



TECHNICAL REPORT 24-18

Radiological Consequence Analysis for a
Deep Geological Repository in Northern
Switzerland

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Disposal of Radioactive Waste**

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Abstract

The radiological consequence analysis assesses the potential radiation dose to individuals from a deep geological repository in Opalinus Clay. This analysis is conducted as part of the general license application process, following regulatory guidelines, for two key purposes: A) to support the safety-based site comparison, and B) as part of the safety case for the repository at the selected site. The analysis includes various cases defined by safety scenarios: a reference safety scenario, several alternative safety scenarios, and a series of “what-if?” cases. Dose calculations based on both the reference and alternative safety scenarios are carried out for both site comparison and the site-specific safety case. Additionally, “what-if?” cases are evaluated exclusively for the safety case of the repository at the chosen location, in accordance with ENSI requirements (ENSI 2018).

Two modelling approaches are adopted, one addressing the transport of radionuclides that are dissolved in porewater within the repository and the surrounding rock, and the other addressing the transport of C-14 methane, along with other repository-generated gases. Model concepts and assumptions are based on system understanding from the assessment basis, including site characterisation and an understanding of radionuclide release, retention and migration processes acquired within Nagra’s RD&D programme, as well as from performance assessment, where, for example, detailed modelling of the fate of repository-generated gas has been calculated. Model assumptions and simplifications are justified on the grounds that they are either in line with this system understanding or are conservative in that they are expected to overestimate the radiological consequences. The models have undergone validation and are benchmarked. The used numerical codes have been verified and shown to be reliable.

Probabilistic simulations are performed for the reference safety scenario for each siting region. The probabilistic simulations are analysed using graphical methods and by evaluating a range of sensitivity measures. These probabilistic simulations are complemented by deterministic calculation cases, in which selected sensitive parameters (identified by the sensitivity analysis) are set to pessimistic bounding values. These are accompanied by the analysis of “combined pessimistic cases”, in which the selected sensitive parameters are assigned pessimistic bounding values. Deterministic analysis is then performed for the alternative safety scenarios. In addition, for the repository at the selected site, “what-if?” cases have been analysed deterministically to assess safety margins in less likely and in extreme, hypothetical cases, and to test the robustness of the system.

The radiological consequence analysis demonstrates that all siting regions offer a robust safety margin across all repository types, with equivalent radiological impact. Even in the highly conservative or hypothetical “what-if?” cases (such as case assuming no sorption throughout the entire containment-providing rock zone), substantial safety margins are maintained. This underscores the strength and safety of the repository, ensuring long-term protection.

Zusammenfassung

Die radiologische Konsequenzenanalyse bewertet die potenzielle Strahlendosis für Einzelpersonen, die von einem geologischen Tiefenlager im Opalinuston ausgeht. Diese Analyse wird im Rahmen des allgemeinen Rahmenbewilligungsverfahrens gemäss den behördlichen Richtlinien für zwei wichtige Zwecke durchgeführt: A) zur Unterstützung eines sicherheitstechnischen Standortvergleichs und B) als Teil des Sicherheitsnachweises für das Tiefenlager am ausgewählten Standort. Die Analyse umfasst verschiedene Rechenfälle, die durch Sicherheitsszenarien definiert sind: ein Referenzsicherheitsszenario, mehrere alternative Szenarien und eine Reihe von „What-if?“-Fällen. Dosisberechnungen auf der Grundlage des Referenzszenarios und alternativer Sicherheitsszenarien werden sowohl für den Standortvergleich als auch für den standortspezifischen Sicherheitsnachweis durchgeführt. Zusätzlich werden „What-if?“ Fälle ausschliesslich für den Sicherheitsnachweis des Tiefenlagers am gewählten Standort gemäss den Vorgaben des ENSI bewertet (ENSI 2018).

Es werden zwei Modellierungsansätze verfolgt: der eine befasst sich mit dem Transport von Radionukliden, die im Porenwasser innerhalb des Tiefenlagers und des umgebenden Gesteins gelöst sind, der andere mit dem Transport von C-14-haltigem Methan und anderen Gasen, die im Tiefenlager entstehen. Die Modellkonzepte und -annahmen beruhen auf dem Systemverständnis aus der Bewertungsgrundlage, einschliesslich der Standortcharakterisierung und des Verständnisses der Freisetzungs-, Rückhalte- und Migrationsprozesse von Radionukliden, die im Rahmen des F&E-Programms der Nagra erworben wurden, sowie aus der Prüfung der Barrierenwirksamkeit («Performance Assessment»), bei dem zum Beispiel der Verbleib des im Tiefenlager produzierten Gases detailliert modelliert wurde. Die Modellannahmen und Vereinfachungen werden damit begründet, dass sie entweder mit dem Systemverständnis übereinstimmen oder, dass sie konservativ sind, d.h. dass sie die radiologischen Folgen voraussichtlich überbewerten. Die Modelle werden einer Validierung unterzogen. Die verwendeten numerischen Codes werden überprüft und haben sich als zuverlässig erwiesen.

Für das Referenzsicherheitsszenario werden probabilistische Simulationen für jeden Standort und das geologische Tiefenlager am ausgewählten Standort durchgeführt. Die Ergebnisse werden mit grafischen Mitteln sowie durch die Auswertung einer Reihe von Sensitivitätsmassen analysiert. Diese probabilistischen Simulationen werden durch deterministische Rechenfälle ergänzt, in denen ausgewählte sensitive Parameter (die durch die Sensitivitätsanalyse ermittelt wurden) auf pessimistische Eckwerte gesetzt werden. Hinzu kommt die Analyse von «kombinierten pessimistischen Fällen», bei denen allen sensitiven Parametern pessimistische Eckwerte zugewiesen werden. Anschliessend werden deterministische Analysen für die alternativen Sicherheitsszenarien für den Standortvergleich sowie das Tiefenlager am ausgewählten Standort durchgeführt. Darüber hinaus werden «What-if?»-Fälle für Tiefenlager am ausgewählten Standort deterministisch analysiert, um die Sicherheitsmargen in weniger wahrscheinlichen und in extremen, hypothetischen Fällen zu bewerten und die Robustheit des Systems zu testen.

Die Analyse der radiologischen Konsequenzen zeigt, dass alle Standortregionen über alle Tiefenlagertypen hinweg eine solide Sicherheitsmarge bieten, mit gleichwertigen radiologischen Auswirkungen. Selbst in den sehr konservativen oder hypothetischen „What-if?“-Fällen (wie z.B. der Fall mit der Annahme, dass keine Sorption im gesamten einschlusswirksamen Gebirgsbereich stattfindet) werden beträchtliche Sicherheitsmargen eingehalten. Dies unterstreicht die Stärke und Sicherheit des Tiefenlagers, das einen langfristigen Schutz gewährleistet.

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Note: The appendices are only included in the digital version of the report. As a supplement to the printed version, they can be downloaded from the Nagra website.

List of Acronyms

ATW	Alpha-toxic waste
BDCF	Biosphere dose conversion factors
CRF	Congruent release fraction
CRZ	Containment-providing rock zone
CU	Confining geological units (geological units over and under the Opalinus Clay in the CRZ)
EDZ	Excavation-damaged zone
ELB	Disposal canister (<i>Endlagerbehälter</i>)
ENSI	Swiss Federal Nuclear Safety Inspectorate (<i>Eidgenössisches Nuklearsicherheitsinspektorat</i>)
FHA	Future human action(s)
FEP	Feature(s), event(s) and process(es)
HLW	High-level waste (SF and RP-HLW)
IRF	Instant release fraction
JO	Jura Ost siting region
KEG	Nuclear Energy Act (<i>Kernenergiegesetz</i>)
KEV	Nuclear Energy Ordinance (<i>Kernenergieverordnung</i>)
LCU	Lower confining geological units (geological units under the Opalinus Clay in the CRZ)
L/ILW	Low- and intermediate-level waste
MIRAM-RBG	Model Inventory of Radioactive Materials for the general licence application
NAB	Nagra Work Report (<i>Nagra Arbeitsbericht</i>)
NEA	Nuclear Energy Agency
NL	Nördlich Lägern siting region
NPP	Nuclear power plant
NTB	Nagra Technical Report (<i>Nagra Technischer Bericht</i>)
OPA	Opalinus Clay
PA	Performance assessment
PHAU	Potential hydraulically active unit
QA	Quality assurance
RBG	General licence application (<i>Rahmenbewilligungsgesuch</i>)
RN	Radionuclide

RP-HLW	High-level waste from reprocessing
SA	Safety analysis (radiological consequence analysis)
SF	Spent fuel
SGT	Sectoral Plan for Deep Geological Repositories (<i>Sachplan geologische Tiefenlager</i>)
UCU	Upper confining geological units (geological units over the Opalinus Clay in the CRZ)
THMC	Thermal-hydraulic-mechanical-chemical coupled processes
ZNO	Zürich Nordost siting region
ZWILAG	Zwischenlager Würenlingen AG (interim storage facility)

Geological units

AAK	Anhydritic-Argillaceous Keuper
AD	Argillaceous Dogger
AK/SK	Argillaceous Keuper/Sandy Keuper
ANK	Anhydritic Keuper
AL	Argillaceous Lias
CAD	Calcareous-Argillaceous Dogger
E-CD / W-CD	Calcareous Dogger («Herrenwis Unit»)
CL	Calcareous Lias
DAK	Dolomitic-Anhydritic Keuper
DK	Dolomitic Keuper
MAK	Massive Anhydritic Keuper
ML	Marly Lias
MM	Marly Malm
OPA	Opalinus Clay
SCD	Sandy-Calcareous Dogger
SCAD	Sandy-Calcareous Argillaceous Dogger

1 Introduction

1.1 Context

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

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

In SGT-E3, the three remaining siting regions have been investigated in depth – Jura Ost (JO), Nördlich Lägern (NL) and Zürich Nordost (ZNO) – with the objective of selecting one siting region for an HLW repository, one for an L/ILW repository, or one for a repository for all waste types.

Following a comparison of these siting regions, Nagra concluded that NL is the safest siting region and offers the most flexibility. It is therefore applying for a general licence for a repository for both HLW and L/ILW (termed “combined repository” in this report) with the surface facility to be located at the Haberstal site (in the community of Stadel, Canton Zürich).

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). The reports relating to post-closure safety, shown in Fig. 1-1, are structured as follows:

- The overall safety-related argumentation, including post-closure and operational safety, is summarised in an overarching safety report (“*Sicherheitsbericht*”) (Nagra 2025b) shown at the top of Fig. 1-1.
- The upper left side of Fig. 1-1 shows the reports supporting Nagra's site comparison. The available options are compared with respect to safety and technical feasibility and the results are synthesised in Nagra (2025a) (“*Bericht zur Begründung der Standortwahl*”).
- The upper right side of Fig. 1-1 shows the reports documenting the post-closure safety case for the combined repository at the site, including its synthesis in the post-closure safety report (Nagra 2024j).
- The lower part of Fig. 1-1 shows a report that presents the safety and provisional repository concept, including the provisional design, and reports providing the assessment basis.

The present report (red box in Fig. 1-1) documents the radiological consequence analysis supporting the site comparison and the post-closure safety case for a combined repository, based on the provisional repository design.

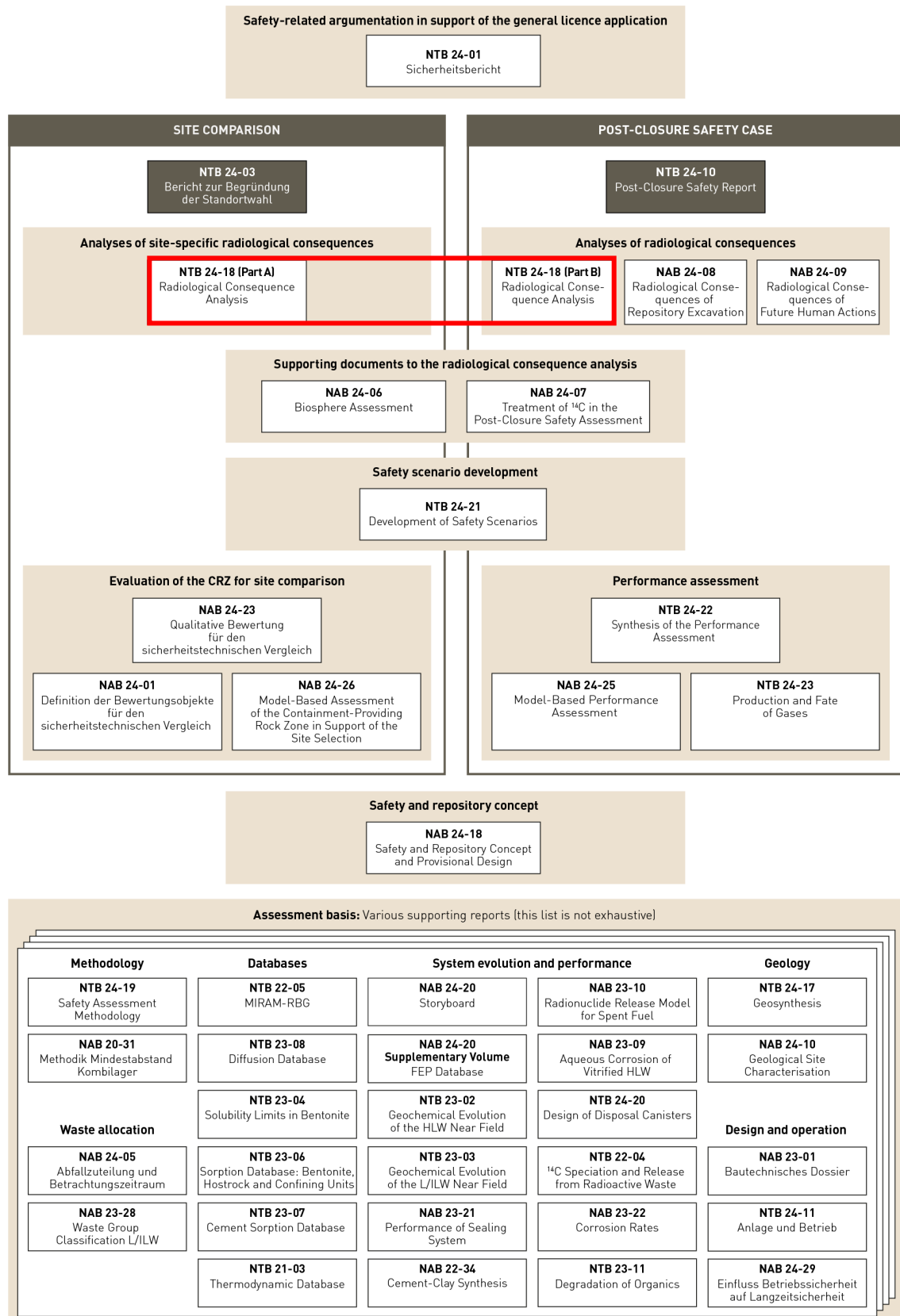


Fig. 1-1: Structure of reports covering post-closure safety aspects of the site comparison and the post-closure safety case

1.2 Scope of the present report

According to the regulatory requirements provided in ENSI (2018), radiological consequence analysis is involved both in the site comparison and the post-closure safety case for a combined repository in the selected site.

Radiological consequence analysis consists of an evaluation of radionuclide release rates to the biosphere as a function of time in a defined set of safety scenarios. According to Swiss regulatory guidance (ENSI 2023), safety scenarios are possible evolution of waste, engineered and geological barriers, the biosphere and the human lifestyle under the influence of assumed features, events and processes (FEPs). 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 excavation of the underground openings and emplacement of the waste and engineered barriers, and extending into the future, generally for as long as the waste presents a potential hazard. Safety scenarios are developed in a separate report (Nagra 2024b), and also briefly introduced in the present report.

The radiological consequence due to radionuclide transport both in the liquid and gas phases is systematically analysed, using different model setups, both for the site comparison and the post-closure safety case for a combined repository.

The workflow for the comparison of the three siting regions begins with the allocation of waste to the HLW or L/ILW repository (or to the HLW or L/ILW section of a combined repository). Thereafter, the workflow involves:

- The comparison of siting regions with regard to HLW disposal, culminating in a decision on a preferred HLW siting region.
- The comparison of siting regions with regard to L/ILW disposal, culminating in a decision on a preferred L/ILW siting region, including the possibility of a combined repository in the preferred HLW siting region.

Both of these steps involve site-specific radiological consequence analysis, which is documented in Chapter 6 of the present report.

Safety assessment is carried out for a combined repository as illustrated in Fig. 1-2. The high-level workflow of the safety assessment involves:

- **Performance assessment (PA)**, defined by Nagra as an analysis of the thermal, hydraulic, mechanical, and chemical evolution of the repository system, which is documented in a number of reports and synthesised in Nagra (2024p)
- **Safety scenario development**, documented in Nagra (2024b), which entails the identification and description of a set of safety scenarios, variants and calculation cases that capture uncertainty in the initial state of the repository system and different ways in which it could evolve over time, as well as “what-if?” cases representing extreme, often purely hypothetical situations to demonstrate system robustness.
- **Analysis of radiological consequences**, as documented in Chapter 7 of the present report, which consists of an evaluation of radionuclide release rates to the surface environment as a function of time for the calculation cases selected during safety scenario development.

