functions over time, as well as additional hypothetical "what-if?" cases, which are aimed at further demonstrating the robustness of the disposal system.

**Analysis of radiological consequences**, which uses quantitative models to evaluate annual individual dose rates or risks and complementary safety indicators. The results are compared with the regulatory protection criteria and the safety margin for each calculation case is determined.

**Demonstration of post-closure safety**, which is achieved by joining the results of the three previous steps with other information supporting the quality of the safety assessment, the safety and robustness of the repository system, and the strength of the stepwise repository siting, design and implementation processes, in the post-closure safety case.

Safety scenario development, which is highlighted in the orange box in Fig. 2-1, involves the definition of:

- A reference safety scenario, which is a general description of the expected initial state of the repository barriers, their expected evolution over time, including the release, retention and transport of radionuclides within the repository system, and the assumptions made regarding the biosphere for the analysis of radiological consequences.
- A set of alternative safety scenarios, which include deviations in performance that are judged to be unlikely, or highly unlikely, but scientifically non-excludable, based on the assessment and the findings of the performance assessment, and lead to a general description of the initial state of the repository barriers and their evolution over time that differs substantially from that of the reference scenario.
- A set of safety scenarios considering FHA, which concern the long-term impact of potential actions undertaken by human society on the performance and safety of the repository.

FHA scenarios are handled in a broadly similar manner to the alternative safety scenarios but are treated as a separate class of safety scenarios, due to their particularly speculative nature. The main difference in their development compared with the alternative safety scenarios is that, instead of being derived from the assessment basis and deviations in performance identified in the performance assessment, they are derived from a set of safety-relevant FHA FEPs.

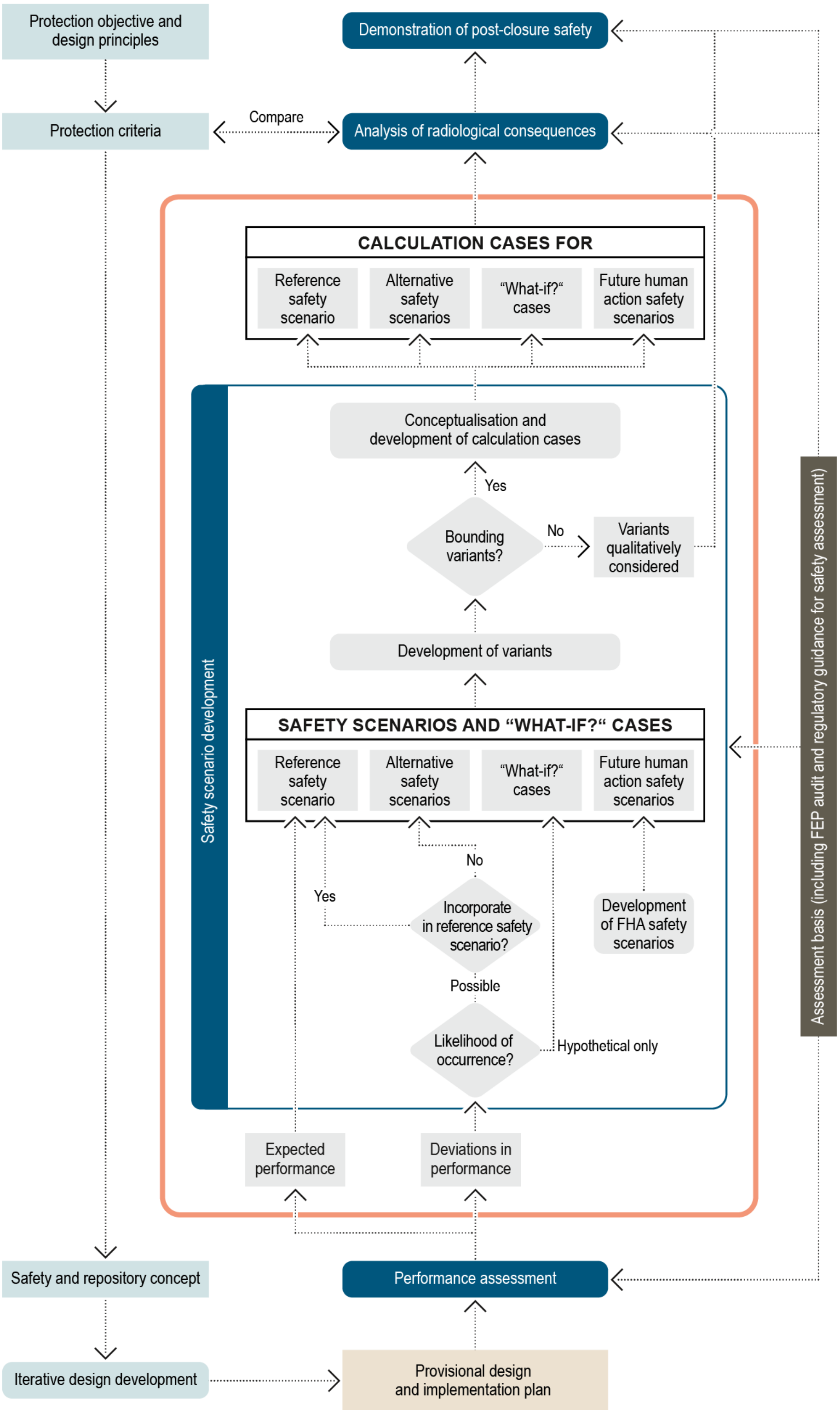


Fig. 2-1: Workflow for the post-closure safety case, highlighting, in the orange box, the main elements of the safety scenario development process, including the development of FHA safety scenarios

The development of FHA safety scenarios differs from all other scenarios, which are based on the findings of performance assessment

The following sections describe:

- FHA FEPs, and how a set of safety-relevant FHA FEPs is derived (Section 2.2),
- how FHA safety scenarios are developed from the FHA FEPs (Section 2.3), and
- the analysis of the radiological consequences of the FHA safety scenarios (Section 2.4).

## 2.2 Identification of relevant FHA FEPs

Nagra's FEP database has been developed iteratively over many years, largely independently of the main safety assessment process. Each version has been reviewed by internal and external experts and compared with other relevant FEP databases compiled by national organisations in other countries and by international bodies (see Section 5.5 of Nagra (2024g) and Section 1.2 of the supplementary volume of Nagra (2024e) on the handling of FEPs in safety assessment). Nagra's FEP database is organised into 17 categories, including the category of FHA FEPs. Each FEP in the database is recorded with a unique numerical identifier, a short title and a description. 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.

A key role of the FEP database in the safety assessment is to address the issue of phenomenological "completeness" by demonstrating that:

- FEPs and their interactions that could affect post-closure safety have been thoroughly identified; and
- these FEPs have been adequately accounted for in the safety assessment.

To this end, an FEP audit, has been performed and documented in the above-mentioned supplementary volume of NAB 24-20 (Nagra 2024e). It considers whether all the FEPs in the FEP database have been adequately treated in the safety assessment and whether omission of any FEPs is well justified. In addition, however, FHA FEPs play a primary role in stylised FHA scenario development.

Not all FHA FEPs are safety-relevant, and those that are not, are screened out as a first step in the assessment process. Specifically, each individual FHA FEP from within the FHA FEP catalogue is evaluated for its potential to impact the safety functions[3] of the deep geological repository, the most relevant safety functions in this context being:

- isolation of radioactive waste from humans and the environment;
- complete containment of radionuclides for a period of time; and
- immobilisation, retention, and slow release of radionuclides.

[3] In all, five safety functions have been defined as part of the post closure safety report (Section 3.2.2 of Nagra 2024g). However, the safety functions of compatibility of the components of the repository system and long-term stability of the multi-barrier system regarding long-term geological and climatic evolution are not relevant in the context of FHA.

The screening is based on qualitative arguments (i.e. when no potential impact on the safety functions of the repository is foreseen or identified) and on the findings of previous safety assessments (Nagra 2002). The depth of the proposed repository and the favourable properties of the Opalinus Clay as the primary geological barrier (e.g., low permeability, high self-sealing, and high sorption capacities for radionuclides, etc.), reduce the relevance of many FHA FEPs. Thus, for example, many of the FEPs that affect only the surface and near-surface environment can be screened out because of the depth of the repository.

As depicted in Fig. 2-2, the remaining FHA FEPs, which cannot be excluded by argument alone, are taken up for further analysis and provide the basis for the formulation of FHA safety scenarios.

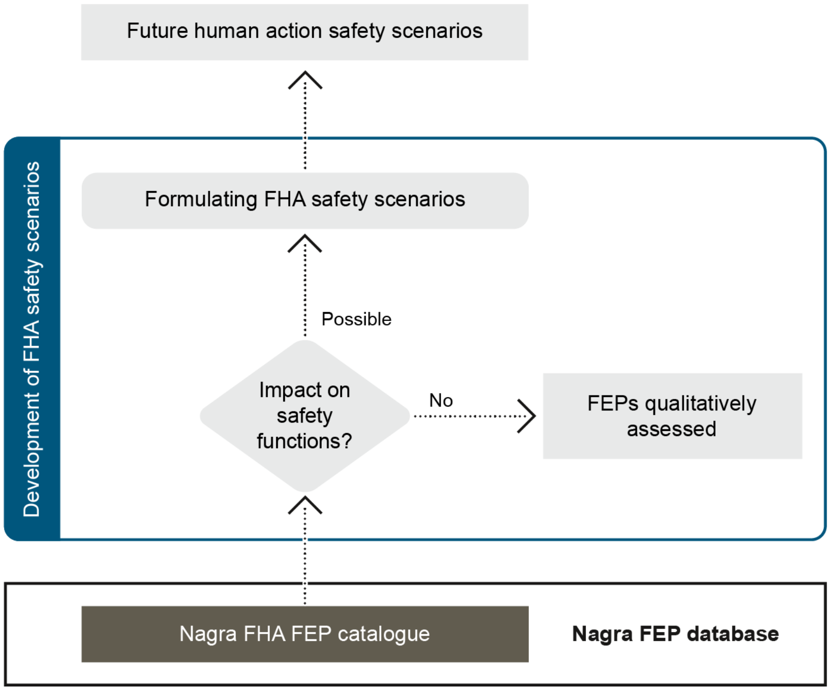


Fig. 2-2: Schematic representation showing FEP screening in terms of their impact on the repository safety functions and the propagation of FHA FEPS that are not screened out to the formulation of FHA scenarios

Although Fig. 2-2 depicts a linear process, the identification and treatment of relevant FHA FEPs is in practice iterative, whereby the qualitative analysis of FHA FEPs promotes the identification of any that are missing. This systematic approach to FHA FEP evaluation is a continuous iterative process where new or additional information or data that become available, or are identified during scenario assessment (quantitative or sensitivity analysis and regulatory compliance), can be integrated for a renewed assessment of all the processes and features. The resulting updated review of potential FHA as basis for scenario development allows updating the evaluation of FHA scenarios and their consequences at any time, even when an analysis of radiological consequences has been determined to be unnecessary.

## 2.3 FHA safety scenario development

Safety scenarios describe the different possibilities for the initial state and subsequent evolution and performance of key features of the repository system. Each safety scenario consists of a general description of the evolution of the repository system and its environment, starting from its initial state at the time of repository closure, and extending into the future, at least up to the end of the time period for assessment. A safety scenario can have one or more variants. Variants of a given safety scenario share largely the same general description of features, events and processes occurring over time, but may differ, for example, in the extent or timing of key phenomena associated with that safety scenario as well as positioning or properties of a key feature. In addition, each safety scenario or variant will typically be associated with one or more "calculation cases". The calculation cases define specific calculations that are carried out to analyse the radiological consequences of a particular safety scenario or variant, each with its own set of parameter values.

FHA FEPs include a wide range of existing commonplace human activities and technologies. Therefore, FHA safety scenarios have a broad spectrum of boundary conditions, variants and parameters. Nonetheless, many FHA FEPs have common features and can thus be grouped together and captured in a relatively small number of FHA safety scenarios. For example, as described in Chapter 3, most FHA FEPs related to deep geological activities involve the drilling of deep boreholes, and it is this common feature that can impact the repository safety functions.

In describing the safety scenarios, their variants and calculation cases, conservative assumptions are generally made that are likely to maximise radiological consequences. For example, with regard to deep boreholes, the FHA safety scenario assumes that these penetrate the repository and then continue to an underlying aquifer, such that the boreholes provide a pathway for the upward flow of water from the aquifer to the surface and for the advective transport of radionuclides released to this aquifer from the waste forms. Furthermore, variants of this scenario consider only instances where the borehole penetrates the emplacement drifts and caverns, since these are clearly more penalising than variants where the borehole passes close to, but does not penetrate, these structures containing the waste.

FHA scenario formulation and assessment, including the development of variants for subsequent quantitative analysis, may allow the identification of conditions or features that may not have been addressed by the current content or evaluation of the FEP database (Nagra 2024e). If missing items or processes are identified, the FHA FEP catalogue is updated. Thus, once again, the identification of safety-relevant FHA FEPs is an iterative process.

## 2.4 Radiological consequence analysis

The radiological consequence analyses of the FHA safety scenarios propagated generally use the same quantitative models described in NTB 24-18 (Nagra 2024i) for other safety scenarios. Model input and calculation methods specific to the FHA scenarios are specified in the present report. Two main modelling approaches are used:

- A single-phase (liquid) modelling approach for the migration of dissolved radionuclides; and
- A two-phase modelling approach for the migration of volatile radionuclides, mainly C-14 methane.

Models and codes for the two approaches are described in detail in NTB 24-18 (Nagra 2024i). For comparison purposes, FHA references cases are also introduced that deviate from the reference case in the reference scenario (RS-RC) (Nagra 2024i). Details are explained below.

# 3 FEPs, safety scenarios, variants and calculation cases

## 3.1 Screening of FEPs

Nagra's FHA FEPs that relate to inadvertent human intrusion are divided into: 1) technical FEPs, and 2) societal FEPs. Technical FEPs relate to technical methods and applications and their potential impact on the performance of the deep geological repository. Examples of these include excavation, drilling or construction work. There are two subcategories of technical FEPs:

i. shallow activity FEPs associated with activities between the surface and a depth of 300 m; and

ii. deep geological activities, considering only FEPs associated with activities 300 m below the surface and deeper.

Societal FEPs are related to governance or societal changes and chosen to be credible within the current societal context or environment and may or may not impact the natural and engineered barriers.

These different categories and subcategories and their impact (or lack thereof) on the repository barriers and safety functions are described in the following sections.

### 3.1.1 Shallow geological activities (depth <300 m)

Nagra's surface/shallow FHA FEPs (App. B and Nagra 2024e) are screened out because they have no impact on the natural and engineered barriers of the deep geological repository. This substantially limits the number of scenarios qualified as FHA safety scenarios.

### 3.1.2 Deep geological activities (depth >300 m)

Nagra's repository will be located deep underground. FHA FEPs considering human activities 300 m or deeper below the surface are thus the most relevant to safety. Possible future activities of this type consist of geological resource development, deep water and waste management or geothermal heat extraction (App. B), and are categorised into:

- deep geological resources (FEP 17.1 and those hierarchically below) (see Fig. 3-1);
- deep groundwater management (FEP 17.2 and those hierarchically below); and
- deep infrastructure and waste management (FEP 17.3 and those hierarchically below).

The subsurface of Northern Switzerland is geologically one of the most studied areas in the country. The extensive exploratory campaigns conducted as part of the site selection process revealed that, from today's perspective, there are no economically viable or significantly extensive resources (Nagra 2024d). Therefore, no impact on the multi-barrier system due to resource conflicts is expected.

Regardless of the fact that past drilling activities have been limited due to the low resource potential in the siting region, Nagra's FHA FEP catalogue considers all potential activities involving FHA, including deep geological exploratory activities and waste disposal activities (such as $CO_2$ injection). Any FEPs associated with exploration, storage, and exploitation within and below the repository are fully assessed and investigated (App. B). All of these FEPs involve the creation of one or more deep boreholes. Therefore, a borehole is the common factor in all of these FEP groups and can be combined into a single safety scenario (Tab. 3-1).

### 3.1.3 Societal activities and knowledge preservation

FEPs associated with societal activities (FEP 17.9 and those hierarchically below) are also relevant (Fig. 3-1). Repository records and markers (FEP 19.1) are part of the FHA-1 safety scenario, since, as explained below, their presence is assumed to deter creation of any deep boreholes that could disturb the repository for a limited period. Societal changes (FEP 19.2) leading to abandonment of the repository prior to its closure (FEP 19.3) are included in safety scenario FHA-2.

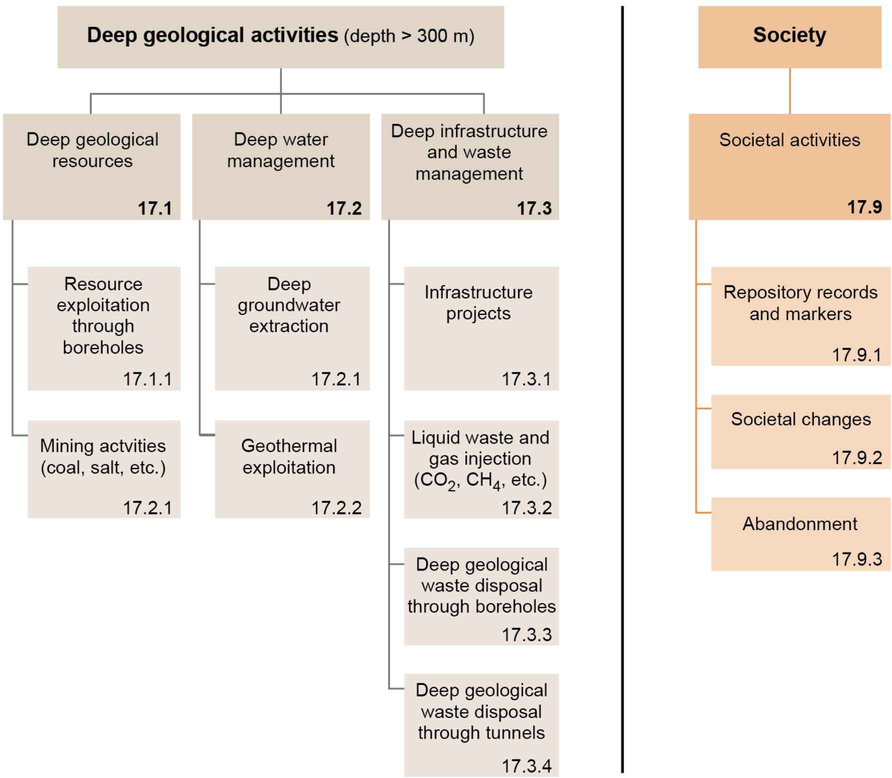


Fig. 3-1: FHA FEP structure for deep geological and societal activities containing Nagra's FEP database numbers (Nagra 2024e).

FHA FEPs are allocated to Section 17. Therefore, FHA FEPs are numbered 17.x.x.

Knowledge of the existence of a deep geological repository will exist for a considerable period following repository closure because of the formal record-keeping which will be undertaken. Most radioactive waste management organisations assume institutional control or information preservation periods of between 200 and 500 years with a maximum of 1,000 years (Posiva 2021, SKB 2014, SKB 2010, ANDRA 2022, NUMO 2021, ESK 2012, NWMO 2018, Medri 2015).