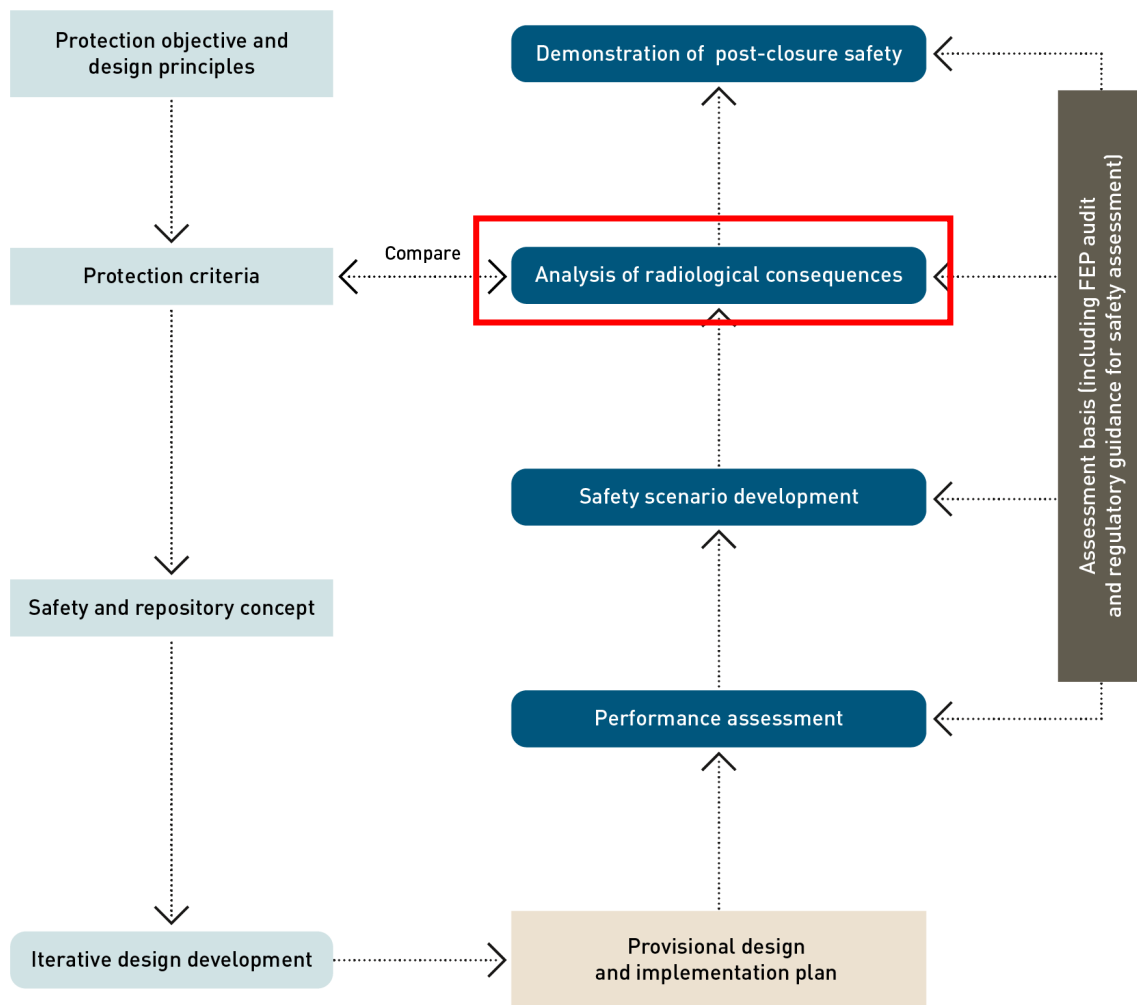


Fig. 1-2: Overview of the workflow for the post-closure safety case. As part of this workflow, the present report provides the site-specific safety analyses (red box).

- **Demonstration of safety**, documented in Nagra (2024j), in which evidence, arguments and analyses from the three previous steps are brought together in the safety case with further 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.

Most of the radiological consequence analysis carried out for the safety case is documented in the present report, with the exception of the analyses regarding future human actions (Nagra 2024m) and a specific set of “what-if?” cases concerning excavation (Nagra 2024l) of the repository, which are outside the scope of the present report.

1.3 Structure of this report

The following chapters of this report are organised as follows:

- Chapter 2 outlines the main features of the provisional repository design, applicable to all three siting regions, which are the basis for the models used in consequence analysis. It also describes the conceptualisation of the geological structure of each siting region that provides a basis for modelling the retention and transport of radionuclides.
- Chapter 3 describes the basic concept and approaches (including safety indicators, time period for assessment and selection of radionuclides, etc.) used in the analyses for the present report.
- Chapter 4 summarises the safety scenarios and calculation cases (including “what-if?” cases) that are analysed.
- Chapter 5 summarises the main features of the models and codes that are used for the analyses.

The results are presented in two parts (see Fig. 1-1):

- Part A, presented in Chapter 6, presents the site-specific radiological consequence analysis that contributes to the safety-based comparison of the siting regions, and
- Part B, presented in Chapter 7, presents further analyses of radiological consequences specific to a combined repository at the selected site.

In the present report, radiological consequence due to radionuclide transport in both the liquid and gas phases is considered. The results focusing on the radionuclide transport in the liquid phase are documented in Sections 6.1, 6.2 and 7.1. Sections 6.3 and 7.2 document the results of the radiological consequence analysis concerning gas-mediated radionuclide (C-14 methane) migration. At the end of the report, the main conclusions are summarised in Chapter 8.

The significance of simplifications in the conceptualisations and calculation models is addressed in App. A. The configuration of the models used in the radiological consequence analysis, including justifications for assumptions and simplifications, is provided in App. B, while assumptions in parametrisation and the treatment of parameter uncertainty are documented in App. C. App. D provides version and verification information on the computer codes used for the modelling. App. E contains the results of model benchmarking. Quality assurance (QA) processes performed with respect to the consequence analysis are documented in App. F. Furthermore, the methodology of the probabilistic analysis is documented in App. G. Some data tables and digital appendices describing the input and output parameters, are attached as App. H. Finally, a table describing the compliance of the analysis in this report with the regulatory guidance is included in App. I.

2 Repository concept and design, and geological barrier

2.1 Provisional repository concept and design for the RBG

The post-closure safety of the deep geological repository rests on multiple, passive, engineered and geological barriers. In Switzerland, two separate repositories, one for HLW (SF and RP-HLW) and one for L/ILW (including ATW) could be constructed in the Opalinus Clay (OPA) host rock, which is present in all three siting regions. If the decision is made to dispose of both waste types in the same siting region, a provisional combined repository design could be implemented. A schematic illustration of the combined repository for HLW and L/ILW is shown in Fig. 2-1. In the concept for HLW disposal (right), SF assemblies containing fuel rods and RP-HLW (not shown in Fig. 2-1) are packaged in steel disposal canisters. The canisters are emplaced in drifts, which are backfilled with a compacted bentonite buffer and then sealed. In the concept for L/ILW disposal (left), waste packages for L/ILW are placed inside disposal containers, which are themselves emplaced in caverns that are backfilled with cement-based mortar.

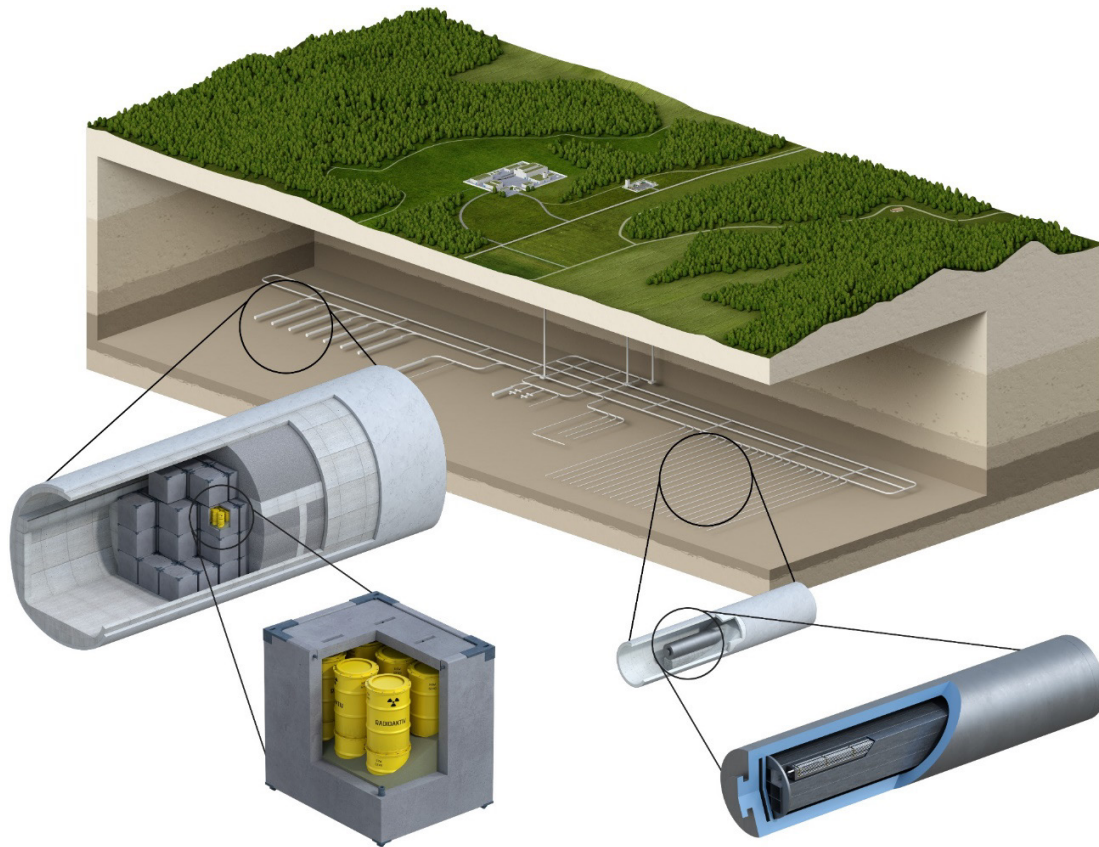


Fig. 2-1: Illustration of the provisional concept for a combined repository for HLW and L/ILW

Following repository operations and a subsequent monitoring period, all underground openings and access structures will be closed using a system of seals and backfill. The provisional design for the combined repository foresees three different types of seals:

- **V1 seals**, which are situated at the entrances to the HLW emplacement drifts and L/ILW emplacement caverns. The provisional design of the V1 seals for the HLW emplacement drifts is somewhat different to that for the L/ILW emplacement caverns because of the requirement for the latter to be gas-permeable. Thus, the notations “V1-HLW” and “V1-L/ILW” are adopted.
- **V2 seals**, which close off the L/ILW and HLW disposal areas and the pilot repositories for the two waste types, after the waste has been emplaced. As in the case of the V1 seals, the two seal types are denoted “V2-HLW” and “V2-L/ILW”.
- **V3 seals**, which are located in the access shafts to seal the repository from the surface environment and protect it from external impacts, including the possibility of future human intrusion.

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

For the site-specific radiological consequence analysis for the safety-based comparison of the siting regions, the same engineered barrier layout and properties are assumed in the analyses of all three siting regions, with the exception that, for the two-phase flow model, the length of the access tunnel system is different for each siting region, and additionally, for the JO siting region, access to the underground is assumed to be via a ramp. Here, a V4 seal is placed at the lowest section of the ramp to seal the repository from the surface environment (Nagra 2023a).

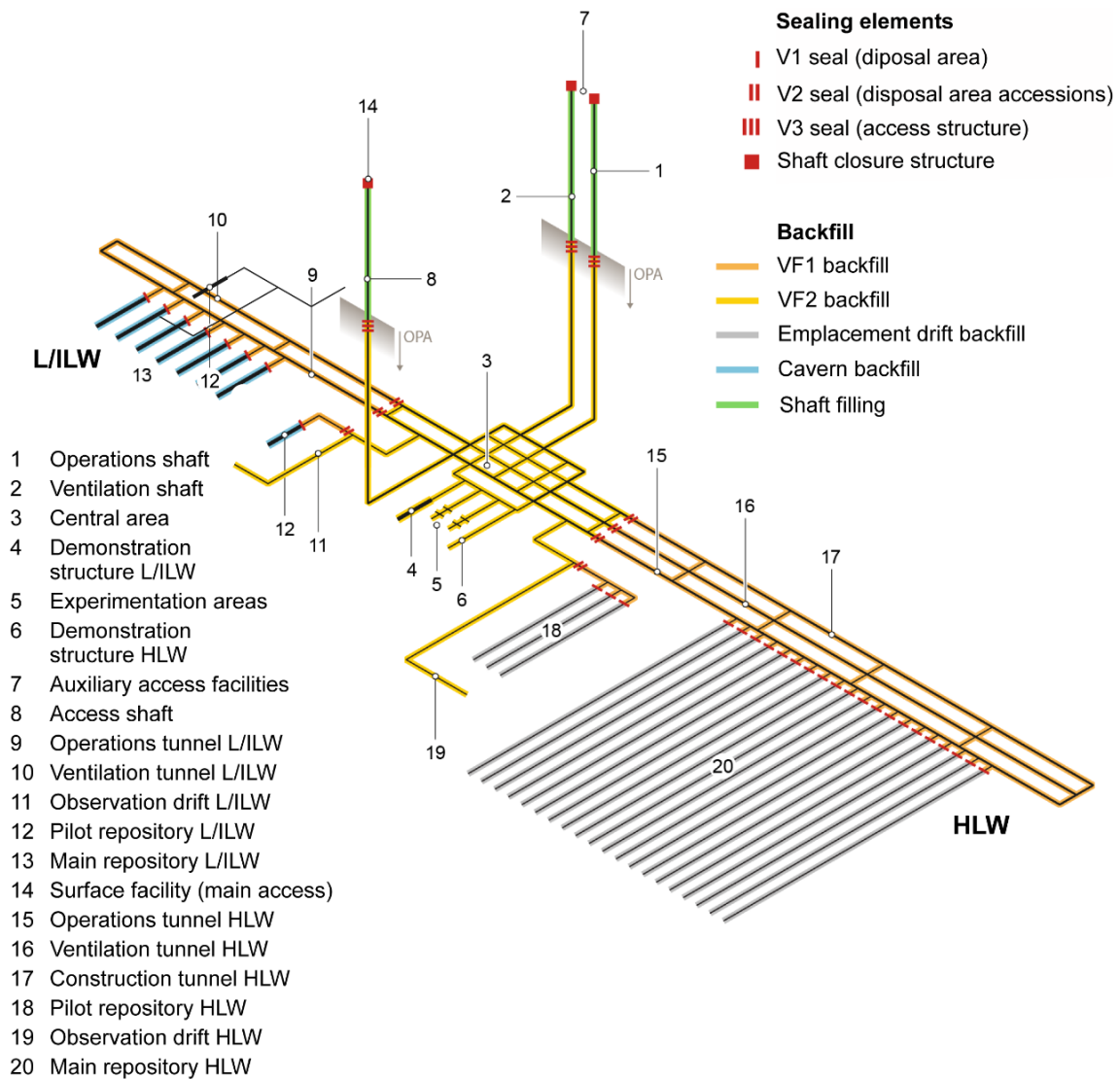


Fig. 2-2: The arrangement of the V1, V2 and V3 seals and the VF1 and VF2 backfill within a generic repository layout. Note that the design is provisional for the RBG and will be refined and modified in future stages of the project.

The radiological consequence analysis focuses on the radionuclide transport in the containment-providing rock zone (CRZ). The geological formations of the Opalinus Clay (OPA) and its confining geological units form the CRZ (illustrated in Fig. 2-3). Criteria laid out by (ENSI 2018) stipulate that the CRZ should be bounded vertically by the first water-conducting features encountered above and below the repository horizon. The Opalinus Clay is characterised by a fine and homogeneous pore structure, extremely low hydraulic permeability, a high clay-mineral content and the associated high sorption capacity for many radionuclides. The rock has self-sealing properties due to its high clay content. It provides an effective and stable barrier against radionuclide transport and a suitable physical and chemical environment for the engineered barriers. The confining geological units (CU) can also possess similarly favourable properties, but with higher variability (Nagra 2024f).

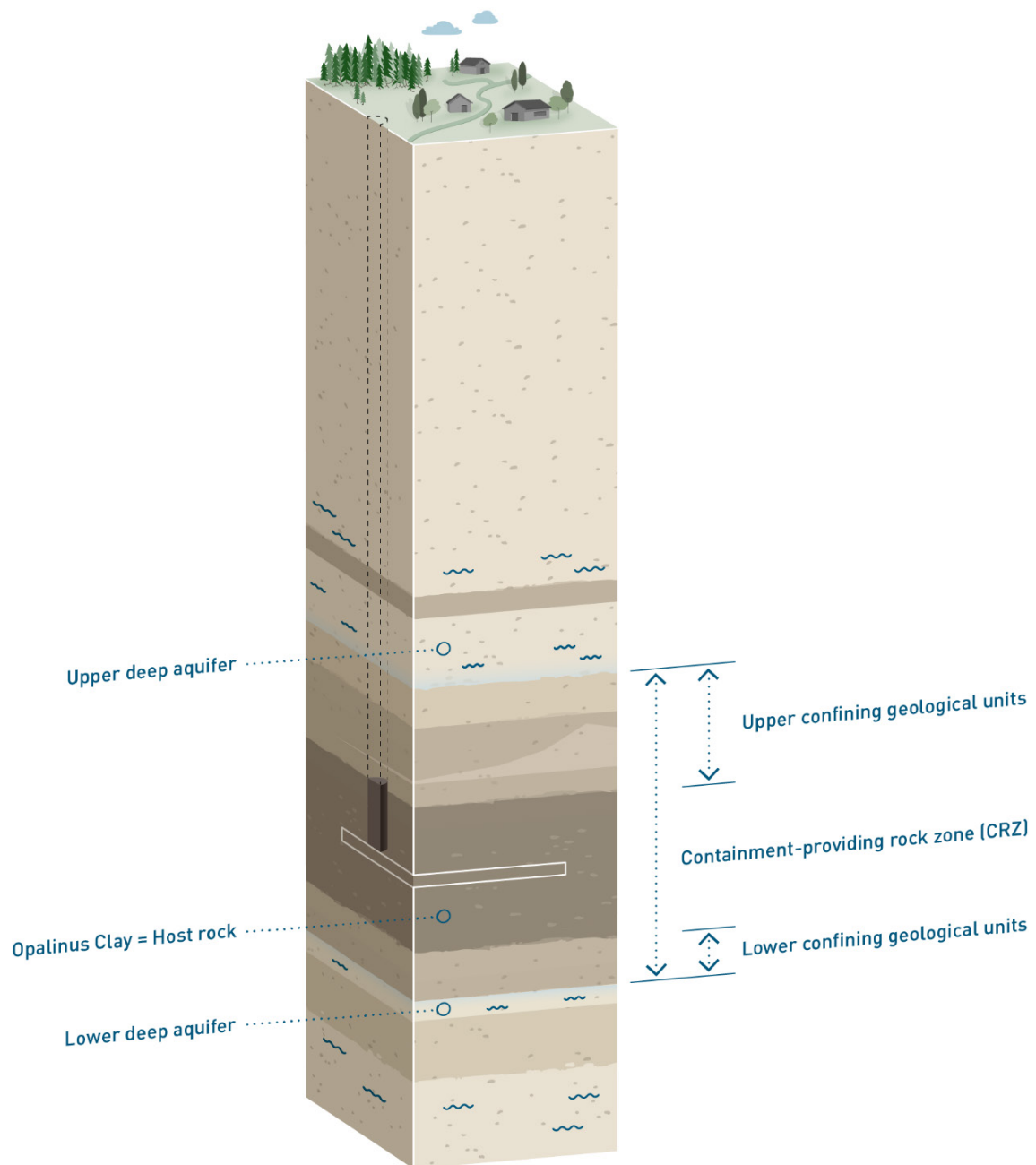


Fig. 2-3: Sketch of the location of the repository within the Opalinus Clay host rock, as well as the containment-providing rock zone, which comprises the Opalinus Clay and its confining geological units, bounded above and below by deep aquifers (not to scale)

2.2 Site-specific description of the geological barrier

The geological situation in Northern Switzerland is documented in the geosynthesis report (Nagra 2024f) with the focus on the potential siting regions JO, NL and ZNO and the most important differences between them.

The characterisation of the geological structures focuses on the rock units bounded by deep aquifers in each siting region. These are the Malm and Muschelkalk in the NL and ZNO siting regions, and the Hauptrogenstein (Calcareous Dogger) and Muschelkalk aquifers in the JO siting region. However, some zones with likely groundwater flow, most notably the Keuper aquifer below the host rock, were detected in some boreholes between the above-mentioned deep aquifers. The Keuper aquifer appears to have different characteristics in the three siting regions. Hydraulic tests and the profiles of natural tracers in adjacent porewaters indicate that the Keuper aquifer is hydraulically active in ZNO, and probably also in JO. By contrast, in NL, permeable layers are limited to locally occurring sandstone channels that were only observed below the provisional site of the L/ILW repository (or the L/ILW section of a combined repository).

The geological information inferred from the geosynthesis (Nagra 2024f) is narrowed down to a local geological characterisation (Nagra 2024e) of the potential repository zones in the central areas of the three siting regions. Nagra 2024e) provides the abstraction of geological formations and facies into rock units with similar transport properties. The abstraction process is exemplified for the NL siting region in Fig. 2-4, including simplifications made to local “layer-cake” models for performance assessment (PA) and for the analysis of radiological consequences (“SA¹ & PA model units”).

The specific “layer-cake” models of the potential repository zones for each siting region are then shown in Fig. 2-5, and Tab. 2-1 unifies the geological formation names with the abstracted model names.

Most of the rock units between these deep aquifers, including the host rock itself, are hydraulically impermeable (Nagra 2024f).

However, in Fig. 2-4 and Fig. 2-5, geological units over- and underlying the host rock include intercalated sandy, calcareous, or dolomitic interlayers and a laterally confined biohermal limestone unit. Overall, they are also characterised by high to intermediate clay-mineral content, but show higher variability compared with the Opalinus Clay and include sections with low clay-mineral contents, typically with thicknesses of up to a few metres (“hard beds”). These thin (i.e., hard and brittle) horizontal features (marked by grey arrows in Fig. 2-5) are embedded between layers of more plastic clay. Despite intensive testing, only low hydraulic conductivities were derived from packer tests, and no relevant excursions in the profiles of natural tracers were observed. Thus, transport of solutes in these units, including any radionuclides released from the repository, is expected to be diffusion-dominated.

Furthermore, a biohermal limestone unit (the «Herrenwis Unit») with low clay content occurs in the upper confining units of eastern NL. The available geological and hydrogeological data, such as the low hydraulic conductivities observed within this unit, the existence of hydraulic underpressure and the fact that the unit is embedded in other clay-mineral-rich units, indicate that it is also hydraulically isolated from the regional flow systems where the transport of solutes in this unit is expected to be diffusion-dominated as well.

¹ “SA” here means radiological consequence analysis.

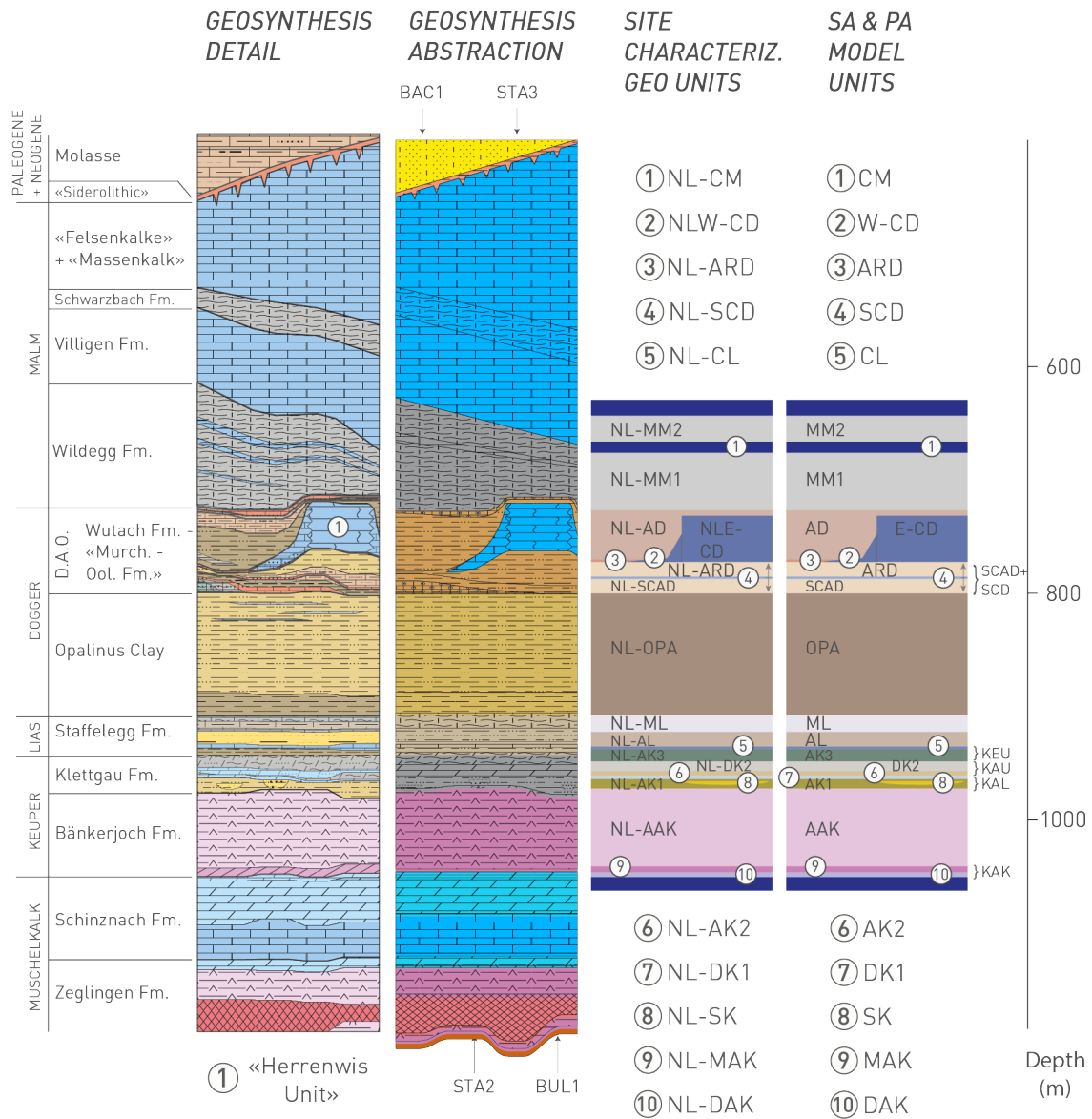


Fig. 2-4: Example of the abstraction of the sedimentary Mesozoic sequence in the NL siting region into units of comparable transport parameters, as described in Nagra (2024e)

The abstraction results in the generation of the local “layer-cake” model for performance assessment and for the analysis of radiological consequences (“SA & PA model units”).

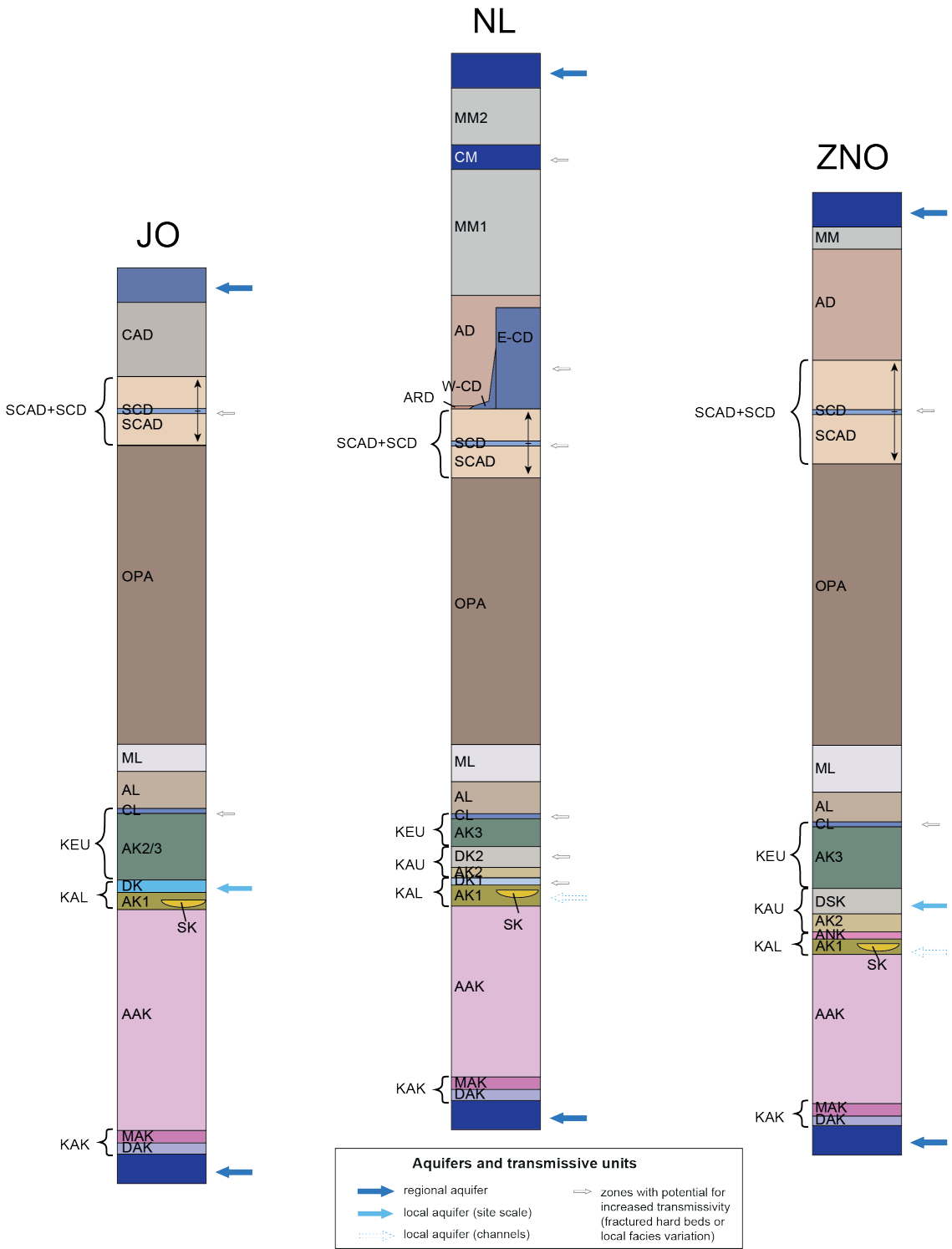


Fig. 2-5: Abstracted local “layer-cake” models of the siting regions for the analysis of radio-logical consequences

The positioning of each stratigraphic model is normalised to the base of the Opalinus Clay (OPA) unit. The unit thicknesses are not to scale.

*Unit thicknesses shown in the table below are the thicknesses obtained when slicing through the “layer-cake” centre of the HLW repository in the modelling.

Jura Ost (JO)			
Stratigraphic unit	Abstracted unit and full name		SA & PA model unit (thickness*)
Passwang Fm.	CAD	Calcareous-Argillaceous Dogger	CAD (18 m)
		Sandy-Calcareous Dogger	
Dogger Group above Opalinus Clay	SCD	Sandy-Calcareous Dogger	SCAD +SCD (27 m)
	SCAD	Sandy-Calcareous Argillaceous Dogger	
Opalinus Clay	OPA	Opalinus Clay	OPA (123 m)
Staffelegg Fm.	ML	Marly Lias	ML (18 m)
	AL	Argillaceous Lias	AL (11 m)
	CL	Calcareous Lias	
Klettgau Fm.	AK2/3	Argillaceous Keuper	KEU (27 m)
	DK	Dolomitic Keuper	KAL (20 m)
	AK1/SK	Argillaceous Keuper/Sandy Keuper	
Bänkerjoch Fm.	AAK	Anhydritic-Argillaceous Keuper	AAK (80 m)
	MAK	Massive Anhydritic Keuper	KAK (12 m)

Nördlich Lägern (NL)			
Stratigraphic unit	Abstracted unit and full name		SA & PA model unit (thickness*)
Wildegge Fm.	MM2	Marly Malm	MM2 (22 m)
	CM	Calcareous Malm	CM (5 m)
	MM1	Marly Malm	MM1 (38 m)
Dogger Group above Opalinus Clay	AD	Argillaceous Dogger	AD (8 m)
	E-CD / W-CD	Calcareous Dogger («Herrenwis Unib»)	E-CD / W-CD (40 m)
	SCD	Sandy-Calcareous Dogger	SCAD+SCD (40 m)
	SCAD	Sandy-Calcareous Argillaceous Dogger	
Opalinus Clay	OPA	Opalinus Clay	OPA (107 m)
Staffelegg Fm.	ML	Marly Lias	ML (16 m)
	AL	Argillaceous Lias	AL (11 m)
	CL	Calcareous Lias	
Klettgau Fm.	AK3	Argillaceous Keuper	KEU (25 m)
	DK2	Dolomitic Keuper	KAU (7 m)
	AK2	Argillaceous Keuper	
	DK1	Dolomitic Keuper	KAL (11 m)
	AK1/SK	Argillaceous Keuper / Sandy Keuper	
Bänkerjoch Fm.	AAK	Anhydritic-Argillaceous Keuper	AAK (60 m)
	MAK	Massive Anhydritic Keuper	KAK (12 m)

Zürich Nordost (ZNO)			
Stratigraphic unit	Abstracted unit and full name		SA & PA model unit (thickness*)
Wildegge Fm.	MM	Marly Malm	MM (14 m)
	AD	Argillaceous Dogger	AD (46 m)
Dogger Group above Opalinus Clay	SCD	Sandy-Calcareous Dogger	SCAD+SCD (38 m)
	SCAD	Sandy-Calcareous Argillaceous Dogger	
	Opalinus Clay	OPA	Opalinus Clay
Staffelegg Fm.	ML	Marly Lias	ML (22 m)
	AL	Argillaceous Lias	AL (14 m)
	CL	Calcareous Lias	
Klettgau Fm.	AK3	Argillaceous Keuper	KEU (40 m)
	DSK	Dolomitic-Sandy Keuper	KAU (15 m)
	AK2	Argillaceous Keuper	
	ANK	Anhydritic Keuper	KAL (5 m)
AK1/SK	Argillaceous Keuper/Sandy Keuper		
Bänkerjoch Fm.	AAK	Anhydritic-Argillaceous Keuper	AAK (65 m)
	MAK	Massive Anhydritic Keuper	KAK (14 m)

To be noted is that the Keuper aquifer is assumed to be the “sandy Keuper” belonging to the unit KAL in the JO and NL siting regions, and the “Dolomitic Sandy Keuper” belonging to the KAU unit in the ZNO siting region. Units with potential elevated local transmissivity in each siting region are marked in Fig. 2-5 with grey arrows. In the case of JO and ZNO, there is one such unit among the upper confining units (SCD: Sandy-Calcareous Dogger) and one among the lower confining units (CL: Calcareous Lias). For NL, there are three among the upper confining units (CM: Calcareous Malm, CD: «Herrenwis Unit» and SCD: Sandy-Calcareous Dogger) and two among the lower confining units (CL: Calcareous Lias and DK2: Dolomitic Keuper).

The main factors affecting tectonic settings and the fault inventory in Northern Switzerland are well described in Nagra (2024f). Regional fault zones are avoided during placement of the repository, along with other seismically mappable faults (Nagra 2024f). Existing faults within the siting regions are small, i.e., within a centimetre to metre scale, and do not show elevated hydraulic activities beyond the bulk matrix (Nagra 2024f).

Future deformation will result in reactivation of existing faults, with movement mainly concentrated on the regional fault zones, which are avoided during placement of the repository along with other seismically mappable faults (Nagra 2024f). If new faults are to develop in the CRZ, their fault architecture will be prone to segmentation (i.e., they will be discontinuous), and they can be expected to be as small in length and small in offset as the currently existing ones (Nagra 2024f). They will also readily reseal if they undergo secondary shear movements in the event of an earthquake centred on a larger-scale fault at a distance from the repository. Such secondary shear movements are not expected to be substantial enough to damage the engineered repository barriers (Nagra 2024c).