For Nagra's safety case and considering Switzerland's historical context, knowledge of the location, content, and purpose of the repository is assumed to be preserved for at least 500 years. Thus, in the present assessment, FHA in Switzerland that could affect the repository are excluded for 500 years after repository closure. Importantly, the safety assessment of a deep geological repository does not assume that knowledge of the repository will be preserved for periods longer than this (i.e. >500 yrs), nor does the safety of the repository depend on it, due to the passive multi-barrier system.

## 3.2 Safety scenarios

Although many different FHA FEPs (Fig. 3-1, App. B) exist and are evaluated, only two FHA safety scenarios are formulated and analysed in terms of their impact on post-closure safety. The two FHA safety scenarios developed are:

- deep borehole (FHA-1), and
- abandonment (FHA-2).

As shown in Tab. 3-1, these two scenarios incorporate all the FEPs identified as being potentially safety-relevant in Section 3.1.

Tab. 3-1: Summary of FHA FEP and their inclusion in FHA safety scenarios

| **FHA FEPs** | | **FHA safety scenarios** | |
|---|---|---|---|
| | | **FHA-1 Deep borehole** | **FHA-2 Abandonment** |
| **17.1** | **Deep geological resources** | | |
| 17.1.1 | Resource exploitation through boreholes | | |
| 17.1.2 | Mining activities (coal, salt, etc.) | | |
| **17.2** | **Deep groundwater management** | | |
| 17.2.1 | Deep groundwater extraction | | |
| 17.2.2 | Geothermal exploitation | | |
| **17.3** | **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 | Deep geological waste disposal through tunnels / caverns | | |
| **17.9** | **Societal activities** | | |
| 17.9.1 | Repository records and markers | | |
| 17.9.2 | Societal changes | | |
| 17.9.3 | Abandonment | | |

Abandonment of the repository is also addressed in the context of FHA and considers that the repository is only partially sealed when final operational activity is abruptly ceased. Repository design, waste emplacement, barrier integrity and geological stability of the site are thus important aspects when considering the performance of an abandoned repository.

### 3.2.1 Deep borehole (FHA-1)

The FHA-1 scenario assessment considers a borehole that is created based on current state-of-the-art technologies, including precision drilling, for reasons of deep resource exploration, water, infrastructure, or energy management. The scenario is associated with specific factors affecting the radiological consequences, such as time of intrusion, borehole depth, and borehole position in relation to the barrier/waste system.

Drilling into and through the containment-providing rock zone (CRZ), i.e. the Opalinus Clay and its confining units of similar quality, and the engineered barrier system, including an HLW disposal canister or the L/ILW emplacement caverns, poses multiple engineering challenges, which all contribute to reducing the likelihood of this scenario at the repository site. Although these challenges are discussed in Chapter 5, the majority are conservatively disregarded when considering variants to be propagated to the radiological consequence analysis. Certain properties of the geological environment that would reduce the consequences of the scenario are also disregarded. For example, the borehole penetration scenario considers a continuous advective flow through a permanently open borehole over tens of thousands of years, which is impossible considering the clay-rich environment and current drilling and completion technologies. This conservative approach allows the robustness of the repository design and the very low likelihood of radiological consequences arising from a borehole penetrating the repository to be demonstrated.

As radioactive decay reduces the radiological consequences over time, the timing of repository penetration by drilling is an important aspect of the scenario definition. The level of decreasing activity of the Swiss waste inventory (HLW and L/ILW) is presented in a radiotoxicity plot (Fig. 3-2), which includes, for comparison, the radiotoxicity levels of natural rocks. The radiological hazard potential of radionuclides from the waste can thus be compared with the radiotoxicity of natural rock occupying the same volume as the HLW emplacement drifts and L/ILW emplacement caverns. After 100,000 years, the radiotoxicity level of the L/ILW repository reaches the level of e.g., La Creusaz, a uranium ore body at the surface in the canton of Valais (VS) of southern Switzerland, while the HLW has a level just above an 8% U-rich rock from Cigar Lake, Canada.

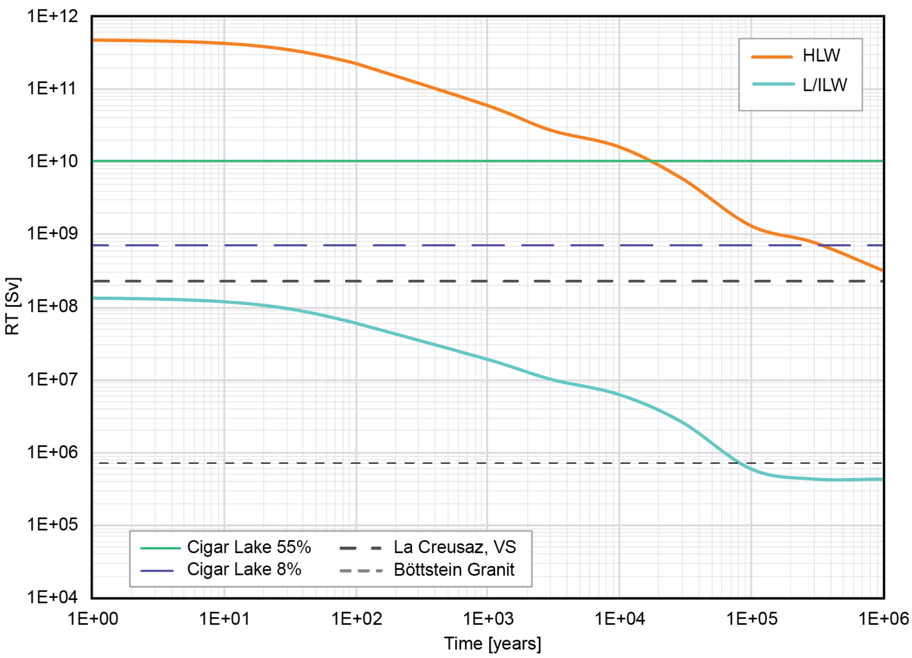


Fig. 3-2: Evolution of the radiotoxicity of the Swiss waste inventory over the next 1 million years

Radiotoxicity is a measure that allows the comparison between radioactive waste and natural rock compositions, such as U-rich (Cigar Lake, La Creusaz) or granitic (Böttstein) rock types.

Because of the low permeability of the Opalinus Clay, any future borehole must provide connectivity between underlying and overlying aquifers (one as a water source and one as an exfiltration pathway) before any fluid flow and plausible transport of dissolved radionuclides to the biosphere can occur. Any borehole that ends above the repository will have no radiological consequences, while boreholes penetrating the repository but without aquifer connectivity will have no or very limited consequences.

Drilling through the Opalinus Clay during Nagra's borehole campaigns (1999 – 2002, 2019 – 2023) revealed the significant plastic behaviour and swelling capacity of the rock (Ammen & Palten 2021, Nagra 2001). Clay minerals capable of swelling, such as illite-smectite mixed layers or smectite (found in the CRZ and bentonite), tend to expand rapidly when in contact with water-based drilling muds. This can lead to bit-balling, when clay solids adhere to the metal surfaces of the bit, or cause borehole narrowing due to expansion. Strategies and additives must be employed to ensure effective drilling, while minimising the risks of borehole closure or other complications associated with the behaviour of the Opalinus Clay. KCl, oil- or silicate-based muds, or thermally activated mud-emulsion systems, can reduce swelling (see also Ammen & Palten 2021), but artificial liners or borehole casings will be required to ensure borehole stability and integrity.

In the unlikely event of a borehole penetration through the repository into an aquifer underlying the CRZ and forming an advective pathway to the biosphere, borehole casings would initially prevent radionuclides from freely accessing the fluids within the borehole. However, liners or casings have a relative short (tens to a few hundreds of years) lifespan as they degrade over time. After degradation of the casing, borehole collapse and subsequent self-sealing are expected. These factors illustrate that, for the deep drilling FHA-1 safety scenario, any borehole would have a limited lifespan for advective flow. However, the FHA-1 safety scenario pessimistically considers an open borehole with a gradient and permeabilities established in previous safety assessments (Nagra 2002).

Additional challenges arise with drill bits, as they are specifically engineered for certain rock types and exploratory objectives. Deep drilling through sedimentary sequences involves 3.5" or larger diameter drills with mostly polycrystalline diamond compact (PDC) drill bits. These cutters generate shear at the tip and cut through the rock, but they cannot effective penetrate even a few centimetres of uncorroded steel, such as that of HLW disposal canisters or MOSAIK containers (Tab. 3-2). The canisters are designed to ensure a complete containment for a prolonged period under all reasonably foreseeable circumstances (Nagra 2024b). The canister wall thickness will prevent any PDC drill bit penetration within the first few thousands to tens of thousands of years. Since FHA scenarios are stylised, the timing of the borehole penetration scenarios conservatively disregards regulatory requirements for a minimum canister lifetime (ENSI 2023, ENSI 2020), the likely strength of the canisters according to the provisional design (Diomidis et al. 2023), and the drilling challenges that would be faced on entering an HLW drift or an L/ILW cavern, as these are difficult to quantify.

Tab. 3-2: Engineering challenges involved in drilling into different materials relevant to the FHA-1 safety scenario

| **Repository section** | **Material** | **Conditions** | **Technical challenges** |
|---|---|---|---|
| HLW, L/ILW | Opalinus Clay | Clay-rich host rock >100 m thick | Borehole instability in clays due to swelling requires the use of oil-, salt-based or synthetic drilling fluids. Soft, clay-rich rock has a strong self-sealing behaviour. |
| HLW | Bentonite | Smectite clay surrounding steel canister as buffer | Loss of drilling fluids due to rapid swelling of the smectites, deterioration of the bentonite matrix with fluidising effects and steering issues. |
| HLW, L/ILW | Steel | Thick-walled HLW disposal canister (14 cm), MOSAIK-II casks (16 cm), metal drums, etc. | High-density contrast, intact steel material and canister shape will lead to deflections of PDC drill bits. PDC drill bit will also wear out quickly upon encountering durable metals. Penetration possible only far into the future after corrosion has substantially weakened the steel. |
| L/ILW, HLW | Cement | Concrete tunnel linings, concrete containers, mortar for embedding waste material and backfilling tunnels. | Density and property contrasts between the Opalinus Clay and the engineered barriers, concrete tunnel support structures are often reinforced by metal rebars, which will impact drilling rates and penetration. |

At present, in unconventional oil and gas plays, most production of liquid or gaseous hydrocarbons employs horizonal borehole designs, while conventional oil and gas and geothermal energy are exploited by means of vertical or deviated boreholes. Since the total organic carbon content (0.5 – 1 wt.%) (Nagra 2024d) and low thermal maturity (i.e. 0.6 vitrinite reflectance %) of the Opalinus Clay and CRZ are below the thermal maturity of oil or gas production (Leu & Gautschi 2014), sub-horizontal boreholes placed into these formations for the purpose of energy extraction can be excluded from further consideration. Thus, only vertical or slightly deviated boreholes within the Opalinus Clay are considered in this scenario, which may create a direct pathway for gaseous phases or groundwater flow and radionuclide transport. Of all plausible borehole positions in the vicinity of a deep geological repository, a borehole penetrating either the HLW disposal canisters or the L/ILW caverns with their waste packages is considered most adverse because these features contain the bulk of the radioactivity in the repository at any time.

Furthermore, most deep exploratory campaigns employ non-intrusive investigations (e.g. seismic) prior to drilling to assess subsurface composition, identify potential targets, or address potential drilling challenges (hazards). It is likely that inverse seismic modelling would reveal the repository as a density anomaly within the non-competent units of the Opalinus Clay and the adjacent clay-rich units of the CRZ. In general, anomalies are avoided during deep drilling campaigns to avoid potential drilling issues.

Lastly, although Nagra's site selection process resulted in the selection of an area with no observable seismic-scale faults above and within the Opalinus Clay (Nagra 2024d), FHA drilling activities could induce future slippage (through salt removal or completion activities). Geomechanical modelling suggests that slippage induced by borehole activities (fracking, salt removal) would have minor impacts on the Opalinus Clay with negligible displacements.

Thus, FHA radiological consequence analysis considers only the direct effects of a borehole penetrating the repository. Note that the radiological consequences of a large fault intersecting the repository, which is either newly created or re-activated by geological processes or repository-induced effects, is assessed in Nagra (2024i).

### 3.2.2 Abandonment (FHA-2)

The FHA-2 scenario addresses the abandonment of the repository during the monitoring phase before final closure and is motivated by the FHA FEPs of abandonment (FEP 17.9.3) and societal changes (FEP 17.9.2). Regulations (ENSI 2018) require an assessment of the potential impact both on the repository barriers and on radionuclide release and transport. The details of this FHA safety scenario are described below. Importantly, this safety scenario considers only a situation where all waste material is below ground. Any scenario involving HLW or L/ILW remaining at the surface poses a significantly greater risk to the population. The loss of institutional control during the operational phase (waste on the ground) is not, however, covered by repository regulations and requirements and is not covered by the present report. Given that successive and progressive sealing of the repository takes place during the operational phase, the most plausible and adverse scenario involves a situation where a few seals are missing or unfinished structures remain open (see Fig. 3-3).

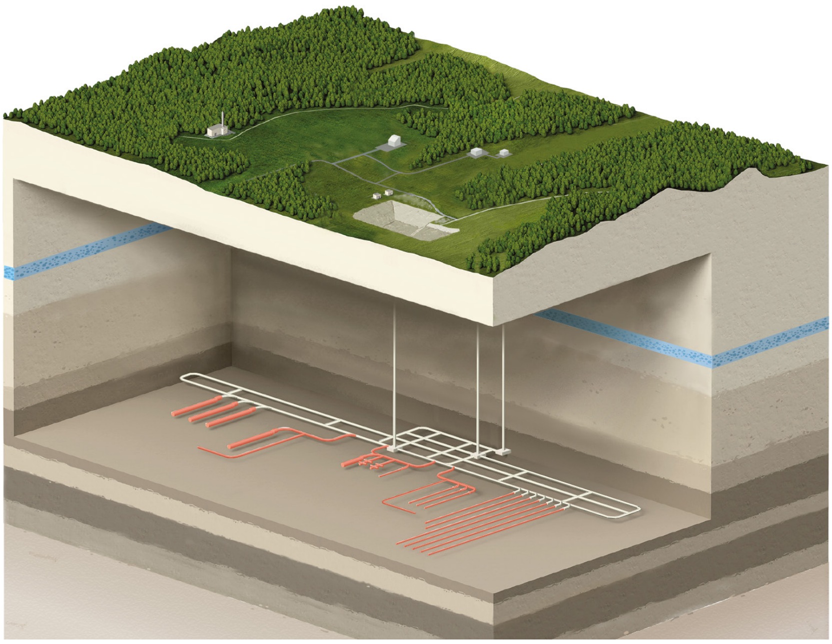

Fig. 3-3: Schematic illustration of an abandonment scenario during which it is assumed that all emplacement drifts and caverns remain unsealed (white sections) and susceptible to water inflow

In the event of an unplanned cessation of repository operations, some HLW disposal canisters or L/ILW containers may remain accessible after the majority of the waste has already been securely sealed. While sections of the L/ILW caverns may remain open, the HLW emplacement drifts are continuously backfilled and sealed during emplacement as per regulatory requirements (ENSI 2023), specifically to mitigate the consequences of potential abandonment.

Thus, key elements to consider when evaluating the implications of abandonment are:

- the timing of abandonment, which determines the amount of waste still present in unsealed conditions in the repository; and
- the duration of abandonment, i.e. whether it is temporary (with waste emplacement, backfilling and sealing being resumed after some time) or permanent.

In the event of a permanent loss of control, there are three main potential consequences for the repository:

1. Non-backfilled underground openings, including shafts, may provide enhanced radionuclide transport pathways to the surface environment. Although these pathways are likely to fully or partially collapse or close over time due to rock creep, collapsing shaft structures and the expanding clays, they may, at least for a short period of time, represent preferential pathways.
2. Collapse of non-backfilled underground openings may cause damage to, and influence the effectiveness of, the adjacent geological barrier. This effect has been demonstrated to have negligible performance impacts (Nagra 2024l).
3. Water influx may take place from the surface facilities or from aquifers along the access shafts, increasing the rate of saturation of the repository and potentially affecting the seals of the emplacement caverns and drifts. This effect has been demonstrated to have negligible impacts on the performance of the seals (Martin et al. 2023, Nagra 2024b)

For the FHA-2 safety scenario, the parameter variation of the time of abandonment strongly impacts potential outcomes. If abandonment occurs when parts of the drifts and caverns are open and accessible, abandonment may lead to elevated water entry and thus to enhanced saturation of engineered barriers, which would deviate from the expected evolution.

## 3.3 Variants propagated to the analysis of radiological consequences

### 3.3.1 Deep borehole (FHA-1)

From the considerations and discussion above, variants of the FHA-1 safety scenario where both barrier and waste are intersected by a future borehole are propagated to the specific and detailed conservative calculation cases. Although technology, methods, and knowledge have markedly changed since the previous assessments (Nagra 2002), similar variants emerge, namely:

- direct penetration of an HLW disposal canister (i.e. FHA-1a variant), and
- direct penetration of an L/ILW emplacement cavern (i.e. FHA-1b variant).

These variants and their calculation cases are detailed in the sections below.

#### 3.3.1.1 Direct hit of an HLW disposal canister [FHA-1a variant]

In the FHA-1a safety scenario variant, a borehole penetrates the HLW repository tunnel system and an SF canister is breached by the drilling and borehole construction. It is assumed that no release of radionuclides occurs prior to the breaching of the canister. The radionuclides present in the grain boundaries of the SF and in the gaps between the fuel pellets and the cladding, the so-called "instant release fraction", or IRF, of the inventory, will readily be available and will be released rapidly into the borehole. The IRF radionuclides are also assumed to be conveyed rapidly as a "pulse release" to the reference biosphere via a local aquifer. The IRF is described in detail in Nagra's report on the radionuclide release model (Johnson et al. 2023). Fluid flow and a gradient within the borehole are also assumed to remain constant indefinitely (ignoring casings or borehole collapse due to the clay-rich environment). No calculations are performed for a borehole penetration of a reprocessed vitrified HLW canister (as it has lower radiotoxicity and lacks volatile C-14) or between two emplacement drifts (i.e. missed hit) as the radiological consequences are significantly lower, as demonstrated by previous FHA consequence analyses (Nagra 2002).

While core recovery and sample material placement on the surface are assumed for the direct hit (DH) calculation cases, the implications of the drilling team handling SF drill core material are not considered in the FHA safety assessment, as this is classified a workplace accident. Any material recovered would be promptly investigated and properly classified due to the high dose rates (>200 Sv within the first 1,000 years) which exceed current core and cuttings handling protocols in Switzerland (see for example the calculations in Posiva 2021). The significant exposure to radioactivity would result in an immediate termination of the drilling operations, isolation of the exposed equipment, and proper sealing of the borehole using materials like bentonite and cement.