Studies of the erosion processes that will affect the siting regions over the one-million-year time period for assessment indicate that, considering the 5 – 95% probability range, between approximately 120 and 410 m of residual overburden can be expected in JO, between approximately 350 and 670 m in NL and between approximately 220 and 560 m in ZNO (Nagra 2024f). Hence the upper confining units shown in Tab. 2-1 will not be reached even with the most pessimistic estimate of the loss of overburdens.

The efficient self-sealing of reactivated faults in the Opalinus Clay is expected to be maintained as long as the overburden remains > 200 m (Nagra 2024f). In the absence of faulting, the favourable hydrogeological and hydrogeochemical properties of the host rock (matrix permeability, diffusion, porosity, etc.) are expected to be maintained, provided as little as a few decametres of overburden remain (Nagra 2024d). Moreover, the most likely erosion scenarios at the provisional repository sites in all the siting regions result in at least ~ 400 m of overburden remaining above the repository after one million years (Nagra 2024d and Nagra 2024f). Therefore, for these most likely erosion scenarios, key rock properties of the CRZ are maintained. The JO siting region shows a more significant loss of overburden for certain less likely scenarios than the other siting regions. Still, enough overburden is nonetheless expected to be maintained in the immediate surrounding of the provisional repository site (Nagra 2024d) to ensure that the barrier functions of the CRZ in all the siting regions are provided throughout the time period for assessment (Nagra 2024f).

3 Basic concept of and approaches to radiological consequence analysis

3.1 Safety indicators

The calculations presented in the present report focus on the release rates of radionuclides from the CRZ to the surface environment in the different safety scenarios and “what-if?” cases. Calculated radionuclide release rates are converted to individual effective dose rates using a set of nuclide-specific biosphere dose conversion factors (BDCFs); see Section 3.3. The individual effective dose (simply termed “dose rate” in this report) is selected as the main “safety indicator” for the analysis of radiological consequences.

In line with ENSI Guideline G03, the calculated safety indicator “dose rate” is compared with two quantitative protection criteria given as follows (ENSI 2020a, ENSI 2023):

- Criterion point a: For each future evolution classified as likely, the release of radionuclides may not lead to an individual dose exceeding 0.1 mSv per year. The criterion point a is termed as “protection criterion” in this report.
- Criterion point c: After the end of the time period for assessment (discussed in Section 3.2), the effects on the surface must not be significantly higher than the average current radiation exposure of the Swiss population (1.63 mSv/a to 13.67 mSv/a according to the Federal Office of Public Health (BAG 2021)).

The protection criterion point b (ENSI 2023) regarding future human activities is not relevant to the present report.

In addition to the calculation of dose rate, the safety and behaviour of the disposal system can further be illustrated using a range of additional, complementary safety indicators, which include:

- **Hypothetical dose rate** due to radionuclide fluxes (radioactivity flux) from different components or parts of the repository system over time, which are converted to hypothetical dose rates by multiplying the total flux rate of radionuclides with their corresponding BDCFs (the same process as the calculation of individual effective dose rates mentioned above).
- **Radiotoxicity** in the CRZ and individual repository components, as functions of time, which are compared with the initial radiotoxicity of the emplaced waste inventory. Radiotoxicity (RT), in units of Sieverts, is calculated from the activity $A_i(t)$ [Bq] of a nuclide i at a time t and the ingestion dose conversion factor F_i [Sv/Bq] (ICRP 2012) of the nuclide i :

$$RT(t) = \sum_i A_i(t) \times F_i \quad [1]$$

The consideration of these complementary indicators can provide additional arguments for safety that avoid, to some extent, the difficulties faced in evaluating and interpreting doses and risks for individuals that could occur in the far future (OECD/NEA 2004), (OECD/NEA 2012b). Collectively, these indicators can contribute to the demonstration of the functioning and robustness of the multi-barrier system. A comprehensive review of complementary indicators, including the reference values for safety indicators, is reported in OECD/NEA (2012a).

3.2 Time period for assessment

The time period for assessment extends up to 100,000 years post-closure for an L/ILW repository and up to 10^6 years for an HLW repository or a combined repository, the latter being consistent with ENSI guidance (ENSI 2023). There is, however, an additional requirement given in ENSI (2023) that the dose calculations shall be performed up to the time of the maximum radiological impact of the repository. To meet this requirement, the timeframe covered by the calculations is extended, where necessary, to 10^7 years for releases from the HLW repository section of a combined repository and to 10^6 years for releases from the L/ILW repository section. The year 2075 is assumed to mark the beginning of the post-closure phase and the radionuclide inventory for the year 2075 based on the Model Inventory of Radioactive Materials for the General Licence Application (Nagra 2023c), which is considered to be the initial inventory for the radiological consequence analysis documented in this report.

Considering the safety indicator and time period for assessment discussed above, a typical sample graphic illustration of the simulation result of the radiological consequence analysis is shown in Fig. 3-1. Time-dependent dose rates as a function of time are plotted along a double-logarithmic axis. The grey-shaded areas in Fig. 3-1 indicate two key aspects:

Dose rate: Many of the calculations in the radiological consequence analysis show very low dose rates. A dose of 10^{-7} mSv/a to an individual corresponds to an overall fatal risk coefficient for the exposed person of $5 \times 10^{-12} \text{ a}^{-1}$. This estimate is based on the factor recommended by the International Commission on Radiological Protection (ICRP) for the conversion of dose to risk for fatal cancer of 0.05 Sv^{-1} (IAEA 2011). However, this level of risk is negligibly low. The point in time, when the dose rate increases to above 10^{-7} mSv/a, is considered as “breakthrough point” in the analysis in Chapters 6 and 7.

Extended time period: Shading is also used in the dose-rate evolution graphic, where results are presented beyond the time period for assessment of 10^5 years for an L/ILW repository and 10^6 years for an HLW repository, to ensure that maximum dose rates are captured.

The difference between the maximum dose rate in the time period for assessment (1 million years) and the protection criterion of 0.1 mSv/a in ENSI (2023) is evaluated as the “safety margin”. Furthermore, in case the dose rate still increases after the time period for assessment, the safety margin is also measured by comparing the maximum dose rate over the whole simulation time (10 million years) with criterion point c mentioned in Section 3.1 (1.63 mSv/a to 13.67 mSv/a) according to BAG (2021).

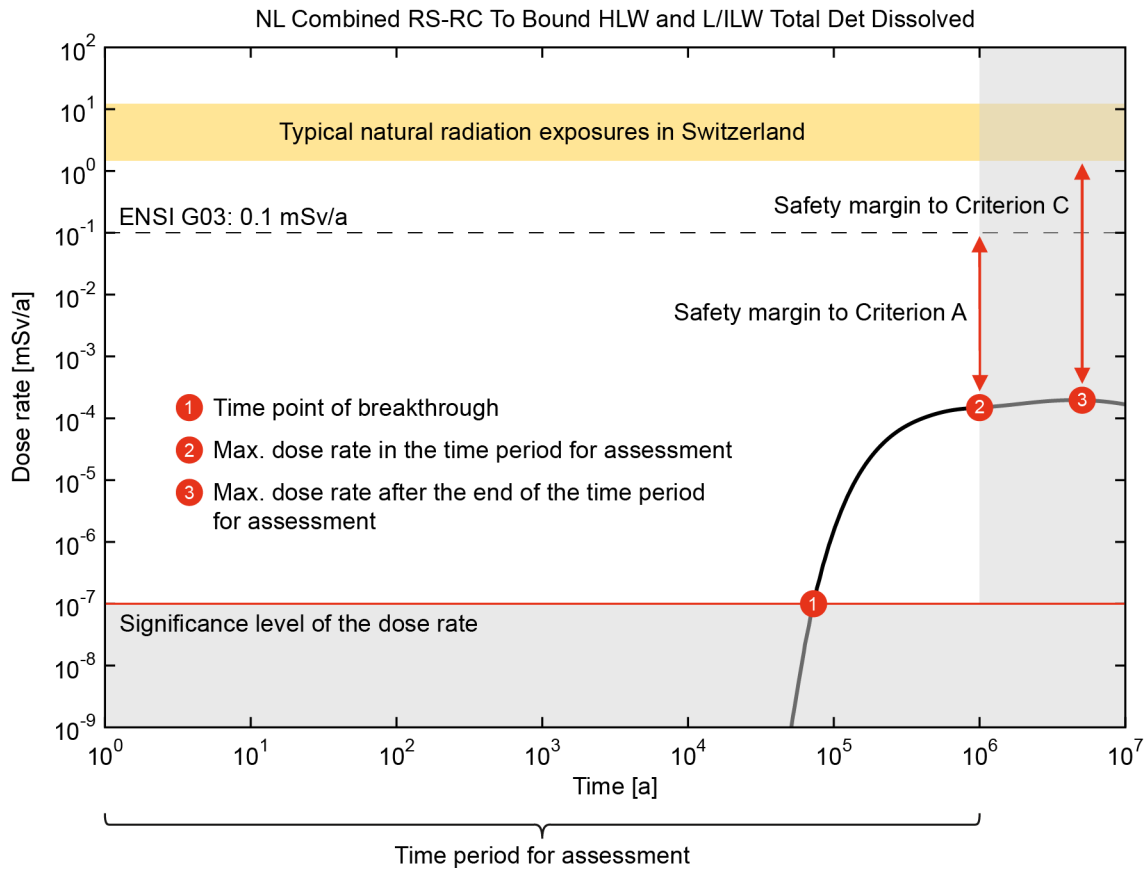


Fig. 3-1: Sample graphic illustration of the result of radiological consequence analysis

3.3 Biosphere dose conversion factors

As noted above, calculated radionuclide release rates are converted to annual individual dose rates using a set of nuclide-specific biosphere dose conversion factors (BDCFs). These BDCFs are derived from the biosphere modelling of both radionuclide transport and accumulation processes in the surface environment and radionuclide pathways that lead to human exposure (Nagra 2024i).

A key feature of radionuclide release rates to the surface environment is that, in most safety scenarios, they vary over timescales that are much longer than those of the most relevant transfer and accumulation processes at the surface environment. This allows radionuclide concentration equilibrium to be assumed within individual biosphere model compartments. Thus, release rates to the surface environment are not used directly as a source term for biosphere modelling. Rather, Nagra's biosphere model is used to calculate a set of BDCFs, which correspond to the calculated dose rate (Sv/a) at equilibrium for a constant unit release of a given radionuclide (Bq/a) in groundwater to the biosphere. Thus, multiplication of each BDCF with the calculated release rates of each respective radionuclide to the surface environment, and then summing the result, allows conversion of release rates to an effective dose rate.

Reference BDCFs are based on potential radionuclide releases to a valley, with characteristics consistent with present-day conditions in Northern Switzerland, which allows assessing a comprehensive range of exposure pathways. The modelling aims to be realistic in terms of representing radionuclide migration in the biosphere, but conservative in evaluating potential doses. The latter is achieved by assuming that people are present close to the area of release and that they make reasonable maximum use of local resources by spending all of their time in the local area, drawing local groundwater and living self-sufficiently (Nagra 2024i).

In respect to the requirement concerning biosphere modelling, alternative biosphere conditions are also considered. A warmer-drier climate would result in BDCFs that are higher than those based on the present-day climate, due to lower water flows in the surface and near-surface and higher irrigation requirements. Conversely, releases to an area drained for farming and releases under cold climate conditions (given that the time period for assessment will include glacial-interglacial cycles) result in BDCFs that are lower than those of the reference biosphere. Consistent with the BDCF approach, each climate state is assumed to persist throughout the time period for assessment, i.e., no transitions between different climate states are considered.

In the consequence analysis in support of both the site comparison and the safety case for a combined repository, the individual dose (dose rate) is generally calculated by multiplying the reference BDCFs by the radionuclide release rates to the biosphere, although the impact of using the alternative BDCFs is also investigated; see Section 4.1.3. The BDCF values can be found in the digital appendix. (Enclosure D: BDCFs.html)

3.4 Treatment of uncertainty in the radiological consequence analysis

It is common practice to categorise uncertainty based on its source, typically as scenario uncertainty, model uncertainty (also termed conceptual uncertainty), and data uncertainty (also termed parameter uncertainty) ((OECD/NEA 2012b), (Nummi 2019), (IAEA 2012)).

Concerning scenario uncertainty, a systematic screening provided by the performance assessment is the primary means by which the selected set of safety scenarios are ensured to bound and represent all possible ways in which the repository could evolve (Nagra 2024b). In addition, one or more variants can be defined for each safety scenario to capture the uncertainty. Variants of a given safety scenario share the same general description of FEPs occurring over time, but differ in one or more key factors that significantly affect the radiological consequences of that particular scenario. Key factors could include, for example, the extent or timing of key phenomena associated with the scenario or variant, as well as the location or properties of key features. The assumptions made regarding the identified key factor(s) are plausible and based on current knowledge. The calculation cases are then derived for the safety scenario, “what-if?” cases and their variants to capture a comprehensive picture of the radiological consequence. The simulation cases performed for the radiological consequence analysis are introduced in Chapter 4.

The model set used in the present report should be able to bound the radiological consequences for different safety scenarios and “what-if?” cases. Based on the current system understanding given by the geological investigation and performance assessment, model uncertainties caused by conceptualisation, simplification, abstractions and assumptions (including four aspects: geometric abstraction, process abstraction, homogenisation and the assumptions made regarding boundary and initial conditions) are identified and enveloped systematically. The impact of model uncertainty can be found in App. A. Furthermore, verification, validation and benchmarking tests are done for the codes and model configurations used in the radiological consequence analysis. These processes are documented in App. D and App. E.

The parametric data considered in radiological consequence analysis are taken from the reports comprising the assessment basis, e.g., the diffusion database (Glaus et al. 2024). The data uncertainty of the input parameters is usually quantified as a reference value and bandwidths in assessment basis reports. A deterministic reference case is calculated by combining the reference values to best estimate the radiological consequence. Probabilistic simulations are then performed to have a comprehensive picture of the radiological consequences by generating samples with truncated distribution covering the given parameter bandwidths. Parameter values, bandwidths and probability distributions are documented in App. H. For a parameter without a given bandwidth in the assessment basis, or considering that the bandwidth could cause an unrealistic value combination, either its best-estimate values (i.e., initial inventory of radionuclides) or its pessimistic boundary values (i.e., properties of the altered zones of bentonite) are considered in the probabilistic simulations.

A systematic sensitivity analysis is followed to capture the impact of the parameter uncertainty and identify the most important parameters. Additionally, a deterministic calculation case with a combination of pessimistic bounding values for all these parameters is performed to bound the radiological consequence within the framework of the reference safety scenario. In the deterministic calculation cases for the other safety scenarios and “what-if?” cases (documented in Chapter 4), the parameter values are set to either their best estimate based on current knowledge (e.g., instant release fractions of SF and L/ILW) or pessimistic values (e.g., transmissivity of a hypothetical fault) to bound the radiological consequences.

3.4.1 Deterministic and probabilistic calculations

In principle, there are two complementary techniques to quantify the uncertainty in the model output due to the uncertainty in the parametric data: deterministic and probabilistic uncertainty analyses. These techniques are used in combination in the present analysis of radiological consequences.

In a deterministic uncertainty analysis, uncertainty in model output is explored by defining and testing specific input parameter values. The starting point for deterministic uncertainty analysis is a reference case, against which a series of cases is compared. In a probabilistic uncertainty analysis, the selection of input data (referred to as sampling for each probabilistic “run” of a model) is carried out based on the probabilities assigned to the data using the Monte-Carlo method (see App. G.1), and the model output is analysed using graphical and statistical methods of sensitivity analysis. These techniques are used, for example, in the analysis of radiological consequences, in line with ENSI Guideline G03 (ENSI 2023), which states that a sensitivity analysis is to be carried out to identify the most sensitive parameters (or, more precisely, those parameters whose variance most affects variance in the results), as well as with (ENSI 2018). Usually, probabilistic simulation using the Monte-Carlo method consists of more than several thousand simulation runs with the sampled input parameters. Technically, each run of the Monte-Carlo simulations is called realisation.

Correlation coefficients are sensitivity measures used in sensitivity analysis to quantify the correlation between an input parameter and the output of a model. The most common correlation coefficients are the Pearson correlation coefficient, which is based directly on the raw values of the input and output, and the Spearman correlation coefficient, which is computed using the same expression as the Pearson correlation coefficient except that the ranks of each parameter are used instead of the raw values. These coefficients take values between -1 and 1 , with a negative value indicating that they tend to move in opposite directions, and a positive value indicating that the input and output parameter values tend to increase and decrease together. In addition, since the relationship between the input and output parameters is not always monotonic, a variance-based sensitivity measure called “modified EASI algorithm” is needed to avoid any oversight of

parameter sensitivity. The EASI algorithm (Plischke 2010) is a Fourier-based technique for performing variance-based methods of global sensitivity analysis for the computation of first-order effects (sensitivity of individual parameters without considering the interactions between the input parameters). In the present radiological consequence analysis, a modified EASI algorithm is used to investigate the parameter sensitivity (Plischke 2012). The modified first-order EASI sensitivity indices provide a fraction of output variance that is produced by the variation of the input parameters, without considering the interactions between parameters. The modified EASI sensitivity indices take values between 0 and 1. The mathematical background to the sensitivity indices mentioned above is described in detail in App. G.2.

For all these sensitivity measures, an important issue is their significance, given the limited number of Monte-Carlo simulations. To assess this, “dummy parameters” can be used to evaluate a “threshold of significance” for each sensitivity measure. Additionally, system understanding needs to be taken into account in judging the identified parameter sensitivity. The methods are described in App. G.3.

In carrying out the probabilistic analysis for the present report, correlations between the input parameters are considered in order to avoid unrealistic parameter combinations such as the correlation between effective diffusion coefficients (i.e., the diffusion coefficient of iodine-129 and chlorine-36 should be similar in each individual simulation). Such correlations are handled by assigning a value to each radionuclide that corresponds to the same percentile from the respective uncertainty bandwidths of the correlated parameters when carrying out probabilistic sampling (e.g., for diffusion coefficient of Cl-36 and I-129). Other strong correlations that are not radionuclide-specific, such as those between the properties of the Opalinus Clay and the properties of the excavation-damaged zone (EDZ), the correlation between permeability and capillary pressure, or the correlations between the corrosion rates of different metals, are handled by deriving mathematical relationships between the correlated parameters. The treatment of parameter correlations in probabilistic simulations is documented in App. C.2.

Risk dilution is not an issue in the present probabilistic approach since:

- the timing of safety-relevant events, such as canister failure, and spatial uncertainties, such as the location of exfiltration points to the biosphere, are not varied probabilistically;
- significant parameter correlations are considered; and
- the probabilistic analysis is complemented by deterministic calculation cases that quantify the radiological consequences when all parameters to which the results are most sensitive are assigned their most pessimistic values.

3.5 Radionuclide screening

The present description of the waste and of the nuclide inventory is based on MIRAM-RBG (Nagra 2023c). Due to the excellent retention properties of the repository barrier system, particularly the CRZ, only a small fraction of the MIRAM-RBG radionuclide inventory will be able to migrate out from the CRZ and needs to be considered when calculating dose rates. A screening process is carried out before the radiological consequence analysis in order to identify those radionuclides that need to be considered in the deterministic and probabilistic analysis. This process is described fully in Section 5.4.1 of Nagra (2024o) and summarised below.

The majority of radionuclides are expected to be transported in the liquid phase. For these, a two-step screening is implemented. The first step yields a set of radionuclides for consideration in the deterministic calculations, as listed in App. H.1 of this report. For the computationally demanding analysis using probabilistic calculations, a second screening step is then applied to further reduce

the set of calculated radionuclides to those shown in Tab. 3-1. This reduction of the number of radionuclides does not have a negative impact on the reliability of the assessment result. Rather, a reduced number of radionuclides can help to avoid unrealistic parameter combinations that can arise from the complex correlations between the nuclide-specific parameters, that quantify the migration processes. This is consistent with guidance in ENSI's explanatory report (ENSI 2020a) for ENSI Guideline G03 (ENSI 2020a).

Tab. 3-1: Reduced set of radionuclides considered in the probabilistic calculations²

Ag-108M
Ca-41
C-14inorg (C-14 in inorganic form)
C-14org (C-14 in organic form)
Cl-36
I-129
Se-79
Hg-194

A few radionuclides are gaseous or can form volatile species that can be transported through the repository barriers by repository-generated gas. The screening process shows that C-14org (as methane) is the only radionuclide that can be transported in the gas phase (Nagra 2024r). Other radionuclides that could be gaseous under repository conditions are not relevant when considering gas-mediated transport, either due to their high solubility (i.e., I-129 and C-14 in inorganic form) or their short half-lives (i.e. H-3 and Rn-210). Thus, deterministic and probabilistic calculations that consider gas-mediated radionuclide transport only consider C-14org in the form of methane.

3.6 Conformance with regulatory guidance

Requirements for the final stage of the site selection process and for the safety assessment for the site selected by Nagra, in the context of the RBG, are detailed in ENSI (2018). Specific requirements for the safety assessment for the selected site are set out in ENSI Guideline G03 (ENSI 2023) and further elaborated in the explanatory report (ENSI 2020a). The radiological consequence analysis is performed fully in line with the regulatory requirements. Compliance of the approaches used for the analysis of radiological consequences with these requirements is described further in App. I.

² Radionuclide screening for inclusion in probabilistic assessments relies on their transport properties and inventory. The inventory is typically well-established with minor uncertainties. However, the evolving chemical environment surrounding the waste can significantly influence radionuclide mobility. To account for uncertainties in this evolving environment, a conservative approach assumes the chemical form with higher mobility. In the future stage of the project, scientific advancements can lead to a reduction in the list of considered radionuclides.

4 Safety scenarios, variants and calculation cases

The radiological consequence analysis is a model-based assessment performed based on the safety scenarios defined and fully characterised in Nagra (2024b). Safety scenarios are general descriptions of the evolution of a repository system and its environment, starting from its initial state at the time of excavation of the underground openings and emplacement of the waste and engineered barriers, and extending into the future, generally for as long as the waste presents a potential hazard. It also includes the assumptions made regarding the biosphere for the analysis of radiological consequences (Nagra 2024b).

In addition, one or more variants can be defined for each safety scenario. Variants of a given safety scenario share the same general description of FEPs occurring over time, but differ in one or more key factors that significantly affect the radiological consequences of that particular scenario (Nagra 2024b). Key factors could include, for example, the extent or timing of key phenomena associated with the scenario or variant, as well as the location or properties of key features. The assumptions made regarding the identified key factor(s) are plausible and based on current knowledge. However, safety scenarios and their variants do not need to accurately represent real-world conditions but rather “envelop” the scenario uncertainty in order to bound the radiological consequences.

Based on the developed safety scenarios and variants, a set of calculation cases has been derived and described in Nagra (2024b), along with additional, hypothetical “what-if?” cases. In order to bound and understand the consequence of the parameter uncertainty in the framework of the reference safety scenario, multiple calculation cases – deterministic and probabilistic – are defined and analysed. In addition, since the main goal of the consequence analysis considering the alternative safety scenarios and “what-if?” cases is to bound the radiological consequences, only conservative, deterministic calculation cases are considered.

The safety scenarios analysed in the present report are summarised briefly in this chapter, along with their variants, calculation cases and hypothetical “what-if?” cases. As illustrated in Fig. 4-1, the reference and alternative safety scenarios are analysed for all three siting regions under consideration in SGT-E3 for both an HLW repository and an L/ILW repository. In addition, all safety scenarios, as well as the “what-if?” cases, are analysed for a combined repository for all waste types at the selected site, in support of the post-closure safety case.

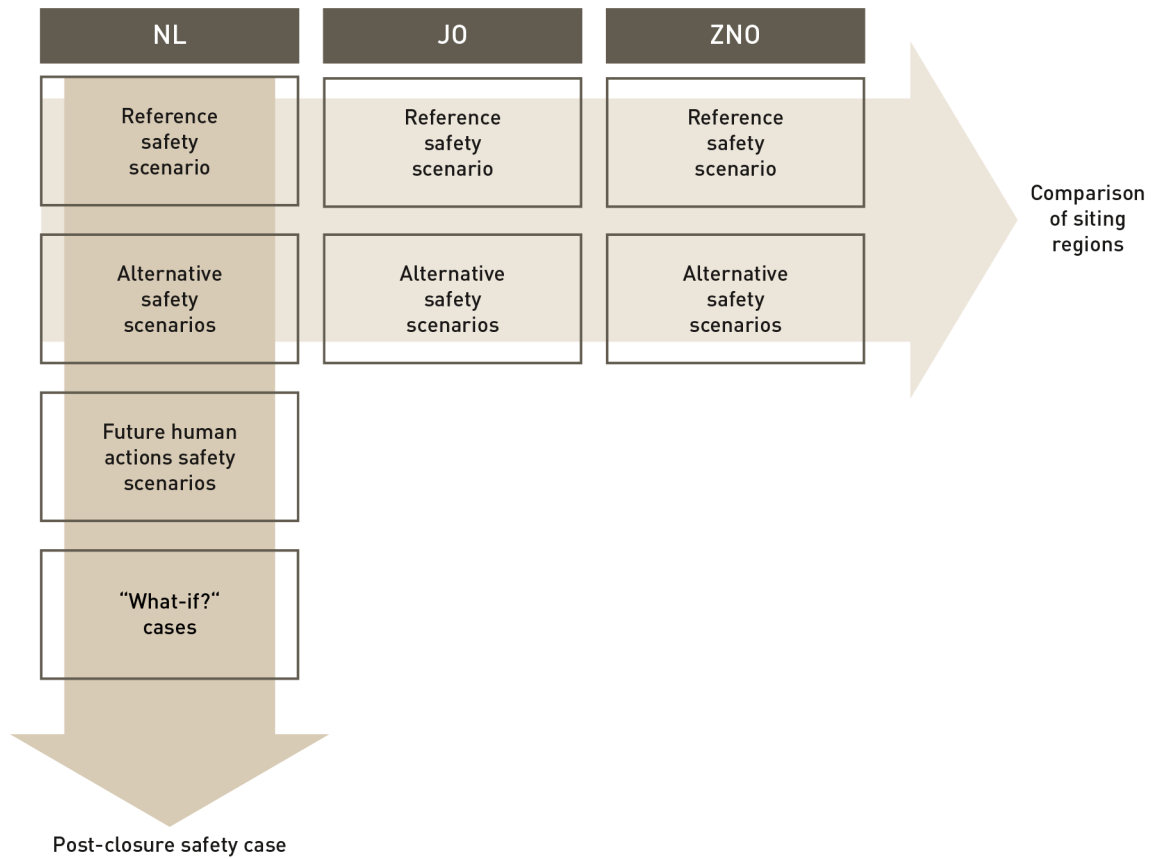


Fig. 4-1: Safety scenarios and “what-if?” cases as input to the post-closure safety case and to the comparison of the siting regions

4.1 Reference safety scenario

4.1.1 General description

The reference safety scenario is a general description of the initial state of the repository barriers, their expected evolution over time, and the assumptions made regarding the biosphere for the analysis of radiological consequences. A detailed description of the reference safety scenario can be found in Section 5.1 in Nagra (2024b). Some key aspects of the safety scenario related directly to the radiological consequence analysis are briefly documented in this section.

In the reference safety scenario, the engineered barriers are assumed to be implemented according to the provisional repository design, as described in Section 2.1. The geological barrier (i.e., the CRZ) assumes the characteristics and the evolution inferred from site characterisation and understanding, as described in Section 2.2.

Based on the performance assessment, repository-induced effects associated with thermal, hydraulic, mechanical and chemical (THMC) processes are expected to have minimal effects on the geological environment (Nagra 2024p). The following impacts are, however, included in the definition of the reference safety scenario:

- Repository-induced thermal effects could lead to a narrow zone of altered bentonite around the HLW disposal canisters (Curti 2023 and Nagra 2024h).
- Stress changes during the construction of the underground openings will result in the formation of EDZs, which will largely reseal over time (Nagra 2024h). However, their constant presence is conservatively accounted for in the description of the reference safety scenario.
- Ventilation during the operational phase leads to depressurisation and partial desaturation of the EDZ (Nagra 2024h). This process will be reversed during the early post-closure phase.
- Repository-generated gas will not impact the mechanical integrity of the multi-barrier system (Nagra 2024p).

The release, retention and transport of radionuclides from the repository in the reference safety scenario follow its expected evolution as described below.

Radionuclide release following the breaching of HLW disposal canisters. HLW disposal canisters are assumed to provide complete containment over a period of up to 10,000 years (Nagra 2024a). They will, however, eventually breach, most likely at weld flaws, allowing porewater from the bentonite buffer to enter.

In the case of SF, water will first contact the Zircaloy SF cladding. The cladding has a low corrosion rate (Diomidis et al. 2023) and is likely to prevent the contact of water with the SF pellets until it has substantially corroded. Nevertheless, the cladding of a small fraction of the fuel rods may have suffered from embrittlement, either in the reactor or during interim storage, or could have been damaged during handling. For this reason, in the reference safety scenario, no credit is taken for the Zircaloy cladding in delaying contact between the buffer porewater and the SF pellets. Activation products within the Zircaloy will mainly be released congruently as it corrodes, although a small fraction of the C-14 will be released more rapidly (Nagra 2024r).

As water contacts the SF pellets, a fraction of the inventory of some radionuclides will also be released relatively rapidly; this is the so-called instant release fraction (IRF) (Johnson et al. 2023). These gaseous or volatile species (I-129, C-14, Cl-36, Cs-135) are segregated from the fuel matrix and accumulate in the gap between the pellet and the cladding, and at grain boundaries. However, the majority of the radionuclide inventory resides in the uranium dioxide and MOX pellets and is released slowly and congruently with their dissolution rates.

The vitrified RP-HLW is protected by the outer disposal canister and the inner stainless-steel flask. When the canister has breached after the assumed complete containment time (10,000 years), the stainless-steel flask can prevent contact of porewater with the RP-HLW until it has largely corroded. Despite this, no credit is taken for the stainless-steel flasks in delaying contact between the buffer porewater and the RP-HLW matrix in the reference scenario. Once water contacts the waste, radionuclides in the waste matrix will be released congruently during the slow dissolution of the glass (Curti 2022).

Radionuclides that enter solution will migrate through the saturated bentonite buffer, the degraded lining and into the host rock (Hummel et al. 2023). Some, however, will be temporarily immobilised by precipitation and co-precipitation within and around the waste packages for as long as the respective solubility limits are exceeded.

The retention capacity of radionuclides in the lining can be neglected. Furthermore, any colloids formed within and around the waste packages will not migrate into the bentonite buffer due to its fine and homogeneous pore structure.

Some radionuclides, notably C-14, can also be released in the gaseous form congruently (Nagra 2024r). However, due to the earlier saturation of the bentonite used in the seals and backfill, which can give a high resistance against the gas migration, the gas generated in the HLW emplacement drifts will not have significant advective migration through the drifts. Instead, a diffusive transport of the gas from the HLW near-field into the rock will be the dominating gas transport pathway (Nagra 2024k).

Radionuclide release from the L/ILW disposal containers. L/ILW disposal containers provide containment for the radionuclides for a limited period, though no credit is taken for any L/ILW containment in the reference safety scenario. Soluble radionuclides released from the waste barrels into the container infill mortar will dissolve in the porewater that initially accumulates at the bottom of the emplacement caverns. The radionuclides will then diffuse through the backfill mortar and lining of the partly saturated emplacement cavern, and into the host rock. Some dissolved radionuclides can be immobilised by precipitation and retained by sorption and adsorption within the cement paste of the cement-based near-field (Tits & Wieland 2023). No colloids formed within and around the waste packages will be able to migrate in the host rock or through the repository section seals due to the fine and homogeneous pore structure of the rock and of the sealing elements (Kosakowski et al. 2023).

Gaseous radionuclides will be conveyed with other repository-generated gas via two-phase flow processes through the backfill mortar and into the gas-permeable sealing system of the L/ILW repository section, with two-phase flow processes (Nagra 2024k).

Radionuclide retention and transport processes in the repository barriers. Dissolved radionuclides in the porewater of the emplacement drifts and caverns will migrate through the near-field porewater and into the CRZ (Nagra 2024h). The migration of many radionuclides will be strongly retarded by sorption on solid phases in both the near-field and geosphere (Marques Fernandes et al. 2024). Retardation by sorption in the cement-based L/ILW near-field will be affected by the evolving cement mineralogy as cement phases, as is accounted for by the cement sorption database (Tits & Wieland 2023).

Transport of radionuclides in the CRZ occurs by advection and diffusion, with diffusion being the dominant transport mode for dissolved radionuclides (Nagra 2024f). Any discontinuities within the CRZ are assumed to have no significant impact on porewater flow and radionuclide transport because of their limited transmissivity and connectivity as well as their self-sealing properties (Nagra 2024f). Diffusion is also the dominant transport mode for radionuclides in the repository near-field, due mainly to the low hydraulic conductivity of the sealing system, the bentonite buffer and the surrounding CRZ and also due to the dead-end architecture of the emplacement drifts and caverns. The EDZ around the HLW emplacement drifts does not represent a significant lateral transport pathway for dissolved radionuclides (Nagra 2024p). Advection of dissolved radionuclides due to the displacement of near-field porewater by gas can be considered negligible (Nagra 2024p).

Radionuclides that form volatile species are transported along with repository-generated gases through the engineered barriers and enter the CRZ via two-phase flow processes. These eventually dissolve in porewater within the repository barrier system, including the confining units, or within groundwater flowing through the deep aquifers (Nagra 2024r).

4.1.2 Variants and cases defined for the reference safety scenario

According to the description in Section 2.2, the CRZ extends from the upper deep aquifer above the repository (located within the Malm unit in the case of NL and ZNO, and within the Calcareous Dogger in the case of JO) to the Keuper aquifer below the repository. Since any discontinuities within the CRZ are assumed to have no significant impact on porewater flow and radionuclide transport, geological units in the CRZ are considered as homogeneous porous media for radionuclide transport. Diffusive and advective transport can take place in the geological units and between the connected geological units.

Within the CRZ, there are a number of (i.e., hard and brittle) horizontal units embedded between units of more plastic clay. In the reference safety scenario, these units do not form connected pathways for radionuclide transport (the possibility of a hydraulically active confining unit is addressed as an alternative safety scenario; see Section 4.2.1).

According to geological investigations (Nagra 2024e), the Keuper aquifer is hydraulically active in the three siting regions, with an exception, that the Keuper below the HLW repository section in the NL siting region is hydraulically inactive, however, this geological finding remains somewhat uncertain. Thus, for the reference safety scenario, this results in the main “reference conceptualisation of the CRZ”, in which the Keuper is assumed to be hydraulically active (allowing a single common scenario to be formulated for all three siting regions). A variant considers an inactive lower aquifer (Keuper) in the NL siting region only (see Fig. 4-2):

- **Reference conceptualisation of the CRZ:** it is conservatively assumed that the Keuper aquifer is active and forms a significant lateral advective transport pathway below the repository.
- **Variant specific to NL:** the Keuper aquifer below the HLW repository section in the NL siting region is inactive and radionuclides are transported vertically across it; the CRZ extends vertically downwards to the Muschelkalk aquifer. However, according to the geological investigation results (Nagra 2024e), this variant is only relevant to the HLW repository section in the NL siting region.

The domain of the geosphere transport models for the liquid phase always extends from the overlying aquifers (within the Malm or Calcareous Dogger units) to the Muschelkalk aquifer below the repository. Radionuclides reaching the hydraulically active Keuper aquifer in the reference conceptualisation can either be transported vertically across it, predominantly by diffusion, or be diverted into the aquifer and conveyed by groundwater flow to a regional aquifer (considered part of the biosphere). Radionuclides that reach the other deep aquifers, at the boundaries of the geosphere model, are also conveyed to the biosphere. However, in the variant with the hydraulically inactive Keuper below the HLW repository section in NL, the horizontal flow in the Keuper to a regional aquifer is excluded.