The different calculation cases for a DH are summarised in Tab. 3-3. In each case, an SF disposal canister is penetrated, releasing radionuclides. The radiological consequences are assessed with two different modelling approaches to account for the different types of radionuclides considered. Specifically, all soluble (dissolved) radionuclides are treated using a single-phase (liquid) modelling approach, whereas volatile radionuclides are treated using a two-phase modelling approach. For each of the modelling approaches, different calculation cases are established.

For modelling *dissolved* radionuclides, the calculation case considers a DH at 500, 1,000, 5,000, 10,000, or 50,000 years (Tab. 3-3). Modelling assumptions include that no overpressure is present in the Opalinus Clay and that the water flow in the borehole is driven by the hydraulic gradient between two deep aquifers, one above and one below the CRZ, that are connected by the borehole. Thus, the flow rate is determined by the hydraulic pressure difference between these aquifers and by the hydraulic conductivity of the borehole, which is assumed conservatively to be time independent. The selected steady-state flow rates are 0.0001 $m^3 a^{-1}$, 0.01 $m^3 a^{-1}$, and 1 $m^3 a^{-1}$, assuming unlimited availability of fluids for steady flow from a deeper (possible Keuper or deeper) to a shallower (possible Malm or shallower) aquifer (see also Nagra 2002).

The radiogenic C-14 (with a half-live of 5,730 years) represents the only dose-relevant *volatile* radionuclide and is modelled in the chemical form of methane. Any C-14 present as $CO_2$ is not considered due to the high likelihood of mineral precipitation within the repository environment. Borehole penetration is assessed at various intervals following repository closure, specifically at 500, 1,000, 5,000, 10,000 and 50,000 years.

Tab. 3-3: Overview of calculation cases for the FHA-1a variant

| Calculation case | Description |
|---|---|
| FHA-1a-DH-Diss | Release of dissolved radionuclides from a DH of a PWR-MOX canister, where drilling brings 10% of the SF assemblies as cuttings or core material from the canister to the surface together with the SF canister's IRF. The recovered material is assumed to be disposed of at the surface in a gravel pit that is in contact with the local biosphere aquifer. While the IRF leads to a short-term exposure, the cuttings or core material of the SF assemblies leach into the biosphere aquifer upon corrosion/dissolution leading to a long-term radionuclide release. For an SF matrix disposed at the surface, fractional release rates of $3.7 \times 10^{-5}$ $a^{-1}$ (Johnson et al. 2023) are assumed, based on oxidising conditions. For the cladding, an elevated dissolution rate of $10^{-4}$ $a^{-1}$, corresponding to the "what-if?" case WI-SF-DISS (Nagra 2024i), is assumed.<br>The remaining 90% of the SF assemblies within the penetrated canister contribute to long-term radionuclide release and transport to the biosphere under assumed upward water flow rates of 0.0001 $m^3$ $a^{-1}$, 0.01 $m^3$ $a^{-1}$, and 1 $m^3$ $a^{-1}$. Reducing conditions, as in the reference case (RS-RC), are assumed to prevail (fractional dissolution rate of the SF matrix and cladding are $10^{-7}$ $a^{-1}$ and $7.7 \times 10^{-6}$ $a^{-1}$, respectively).<br>This case considers a DH 500, 1,000, 5,000, 10,000 and 50,000 years after repository closure. |
| FHA-1a-DH-Vol | The SF canister is breached, and the borehole forms a preferential pathway for the transport of volatile C-14 as methane in both gaseous and aqueous forms released from the corrosion/dissolution of the SF assemblies and matrix to the biosphere aquifer. For all canisters, a containment period of 500 years is assumed. The IRF of volatile C-14 is released from the waste, followed by the congruent (slow) release of C-14 through corrosion of activated metals (Diomidis et al. 2023, Nagra 2024h). The thermo-hydraulic two-phase evolution of the full repository is modelled explicitly. Gas and water flow through the borehole are not prescribed, but are calculated from the dynamic saturation, pressure and temperature conditions in the repository as well as the permeability and cross-section of the borehole. An upward hydraulic gradient between the Keuper and Malm aquifers of 1 m/m is assumed.<br>This case considers a DH 500, 1,000, 5,000, 10,000 and 50,000 years after repository closure.<br>The resulting radiological consequences are compared with an FHA reference case (FHA-1-RC), which is identical to the reference case of the reference safety scenario (RS-RC) (Nagra 2024i) with the exception that an upward hydraulic gradient of 1 m/m and SF canister breaching after 500[4] years are assumed (compared with zero gradient and breaching after 10,000 years in the RS-RC). |

The calculation cases for an DH of a SF canister (FHA-1a) are illustrated in Fig. 3-4. The radiological consequence analysis considers the combined effect of the different radionuclide transport modes (of dissolved radionuclides) shown in the figures and different dissolution rates (depending on surface disposal or in situ fuel matrix and cladding).

[4] ENSI requires a minimal canister lifetime of 1,000 years (ENSI 2023; ENSI 2020).

The short-term effects of a DH (waste transported to and disposed at the surface) are shown on the left (Fig. 3-4), while the right diagram shows the long-term and congruent release of radionuclides from the waste at the surface and from the remaining in situ waste material through the preferential flow path of the (open) borehole.

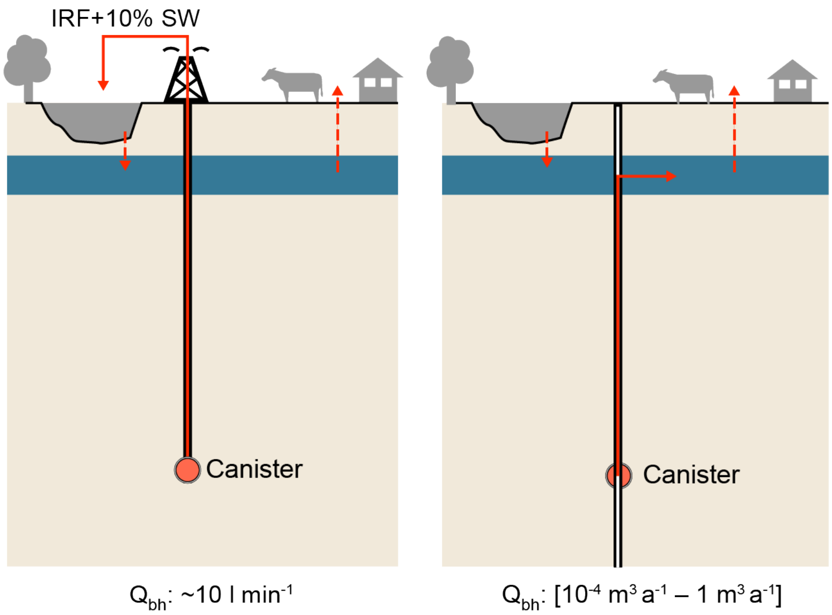


Fig. 3-4: Schematic illustration of a direct hit of a disposal canister for spent fuel assemblies

Left: 10% of the SF assemblies in a canister are transported to the surface as part of the cuttings fraction (SW) and drilling fluids together with the IRF. Right: Radionuclides released from the remaining 90% of in situ waste are transported with upward water flow through the borehole. IRF = instant release fraction, SW = solid waste.

### 3.3.1.2 Direct hit of an L/ILW emplacement cavern [FHA-1b variant]

The undisturbed L/ILW emplacement caverns are expected to remain only partially water saturated for at least some hundreds of thousands of years. This is due to the sizes of the caverns, the low permeability of the host rock, and the pressure build-up in the emplacement caverns as a result of gas generation (see (Nagra 2024i), Section 6.3). The waste composition of each L/ILW cavern is highly heterogenous, as the Swiss waste inventory (Nagra 2023) has at least 642 different types of L/ILW (including ATW) present.

In the FHA-1b deep borehole safety scenario, a borehole intersects and penetrates an L/ILW emplacement cavern and L/ILW disposal containers. This direct breach of both the geological and engineered barriers leads to an infiltration of drilling circulation fluids into the L/ILW near field, releasing radionuclides to the surface (assuming an open hole). Penetration of L/ILW packages is conservatively considered plausible for modelling purposes shortly after knowledge of the repository is lost.

The L/ILW emplacement caverns may contain methane with certain levels of C-14 that may escape through a borehole[5] at a rate that depends on the production and buildup of gas, overall gas pressure within the cavern, permeability, and timing of the penetrating borehole. Similar to the calculations for the FHA-1a variant, the timing of the borehole drilling is an important factor, as the radioactive decay of the inventory over time affects the magnitude of the resulting doses (see Fig. 3-2).

Similar to the FHA-1a variant calculations, the radiological consequences of a DH into an L/ILW cavern and waste package by a deep borehole are also assessed using different modelling approaches and distinct calculation cases. These assessments vary based on the type of radionuclides involved (dissolved or volatile). For dissolved radionuclides, two complementary cases are defined that consider different aspects of:

- the short-term effects of radionuclides that are retrieved from a penetrated waste package (WP); and
- the long-term effects of radionuclides that are released through an established preferential flow path (PFP) provided by the borehole.

For volatile C-14, only the latter case is relevant. The following calculation cases are considered for the FHA-1b variant (Tab. 3-4).

[5] Limitations of radionuclide transport due to borehole casings are neglected for modelling purposes.

Tab. 3-4: Overview of the L/ILW calculation cases for the FHA-1b variant

| Calculation case | Description |
|---|---|
| FHA-1b-WP-Diss | A drill bit penetrates a WP and its entire radionuclide inventory is released through the drilling circulation system. The recovered material is then unknowingly disposed of in a gravel pit, where the radionuclide inventory immediately enters the biosphere aquifer of the reference biosphere. Only WPs that have the highest adverse impact are considered.<br>This case considers a DH 500, 1,000 and 5,000 years after repository closure. |
| FHA-1b-PFP-Diss | The borehole acts as a preferential flow path (PFP), leading to an immediate saturation of the affected section of the emplacement cavern after the hit (i.e. it becomes fully liquid saturated). Additionally, the radionuclide inventory of all waste packages is dissolved and homogeneously distributed within the porewater of the cavern, taking into account sorption of radionuclides. The dissolved radionuclides then diffuse to the borehole, where they are transported by advection (flowrates of 0.0001 $m^3$ $a^{-1}$, 0.01 $m^3$ $a^{-1}$, 1 $m^3$ $a^{-1}$) directly to the aquifer of the reference biosphere.<br>This case considers a DH 500, 1,000 and 5,000 years after repository closure. |
| FHA-1b-PFP-Vol | The borehole creates a PFP for the transport of gas, liquid, and volatile C-14 to the biosphere aquifer. The IRF of volatile C-14 is released from the waste, followed by the congruent (slow) release of C-14 through corrosion of activated metals (Diomidis et al. 2023, Nagra 2024h).The two-phase evolution of the entire repository is explicitly modelled, where gas and water flows through the borehole are not prescribed but are calculated from the dynamic saturation and pressure conditions within the repository, as well as the borehole's permeability and cross-section. This case considers a DH 500, 1,000, 5,000 years after repository closure, as well as after 10,000 and 50,000 years.<br>The resulting radiological consequences are compared with a reference case (FHA-1-RC) introduced in Tab. 3-3 for the calculation case FHA-1a-DH-Vol. |

Fig. 3-5 illustrates the two calculation cases (FHA-1b-WP-Diss and FHA-1b-PFP-Diss) for the release of dissolved radionuclides upon a DH of an L/ILW emplacement cavern considering the short-term effects of a penetrated waste package (left) and the long-term effects of the preferential pathway (right), respectively.

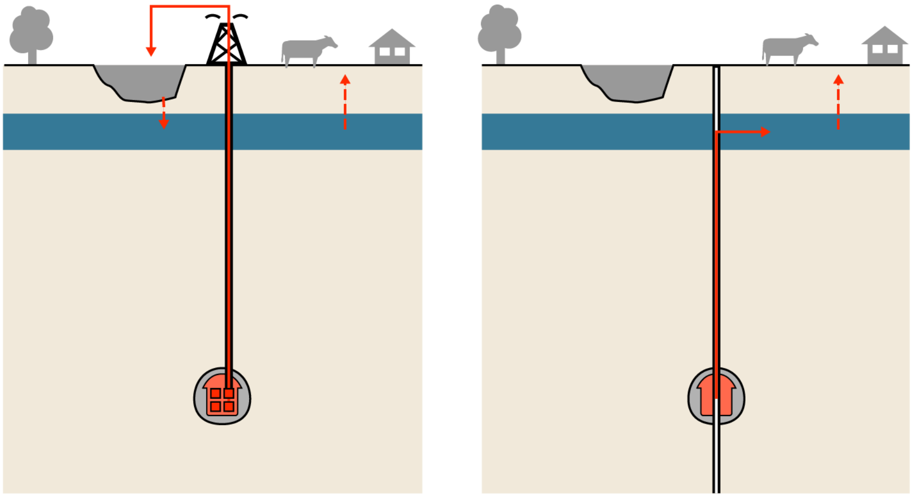


Fig. 3-5: Schematic illustration of the calculation cases of a direct hit into an L/ILW emplacement cavern to assess the radiological consequences

Short-term effect resulting from a shredded and washed-out waste package (left) and long-term effect from the established preferential flow path through the borehole (right).

### 3.3.2 Abandonment (FHA-2)

The potential impact of repository abandonment during waste emplacement is quantitatively assessed in two calculation cases. These include:

- dissolved radionuclides; and
- volatile C-14 (in the form of methane).

Both cases are assessed with a two-phase modelling approach, and assumptions are made concerning the underground repository structures, their backfill and their saturation state (Tab. 3-5). Both cases assume that the emplacement drifts and caverns are properly backfilled, while the remaining tunnels and shafts remain open.

Tab. 3-5: Overview of the repository abandonment calculation cases

| **Calculation case** | **Description** |
|---|---|
| FHA-2-Diss | Radiological consequences of dissolved radionuclides (represented by I-129) released from an abandoned repository. Emplacement drifts and caverns are properly backfilled, but seals are not yet in place and other underground structures, including shafts, are not backfilled. Collapsed tunnel structures and subsequent progressive self-sealing are accounted for by applying different permeability values ($10^{-17}$ m$^2$, $10^{-14}$ m$^2$, $10^{-11}$ m$^2$). |
| FHA-2-Vol | Identical to FHA-2-Diss, but the model calculations are performed for volatile C-14 in the form of methane. |
| FHA-2-RC | The reference case (FHA-2-RC) for a properly sealed repository is defined for comparison purposes and is identical to the reference case of the reference safety scenario (RS-RC) (Nagra 2024i), except for an assumed upward gradient of 1 m/m. |

### 3.4 Summary of FHA safety scenarios, variants and calculation cases

The full set of FHA safety scenarios and their variants identified in the present chapter and propagated to the analysis of radiological consequences is summarised in Table 3-6.

Tab. 3-6: Summary of the FHA safety scenarios and their variants propagated for radiological consequence analysis in this report

DH: direct hit; WP: waste package hit; PFP: preferential flow path (cavern hit).

| FHA safety scenario | FHA variant | Waste | Calculation case | Radionuclides |
|---|---|---|---|---|
| **Deep borehole** | FHA-1a | HLW | FHA-1a-DH-Diss | Dissolved |
| | | | FHA-1a-DH-Vol | Volatile |
| | FHA-1b | L/ILW | FHA-1b-WP-Diss | Dissolved |
| | | | FHA-1b-PFP-Diss | Dissolved |
| | | | FHA-1b-PFP-Vol | Volatile |
| **Abandonment** | FHA-2 | HLW & L/ILW | FHA-2-Diss | Dissolved |
| | | | FHA-2-Vol | Volatile |

The deep borehole (FHA-1) safety scenario has two variants:

- FHA-1a: borehole penetrating an SF disposal canister, with calculation cases for both dissolved and volatile radionuclides (C-14 as methane); and
- FHA-1b: borehole penetrating an L/ILW emplacement cavern with calculation cases that consider both a single penetrated waste package (dissolved radionuclides only) and the effects of a preferential flow path from the penetrated cavern to the biosphere via the borehole (dissolved and volatile radionuclides).

The abandonment (FHA-2) safety scenario has only one variant, but again two calculations cases, one for dissolved and one for volatile radionuclides.

The modelling concepts, their implementation and the results used to analyse these safety scenarios, variants and cases are presented in the next chapter.

# 4 Analysis of radiological consequences

## 4.1 Borehole penetration of an SF canister (FHA-1a)

### 4.1.1 Model concept and implementation

**FHA-1a-DH-Diss**

The near-field code STMAN (see details in Nagra 2024i) was used to model the FHA-1a-DH-Diss calculation case, which considers a borehole penetration of a single PWR-MOX SF canister. The variant FHA-1a assumes that all canisters are intact and that thus no radionuclide dissolution or release has occurred before borehole penetration. Prior to this time, the radionuclide inventory is affected only by radioactive decay and ingrowth. When the borehole penetrates the canister, the IRF is assumed to be immediately released as a pulse to the biosphere aquifer of the reference biosphere. The maximum dose consequences due to the IRF are calculated by multiplying the radionuclide-specific pulse releases by a set of biosphere dose conversion factors (BDCFs) derived for such releases from the SwiBAC software (Nagra 2024f). The same input parameters and assumptions used to derive the BDCFs of the reference biosphere for steady-state release were used to calculate these factors.

In addition to the IRF, there is also a long-term release, which is divided into two parts:

- 10% of the SF assemblies are assumed to be recovered directly by the drilling process and brought to the surface, where they undergo (oxidative) dissolution, with elevated (oxidative) fuel matrix and cladding dissolution rates (see Tab. 3-3), resulting in a congruent radionuclide release that is directly transferred to the biosphere aquifer.
- The radionuclide inventory of the remaining 90% of the SF assemblies in the canister is released congruently from the matrix and cladding based on the reference dissolution rates for reducing conditions described in NTB 24-18 (Nagra 2024i). The radionuclides that are released are continuously mixed with the deep groundwater that flows through the borehole (assumed to be open) from the aquifer underlying the CRZ to the biosphere aquifer. The steady-state flow rates through the borehole are 0.0001 $m^3 a^{-1}$, 0.01 $m^3 a^{-1}$, and 1 $m^3 a^{-1}$.

All radionuclides released from the breached canister are assumed to migrate to the biosphere via the borehole. The release of radionuclides to the bentonite buffer and to the geosphere is conservatively neglected. The transfer of radionuclides along the borehole and from the borehole to the biosphere is assumed to occur instantaneously and is not explicitly modelled. The dose rates are calculated by multiplying the radionuclide-specific release rates along the borehole by the respective BDCFs for the reference biosphere. It is assumed that the other canisters not affected by the borehole have no dose contributions.

**FHA-1a-DH-Vol**

Modelling of the FHA-1a-DH-Vol calculation case addressing the release of volatile C-14 was carried out using the same 3D two-phase macroelement model as applied in the safety analysis for modelling radionuclide migration in the gas phase in other safety scenarios (reference model). The model was implemented in TOUGH3 with the EOS75r module (Jung et al. 2018, Zhang et al. 2024). Detailed information on the model setup and the macroelement approach can be found in App. B of NTB 24-18 (Nagra 2024i). The thermo-hydraulic two-phase evolution of the entire repository is modelled explicitly during various operational stages, as well as during the post-closure phase before and after the borehole penetrates the repository. The two-phase transport of volatile C-14 is accounted for along repository structures, through the CRZ, and through the borehole.

The macroelement that represents the affected drift is subdivided axially and laterally to allow modelling of the borehole, which is represented as having a square cross-section of 0.5 m × 0.5 m (area includes the damaged zone around the borehole). Gas and water flow through the borehole are not prescribed, but are instead derived from the dynamic saturation, pressure and temperature conditions within the repository, as well as the permeability and cross-sectional area of the borehole. The C-14 gas release rate is calculated from the cladding and matrix dissolution rates plus the IRF as in the RS-RC case (Nagra 2024i). The assumed borehole permeabilities are $10^{-17}$, $10^{-14}$, and $10^{-11}$ $m^2$, values approximated during the previous safety assessment (Nagra 2002). The highest permeability value of $10^{-11}$ $m^2$ is chosen as a conservative upper bound. An upward hydraulic gradient between the underlying (Keuper) and overlying (Malm) aquifer of 1 m/m is assumed. Radionuclide transport through the borehole to the Malm aquifer is explicitly modelled, while the transfer from the Malm to the biosphere aquifer is assumed to occur instantaneously.

### 4.1.2 Results of radiological consequence analysis

#### 4.1.2.1 FHA-1a-DH-Diss

The dose rates due to dissolved radionuclides calculated for a canister penetrated by a borehole after 500 years are shown in Fig. 4-1. The dose rates are compared with those calculated for releases from the HLW repository section for the reference case of the reference safety scenario (NL HLW RS-RC), where there is no borehole penetration, but all canisters are assumed to fail at 10,000 years post-closure (Nagra 2024i).

The results show that the initial dose of the IRF, which is dominated by I-129, is $1.4 \times 10^{-3}$ mSv/a (shown as a black circle labelled IRF), while higher doses occur as a result of the long-term radionuclide release. These dose rates are dominated initially by actinides such as Am-241, Pu-239, whereas, at later times, Th-230 dominates (see Fig. 4-2 for details showing all radionuclides contributing at least 10% to the total dose rate). The slight increase in the long-term maximum dose rate up to 200,000 years post-closure is the result of ingrowth of Th-230 from the decay of U-234.

Both the maximum dose rate due to this long-term release, $3.6 \times 10^{-3}$ mSv/a, and the IRF dose rate ($1.4 \times 10^{-3}$ mSv/a) are more than two orders of magnitude below the regulatory guideline of 1 mSv/a for FHA. The long-term release is made up of contributions from the drill waste disposed of at the surface (10%) and the releases from the remaining assemblies which are carried by groundwater flow along the borehole. The former initially provides the largest dose contribution, as the dissolution rate assumed for the SF waste material (cladding and matrix) at the surface is more than two orders of magnitude larger than the dissolution rate of the remaining 90% of SF in the canister. After about 27,000 years, the inventory from the exposed surface waste is fully dissolved and the borehole contribution becomes dominant.

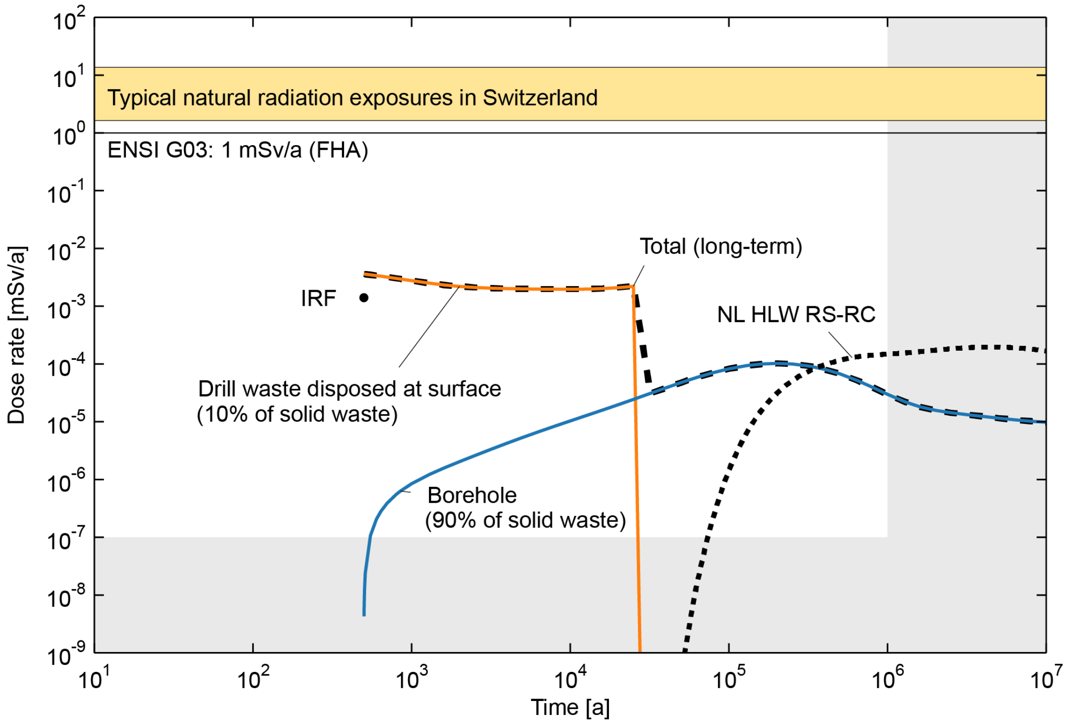


Fig. 4-1: Dose rates with contributions from the IRF (black dot), surface waste (orange) and the remaining in situ waste through the borehole (blue) derived for an SF canister penetrated by a borehole 500 years after repository closure. It is compared with the dose rates calculated for releases from the HLW repository section for the reference case of the reference safety scenario (NL HLW RS-RC)

The long-term dose contribution from the borehole is illustrated assuming a water flow rate of 0.0001 $m^3 a^{-1}$. The grey shading indicates: x-axis = values exceed the formal assessment period (one million years), y-axis = significance level according to IAEA (2011a).

The effects of the time of borehole penetration and of the different flow rates along the borehole are shown in Fig. 4-3. The highest maximum dose rate of $3.7 \times 10^{-3}$ mSv/a (more than two orders of magnitude below the FHA dose limit) is observed for the case of borehole penetration at the earliest time assumed of 500 years and with the highest flowrate of 1 $m^3 a^{-1}$ through the borehole. However, the effects of varying the borehole penetration time are minor due to decay and ingrowths of the dominating radionuclides (Am-241, Pu-239, Th-230). The insensitivity to flow rate of the borehole is explained by the fact that maximum dose rates are dominated by the contribution of long-lived radionuclides of the drilling waste disposed of at the surface, which is unaffected by this parameter.

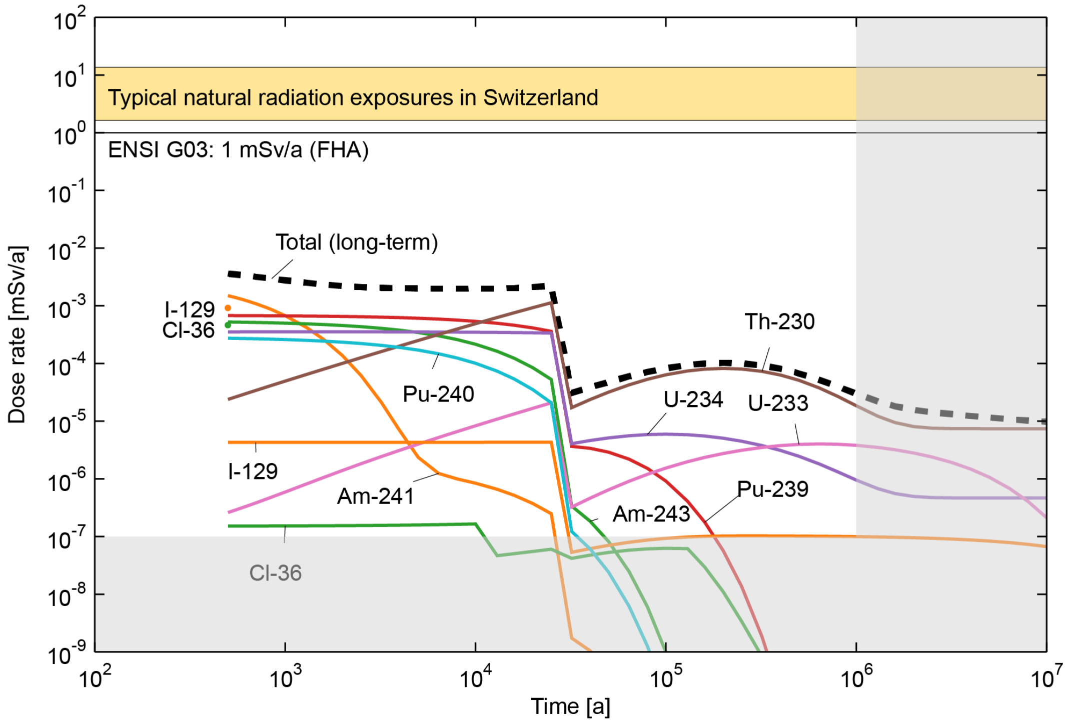


Fig. 4-2: Radionuclide-specific dose rates derived for an SF canister penetrated by a borehole 500 years after repository closure

Radionuclides shown in the figure contribute at least 10% to the total dose rate at any point in time. IRF is represented by the dots (orange I-129, green Cl-36).

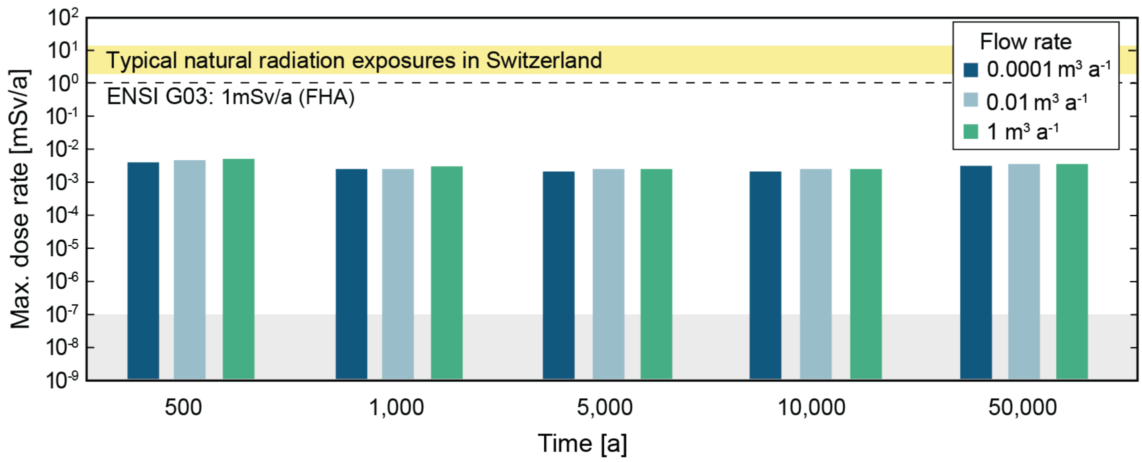


Fig. 4-3: Maximum dose rates for all event times and borehole flow rates considered in the analysis of an SF canister penetrated by a borehole

The maximum dose rate is dominated by Am-241, Pu-239, and Th-230, retrieved as a consequence of the drilling process. Therefore, the dose rates show minimal dependence on event time or long-term flow rate through the borehole.

### 4.1.2.2 FHA-1a-DH-Vol

The FHA-1a-DH-Vol calculation case considers the possibility that gas forming as a result of corrosion processes has accumulated around the canister at the time of borehole penetration and continues to be generated by corrosion thereafter. The gas is released, along with C-14 as methane, as soon as the borehole penetrates the drift and the canister is breached. The gas then migrates via the borehole to the subsurface aquifer of the reference biosphere, where it dissolves. The resulting C-14 dose rates are shown in Fig. 4-4 for two different borehole penetration times, 500 years and 50,000 years, together with those of the FHA reference case (FHA-1-RC), in which there is no borehole. However, the FHA reference case assumes that all canisters fail after 500 years, and volatile C-14 is transported to regional aquifers (Malm/Keuper) primarily driven by advective and diffusive processes through the CRZ. In the event of borehole penetration into an emplacement drift 500 years post-closure, only small volumes of gas (hydrogen and C-14) will be present around the canister, leading to a maximum dose rate of only $6 \times 10^{-8}$ mSv/a. After 50,000 years, the gas release rate will be higher due to increased gas pressure and saturation in the HLW emplacement drift from ongoing gas generation. However, peak C-14 dose rates ($6 \times 10^{-9}$ mSv/a) are significantly lower at this stage due to radioactive decay of the relatively short half-life of C-14 and the higher dilution of C-14 concentrations by hydrogen ($H_2$) from corrosion.

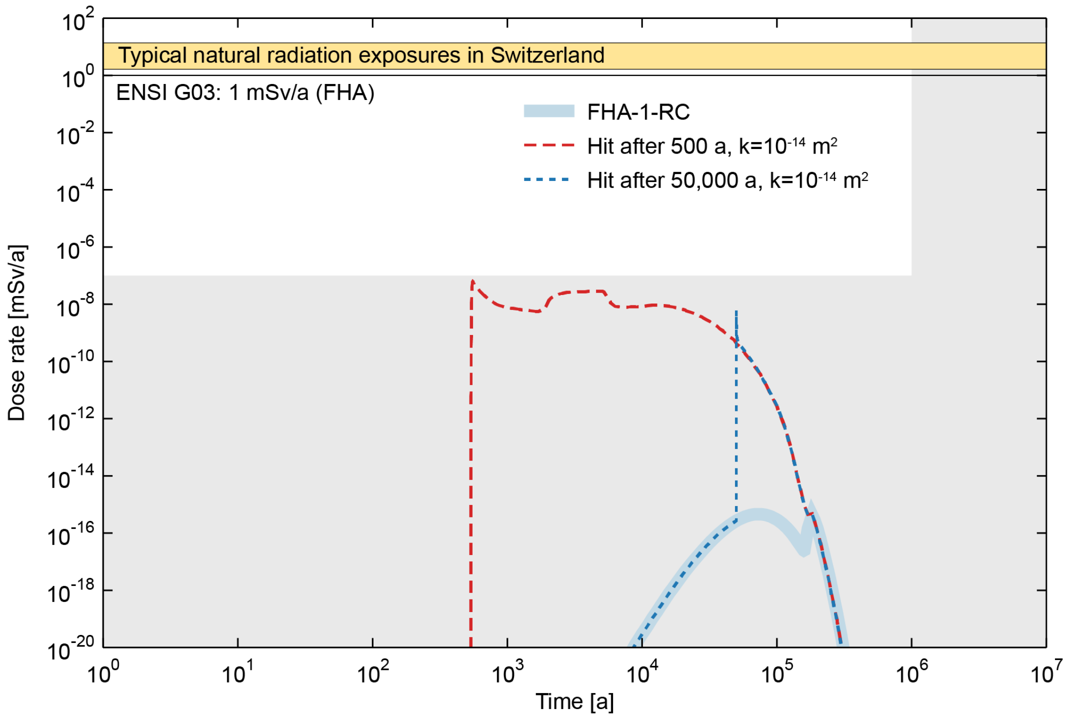


Fig. 4-4: C-14 dose rate for an SF canister penetrated by a borehole 500 and 50,000 years after repository closure (FHA-1-RC also shown)

For illustrative purposes, only the results calculated for a borehole permeability of $10^{-14}$ m$^2$ are provided. Dose rates are evaluated considering releases to the Malm and Keuper aquifers via the host rock, via the shaft, and via the borehole.

The maximum dose rates for all borehole penetration times and all borehole permeabilities considered in the analysis are presented in Fig. 4-5. The highest maximum dose rates are obtained for the highest borehole permeability. The dependency on borehole penetration time is less straightforward, as early penetration times give rise to relatively low maximum dose rates because of the limited amounts of accumulated gas, and later penetration times give rise to relatively low maximum dose rates because of the radioactive decay of C-14. The highest maximum dose rate of $2 \times 10^{-6}$ mSv/a, which occurs for borehole penetration times of a few thousand years, is still at least five orders of magnitude below the regulatory guideline for FHA of 1 mSv/a.

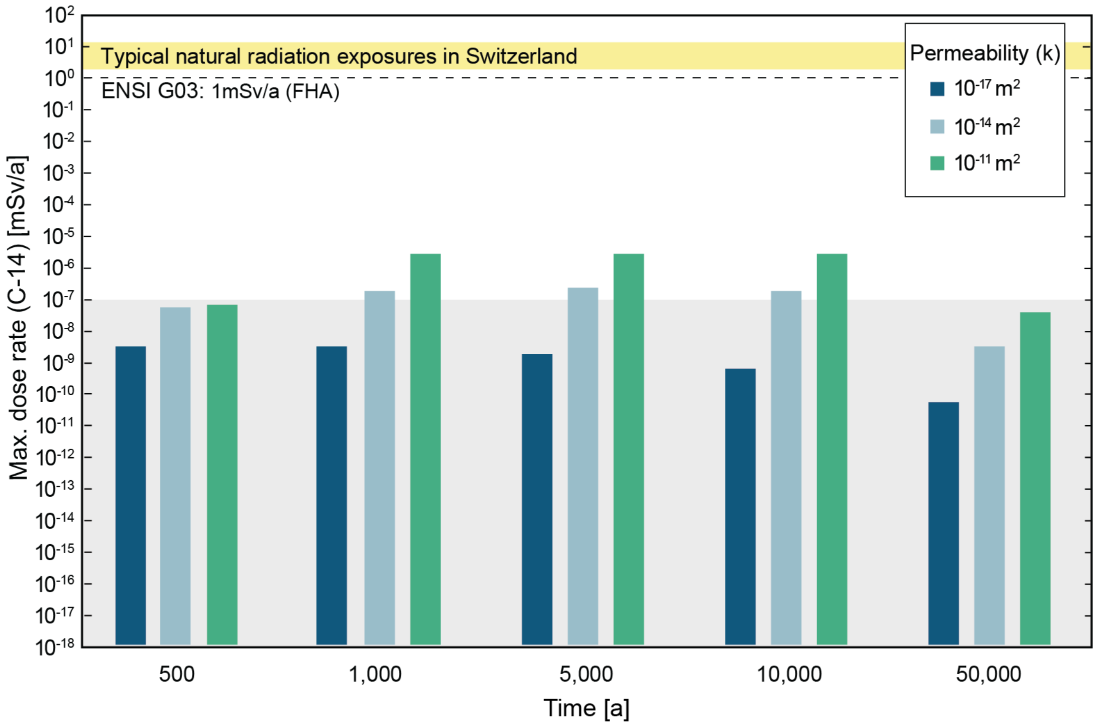


Fig. 4-5: Maximum dose rates (C-14) due to borehole penetration of an HLW emplacement canister for all event times and borehole permeabilities considered

## 4.2 Borehole intersecting an L/ILW emplacement cavern (FHA-1b)

### 4.2.1 Model concept and implementation

**FHA-1b-WP-Diss (DH of a single waste package)**

The radiological consequences of a borehole penetrating a single L/ILW package is modelled under the assumption that the waste package has not lost any radionuclides except through radioactive decay over time (i.e. no release or loss prior to penetration). Radioactive decay was calculated using the code RAPIDE, with details provided in NTB 24-18 (Nagra 2024i). At the time of penetration, the entire radionuclide inventory of a waste package is assumed to be released as a pulse to the local aquifer of the reference biosphere. Dose consequences are calculated for a single waste package of each waste type by multiplying the radionuclide-specific inventory of the waste package by the corresponding BDCF for pulse release. Further details are found in NAB 24-06 (Nagra 2024f).