In the reference conceptualisation for the radiological consequence analysis concerning gaseous radionuclide migration (C-14 methane), the model lower boundary is the Keuper aquifer and, conservatively, the rock formations below the Keuper aquifer are not taken into account.

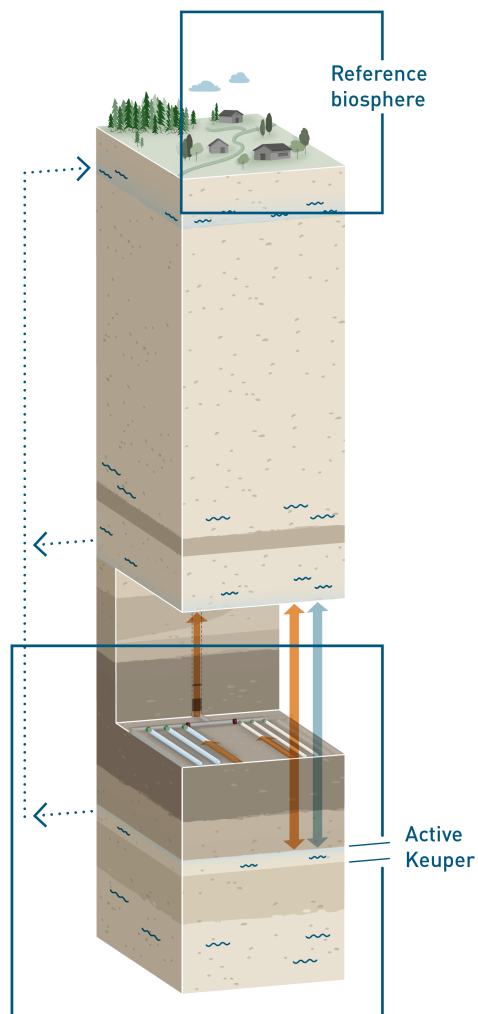
All the aspects mentioned in Section 4.1.1 are well covered both in the reference conceptualisation and in the variant to ensure a reliable consequence analysis.

4.1.3 Definition of calculation cases

For each siting region, and for the reference conceptualisations and variant of this safety scenario, the calculation cases shown in Fig. 4-2 and in Tab. 4-1 are considered.

Reference safety scenario

Reference calculation case



Additional calculation cases (list not exhaustive)



Main pathways of radionuclides:

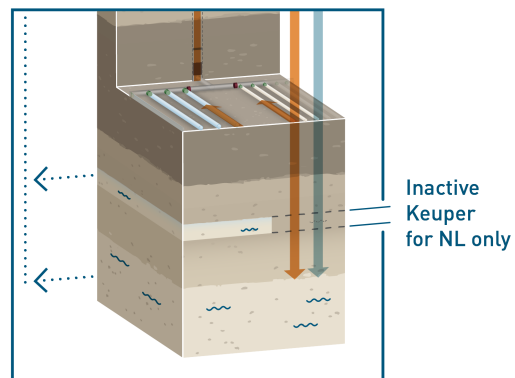
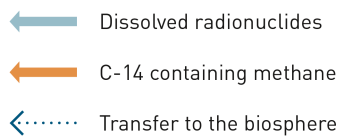


Fig. 4-2: Main pathways for radionuclide transport in the reference safety scenarios, showing, in the bottom left box, the reference conceptualisation with a hydraulically active Keuper aquifer and, in the bottom right box, the variant with the inactive Keuper aquifer. The figure also illustrates alternative biosphere assumptions

The blue and orange arrows in this and subsequent similar figures indicate, respectively:

- Radionuclide migration in the liquid phase, in which radionuclides are released to porewater that contacts the waste packages and are subsequently transported by aqueous diffusion and, where there is porewater flow, by advection.
- Radionuclide migration of C-14 in the gas phase, in which gaseous radionuclides mix with, and are transported by, repository-generated gas via two-phase flow processes.

The modelling approaches used to simulate these migration pathways are described in Chapter 5 and, in more detail, in App. B of this report.

The reference case, denoted as RS-RC, is a single, deterministic calculation case, based on the reference conceptualisation with the hydraulically active Keuper aquifer. A reference biosphere based on present-day climatic conditions is assumed. The reference case is analysed in more detail in Chapters 6 and 7, which outline the analysis concerning the “efficiency” of the different repository barriers.

Additional calculations are also defined that aim to identify, illustrate and quantify the impact of uncertainty in the parameters that control radionuclide retention and transport in the repository barriers:

- RS-PROB, which is a probabilistic calculation case with multiple realisations where all relevant parameters are sampled randomly from probability distributions. The distributions are derived from an assessment of parameter uncertainty to illustrate the range of uncertainty in calculated consequences and to provide the data for a global probabilistic sensitivity analysis.
- RS-PROB-*Param*, is a set of deterministic calculation cases in which each parameter to which the radiological consequences are most sensitive is set to its most pessimistic value within its probability distribution. Additionally, a calculation case with a combination of pessimistic values for all these parameters is defined and termed RS-CMB (“combined pessimistic case”)

Three additional deterministic calculation cases are defined that assume different, though still steady-state, climatic and surface conditions:

- RS-BIOS/WARM_DRY, based on a warmer and drier climate;
- RS-BIOS/COLD, based on a colder climate; and
- RS-BIOS/DRAINED_FARMLAND, which assumes a drained farmland.

Further details of the reference and alternative biospheres, and of biosphere modelling in general, are provided in Nagra (2024i).

Finally, for the NL siting region only, a single deterministic calculation, RS-KEUPER_INACTIVE, is defined for the variant in which the Keuper aquifer is hydraulically inactive.

Tab. 4-1: Calculation cases for the reference safety scenario

Variant	Case	Description
Reference conceptualisation of CRZ; hydraulically active Keuper aquifer	RS-RC	Reference case (reference biosphere)
	RS-PROB	Probabilistic simulation based on considering the parameter uncertainty
	RS-PROB- <i>Param</i>	Multiple cases in each of which a single sensitive parameter (<i>param</i>) is set to its pessimistic, bounding value.
	RS-CMB	All sensitive parameters are set to their pessimistic, bounding values.
	RS-BIOS/WARM_DRY	Warmer and drier climate
	RS-BIOS/COLD	Colder climate
	RS-BIOS/DRAINED_FARMLAND	Biosphere with drained farmland
Specific to the selected site: hydraulically inactive Keuper aquifer	RS-KEUPER_INACTIVE*	Hydraulically inactive Keuper aquifer below the HLW repository in NL, or below the HLW section of a combined repository at the selected site

* Considered only for HLW repository at the selected site, or below the HLW repository section of a combined repository.

4.2 Alternative safety scenarios, variants and calculation cases

As described in Nagra (2024b), specific uncertainties flagged for further consideration as alternative safety scenarios concern uncertainties in geological characterisation, and, specifically, the possibility that there could be:

- a hydraulically active confining unit above or below the Opalinus Clay host rock; or
- an undetected fault in the vicinity of the repository emplacement rooms.

Alternative safety scenarios incorporating these deviations in performance, as well as their variants and calculation cases, are described in the following sections.

4.2.1 Hydraulically active confining geological unit

This alternative safety scenario assumes that one of the horizontal features within the confining geological units provides a horizontally connected advective pathway to the regional aquifer, and thus an additional pathway for the advective transport of radionuclides to the biosphere. Although no geological evidence has so far been established, it is speculated that this could be due to fractures within a lower-clay-content unit that is denser and has a higher degree of connectivity than currently understood (Nagra 2024e).

Units with potential for elevated local transmissivity in each siting region are marked in Fig. 2-5 with grey arrows. In the case of JO and ZNO, there is one such unit among the upper confining units (SCD: Sandy-Calcareous Dogger) and one among the lower confining units (CL: Calcareous Lias). For NL, there are three among the upper confining units (CM: Calcareous Malm, CD: «Herrenwis Unit» and SCD: Sandy-Calcareous Dogger) and two among the lower confining units (CL: Calcareous Lias and DK2: Dolomitic Keuper)³.

The variants propagated to the analysis of radiological consequences are summarised in Tab. 4-2. Each potentially active unit present in a siting region is considered, in turn, to be active, while the remaining units are considered inactive.

Tab. 4-2: Variants of the alternative safety scenario considering hydraulically active confining units that are propagated to the analysis of radiological consequences.

UCU = upper confining units; LCU = lower confining units: See Fig. 2-5 for an illustration of the locations of the individual, potentially hydraulically active rock units in each siting region.

Variant	Case	Description
Additional hydraulically active unit within the CRZ above the Opalinus Clay	AS-HA/SCD	hydraulically active SCD unit (Sandy-Calcareous Dogger)
	AS-HA/CD	hydraulically active CD unit («Herrenwis Unit», NL only)
	AS-HA/CM	hydraulically active CM unit (Calcareous Malm, NL only)
Additional hydraulically active unit within the CRZ below the Opalinus Clay	AS-HA/KEU	hydraulically active KEU unit (Calcareous Lias)
	AS-HA/KAU	hydraulically active KAU unit (Dolomitic Keuper, NL only)

In each of these calculation cases, radionuclides reaching a hydraulically active unit can either be transported vertically across it, predominantly by diffusion, or be diverted into the unit, in which case they are assumed to be conveyed instantaneously to the biosphere (see Fig. 4-3). In the modelling concerning C-14 with two-phase flow, any C-14 reaching a hydraulically active unit in the form of methane is assumed to dissolve. Compared to the conceptualisation for the reference safety scenario, the transport length and dilution capacity of in the CRZ will be accordingly reduced, depending on the distance of the hydraulically active units to the repository.

The transport time for dissolved radionuclides within these units and between these units and the biosphere is conservatively neglected. This is the same assumption made for radionuclides released to the deep aquifers. Furthermore, the same horizontal gradients as assumed for the deep aquifers overlying the repository given in Nagra (2024e), i.e., the Malm aquifer in NL and ZNO and the Calcareous Dogger in JO, are assumed for hydraulically active units in the upper confining units (UCU), and the same gradient as for the Keuper aquifer is assumed for hydraulically active units in the lower confining units (LCU).

³ Locations of these units can be found in Fig. 2-5.

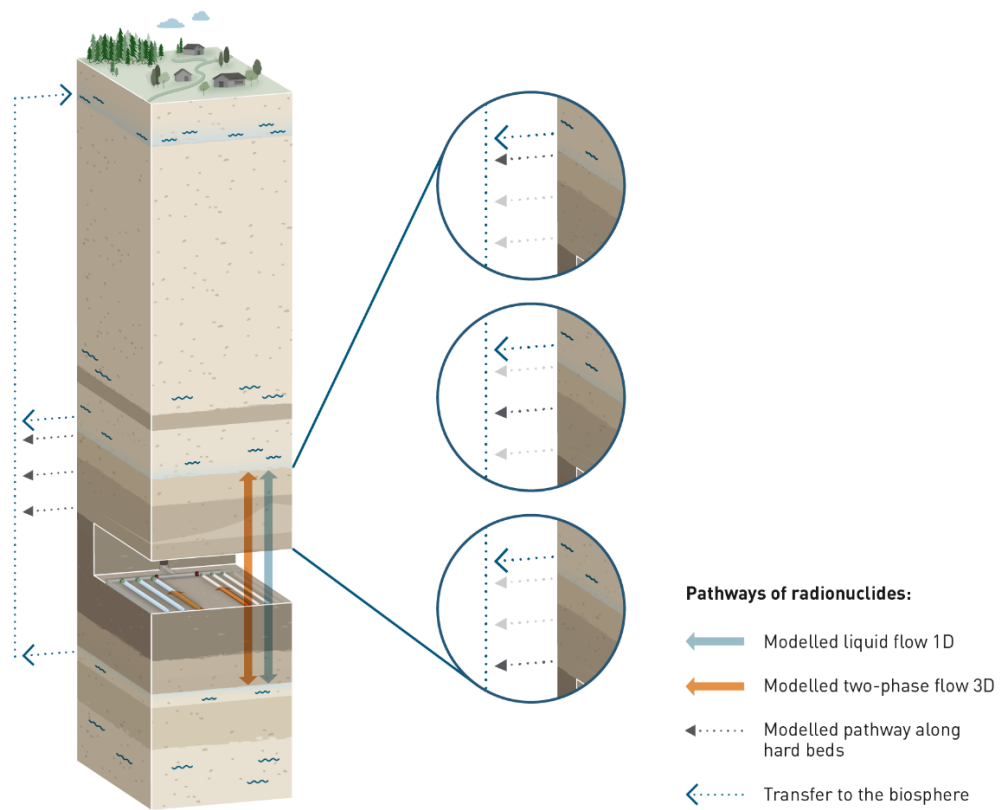


Fig. 4-3: Main pathways for radionuclide transport where it is assumed that any hydraulically active confining unit is hydraulically connected to the regional aquifer and thus provides an additional pathway for the advective transport of radionuclides (grey arrows illustrate that one individual hard bed is assumed to be hydraulically active in each simulation case)

4.2.2 Undetected fault

No evidence has so far been established in the geological findings by Nagra (Nagra 2024e) for a hydraulically active fault in the CRZ. It is speculated that an undetected fault, with a transmissivity in the range of what could be expected in such a scenario, exists in the vicinity of the repository at the time of its construction. Four calculation cases are defined and analysed, two for each of the two variants of this safety scenario, as shown in Tab. 4-3.

Tab. 4-3: Calculation cases for the undetected fault alternative safety scenario

Variant	Case	Description
Fault intersects the HLW emplacement drifts	AS-FLT-HLW-Along	Fault (with transmissivity of 10^{-10} m ² /s) strike runs along the axis of a single emplacement drift
	AS-FLT-HLW-Across	Fault (with transmissivity of 10^{-10} m ² /s) strike runs perpendicular to drifts, cutting each drift at its centre
Fault intersects L/ILW emplacement caverns	AS-FLT-L/ILW-Along	Fault (with transmissivity of 10^{-10} m ² /s) strike runs along the axis of a single emplacement cavern
	AS-FLT-L/ILW-Across	Fault (with transmissivity of 10^{-10} m ² /s) strike runs perpendicular to emplacement caverns, cutting each cavern at its centre

The undetected fault is conceptualised for bounding the radiological consequence as a vertical planar feature running through the entire CRZ with a transmissivity and hydraulic gradient that are constant in space and time. This conceptualisation is very conservative compared to the geological finding showing that the existing faults are, in reality, small in scale.

Where the fault strike is parallel to the emplacement rooms, the fault is assumed to pass through one single emplacement room. Where the fault strike is perpendicular to the emplacement rooms, the fault is assumed to pass through all emplacement rooms in the HLW or L/ILW disposal area (but not the emplacement rooms of the pilot repositories). These different fault configurations are illustrated in Fig. 4-4.

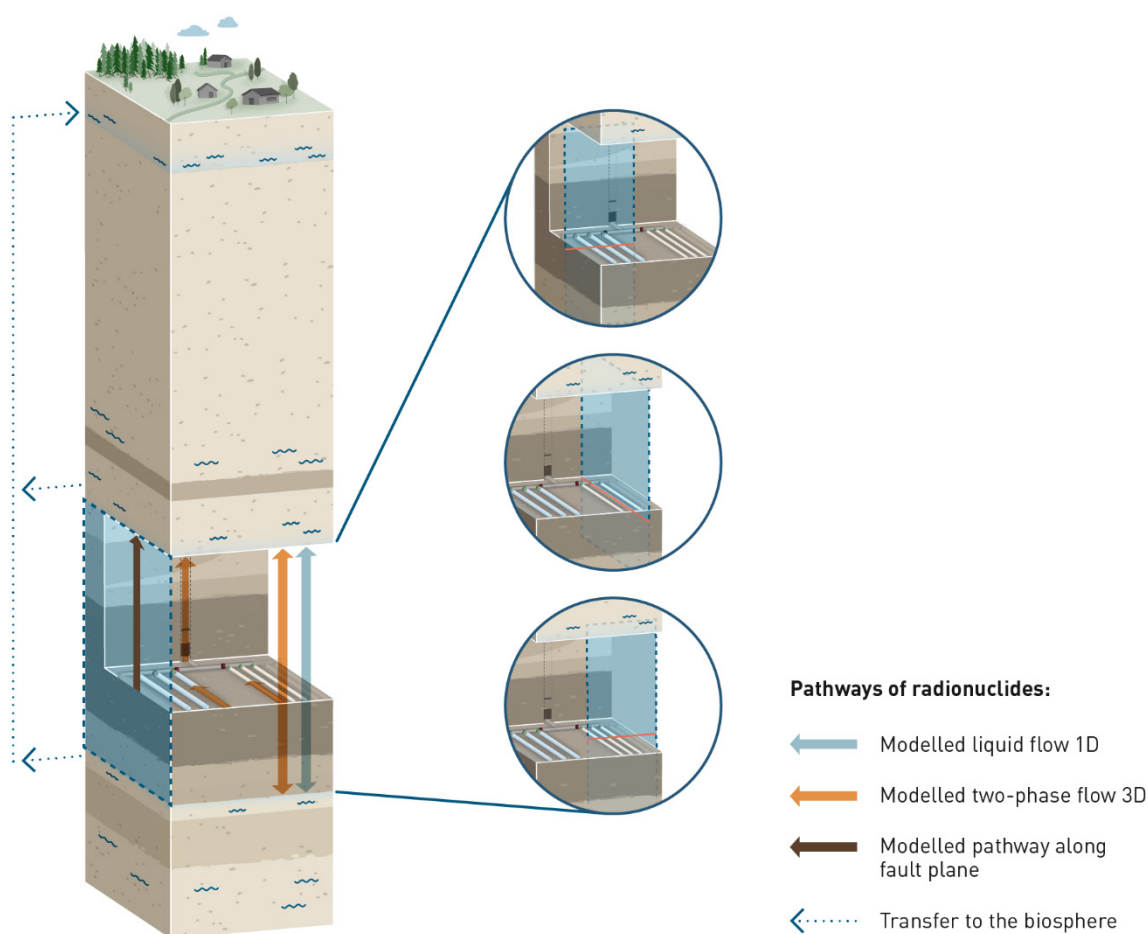


Fig. 4-4: Pathways for radionuclide transport, where it is assumed that there is an undetected fault that intersects one or more L/ILW emplacement caverns or HLW emplacement drifts

The small inset figures show the different ways in which the fault is conceived to intersect these repository features in the modelling.