**FHA-1b-PFP-Diss (DH of cavern with homogenous radionuclide distribution)**

To model the FHA-1b-PFP-Diss calculation case, the VPAC code was applied to determine the radiological consequences of penetrating an L/ILW cavern, assuming the total radionuclide inventory of L/ILW is assumed to be homogeneously distributed across all caverns. However, only a single L/ILW cavern is assumed to be affected by the borehole penetration and the cavern is assumed to be fully water saturated at the time of penetration.

For the model setup, a rectangular 3D mesh was used to represent the interior of an L/ILW cavern in VPAC. For computational reasons, symmetry is employed such that the mesh only needs to represent a quarter of a cavern. The dimensions of the mesh are 100 m (length) × 5 m (width) × 12 m (height), which corresponds to a stylised representation cavern of an actual cavern. A quarter of the borehole is also represented, with a cross-section of 0.5 m × 0.5 m. Boundary conditions assume no flow at the lateral boundaries of the model, except at the upper and lower ends of the borehole, where constant heads (over time) are applied to obtain the flow rates. The transport parameters of the homogenised cavern are taken from the reference case of the reference safety scenario (Nagra 2024i).

**FHA-1b-PFP-Vol**

To model the FHA-1b-PFP-Vol calculation case, which addresses the release of volatile C-14 in the event of borehole penetration of an L/ILW cavern, the same 3D two-phase macroelement model applied in the safety assessment for modelling radionuclide migration in the gas phase in other safety scenarios (reference model) is used. This model is implemented in the TOUGH3 code using the EOS75r module (Jung et al. 2018, Zhang et al. 2024). The model concept and implementation are identical to those used for FHA-1a-DH-Vol.

### 4.2.2 Results of radiological consequence analysis

#### 4.2.2.1 FHA-1b-WP-Diss

The radiological consequences of the FHA-1b-WP-Diss calculation case, where a single L/ILW package or container is penetrated, are summarised in Tab. 4-1. This table lists the waste package types along with the calculated radiological consequences (i.e. dose rates). It also includes information about the waste package, container type, number of packages, and volume of packaged waste.

Different times for borehole penetration of the waste packages were considered: 500, 1,000 and 5,000 years after repository closure. The dose rates resulting from the penetration of a single package or container remain below the regulatory FHA limit of 1 mSv/a across all waste packages and container types.

The highest dose rate, 0.43 mSv/a, is associated with a borehole penetration 500 years after repository closure into a waste package containing reactor products. This waste is currently planned to be packaged in cast-iron MOSAIK-II casks, which cannot be penetrated by conventional PDC drill bits unless significant corrosion has weakened and thinned the metal. According to current planning, the total number of these casks in the repository is 46. For other waste package and container types, the highest dose rate for borehole penetration 500 years after repository closure is 0.18 mSv/a, obtained if the borehole were to penetrate one of the KC-T12/30 waste containers. Other waste packages have significantly lower dose consequences. Moreover, only 0.067% of the total waste volume in the L/ILW emplacement cavern could potentially result in a dose rate exceeding 0.044 mSv/a, which indicates a very low risk of a DH of those waste packages.

Tab. 4-1 also lists the dominant radionuclides contributing to the maximum dose rate for different assumed borehole penetration times. Most of these radionuclides have relatively short half-lives, including Ag-108m (half-life of 418 years), Ti-44 (half-life of 59 years), and Hg-194 (half-life of 444 years). Five thousand years after repository closure, the relatively long-lived Cl-36 (and to a lesser extent Fe-60) becomes the dominant radionuclide for all waste packages considered.

Tab. 4-1: Hypothetical radiological dose consequences of a single L/ILW package when released into the biosphere aquifer (FHA-1b-WP-Diss calculation case)

The table provides details of the waste container or package types, the total number of these in the L/ILW repository, and their packaged volumes. It also lists the maximum dose rates and the corresponding dominant radionuclide for a single package/container breach occurring 500, 1,000 or 5,000 years post-closure.

| **Waste package type** | **Waste container type** | **Number of packages** | **Volume packaged** [$m^3$] | **Maximum dose rate** [mSv/a] **Dominant RN** | | |
|---|---|---|---|---|---|---|
| | | | | t = 500 years | t = 1,000 years | t = 5,000 years |
| J-G-000089 | MOSAIK-II cask | 1 | 4.5 | 0.43<br>Ag-108m | 0.19<br>Ag-108m | 0.003<br>Cl-36 |
| J-B-920001 | MOSAIK-II cask | 30 | 135 | 0.43<br>Ag-108m | 0.19<br>Ag-108m | 0.002<br>Cl-36 |
| J-G-000087 | MOSAIK-II cask | 15 | 67.4 | 0.42<br>Ag-108m | 0.19<br>Ag-108m | 0.002<br>Cl-36 |
| J-P-970500 | KC-T12/30 | 7 | 31.5 | 0.18<br>Ti-44 | 6.9E-4<br>Ti-44 | 6.9E-4<br>Cl-36 |
| J-P-010013T | KC-T12/30 | 2 | 9.0 | 0.14<br>Hg-194 | 0.060<br>Hg-194 | 0.006<br>Fe-60 |
| J-Z-003003 | 180-litre reprocessing waste canister | 20 | 15.7 | 0.044<br>Cl-36 | 0.042<br>Cl-36 | 0.043<br>Cl-36 |
| Other | … | 66,799 | 83,578 | <0.044 | <0.043 | <0.043 |

#### 4.2.2.2 FHA-1b-PFP-Diss

The FHA-1b-PFP-Diss calculation case again assesses the long-term radiological consequences of radionuclides released through a borehole drilled into an L/ILW emplacement cavern. In this case, however, the entire radionuclide inventory of one L/ILW cavern is assumed to be homogenously available within the cavern and released via the borehole (Fig. 3-5).

Unlike scenarios involving a borehole breaching an SF disposal canister, where the flow rate through the borehole has minimal impact on the results (see, e.g., Fig. 4-3), the dose consequences of the L/ILW case FHA-1b-PFP-Diss (Fig. 4-6) show a significant dependence on assumed flow rates. The highest flow rates result in the highest dose rates, reaching $6 \times 10^{-2}$ mSv/a 500 years after repository closure when considering a flow rate of 1 $m^3$ $a^{-1}$. For flowrates of 0.01 and 0.0001 $m^3$ $a^{-1}$, the maximum dose rates are $1 \times 10^{-3}$ and $1 \times 10^{-5}$ mSv/a, respectively. Due to the decay of short-lived radionuclides, the maximum dose rate decreases with increasing borehole penetration time. A borehole penetration 5,000 years post-closure results in a maximum dose rate of $3.9 \times 10^{-4}$ mSv/a, which is almost two orders of magnitude lower than the dose rate from a borehole penetration 1,000 years after repository closure ($2.5 \times 10^{-2}$ mSv/a). In all calculation cases, including the most pessimistic case, the dose rates are at least one order of magnitude below the regulatory guideline for FHA of 1 mSv/a.

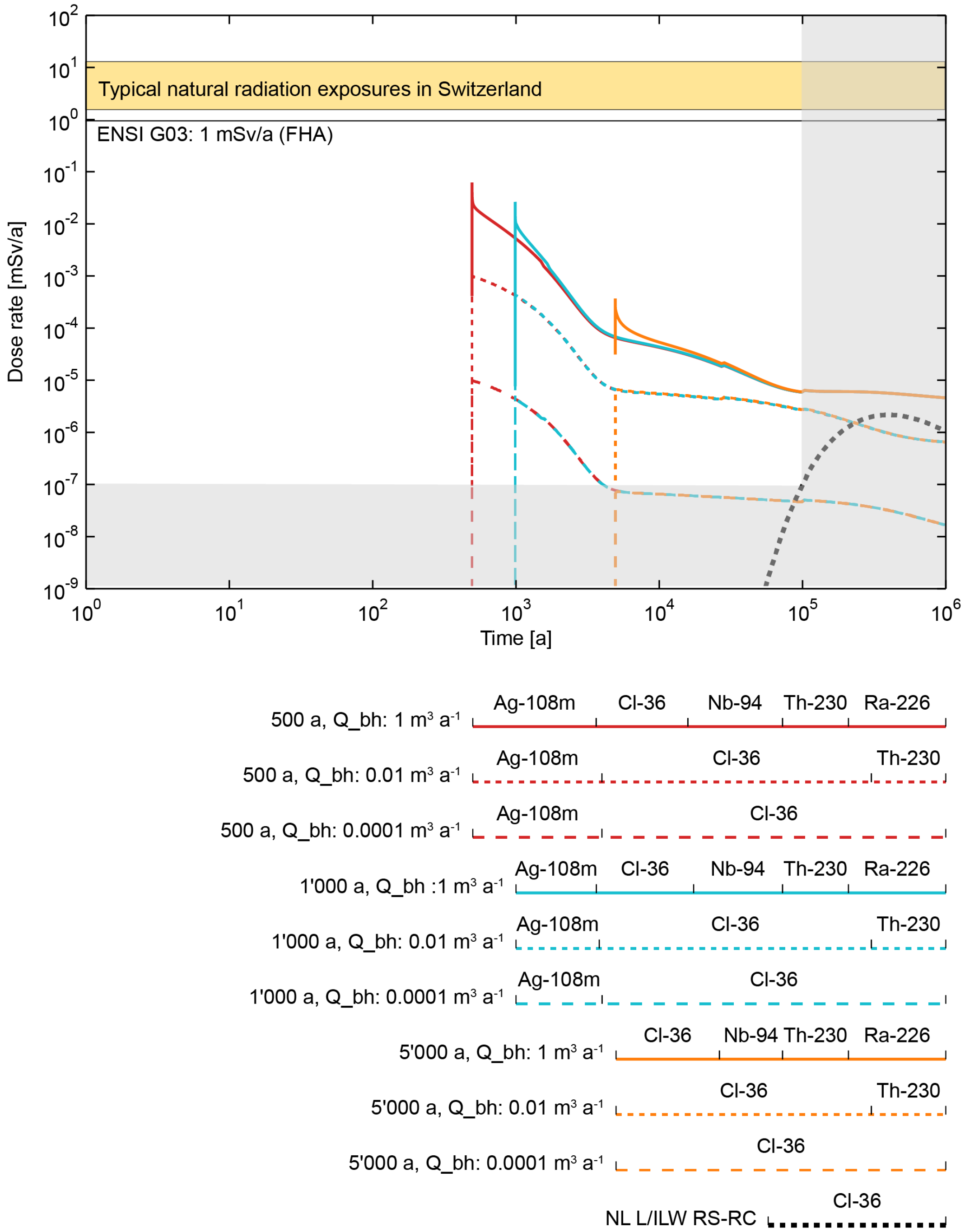


Fig. 4-6: Dose rates for different borehole flow rates and different borehole penetration times (500, 1,000, 5,000 years) into an L/ILW emplacement cavern, assuming a homogenised radionuclide distribution throughout the cavern. Dose rates of the L/ILW reference case of the reference scenario (NL L/ILW RS-RC) is also shown

The early-stage high dose rates are dominated by radionuclides with short half-lives, such as Ag-108m. The subsequent dose-dominating radionuclides include Cl-36, Nb-94, Th-230, and Ra-226. All cases result in dose consequences well below the ENSI regulatory guideline for FHA. This demonstrates that, although different borehole flow rates and borehole penetration times do influence the result, the overall consequences of borehole penetration into an L/ILW cavern remain limited.

#### 4.2.2.3 FHA-1b-PFP-Vol

The FHA-1b-PFP-Vol calculation case is formulated to evaluate the radiological consequences of gas release, specifically for the radioisotope C-14, following borehole penetration into an L/ILW emplacement cavern. Fig. 4-7 illustrates the dose rates due to the release of C-14 from an L/ILW emplacement cavern when it is penetrated by a borehole 500 and 50,000 years after repository closure, alongside the FHA reference case (FHA-1-RC).

In the calculation case where a borehole penetrates the L/ILW emplacement cavern 500 years post-closure, water inflow through the borehole results in rapid fluid saturation of the impacted sections of the L/ILW emplacement cavern. This influx of fluids contributes to a pressure increase and potentially initiate advective $H_2$ and methane (including C-14) gas outflow. For this scenario, a calculated maximum dose rate of $5 \times 10^{-5}$ mSv/a is determined, assuming radionuclide release to an aquifer directly connected to the reference biosphere.

In the case where a borehole penetrates the L/ILW emplacement cavern 50,000 years post-closure, the pressure in the cavern due to gas may exceed the hydrostatic pressure, causing immediate gas outflow through the borehole. This could lead to a rapid decrease in pressure followed by resaturation of the cavern. Although the peak gas flow rate from the cavern is much higher in this case compared with the gas flow from the cavern at 500 years, the dose rate is lower at $6 \times 10^{-7}$ mSv/a. This reduction is due to a decreasing C-14 methane concentration in the cavern, resulting from dilution by increasing $H_2$ production over time, the relatively short half-life time of C-14 (5,730 years), and the migration of C-14 methane into the adjacent host rock and repository structures, including operation tunnels.

Fig. 4-8 shows maximum dose rates for all borehole penetration times that have been considered (500, 1,000, 5,000, 10,000 and 50,000 years after repository closure), as well as all borehole permeabilities ($10^{-11}$, $10^{-14}$, and $10^{-17}$ $m^2$), illustrating that permeabilities have the largest impacts on C-14 dose consequences. Maximum dose rates tend to decrease with increasing borehole penetration time due to the dilution and decay of C-14 over time. This effect is more pronounced for high borehole permeabilities that allow faster propagation of the gas front through the borehole. The maximum dose rate in all cases considered here (Fig. 4-8) is $6 \times 10^{-3}$ mSv/a and is much higher than in the FHA reference case (where the maximum dose rate is $5 \times 10^{-16}$ mSv/a), but the calculated value is still two orders of magnitude below the regulatory guideline of 1 mSv/a for FHA.

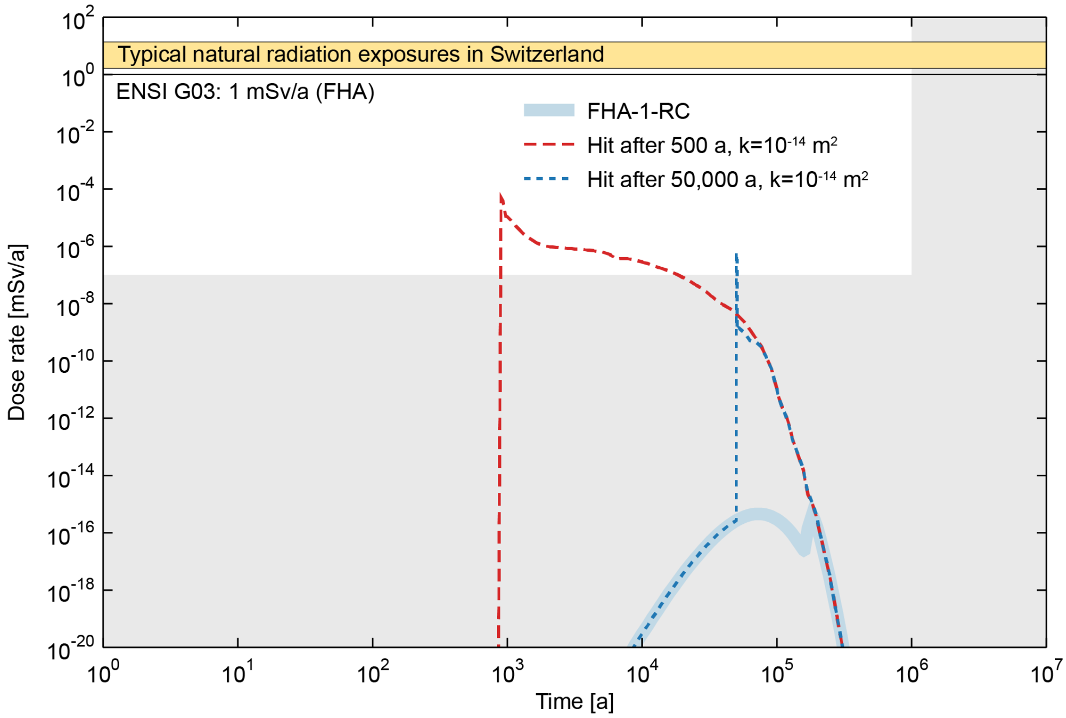


Fig. 4-7: C-14 dose rates of a borehole penetration into an L/ILW cavern (FHA-1b-PFP-Vol calculation case)

For illustration purposes, only the case of borehole permeability of $10^{-14}$ $m^2$ is provided and the data are compared with the undisturbed evolution of the FHA reference case (FHA-1-RC).

The C-14 dose rate is evaluated from releases to the Malm and Keuper aquifers via the host rock, via the shaft, and via the borehole.

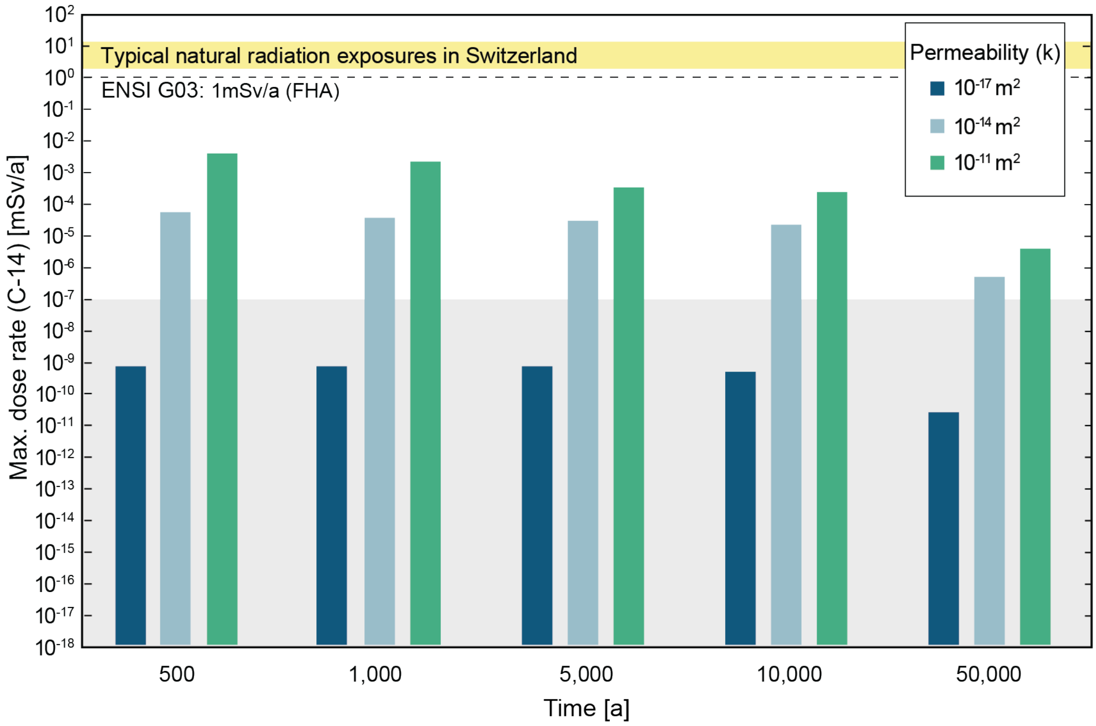


Fig. 4-8: Maximum dose rates (C-14) due to a borehole penetration of an L/ILW emplacement cavern for all considered borehole penetration times and borehole permeabilities

## 4.3 Abandonment (FHA-2)

### 4.3.1 Model concept and implementation

To assess the radiological consequences of repository abandonment, the following analysis is limited to the radionuclides I-129 (dissolved) and C-14 (volatile) for the following reasons:

- I-129 is the primary dose-contributing radionuclide in the reference case of the reference safety scenario (RS-RC) (see Nagra 2024i).
- C-14, in the form of methane is the dominant radionuclide in unfavourable calculation cases in which significant amounts of gas are released via repository structures and shafts.

All model calculations use the same 3D two-phase macroelement model as applied in the safety assessment for modelling radionuclide migration in the gas phase in other safety scenarios (corresponding to the reference model), implemented in TOUGH3 with the EOS75r module (see Jung et al. (2018) and Zhang et al. (2024) for details). Detailed information on the model setup and the macroelement approach are provided in App. B of NTB 24-18 (Nagra 2024i). In contrast to C-14, a high solubility is assumed for I-129. The following assumptions are made for the repository structures:

- all waste packages are emplaced, and the emplacement tunnels and caverns backfilled;
- the seals between the central area and the emplacement rooms and the shafts are not yet installed; and
- operation and ventilation tunnels are not yet backfilled.

To assess the impact of collapsing tunnel structures and the subsequent progressive self-sealing under the influence of water entry, various calculation cases are carried out assuming different permeability values of $10^{-17}$ m$^2$, $10^{-14}$ m$^2$ and $10^{-11}$ m$^2$. This differs from the FHA reference case, where the seal permeabilities for the L/ILW and HLW repository sections are $5 \times 10^{-18}$ m$^2$ and $1 \times 10^{-20}$ m$^2$, respectively, and the shaft seal is assigned a permeability of $1 \times 10^{-20}$ m$^2$. All model calculations apply a conservative large-scale vertical gradient of 1 m/m, giving rise to an upwardly directed water flow.

### 4.3.2 Results of radiological consequence analysis

Fig. 4-9 illustrates the hydrogeological evolution of the abandoned repository compared with the evolution in the FHA reference case. In the reference case, full saturation is prevented due to the effective sealing of all repository structures (especially the shafts), the low permeability of the Opalinus Clay and the pressure buildup from gas generation. Full saturation only occurs at very late times (>1 million years) when gas generation ceases.

In an abandonment scenario, however, repository resaturation can occur much earlier. Assuming high tunnel permeabilities of $10^{-14}$ m$^2$ or more, significant water inflow through the shafts can lead to resaturation of the repository or significant parts of it within less than 100 years. Once hydrostatic pressure is exceeded, gas generation reverses the pressure gradient, initiating water and gas flow through the shafts back towards the bounding aquifers. Gas flow decreases with decreasing gas generation and eventually stops upon full resaturation at around 1 million years. Water flow, driven by the large-scale hydraulic gradient, then approaches a steady state. These flow rates increase with higher tunnel or shaft permeabilities but are limited to a maximum of 4,000 kg/a by the limited capacity of the low-permeability Opalinus Clay to supply water.

The resulting evolution of the dose rates due to the release of dissolved I-129 and volatile C-14 from the HLW and the L/ILW repository sections is illustrated in Fig. 4-9 and Fig. 4-10, respectively, for a tunnel permeability of $10^{-14}$ m$^2$. Dose rates in the FHA reference case (FHA-2-RC) are also shown for comparison. The release of soluble I-129 is dominated by transport through the host rock and confining units, both in the reference case and in the case of abandonment; diffusive and advective transport in the liquid phase along repository structures is too slow to be relevant. Release via the unsealed shafts increases the dose rate compared with the FHA reference case (FHA-2-RC) but it is still six orders of magnitude below the release via the host rock.

In the reference case, the release of volatile C-14 is primarily driven by advective and diffusive transport through the host rock and confining units. However, in an abandonment scenario, unlike soluble I-129, the advective transport of volatile C-14 is enhanced by increased gas flows along permeable tunnels and the unsealed shafts. This results in a significantly higher C-14 release via the shafts, which dominates the total dose rate. The maximum C-14 dose rates are $8 \times 10^{-10}$ mSv/a for the HLW and $7 \times 10^{-4}$ mSv/a for the L/ILW repository sections, representing increases of almost seven and 13 orders of magnitude, respectively, compared with the reference case. However, these values are still orders of magnitude beneath the FHA regulatory guideline for FHA of 1 mSv/a.

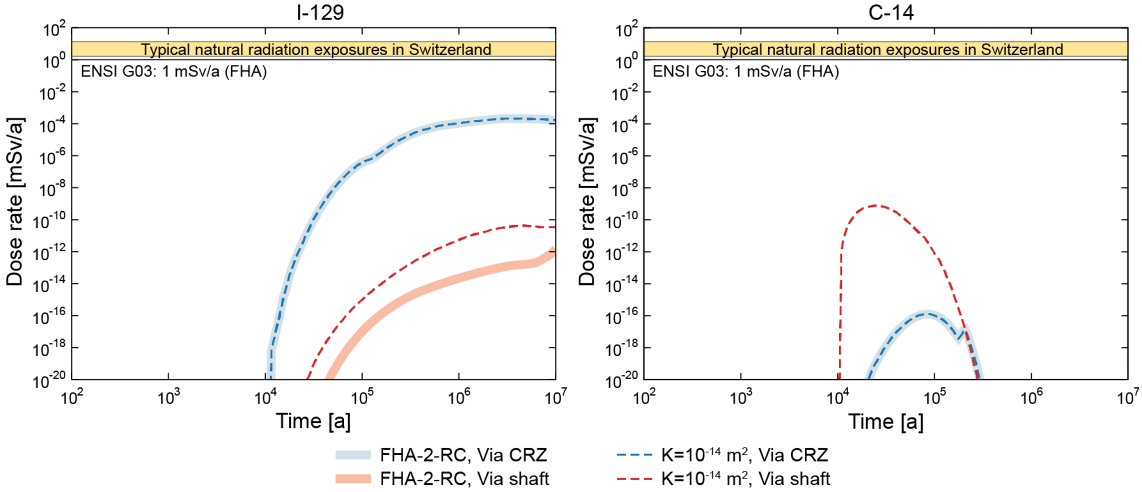


Fig. 4-9: Dose rates due to releases from the HLW repository section under an abandonment scenario assuming a permeability of $10^{-14}$ $m^2$ for those repository structures that were neither backfilled not sealed in comparison with the FHA reference case (FHA-2-RC)

Left: FHA-2-Diss (I-129). Right: FHA-2-Vol (C-14).

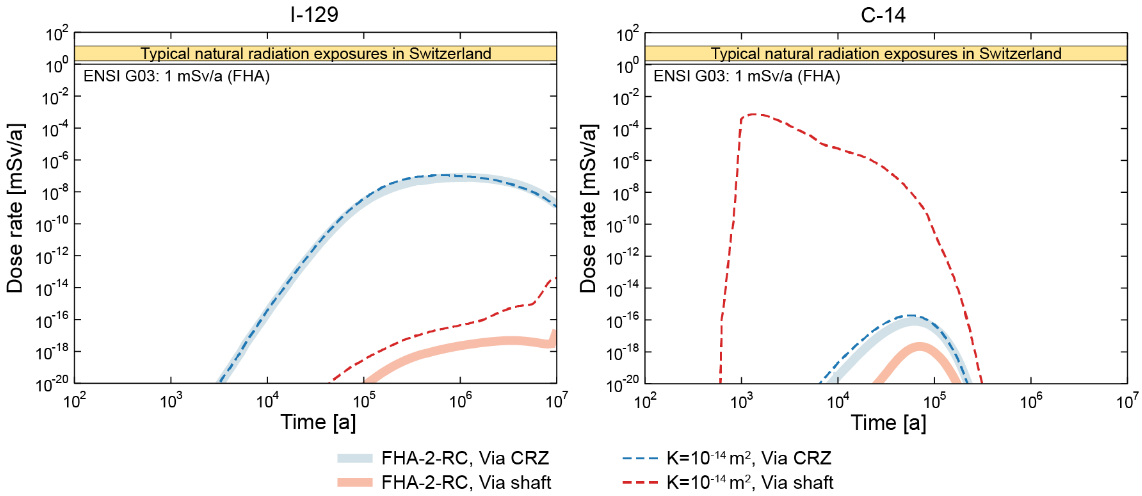


Fig. 4-10: Dose rates due to releases from the L/ILW repository section under an abandonment scenario assuming a permeability of $10^{-14}$ $m^2$ for those repository structures that were neither backfilled nor sealed in comparison with the FHA reference case (FHA-2-RC)

Left: FHA-2-Diss (I-129). Right: FHA-2-Vol (C-14).

Fig. 4-11 summarises the maximum total dose rates for I-129 and C-14 in the abandonment scenario. In comparison with FHA-2-RC, I-129 shows minimal differences, while for C-14, a substantial increase is determined. Interestingly, the highest dose rates for volatile C-14 occur at a permeability of $10^{-14}$ $m^2$ and decrease at $10^{-11}$ $m^2$. This is because, at higher permeability, initial inflow rates are higher, leading to an expedited resaturation.

With higher liquid saturation, more C-14 is dissolved, resulting in less release via gas flow. Additionally, more water must be displaced before gas flow through the shafts can begin, delaying the advective gas and volatile C-14 release.

Despite the significantly higher dose rates for volatile C-14 in the abandonment scenario compared with the reference case (maximum C-14 dose rates for HLW and L/ILW of $8 \times 10^{-10}$ and $7 \times 10^{-4}$ mSv/a, respectively), a robust safety margin of more than three orders of magnitude below the regulatory guideline is maintained.

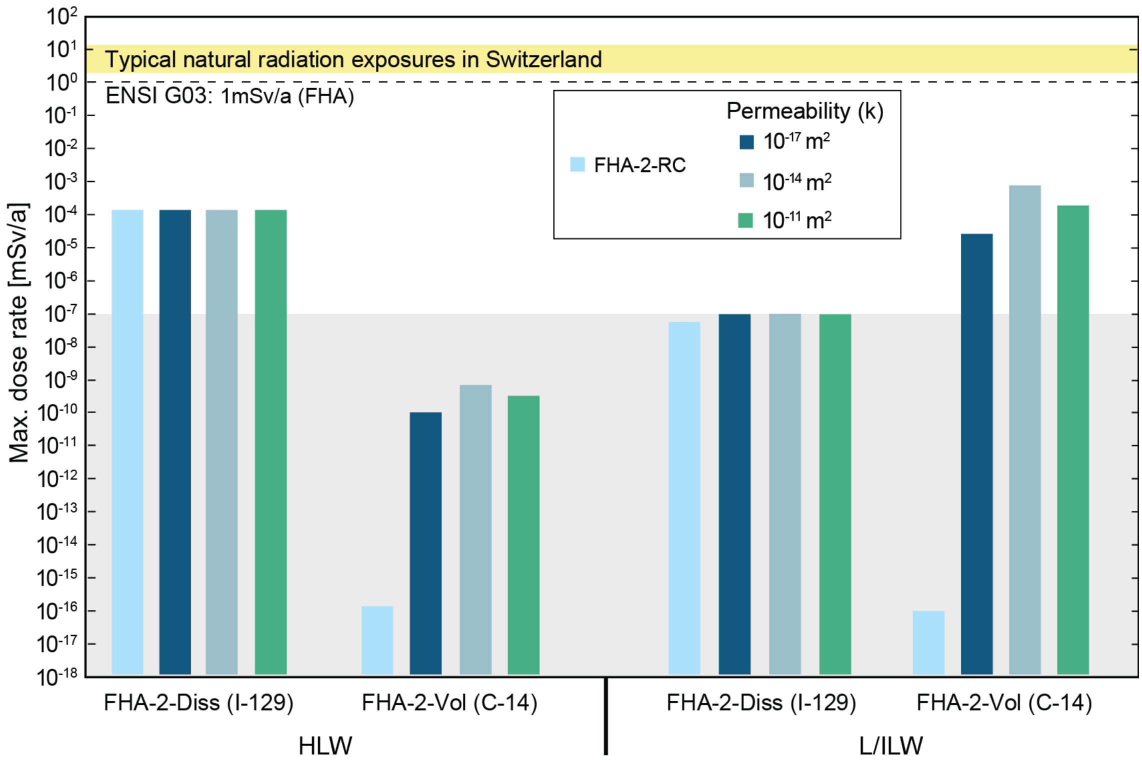


Fig. 4-11: Maximum dose rates for an abandoned repository scenario resulting from releases from the HLW and L/ILW repository sections for various assumed tunnel and shaft permeability values ($10^{-17}$, $10^{-14}$, and $10^{-11}$ $m^2$)

Calculations are performed for both dissolved (I-129) and volatile (C-14) radionuclides for each repository section.

# 5 Discussion and conclusions

## 5.1 Summary of the approach and key findings

In this report, FHA are investigated for scenarios that impact one or more safety functions of either the HLW or L/ILW repository sections. FHA assessments do not consider intentional human intrusion, such as waste retrieval or malicious acts, as these are deemed, by regulation, the responsibility of future generations and fall outside the scope of the assessment. The main objectives of the FHA assessment are to 1) formulate an appropriate set of FHA safety scenarios and evaluate radiological consequences of these and their compliance with regulatory requirements, 2) evaluate whether measures are needed to reduce the potential of FHA, and 3) provide supporting evidence for the robustness of the deep geological repository when impacted by FHA.

The methodological approach for assessing FHA in this study builds on Nagra's previous safety case (Nagra 2002) and a comprehensive understanding of the repository safety functions and their performance, as documented in various reports (Fig. 1-1). This study also incorporates guiding principles and recommendations from Swiss regulations (KEV 2004, ENSI 2020, ENSI 2023) and international guidelines (IAEA 2011a, ICRP 1998, ICRP 2013).

The development of FHA safety scenarios is based on qualitative assessments of FHA FEPs. Nagra's current FEP database (Nagra 2024g), which itself builds on the previous Nagra FEP database (Nagra 2003), FHA FEP catalogues (Nagra 2002, Nagra 2003), and international FEP lists (OECD/NEA 2019), takes into account current system understanding, design concepts as well as technological and scientific advancements. A qualitative screening process identifies all relevant FEPs (App. B) that need to be incorporated in FHA safety scenarios, which are propagated to quantitative analysis.

The depth and properties of the Opalinus Clay and the CRZ limit FHA safety scenarios to those linked exclusively to the deep drilling of boreholes (FHA-1) and repository abandonment (FHA-2). The variants of the deep borehole scenario with the highest potential radiological impacts involve boreholes intersecting: 1) SF disposal canisters and HLW emplacement drifts (FHA-1a), and 2) L/ILW packages and L/ILW emplacement caverns (FHA-1b). Abandonment (FHA-2) of the repository is also addressed in the context of FHA and considers an only partially sealed repository when final operational activity is abruptly ceased during the monitoring phase.

The dose calculations are stylised and use highly conservative assumptions about the release and solubility of radionuclides and assume boreholes that penetrate an SF canister starting at timescales shorter than natural conditions (i.e. the weakening of the canister by corrosion) would allow. The earliest borehole penetration time is conservatively assumed to be 500 years after repository closure, when knowledge of the repository could conceivably be lost. Making conservative assumptions about events and parameters for the assessment of FHA is in line with regulatory and international (IAEA 2017) guidelines. The radiological consequences of all the calculation cases analysed in this report are summarised in Fig. 5-1 and have variable parameters for the timing of borehole penetration, borehole permeabilities, and flow rates for both dissolved and volatile radionuclides. The details of these various cases can be found in Chapter 4.

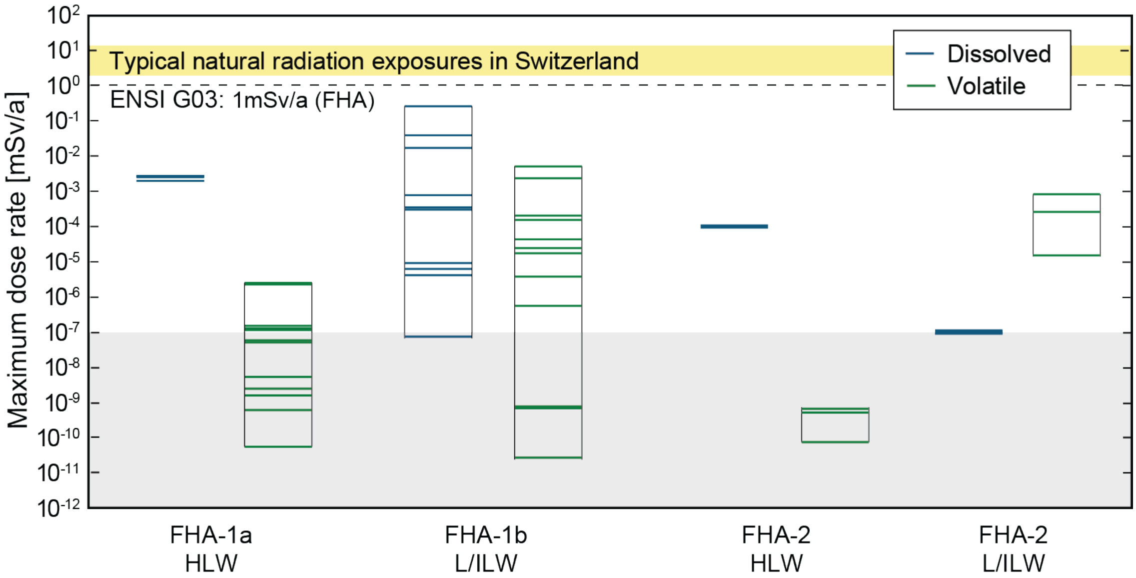


Fig. 5-1: Range of maximum dose rates of all calculation cases and parameter variations conducted for the deep borehole (left) and abandonment (right) scenarios considering both dissolved (blue) and volatile (green) radionuclides

Fig. 5-1 shows that radiological consequences of borehole penetration are higher than for repository abandonment for both the L/ILW and HLW repository sections and for both volatile and dissolved radionuclides. This can be explained by the fact that the conceptualised transport path through the borehole is much shorter and faster compared with the abandoned repository. Furthermore, the figure shows that a borehole penetration of an L/ILW package or the L/ILW cavern penetration results in higher maximum dose rates than a DH on an HLW disposal canister. This is mainly due to the fact that radionuclide release assumptions related to the IRF are more conservative for L/ILW than for HLW (SF). In addition, during a DH hit of an L/ILW cavern, the inventory from all waste packages within a cavern contribute to the release of radionuclides through the borehole. In contrast, the radionuclide release through the borehole penetrating an SF canister is mainly related to the affected SF canister, due to the tight bentonite backfill. These assumptions and results are also consistent with earlier studies (Nagra 2002).