In the cases concerning undetected faults, the near-field (i.e., the bentonite buffer in the HLW repository and cementitious backfill in the L/ILW repository) assumes the same role as in the reference case because the faults are hypothetically not detected during repository construction.

The fault transmissivity is conservatively assumed to be $10^{-10} \text{ m}^2/\text{s}$. This is higher than the highest observed fault transmissivity in the Opalinus Clay measured at relevant depths in Northern Switzerland (Nagra 2024f). It is also conservatively assumed that the fault provides constant groundwater flow over the entire time period for assessment. Consistent with the characterisation of hydraulic heads (Nagra 2024e) and with the assumptions made in the performance assessment (Nagra 2024f), flow of water through the fault is assumed to occur vertically upwards from the aquifer underlying the repository to the aquifer above. However, for the modelling concerning gas migration, the two-phase flow in the fault is mainly caused by the pressure difference between the aquifer and the near-field, where the assumption of constant groundwater flow is irrelevant.

The detailed description of the model assumptions and conceptual configuration concerning an undetected fault can be found in App. A, B.1.2 and B.2.3.

4.3 “What-if?” cases

As discussed in Chapters 7 and 8 in Nagra (2024b), two types of “what-if?” cases need to be considered in the radiological consequence analysis. One is related to physical phenomena documented in Section 4.3.1, another is the cases postulating hypothetically degraded performance of pillars of safety introduced in Section 4.3.2.

4.3.1 “What-if?” cases related to physical phenomena

The “what-if?” cases described in the following sections concern the occurrence of features and processes either with characteristics that lie outside the range of possibilities supported by currently available evidence and knowledge, or whose occurrence during the one-million-year time period for assessment is judged to be exceedingly unlikely. They are nonetheless defined and analysed to demonstrate the robustness of the repository system. Two such groups of “what-if?” cases, defined in Nagra (2024b), are analysed in the present report:

- the occurrence, in the vicinity of the repository, of an undetected fault with elevated transmissivity; and
- the future creation or re-activation of a fault either by geological processes or as a repository-induced effect.

4.3.1.1 Undetected fault with elevated transmissivity

First, “what-if?” cases considering an undetected fault with an elevated transmissivity are defined. Here, the transmissivity is higher than reasonably expected, i.e., much higher than for the fault described for the alternative safety scenario in Section 4.2.2. Thus, these cases consider the hypothetical failure of the self-sealing process in the CRZ, such that the fault exists in the vicinity of the repository at the time of its construction and persists throughout the entire time period for assessment. Four “what-if?” cases are defined and analysed, two cases for each of the two variants of such a fault, as shown in Tab. 4-4. The same conceptualisations are used for these cases as those for alternative safety scenarios concerning an undetected fault as outlined in Section 4.2.2. The only difference is the transmissivity of the fault is assumed to be $10^{-7} \text{ m}^2/\text{s}$, which is similar to the fault transmissivities observed in carbonate-rich geological units such as “hard beds”.

Tab. 4-4: “What-if?” cases for an undetected fault with elevated transmissivity

Variant	Case	Description
Fault with elevated transmissivity intersects the HLW emplacement drifts	WI-FLT-HLW-Along	Fault, with a transmissivity of 10^{-7} m ² /s, with strike running along the axis of a single emplacement drift
	WI-FLT-HLW-Across	Fault, with a transmissivity of 10^{-7} m ² /s, with strike running perpendicular to drifts, cutting each drift at its centre.
Fault with elevated transmissivity intersects the L/ILW emplacement caverns	WI-FLT-L/ILW-Along	Fault, with a transmissivity of 10^{-7} m ² /s, with strike running along the axis of a single emplacement cavern.
	WI-FLT-L/ILW-Across	Fault, with a transmissivity of 10^{-7} m ² /s, with strike running perpendicular to caverns, cutting each cavern at its centre.

4.3.1.2 Fault creation or reactivation by geological processes or repository-induced effects

These “what-if?” cases concern either the generation of a new fault or the reactivation of an existing, non-transmissive fault during the post-closure period. Faulting or fault reactivation are assumed to occur as the result of stress changes induced either by geological processes, such as seismic activity, or by heat generated within the repository. Four “what-if?” cases are defined and analysed, two for each of two variants, as shown in Tab. 4-5.

Tab. 4-5: “What-if?” cases for fault reactivation by geological processes or repository-induced effects

Variant	Calculation case	Description
Newly created or re-activated fault intersects the HLW emplacement drifts	WI-FLT/RA-HLW-Along	Fault, with a transmissivity of 10^{-7} m ² /s created at 10,000 years, with strike running along the axis of a single emplacement drift.
	WI-FLT/RA-HLW-Across	Fault, with a transmissivity of 10^{-7} m ² /s created at 10,000 years, with strike running perpendicular to drifts, cutting each drift at its centre.
Newly created or re-activated fault intersects the L/ILW emplacement caverns	WI-FLT/RA-L/ILW-Along	Fault, with a transmissivity of 10^{-7} m ² /s created at 20,000 years, with strike running along the axis of a single emplacement cavern.
	WI-FLT/RA-L/ILW-Across	Fault, with a transmissivity of 10^{-7} m ² /s created at 20,000 years, with strike running perpendicular to caverns, cutting each cavern at its centre.

The conceptualisation and the transmissivity of the fault is identical to those cases for the faults with elevated transmissivity introduced in Section 4.3.1.1. However, the difference is that the fault is assumed to be created or reactivated 10,000 years after repository closure in cases where the fault intersects the HLW repository section, and after 20,000 years in cases where the fault intersects the L/ILW repository section, according to the timing of occurrence of overpressure in the near-field (Nagra 2024k).

Where the fault intersects the HLW repository section, damage to the bentonite buffer is assumed to result in a degraded performance of this barrier. In the cases concerning radionuclide transport in the liquid phase, a degraded performance is modelled by setting the diffusion coefficient in bentonite to that of free water and setting no solubility limits for radionuclides in solution. For the modelling concerning C-14 methane, an increased permeability of the bentonite buffer is assumed (10 times higher than the reference permeability of bentonite).

In the cases where the fault intersects the L/ILW repository section, no significant impacts on the transport properties of the cementitious near-field are expected because of the already high porosity and hydraulic conductivity. Hence, given the simplifying assumptions used in the L/ILW near-field modelling, as described in Chapter 5, no changes to the transport parameters are made for the modelling of these cases.

4.3.2 “What-if?” cases postulating a hypothetically degraded performance of the pillars of safety

In addition to the “what-if?” cases related to physical phenomena documented above, hypothetical “what-if?” cases are defined to test the robustness of the repository system by illustrating the effects of a hypothetically degraded performance of each system component that is a main contributor to the safety functions of the repository.

Each pillar of safety addressed can be considered as a variant and, depending on the characteristic of each pillar, several calculation cases are defined and propagated to radiological consequence analysis.

For the **CRZ** these are:

- two calculation cases with no sorption (WI-CRZ-NOSORB) or hypothetically high diffusion coefficients (WI-CRZ-DIFF);
- two cases with hypothetically high downwardly- or upwardly-directed hydraulic gradients (WI-CRZ-GRADdown and WI-CRZ-GRADup);
- one case without upper and lower confining units (WI-CRZ-NOCONFINING); and
- a case with hypothetically high radial dimension of the EDZ around the emplacement rooms (WI-CRZ-EDZ).

For the **HLW matrices**, the calculation cases assume a hypothetically high instant release fraction (IRF) for radionuclides in SF (WI-SF-IRF), hypothetically high matrix dissolution rates for SF and the glass matrix of RP-HLW (WI-HLW-DISS) and hypothetically high corrosion rates for SF cladding and other structural parts (WI-SF-CORR).

For the **HLW disposal canisters**, a calculation case (WI-HLW-CAN) assumes the hypothetical early failure of all canisters at 1,000 years after repository closure which is the minimum regulatory requirement for an HLW disposal canister (ENSI 2023).

For the **bentonite buffer in the HLW emplacement drifts**, no solubility limits (WI-HLW-NOSOL) and no sorption (WI-HLW-NOSORB) in the near-field and hypothetically high diffusion coefficients (WI-HLW-DIFF) or a hypothetically high permeability of the bentonite buffer (WI-HLW-BUF) lead to four calculation cases.

For the **L/ILW cementitious near-field**, a case with no sorption (WI-L/ILW-NOSORB) is considered as is an IRF of C-14 methane present (WI-L/ILW-C14).

Finally, the failure of the **closure system** leads to five calculation cases with hypothetically high permeabilities for the different types and locations of the seals: WI-V1-HLW, WI-V1-L/ILW, WI-V2-HLW, WI-V2-L/ILW, WI-V3. In these cases, each seal is conceptually removed, such that the material assumes the same properties as that of the adjacent backfill.

These additional, hypothetical “what-if?” cases are summarised in Tab. 4-6. Given that they are hypothetical, the radiological consequences calculated for these cases do not need to comply with regulatory dose and risk criteria; in effect, the risk is zero since they are considered to have no possibility of occurrence. Although these additional “what-if?” cases are not linked to any causal physical phenomena, some may be considered to bound the effects of poorly manufactured or emplaced engineered barriers, notably the cases related to the HLW disposal canister, the bentonite buffer, the L/ILW cementitious near-field and the sealing system.

Tab. 4-6: Summary descriptions of “what-if?” cases addressing extreme, hypothetical assumptions and parameter variations

Pillar of safety	Case	Transport modelling approach		Description
		Liquid phase	Two-phase	
CRZ	WI-CRZ-NOSORB	✓	×	No geosphere sorption
	WI-CRZ-EDZ	✓	✓	Hypothetically enlarged radius of the EDZ surrounding emplacement rooms (increased by a factor of two).
	WI-CRZ-DIFF	✓	✓	Hypothetically high diffusion coefficients in the geosphere (an order of magnitude higher than the upper bound values).
	WI-CRZ-GRADdown	✓	✓	Hypothetically high downwardly-directed hydraulic gradient (1 m/m, versus zero in the RS-RC, an additional conservatism is given for modelling the radionuclide transport in the liquid phase: a hydraulic conductivity of OPA one order of magnitude higher than the upper bound values).
	WI-CRZ-GRADup	× ⁴	✓	Hypothetically high downwardly-directed hydraulic gradient (1 m/m, versus zero in the RS-RC).
	WI-CRZ-NOCONFINING	✓	✓	Upper and lower confining units disregarded.
HLW matrices	WI-SF-IRF	✓	✓	Hypothetically high IRFs for radionuclides in SF ⁵ .
	WI-HLW-DISS	✓	× ⁶	Hypothetically high matrix dissolution rates for SF and RP-HLW. The dissolution rates are set to an order of magnitude higher than the upper bound values.
	WI-SF-CORR	✓	✓	Hypothetically high corrosion rates of SF cladding and other structural parts (an order of magnitude higher than the upper bound values).

⁴ As the dominant pathway for radionuclide transport in the liquid phase is from the repository downwards to the Keuper aquifer, the “WI-CRZ-GRADup” case is not necessarily performed since the case “WI-CRZ-GRADdown” will cover the critical dose rate.

⁵ The inventory in SF is set to 100% IRF in this case.

⁶ Dissolution rate of RP-HLW is not relevant for the C-14 released as methane. The case concerning C-14 methane in SF is bounded by the cases “WI-SF-IRF” above and “WI-SF-CORR” below.

Tab. 4-6: continued

Pillar of safety	Case	Transport modelling approach		Description
		Liquid phase	Two-phase	
HLW disposal canister	WI-HLW-CAN	✓	✓	Hypothetical early failure of all HLW disposal canisters 1,000 years after emplacement.
Bentonite buffer (HLW)	WI-HLW-NOSOL	✓	×	No near-field solubility limits in HLW repository section (solubility limit in bentonite buffer is not relevant for the C-14 released as methane).
	WI-HLW-NOSORB	✓	×	No near-field sorption in the HLW repository section (sorption in bentonite buffer is not relevant for the C-14 released as methane).
	WI-HLW-DIFF	✓	×	Hypothetically high diffusion coefficients in bentonite buffer (an order of magnitude higher than the upper bound values).
	WI-HLW-BUF	×	✓	Hypothetically high permeability of bentonite buffer in HLW emplacement drifts (set to the same value as the VF2 backfill material, more than five orders of magnitude higher).
L/ILW cementitious near-field	WI-L/ILW-C14	✓	✓	All C-14 present in L/ILW released instantaneously.
	WI-L/ILW-NOSORB	✓	×	No near-field sorption in the L/ILW repository section.
Closure system	WI-V1-HLW	× ⁷	✓	Hypothetically high permeability of V1-HLW seals (set to the same value as the VF2 backfill material).
	WI-V1-L/ILW	×	✓	Hypothetically high permeability of V1-L/ILW seals (set to the same value as the VF2 backfill material).
	WI-V2-HLW	×	✓	Hypothetically high permeability of V2-HLW seals (set to the same value as the VF2 backfill material).
	WI-V2-L/ILW	×	✓	Hypothetically high permeability of V2-L/ILW seals (set to the same value as the VF2 backfill material).
	WI-V3	×	✓	Hypothetically high permeability of V3 seals (set to the same value as the VF2 backfill material).

⁷ No significant lateral radionuclide transport in the liquid phase will take place along the tunnel system.

5 Models and codes

The analysis of radiological consequences uses quantitative models to evaluate dose rate and complementary safety indicators. Suitable models and model configurations are formulated for the analysis of the safety scenarios, as well as the additional “what-if?” cases that are identified for such analysis in the scenario development; see Chapter 4. In line with the regulation requirement in ENSI (2018), site-specific conceptualisations of the CRZ and site-specific data for the properties of the CRZ are used. However, the same engineered barrier layout and properties are assumed in all three siting regions, with the exceptions of the lengths of the access tunnel systems in the different siting regions and, for the JO siting region, access to the underground is assumed to be via a ramp. All the data are consistent with those used in other modelling carried out in support of the site comparison and the post-closure safety case, in line with the requirement in ENSI (2018).

For all safety scenarios and “what-if?” cases, as noted in the previous chapter, two 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 in both the gas and the liquid phase, with gas-mediated transport being predominant if a gas phase exists.

Models and codes for the two modelling approaches are summarised in Sections 5.1 and 5.2. Further details are provided in App. B. In addition, the most important conceptual assumptions and simplifications are elaborated in App. A, showing that they do not lead to an underestimation of radiological consequences.

C-14 is the only radionuclide treated in both approaches mentioned above. It is assumed in the analysis of radiological consequences that C-14 will migrate as both an organic and an inorganic species, depending on the waste materials. In the modelling of radionuclide migration in the liquid phase, all C-14 (including organic and inorganic C-14), irrespective of its speciation, is assumed to be dissolved in porewater and affected by the same migration process as other radionuclides. In the modelling of radionuclide migration of C-14 considering two-phase flow, organic C-14 is assumed to take the form of methane (Nagra 2024r).

5.1 Migration of dissolved radionuclides in the liquid phase

5.1.1 Overview

To describe and simulate radionuclide migration from the repository to the surface environment in the liquid phase, the model domain is divided into the near-field and the geosphere (Fig. 5-1). As described in Section 3.3, biosphere assessment is carried out separately, yielding BDCFs that convert nuclide-specific geosphere release rates to effective dose rate.

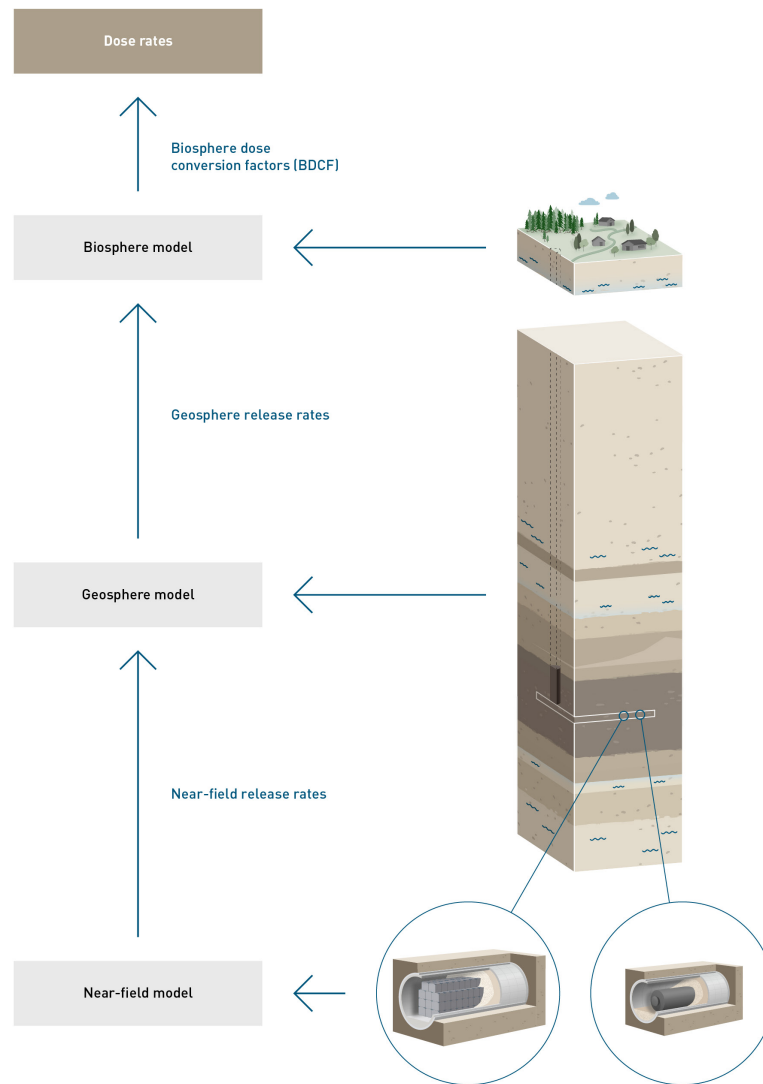


Fig. 5-1: Model chain employed in the dose calculations for radionuclide migration in the liquid phase

In the radiological consequence analysis concerning transport in the liquid phase, the vertical transport from the emplacement rooms in the CRZ is taken into account. This approach is conservative, because:

- It has been shown in the earlier radiological consequence analysis (Poller et al. 2014) and the current performance assessment (Nagra 2024g) that the lateral transport of radionuclides along the tunnel system in the liquid phase plays a negligible role; and
- Lateral radionuclide transport along the repository will reduce the radionuclide concentration in the emplacement rooms, which behaves as the source term of the vertical transport in the CRZ.