For the abandonment scenario, maximum dose rates from volatile radionuclides are also higher for releases from the L/ILW repository section than from the HLW section. The bentonite buffer around the HLW canisters effectively prevent gas release from the HLW emplacement drifts towards unsealed tunnels and shafts, redirecting gas flow into the EDZ and host rock. In contrast, the backfill of the L/ILW caverns is five orders of magnitude more permeable allowing for enhanced gas release through unsealed tunnels and shafts. Release of dissolved radionuclides remains essentially unaffected by repository abandonment compared with the reference case, with higher dose rates resulting from releases from the HLW repository section in both cases. The radiotoxicity instantly released from L/ILW packages, causing high dose rates in the borehole scenario, is effectively retained by the CRZ in the abandonment scenario.

The radiological consequence analysis of all FHA safety scenario calculations (FHA-1 and FHA-2) demonstrates that annual dose levels for those living near the repository site would be below 1 mSv, which is within the guidelines set by ENSI and the IAEA. This demonstration of robustness against a broad range of FHA scenarios implies that no further efforts to reduce the potential of FHA or to lower their consequences are needed and thus support the Swiss safety case for the repository in terms of compliance with the regulatory requirements relevant to FHA.

## 5.2 Conservatism in FHA safety scenarios

The FHA assessment approach is conservative and includes assumptions and expectations which are unlikely to occur in such chain of events (Fig. 5-2). Selected key conservatisms made in the calculation cases for the deep borehole FHA scenario include:

- Humans are unlikely to be motivated to drill at the site: the depth of the repository significantly limits the likelihood of drilling activities. Deep exploratory borehole operations are usually driven by the presence and accessibility of resources such as water, salt, geothermal energy, hydrocarbons, or by storage potential. Previous investigations (Nagra 2014a) demonstrated that the repository site is situated in an area with low resource potential, and the Opalinus Clay and wider CRZ lack economic resources. This lack of resources within the CRZ implies that any future exploratory drilling would target strata well below the CRZ. In addition, no strata with significant storage potential have been identified during the current exploratory campaign (i.e. high permeability) (Nagra 2024d). If deep drilling were to be performed, geophysical exploration would visually identify a local density contrast which would be avoided to limit drilling operation issues.
- A DH of an HLW disposal canister or L/ILW emplacement cavern is unlikely: Only a small fraction of repository footprint contains canisters or caverns. Even if a deep borehole is drilled, the design of the repository, including compartmentalisation and strategic placement of the waste, significantly reduces the risk of directly hitting and penetrating disposal containers or canisters.
- Direct penetration of HLW canisters and L/ILW waste packages (e.g., considering a MOSAIK II cask) is unlikely: Polycrystalline diamond compact drill bits commonly used for sedimentary exploration drilling activities will only be able to penetrate thick carbon steel or cast-iron material far in the future when corrosion would have significantly progressed. Furthermore, canister shape, composition, and EBS-associated drilling challenges would result in steering issues (incl. PDC bit deviations) and would be immediately identified by the drilling crew (drill penetration issues, drill mud loss, etc) and actions would be taken.
- Establishment of borehole advective flow is unlikely: Future deep drilling campaigns are unlikely to connect two regional aquifers above and below the CRZ due to various reasons, including lack of economic incentives, minimal hydraulic head differences (limited flow observed during the site selection process (Nagra 2024d), and drilling issues through the CRZ which require wellbore casings to avoid borehole collapse. Even with the use of casings, the degradation of the casing and the self-sealing properties of the clays would lead to the borehole being sealed within relatively short timeframes.
- Deep drilling protocol violations would be needed: The assumption about drilling and disposing of any radioactive waste brought to the surface contradicts current national guidelines for deep drilling safety protocols. Furthermore, under current practices in Switzerland, the detection of any radioactive substances would lead to immediate drilling termination and careful investigations leading to borehole plugging and isolation. Lastly, even if waste material were disposed of in gravel pits, current environmental conditions would prevent oxidative conditions from being maintained over the extended timescales assumed in this report.

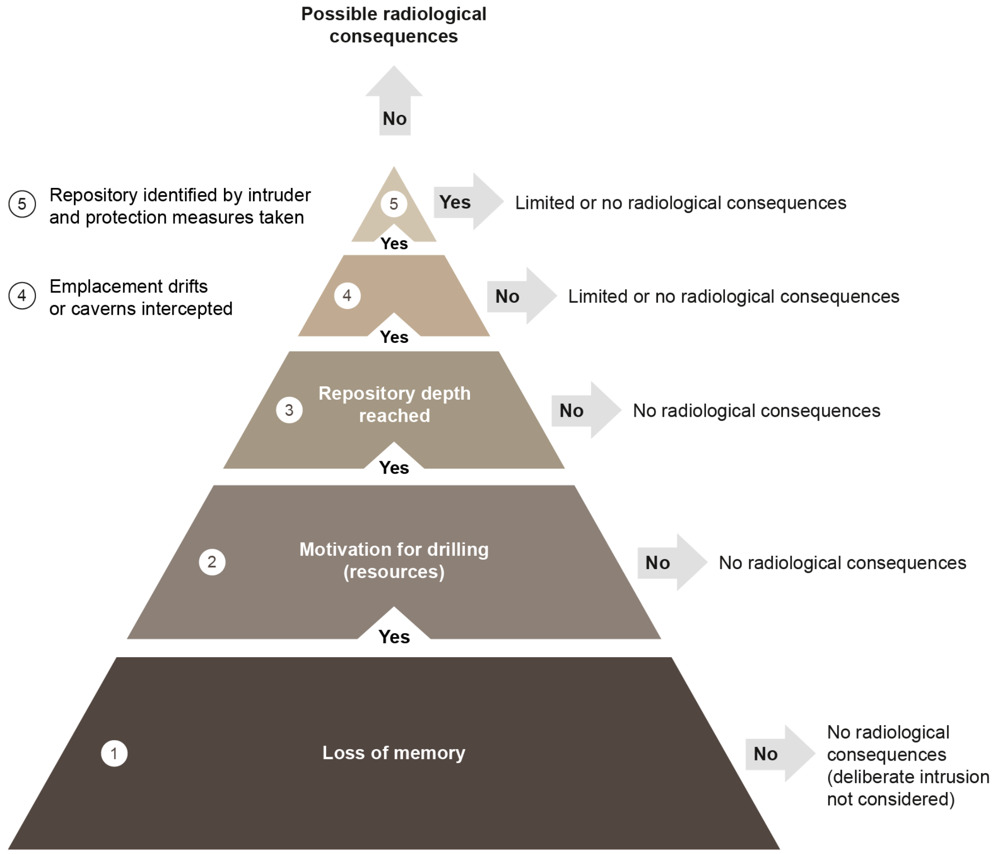


Fig. 5-2: Process pyramid or event tree illustrating the steps required to initiate deep drilling and the likelihood of encountering potential radiological consequences (without considering the timescale)

This figure symbolically depicts the low likelihood of radiological consequences from inadvertent intrusion into radioactive waste emplaced in a deep geological repository.

For the abandonment scenario the following conservative assumptions apply:

- Societal collapse: abandonment of the repository after all waste is in place would only occur in the event of a rapid societal collapse that disrupts the monitoring phase.
- Unfinished seals and backfills: Sealing and backfilling of drifts and caverns will be progressive and continuous according to current operation plans and regulatory requirements (ENSI 2023). More importantly, according to Swiss regulations (ENSI), operational procedures need to be in place for rapid backfilling and closure of the repository in the event of abandonment (before waste emplacement starts).

In summary, a stylised and highly conservative approach was used for the FHA safety assessment. This approach was adopted since no scientific basis for predicting FHA and human development exists. Statements on these matters, including resources needs, global market demands, economic incentives to justify the costs and efforts of deep drilling, or skills and equipment developments, are speculative at best. The radiological consequences of the FHA scenarios can be considered an upper bound for future generations, and the results demonstrate the robustness of the designed system even under the most conservative FHA calculation cases. These findings highlight that post-closure safety requirements for FHA are satisfied for all relevant FHA safety scenarios after memory of the repository is lost.

### 5.3 Conclusions

In this report, the potential radiological consequences of future human actions on repository safety are assessed following a stylised approach. For Nagra's post-closure safety case, knowledge preservation of the location, content and purpose of the repository is assumed to last at least 500 years. Thus, inadvertent human intrusion is excluded in the future human actions assessment for the initial 500 years after repository closure. Repository depth and lack of economic resources or storage potential near the containment-providing rock zone (including the Opalinus Clay), further minimises the likelihood of inadvertent human intrusion.

A bottom-up approach for the development of future human actions scenarios based on the identification and review of relevant features, events and processes for future human actions was applied. All individual features, events and processes were evaluated for their potential to impact the safety functions of the repository. At this point, most of the features, events and processes were excluded by qualitative arguments (i.e. no potential impact on the safety functions of the repository is foreseen). The repository's significant depth, coupled with the favourable properties of the Opalinus Clay, such as low permeability, low conductivity and diffusion-driven transport, high sorption and self-sealing capacities, significantly reduce the relevance of many features, events and processes for future human actions.

Future human actions that could disrupt the repository barriers fall within the scope of just two scenarios, one involving deep boreholes and the other repository abandonment. The analysis of the stylised future human actions safety scenario focusing on the direct penetration of spent fuel disposal canisters or low- and intermediate-level waste containers or caverns by a borehole (FHA-1) demonstrates that radiological consequences of future human actions would remain below regulatory guidelines. Similar findings have been made for the abandonment scenario (FHA-2), where potential future dose consequences are many orders of magnitude below the future human actions protection criteria. Considering these findings, it is important to acknowledge the highly conservative approach and the many pessimistic assumptions, without which the scenarios may not have provided any dose rates, e.g., due to borehole collapse or lack of hydraulic flow. Hence, the radiological consequences of the future human actions scenarios present upper bounding values for future generations and highlight the in-depth robustness of the repository system even under the most conservative cases of inadvertent human intrusion. Host rock properties, repository depth and repository design will ensure long-term passive radiological safety for both humans and the environment throughout any future human actions. The post-closure safety requirements for future human actions remain satisfied even if memory of the repository is lost.

# 6 References


Ammen, M. & Palten, P.-J. (2021): TBO Bülach-1-1: Data Report Dossier I Drilling. Nagra Arbeitsbericht NAB 20-08 I.

ANDRA (2022): Les scénarios d'intrusion humaine involontaire. *In:* ANDRA: Dossier d'autorisation de création de l'installation nucléaire de base (INB) Cigéo - Pièce 7 - Version préliminaire du rapport de sûreté - PARTIE III : démonstration de sûreté - Volume 8 - La démonstration de sûreté après fermeture. ANDRA, Châtenay-Malabry, 603-673.

Bailey, L., Becker, D., Beuth, T., Capouet, M., Cormenzana, J.L., Cuñado, M., Galson, D.A., Griffault, L., Marivoet, J. & Serres, C. (2011): PAMINA : Performance Assessment Methodologies in Application to Guide the Development of the Safety Case (Contract Number: FP6-036404) : European Handbook of the state-of-the-art of safety assessments of geological repositories-Part 1 DELIVERABLE (D-N°: 1.1.4). PAMINA, European Commission.

BFE (2008): Sachplan Geologische Tiefenlager: Konzeptteil. BFE 2. April 2008 (Revision vom 30. November 2011). Departement für Umwelt, Verkehr, Energie und Kommunikation UVEK, Bern.

Diomidis, N., Guillemot, T. & King, F. (2023): Definition of reference corrosion rates for performance and safety assessments. Nagra Arbeitsbericht NAB 23-22.

ENSI (2018): Präzisierungen der sicherheitstechnischen Vorgaben für Etappe 3 des Sachplans geologische Tiefenlager. Sachplan geologische Tiefenlager, Etappe 3. ENSI 33/649. Eidgenössisches Nuklearsicherheitsinspektorat ENSI, Brugg.

ENSI (2020): Deep geological repositories. Explanatory report for Guideline ENSI-G03. Swiss Federal Nuclear Safety Inspectorate ENSI, Brugg.

ENSI (2023): Geologische Tiefenlager. Ausgabe Dezember 2020 (Änderung vom 1. November 2023). Richtlinie für die schweizerischen Kernanlagen ENSI-G03/d. Eidgenössisches Nuklearsicherheitsinspektorat ENSI, Brugg.

ESK (2012): Empfehlung der Entsorgungskommission. Leitlinie zum menschlichen Eindringen in ein Endlager für radioaktive Abfälle. ESK-Empfehlung vom 26.04.2012. RSK/ESK-Geschäftsstelle beim Bundesamt für Strahlenschutz, Salzgitter.

IAEA (2003): Predisposal management of high level radioactive waste. Safety guide. IAEA Safety Standards Series No. WS-G-2.6. International Atomic Energy Agency IAEA, Vienna.

IAEA (2006): Fundamental safety principles. IAEA Safety Standards Series No. SF-1. International Atomic Energy Agency IAEA, Vienna.

IAEA (2011a): Disposal of radioactive waste. Specific safety requirements. IAEA Safety Standards Series No. SSR-5. International Atomic Energy Agency IAEA, Vienna.

IAEA (2011b): Geological disposal facilities for radioactive waste. IAEA Safety Standards Specific Safety Guide No. SSG-14. International Atomic Energy Agency IAEA, Vienna.

IAEA (2012): The safety case and safety assessment for the disposal of radioactive waste. IAEA Safety Standards Series No. SSG-23. International Atomic Energy Agency IAEA, Vienna.

IAEA (2014): Radiation protection and safety of radiation sources: International Basic Safety Standards. General Safety Requirements GSR Part 3. International Atomic Energy Agency IAEA, Vienna.

IAEA (2017): HIDRA - The international project on inadvertant human intrusion in the context of disposal of radioactive waste (Final Draft). International Atomic Energy Agency IAEA, Vienna.

ICRP (1998): Radiation protection recommendations as applied to the disposal of long-lived solid radioactive waste. ICRP publication 81. Annals of the ICRP Vol. 28, No. 4. International Commission on Radiological Protection ICRP.

ICRP (2013): Radiological protection in geological disposal of long-lived solid radioactive waste. ICRP Publication 122. Annals of the ICRP, vol. 42 no. 3. International Commission on Radiological Protection ICRP.

Johnson, L.H., Curti, E. & Spahiu, K. (2023): A radionuclide release model for spent UO2 and MOX fuel for safety assessment with application to waste to be disposed of in a deep geological repository in Switzerland. Nagra Arbeitsbericht NAB 23-10.

Jung, Y., Pau, G., Finsterle, S. & Doughty, C. (2018): TOUGH3 User's Guide. Version 1.0 LBNL-2001093. Lawrence Berkeley National Laboratory (LBNL), Berkeley, CA.

KEG (2003): Kernenergiegesetz (KEG) vom 21. March 2003, Stand am 1. January 2024. Systematische Sammlung des Bundesrechts SR 732.1, Schweiz.

KEV (2004): Kernenergieverordnung (KEV) vom 10. Dezember 2004, Stand am 1. Januar 2024. Systematische Sammlung des Bundesrechts SR 732.11, Schweiz.

Leu, W. & Gautschi, A. (2014): The shale gas potential of the Opalinus Clay and Posidonia Shale in Switzerland – A first assessment. Swiss Bulletin für angewandte Geologie 192/2, 95-107.

Martin, L., Kosakowski, G., Papafotiou, A. & Smith, P.A. (2023): Evolution of the sealing system porosity and its impact on performance. Nagra Arbeitsbericht NAB 23-21.

Medri, C. (2015): Human intrusion model for the Mark II Container in crystalline and sedimentary rock environments: HIMv2.1. NWMO-TR-2015-04. Nuclear Waste Management Organisation NWMO, Toronto.

Nagra (1985): Project Gewähr 1985: Nuclear Waste Management in Switzerland: Feasibility Studies and Safety Analyses. Nagra Project Report NGB 85-09.

Nagra (2001): Sondierbohrung Benken: Untersuchungsbericht : Textband + Beilagenband. Nagra Technischer Bericht NTB 00-01.

Nagra (2002): Project Opalinus Clay: Safety report: Demonstration of disposal feasibility for spent fuel, vitrified high-level waste and long-lived intermediate-level waste (Entsorgungs-nachweis). Nagra Technical Report NTB 02-05.

Nagra (2003): Project Opalinus Clay: FEP management for safety assessment: Demonstration of disposal feasibility for spent fuel, vitrified high-level waste and long-lived intermediate-level waste (Entsorgungsnachweis). Nagra Technical Report NTB 02-23.

Nagra (2008): Vorschlag geologischer Standortgebiete für ein SMA- und ein HAA-Lager: Begründung der Abfallzuteilung, der Barrierensysteme und der Anforderungen an die Geologie (Bericht zur Sicherheit und Machbarkeit). Nagra Technischer Bericht NTB 08-05.

Nagra (2014a): Anhang: Sicherheitstechnischer Bericht zu SGT-Etappe 2: Sicherheitstechnischer Vergleich und Vorschlag der in Etappe 3 weiter zu untersuchenden geologischen Standortgebiete. Nagra Technischer Bericht NTB 14-01.

Nagra (2014b): SGT Etappe 2: Vorschlag weiter zu untersuchender geologischer Standortgebiete mit zugehörigen Standortarealen für die Oberflächenanlage: Charakteristische Dosisintervalle und Unterlagen zur Bewertung der Barrierensysteme. Nagra Technischer Bericht NTB 14-03.

Nagra (2023): Modellhaftes Inventar für radioaktive Materialien MIRAM-RBG. Nagra Technischer Bericht NTB 22-05.

Nagra (2024a): Abfallzuteilung und Betrachtungszeitraum für den Standortvergleich und Nachweiszeitraum für den Sicherheitsnachweis für das geologische Tiefenlager. Nagra Arbeitsbericht NAB 24-05.

Nagra (2024b): Design and performance assessment of HLW disposal canisters. Nagra Technical Report NTB 24-20.

Nagra (2024c): Development of safety scenarios. Nagra Technical Report NTB 24-21.

Nagra (2024d): Geosynthesis of Northern Switzerland. Nagra Technical Report NTB 24-17.

Nagra (2024e): Phenomenological description of the evolution of a combined geological repository for radioactive waste in Opalinus Clay: Handling of FEPs in the safety assessment. Nagra Arbeitsbericht NAB 24-20 Suppl. Vol. Rev. 1.

Nagra (2024f): Post-closure biosphere assessment. Nagra Arbeitsbericht NAB 24-06.

Nagra (2024g): Post-closure safety report. Nagra Technical Report NTB 24-10.

Nagra (2024h): Production and fate of gases in the geological repository. Nagra Technical Report NTB 24-23.

Nagra (2024i): Radiological consequence analysis for a deep geological repository in Northern Switzerland. Nagra Technical Report NTB 24-18.

Nagra (2024j): Safety and repository concept and provisional design. Nagra Arbeitsbericht NAB 24-18 Rev. 1.

Nagra (2024k): Safety assessment methodology. Nagra Technical Report NTB 24-19.

Nagra (2024l): Synthesis of the performance assessment for a combined repository. Nagra Technical Report NTB 24-22.

Nagra (2025): Rahmenbewilligungsgesuch für das geologische Tiefenlager – Sicherheitsbericht. Nagra Technischer Bericht NTB 24-01.

NUMO (2021): The NUMO Pre-siting SDM-based Safety Case. NUMO-TR-21-01. Nuclear Waste Management Organization of Japan NUMO, Tokyo.

NWMO (2018): Postclosure safety assessment of a used fuel repository in sedimentary rock. NWMO-TR-2018-08. Nuclear Waste Management Organisation NWMO, Toronto.

OECD/NEA (2019): International features, events and processes (IFEP) List for the deep geological disposal of radioactive waste. Version 3.0. OECD Nuclear Energy Agency, Paris.

Posiva (2021): Safety case for the operating licence application - Future human actions. Working Report 2021-02. Posiva Oy, Eurajoki.

Seitz, R., Kumano, Y., Bailey, L., Markley, C., Andersson, E. & Beuth, T. (2014): Considerations Related to Human Intrusion in the Context of Disposal of Radioactive Waste – The IAEA HIDRA Project - 14101. Proceedings of Waste Management Symposium WM2014, March 2-6, 2014, Phoenix, Arizona: 40 years of meeting global radioactive waste management challenges, 11.

SKB (2010): Handling of future human actions in the safety assessment SR-Site. Technical Report TR 10-53. Swedish Nuclear Fuel and Waste Management SKB, Stockholm.

SKB (2014): Handling of future human actions in the safety assessment SR-PSU. Technical Report TR 14-08. Swedish Nuclear Fuel and Waste Management SKB, Stockholm.

VeVA (2005): Verordnung über den Verkehr mit Abfällen (VeVA) vom 22. June 2005, Stand am 1. January 2020. Systematische Sammlung des Bundesrechts SR 814.610, Schweiz.

Waters Protection Act, WPA (1991): Federal Act on the Protection of Waters (Waters Protection Act, WPA) of January 24, 1991, status as of February 1, 2023. Systematic Compilation of Federal Legislation SR 814.20, Switzerland.

WPO (1998): Waters Protection Ordinance (WPO) of October 28, 1998, status as of February 1, 2023. Systematic Compilation of Federal Legislation SR 814.201, Switzerland.

Zhang, K., Oldenburg, C., Zhang, Y. & Mayer, G. (2024): Review of adaptation of TOUGH3. Nagra Arbeitsbericht NAB 24-47.

# App. A International FHA assessment guidelines and requirements

Regulating radioactive waste disposal safety is a national responsibility, but radiation safety is promoted through international standards and collaboration. The need for structured international collaboration in the domain of nuclear technology was recognised in 1953, which led to the establishment of the IAEA in 1957. Since then, international collaboration for the promotion of safe and peaceful use of nuclear technology has strengthened.

International efforts to establish globally recognised standards and guidelines related to the safety assessments for a deep geological repository for radioactive waste are highlighted here. The focus is on the treatment of FHA in the post-closure safety case. Several examples illustrating how other countries develop and apply these guidelines in post-closure safety cases are also presented.

International guidelines reflect an international consensus on what constitutes a high level of safety for protecting people and the environment from harmful effects of ionising radiation (IAEA SSG-23) (IAEA 2012). However, local settings, waste characteristics, and technological capabilities play a significant role for the planning, approval, construction and emplacement of radioactive waste. These factors are reflected in detailed country-specific regulations where international requirements are considered.

## A.1 International Atomic Energy Agency

According to Article III of its statute, the IAEA is authorised *"to establish or adapt standards of safety"* and *"to provide for application of these standards"* in the domain of peaceful nuclear activities. IAEA establishes international standards through the publication of the Safety Standard Series, which includes three categories of publications:

- Safety Fundamentals set the objective and principles of safety;
- Safety Requirements are governed by fundamentals and outline the necessary safety requirements that must be met; and
- Safety Guidelines offer suggestions and instructions for adhering to the requirements.

The following sections outline the requirements and guidelines related to FHA published by the IAEA. Thereafter, results of a specific IAEA project on this topic are presented.

## A.2 IAEA Safety Requirements

This section presents an overview of the IAEA Safety Requirements relevant to the treatment of FHA in post-closure safety cases for deep geological repositories for radioactive waste. IAEA Safety Requirements publications consist of General Safety Requirements (IAEA 2014) and Specific Safety Requirements (SSR) (IAEA 2011a, IAEA 2003). The most relevant SSR is SSR-5 on the disposal of radioactive waste (IAEA 2011a). The main objective of SSR-5 is reported in Par. 1.27:

> *The objective of this Safety Requirements publication is to set out the safety objective and criteria for the disposal of all types of radioactive waste and to establish, on the basis of the principles established in SF-1 (IAEA 2006), the requirements that must be satisfied in the disposal of radioactive waste.*

Par. 1.10. lists the specific aims of the deep geological disposal of radioactive waste, among which (b) refers to FHA in the context of isolation of the waste:

*To isolate the waste from the accessible biosphere and to reduce substantially the likelihood of, and all possible consequences of, inadvertent human intrusion into the waste.*

"Human intrusion" is defined as:

*Actions that affect the integrity of a disposal facility and which could potentially give rise to radiological consequences. Only those human actions that result in direct disturbance of the disposal facility (i.e. the waste itself, the contaminated near field or the engineered barrier materials) are considered.*

Par. 1.22 (iii) defines the post-closure period in the lifetime of a disposal facility:

*The post-closure period begins at the time when all the engineered containment and isolation features have been put in place, operational buildings and supporting services have been decommissioned and the facility is in its final configuration. After its closure, the safety of the disposal facility is provided for by means of passive features inherent in the characteristics of the site and the facility and the characteristics of the waste packages, together with certain institutional controls, particularly for near surface facilities. Such institutional controls are put in place to prevent intrusion into facilities and to confirm that the disposal system is performing as expected by means of monitoring and surveillance. Monitoring may also be carried out to provide public assurance. The licence will be terminated after the period of active institutional control, when all the necessary technical, legal and financial requirements have been fulfilled.*

Par. 2.15 (IAEA 2011a) lists the criteria for radiation protection in the post-closure period. Criteria (c)-(e) are directly related to human intrusion into the disposal facility:

- *(c) In relation to the effects of inadvertent human intrusion after closure, if such intrusion is expected to lead to an annual dose of less than 1 mSv to those living around the site, then efforts to reduce the probability of intrusion or to limit its consequences are not warranted.*
- *(d) If human intrusion were expected to lead to a possible annual dose of more than 20 mSv to those living around the site, then alternative options for waste disposal are to be considered, for example, disposal of the waste below the surface, or separation of the radionuclide content giving rise to the higher dose.*
- *(e) If annual doses in the range 1–20 mSv are indicated, then reasonable efforts are warranted at the stage of development of the facility to reduce the probability of intrusion or to limit its consequences by means of optimization of the facility's design.*

These criteria are also incorporated in ENSI Guideline G03 (ENSI 2023), Par. 4.3.2 (see Section 1.3 of this report).

Considering safety in the process of development and operation of a disposal facility, Requirement 4 (IAEA 2011a) suggests that the operator should provide an optimised level of safety during both the operational and post-closure stages:

- *Par. 3.20. Consideration has to be given to locating the facility away from significant known mineral resources, geothermal water and other valuable subsurface resources. This is to reduce the risk of human intrusion into the site and to reduce the potential for use of the surrounding area to be in conflict with the facility. The safety of the facility has to be considered at every step in the decision-making process to ensure that safety is optimized…*

Furthermore, considering site, design, and operation to provide features aimed at isolation of radioactive waste, Requirement 9 (IAEA 2011a) on the isolation of radioactive waste establishes the following statements relevant to FHA:

> *Par. 3.44. Isolation means design to keep the waste and its associated hazard apart from the accessible biosphere. It also means design to minimize the influence of factors that could reduce the integrity of the disposal facility. Sites and locations with higher hydraulic conductivities have to be avoided. Access to waste has to be made difficult to gain without, for example, violation of institutional controls for near surface disposal. Isolation also means providing for a very slow mobility of radionuclides to impede migration from disposal facilities.*
>
> *Par. 3.45. Location of a disposal facility in a stable geological formation provides protection of the facility from the effects of geomorphological processes, such as erosion and glaciation. The disposal facility has to be located away from known areas of significant underground mineral resources or other valuable resources. This will reduce the likelihood of inadvertent disturbance of the facility and will avoid resources being made unavailable for exploitation.*
>
> *Par. 3.46. In some cases, it may not be possible to provide sufficient assurance of separation from the accessible biosphere, owing to phenomena such as uplift, erosion and glaciation. In such cases, and if the remaining activity in the waste is still significant at the time such phenomena occur, the possibility of human intrusion has to be evaluated in determining the degree of isolation provided.*

Following the waste acceptance and waste emplacement recommendations, SSR-5 (IAEA 2011a) establishes the following requirements on the period post closure and on the institutional controls (i.e. passive control) of the disposal facility to assure safety:

> - *Par. 5.6. The long term safety of a disposal facility for radioactive waste has not to be dependent on active institutional control.*
> - *Par. 5.7. The risk of intrusion into a disposal facility for radioactive waste may be reduced over a longer timescale than that foreseen for active controls by the use of passive controls, such as the preservation of information by the use of markers and archives, including international archives.*

Moreover, on the topic of passive safety and long-term considerations, deep geological repositories are not to be dependent on long term institutional control. This is specified as:

> - *Par. 5.12. Geological disposal facilities have not to be dependent on long term institutional control after closure as a safety measure. Nevertheless, institutional controls may contribute to safety by preventing or reducing the likelihood of human actions that could inadvertently interfere with the waste or degrade the safety features of the geological disposal system. Institutional controls may also contribute to increasing public acceptance of geological disposal.*

The following requirements are given for the compliance with the safety objective related to the human intrusion into the disposal facility:

- *A.8. In the event of inadvertent human intrusion into a disposal facility, a small number of individuals involved in activities such as drilling into the facility or mining could receive high radiation doses and exposures of other persons could also arise as a result of the intrusion. The doses and risks involved for any individuals authorized to take part in activities that deliberately disturb the disposal facility or its waste need not be taken into consideration in this context, as such activities would constitute planned exposure situations.*

- *A.9. In general, the likelihood of inadvertent human intrusion into the waste will be low as a consequence of the chosen depth for a geological disposal facility. The likelihood will be low owing to institutional controls in the case of a near surface disposal facility, and because of the decision to site the facility away from known significant mineral resources or other valuable resources. The possible doses that would be received from such an inadvertent intrusion could be high. However, since the likelihood of inadvertent intrusion is low, the associated risk is likely to be outweighed by the higher level of protection and safety afforded by the disposal of waste in comparison with other strategies.*

## A.3 IAEA Safety Guidelines

This section summarises those parts of Specific Safety Guidelines SSG-14 (IAEA 2011b) and SSG-23 (IAEA 2012) that are relevant to human intrusion into the disposal facility.

SSG-14 (Geological Disposal Facilities for Radioactive Waste, IAEA 2011b) offers recommendations on fulfilling the safety requirements specified in SSR-5 (IAEA 2011a).

- *Par. 2.2. Containment of waste and isolation of the waste from the biosphere, is an accepted management strategy for radioactive waste. […] The depth of disposal and the characteristics of the host geological environment provide isolation from the biosphere and reduce the likelihood of inadvertent or unauthorized human intrusion. […].*

On the approach to providing passive means for safety to fulfil Requirement 5 of SSR-5 (IAEA 2011a), SSG-14 states:

- *Par. 4.18. Safety after closure is provided by passive systems such as geological and engineered barriers. Geological disposal, at appropriate depths, provides isolation as an inherent safety feature. Monitoring or institutional controls is not to be relied on for the safety of the facility after closure. This does not mean that post-closure monitoring need not be carried out, if present or future generations choose to do so. It is likely that passive institutional controls, such as the use of markers and control on land use, will be implemented and maintained, at least for a certain period immediately after closure. Active institutional controls such as monitoring may also be applied for a period after closure of a geological disposal facility, for example, to address public concerns and licensing requirements or as protection against human intrusion.*

To fulfil Requirement 13 of SSR-5 (IAEA 2011a) on the scope of safety assessment, it states:

- *Par. 5.15. […] The safety assessment should include some stylized calculations of the consequences of inadvertent human intrusion into the closed disposal facility. […].*

To address Requirement 22 of SSR-5 on institutional control, it states:

- *Par. 6.68. Passive institutional controls should be established to prevent or reduce the likelihood of inadvertent human actions that could interfere with the waste or degrade the safety features of the geological disposal facility. Institutional controls may include the construction of durable markers, the posting of facility records in national and international archives accessible to future populations and the transfer of responsibility for the facility to a successor organization. A suitable mechanism may need to be developed for the transfer of responsibility from one generation to the next.*

The Specific Safety Guide on the post-closure safety case and safety assessment for disposal of radioactive waste (SSG-23; IAEA 2012) provides a section on particular topics that may need to be addressed in a post-closure safety case, where one of the identified topics is human intrusion.

However, it is specified that human intrusion is mostly relevant to disposal facilities at or near the surface (Par. 6.52). Therefore, only one paragraph is devoted to human intrusion into geological disposal facilities:

*Par. 6.65. […] the relevance of human intrusion scenarios for geological disposal facilities is limited, as the depth and location of such facilities makes it unlikely. The time frames of concern are also far too large to enable meaningful estimates of possible impacts from intrusion events to be made. Nevertheless, it may be decided to make an assessment of the consequences to demonstrate the robustness of the disposal system. The scenarios considered are speculative and somewhat arbitrary owing to uncertainties in the boundary conditions and other parameters, such as when it is assumed that the event will take place and what the facility and its host environment will be at the time of intrusion. As a consequence, for geological disposal facilities, care should be taken when making quantitative use of the results obtained for human intrusion scenarios, in particular when comparing these to other scenarios (e.g. for purposes of optimization of protection and design). The most effective measures against inadvertent intrusion involve establishing the disposal facility in deep geological formations and providing knowledge maintenance in the long term.*

## A.4 IAEA Human Intrusion in the Context of Disposal of Radioactive Waste (HIDRA) Project

Between 2013 and 2018, IAEA member states participated in the Human Intrusion in the Context of Disposal of Radioactive Waste (HIDRA) (IAEA 2017), in which they established a framework in line with IAEA safety standards for consideration and treatment of inadvertent human intrusion throughout the life cycle of a radioactive waste disposal project.

In line with international guidelines, the HIDRA project considered only inadvertent human intrusion for both deep geological and near-surface disposal of the radioactive waste. The outcome of the project emphasises that the consideration of human intrusion is an integral part of the iterative process of developing disposal facilities. It also presents the following measures to be the most effective in reducing the potential for inadvertent human intrusion into the facility:

- depth of the disposal facility;
- selecting the site away from mineral resources; and
- maintaining control and knowledge of the facility.

In addition, international guidelines, and often local regulatory bodies, require inadvertent human intrusion to be addressed in the post-closure safety case by analysis of stylised scenarios. The stylised scenarios are to be developed based on present-day knowledge and available technology with the aim of illustrating the potential impacts of human intrusion into the disposal facility. The HIDRA project identified the following three stylised scenarios relevant to the deep geological disposal of radioactive waste:

- deep drilling;
- unconventional mining (solution) and geothermal energy;
- subsurface resource storage; and
- resource exploration.

The HIDRA project provides detailed guidelines for developing FHA scenarios and for incorporating them in the post-closure safety case.

# App. B FEP overview

Nagra's FHA FEP catalogue (Fig. B-1) used for this assessment report is part of Nagra's FEP database (Nagra 2024e).

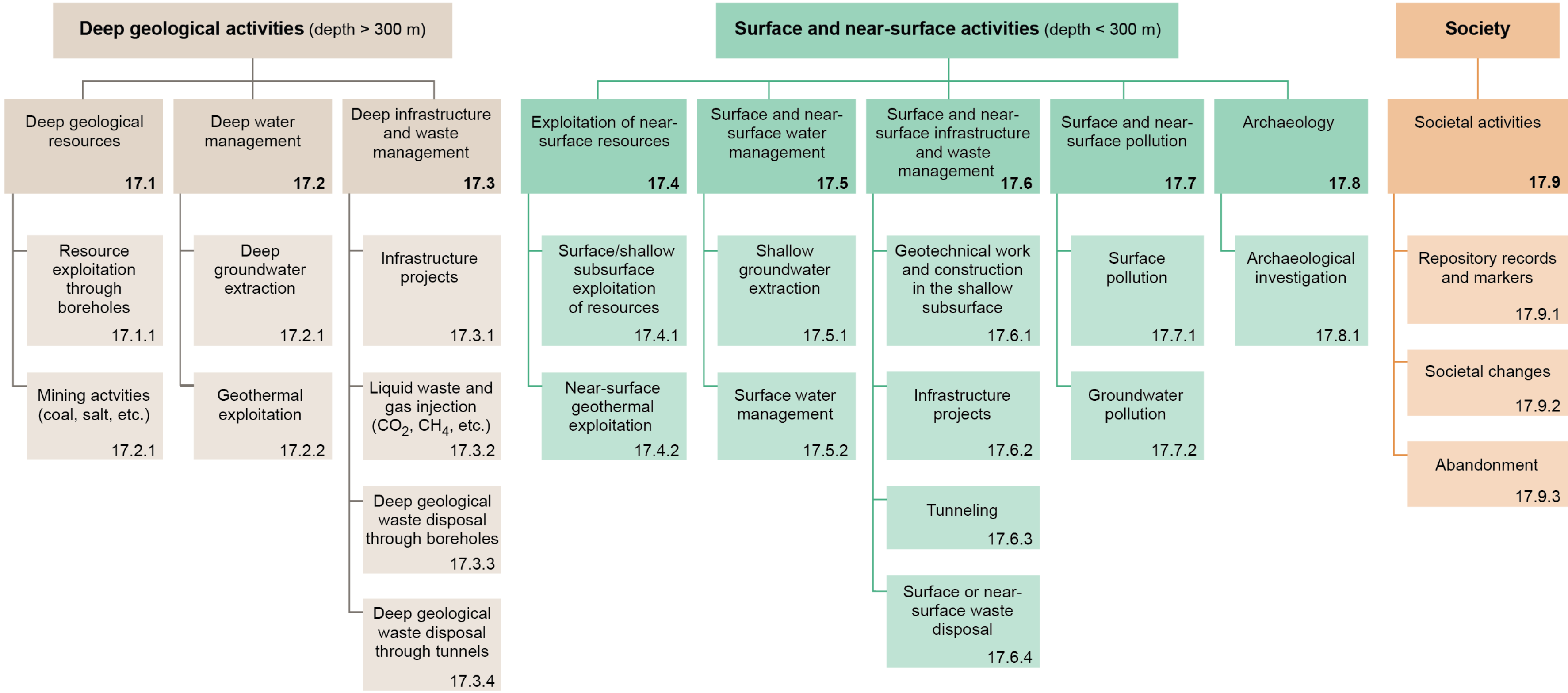


Fig. B-1: FHA FEPs and their corresponding Nagra FEP database numbers (i.e. 17.x.x)