5.1.2 Near-field modelling and the STMAN and VPAC codes

Since the approach used to model radionuclide release and migration in the near-field in the present analysis is broadly the same as in Stage of the SGT-E2, only a brief description of the near-field model is given in the present chapter. A detailed description can be found in App. B.1. The reader is also referred to Section 5.3 of Nagra 2014a) for additional information.

The near-field includes either an individual SF or RP-HLW disposal canister, together with its surrounding bentonite buffer, or an individual L/ILW emplacement cavern. The main model output is the total (positive) radial radionuclide flux across the emplacement drift or cavern into the surrounding rock, which forms the source term for the geosphere model.

The near-field radionuclide release rates from SF and RP-HLW are computed using the STMAN code (Robinson 2022). STMAN simulates the near-field release, retention and transport of radionuclides and radionuclide decay chains. It deals with three different types of materials: SF, RP-HLW and the bentonite buffer. STMAN accounts for diffusive transport, elemental solubility limits, sorption onto repository materials and radioactive decay and ingrowth.

Releases from L/ILW, including ATW, are computed with the VPAC code (Holocher et al. 2008). As in the calculations carried out for Stage 2 of the SGT, VPAC is used to compute porewater flow and the release, retention and transport of radionuclides in the L/ILW near-field. VPAC's transport module includes radionuclide decay chains, diffusive and advective transport, and sorption. VPAC supports 2D and 3D geometries.

An identical near-field model configuration is used for all the three siting regions. The HLW and its surrounding near-field barriers are represented using simplified, radially symmetric geometries. A 2D bilaterally symmetric representation of the K90 emplacement cavern (Nagra 2023a) is used for the L/ILW near-field. The phenomenological understanding for the safety scenarios and “what-if?” cases discussed in Chapter 4 can be fully covered by the modelling:

- Waste-type-specific release properties of the radionuclides (SF or RP-HLW; L/ILW);
- The number of waste packages and the inventory per waste package (activity or molar inventory), as well as the fractional partitioning between waste components, e.g., in the case of SF: the waste matrix, cladding/structural materials and the IRF;
- The properties of the waste and waste packages (IRF, SF degradation rate, glass dissolution rate, containment time of disposal canisters);
- The main characteristics of the emplacement drifts and caverns: geometrical properties, including diameter and length, and hydraulic and physical properties;
- Dissolution, precipitation, sorption in the advective, diffusive transport of the radionuclides;
- Radionuclide-specific accessible porosity covering the anion exclusion effect; and
- Sinkage and ingrowth of radionuclides due to radioactive decay.

In addition, the near-field model configurations are adapted to model the cases concerning fault-relevant behaviour. These model configurations are introduced in App. B.1.2.

5.1.3 Geosphere modelling and the PICNIC-TD code

The geosphere comprises the part of the host rock that is not affected, or only slightly affected, by the repository, as well as additional overlying and underlying confining geological units that contribute to the confinement of radionuclides.

Results of the near-field calculations provide a source term for the geosphere retention and transport model, which is implemented in the PICNIC-TD code (Robinson & Chittenden 2022). PICNIC-TD allows the geosphere to be modelled as a network of one-dimensional transport paths (called “legs” in PICNIC-TD), which can represent porous media or discrete features such as faults.

The phenomenological understanding for the safety scenarios and “what-if?” cases discussed in Chapter 4 can be fully covered by modelling:

- vertical & horizontal transport along the rock units;
- sorption in the advective, diffusive transport of the radionuclides in the CRZ;
- radionuclide-specific accessible porosity covering the anion exclusion effect; and
- sinkage and ingrowth of radionuclides due to radioactive decay.

With regard to the faults discussed in Sections 4.2.2 and 4.3.1, the “leg” structure can be adapted to cover the behaviour of faults (e.g., radionuclide exchange between the fault and rock matrix) in the geosphere.

The networks of PICNIC-TD legs used in geosphere modelling are site-specific, and also vary between safety scenarios. They also have some generic features that are common to the three siting regions investigated in the site comparison and to most of the safety scenarios. These generic and safety-scenario-specific features are described in App. B.1.

5.2 Two-phase migration of volatile radionuclides

5.2.1 Overview

Gas is generated in the repository near-field and provides a medium for the transport of gaseous radionuclides. As discussed in Section 3.5, C-14 is the only radionuclide relevant to the analysis of radiological consequences with the potential to be carried by hydrogen, the main gas generated within the repository (by corrosion of metals).

As shown in the investigations of the expected gas behaviour in the repository near-field in the performance assessment (Nagra 2024k), gas from the L/ILW emplacement caverns will migrate predominantly by advection through the tunnels and sealing system, and potentially carry C-14 methane with it. In contrast, the gas generated in the HLW emplacement drifts will mainly remain within the drifts, flows into the OPA and diffuses through the CRZ. Also, thanks to the assumed 10,000-year-containment time of the HLW disposal canisters, the amount of C-14 methane from the HLW reaching the CRZ boundary will not result in a dose rate exceeding the significance threshold of 10^{-7} mSv/a. This phenomenological understanding is confirmed by the result shown in Fig. 7-18. Thus, there is no need to perform the costly workflow (including probabilistic and deterministic simulations, sensitivity analysis, etc.) for the migration of C-14 in the gas phase in an individual HLW repository. However, this conclusion is not valid for the alternative safety scenarios concerning geological faults and so, in these cases, migration of gaseous C-14 methane is also modelled for an individual HLW repository.

However, for analysis in support of the safety case for a combined repository, C-14 migration in the gas phase is modelled for both the HLW and L/ILW repository sections (Section 7.2).

The evolution of repository saturation and gas generation, migration, and dissolution in the repository near-field and geosphere are closely interrelated and are thus modelled together. The evolution of the repository saturation begins with the excavation of the underground openings and the desaturation of the host rock due to ventilation during the operational phase. The operational phase is thus included within the modelling time frame. Gas migration in the near-field and geosphere is treated in a fully integrated manner, meaning that there are no separate near-field and geosphere models as in the modelling of radionuclide migration in the liquid phase (Section 5.1). Transport processes in the EDZs, which will form around the underground openings following excavation, are accounted for (see model configuration in App. B.2). Similar to the modelling of radionuclide transport in the liquid phase, the C-14 methane flux from the model boundary will be captured as release into the biosphere. BDCF of C-14 is then used to convert geosphere release rates to dose rates.

In general, the following main processes and properties are considered in the modelling:

- waste-specific release behaviour of C-14 methane coupled with gas generation tool in Nagra (2024k);
- de- and resaturation process as well as the two-phase flow with capillary effect in porous media;
- dissolution & volatilisation of hydrogen and methane;
- diffusion in the gas and liquid phases; and
- decay of radioactive C-14.

With regard to the faults discussed in Sections 4.2.2 and 4.3.1, the behaviour of faults is covered as well.

5.2.2 Computer codes and model implementation

An efficient “macroelement” modelling approach, which seeks to combine the advantages of simple and efficient 1D modelling and more detailed 3D modelling, is adopted for the analysis of radiological consequences of C-14 methane releases that concern two-phase flow. The approach, which considers all relevant THM-coupled two-phase flow and transport processes, is implemented in a geometrically simplified model setup that allows short model run times, making probabilistic sensitivity and uncertainty analysis feasible.

The macroelement approach is implemented in the TOUGH3 code, with the EOS75R equation-of-state module. EOS75R is an extended version of the original EOS7R module, which meets the current needs of radiological consequence analysis concerning gas-mediated radionuclide migration (Jung et al. (2018), Zhang et al. (2024)).

Each run of the macroelement model begins with an initial computation in which the system is assumed to be fully saturated with the liquid phase, in order to get to the thermo-hydraulic equilibration stage of pressure and the initial temperature distribution. Three further computations are then performed, covering consecutive time periods in order to model the impact of ventilation on the saturation process:

- Operational phase 1, lasting for the first 21 years from the beginning of the computational period. Here, ventilation of the “central area” of the repository up to the V2 seals at a temperature of 28 °C and a relative humidity of 60% is assumed. The other parts of the repository are assumed to have not yet been excavated.
- Operational phase 2, extending from 21 to 36 years. All remaining underground structures, including the HLW and L/ILW emplacement rooms, with their V1 seals and branch tunnels, are ventilated.
- Post-closure phase, extending from 36 years to end of the simulation. Here, all the waste has been emplaced and the repository has been backfilled and sealed. As noted in Section 3.5, this phase is assumed to begin in the year 2075. Hence, the C-14 inventory and heat source term given in MIRAM-RBG (Nagra 2023c) for 2075 are used as the initial condition for the model.

The configurations of the macroelement models are site-specific and also vary between scenarios. They have some generic features that are common to the three siting regions investigated in the site comparison and to most of the safety scenarios. The main aspects of the approach are described in App. B.2.

6 Radiological consequence analysis for site comparison

Fig. 6-1 gives an overview of the workflow for the comparison of the siting regions, including the site-specific safety analysis described in the present chapter. The site-specific safety analysis is performed taking into account the site selection process. The results are considered in the siting decision.

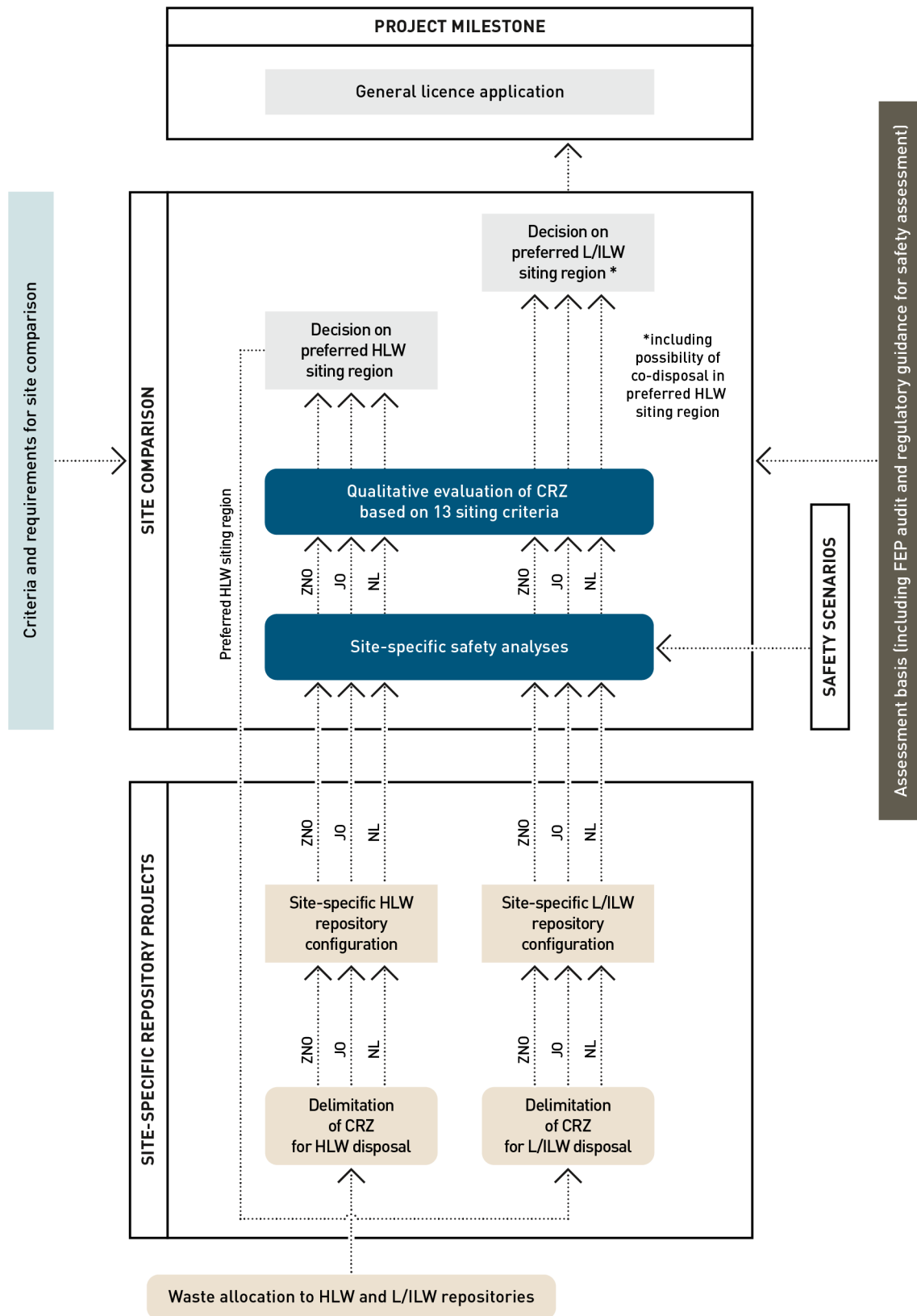


Fig. 6-1: Workflow for the comparison of the siting regions, including the site-specific safety analyses described in the present chapter. Other parts of this workflow are described in Nagra (2024o)

The safety analyses include, for all three siting regions and for each repository type:

- deterministic analyses of the reference safety scenario (reference case and other alternative cases; see Tab. 4-1);
- probabilistic analyses of the reference safety scenario;
- deterministic analyses of pessimistic cases, in which those parameters identified as sensitive in the probabilistic analyses are set to pessimistic values; and
- a deterministic analysis of alternative safety scenarios.

Safety analyses considering radionuclide migration in the liquid phase are carried out first for an HLW repository, with the results presented in Section 6.1, and then for an L/ILW repository, with the results presented in Section 6.2. Further safety analyses considering migration of organic C-14 in the gas phase are presented in Section 6.3.

As described in Section 3.2, organic C-14 is considered as methane in both the liquid phase calculations and in the two-phase flow calculations. Because the entire organic C-14 inventory is considered separately in both calculations, the results are also presented separately in this chapter, i.e., one set of results where all C-14 methane is assumed to be fully dissolved despite its volatility and the low solubility of methane gas and another set of results where methane is partitioned between the dissolved and gaseous phases. In fact, summing up both results would correspond to counting the organic C-14 inventory twice. A further reason for presenting the results separately is because the distinct characteristics of the two-phase flow results would otherwise be barely visible since the absolute values of dose rate contributions for these cases are small when compared with the liquid phase contributions.

The “what-if?” cases described in Section 4.3 are considered only in the context of the post-closure safety case for a combined repository at the selected site (see Chapter 7).

6.1 Radiological consequence analysis considering radionuclide migration in the liquid phase for site comparison for the HLW repository

Following the workflow of the site comparison, radiological consequence analysis is performed for the HLW repository in each of the three siting regions, covering the cases mentioned above with regard to the reference and alternative safety scenarios.

6.1.1 Reference safety scenario analysis including barrier performance and dose rates

The reference safety scenario, including the reference case and a number of additional calculation cases exploring the impact of uncertainty in the hydrogeological characteristics of the Keuper aquifer and of assumptions regarding climatic and surface conditions, is described in Nagra (2024b) and summarised in Section 4.1.

The site-specific deterministic reference calculation case provides a baseline for comparison with other calculation cases. The reference calculation case is the current best estimate (with conservatism in some parametrisations) of the radiological consequences of the deep geological repository. Furthermore, the barrier performance is analysed based on the reference case to develop understanding of the modelled system. The reference calculation case uses a combination of reference values for all parameters; some of the reference parameter values are set to their best-estimate values and some are set conservatively, see App. C.2. A hydraulically active Keuper

aquifer is assumed in the reference cases for all the three siting regions. Additionally, consistent with ENSI guidance, the reference case calculations employ BDCFs that are based on the present-day climatic conditions in Switzerland; see Section 3.3.

However, as noted above, additional deterministic calculation cases are defined that assume a hydraulically inactive Keuper aquifer (for the NL siting region only) and different, though still steady-state, climatic and surface conditions. The concepts and models for analysing radionuclide migration in the liquid phase in the reference safety scenario are described in App. B.1.

In order to support the discussion of the differences in the transport behaviour for the three siting regions, the most important site-specific parameters related to diffusive transport are listed in the following table (since diffusion is the dominating transport process). The other parameters can be found in App. H.3.

Tab. 6-1: Summary of the main characteristics of an HLW repository in the JO, NL and ZNO siting region

	Unit	JO	NL	ZNO
Effective diffusion coefficient of Iodine in the Opalinus Clay	m ² /s	1.45×10^{-12}	2.65×10^{-12}	3.16×10^{-12}
Transport length to Malm aquifer (Calcareous Dogger in JO)	m	106	205	153
Transport length to the Keuper aquifer	m	117	112	131
Ambient temperature at the centre of the Opalinus Clay	°C	28	48	36
Effective diffusion coefficient of Iodine in the Opalinus Clay after temperature correction	m ² /s	1.58×10^{-12}	4.68×10^{-12}	4.23×10^{-12}

One can see from the table above that the JO siting region exhibits a lower diffusion coefficient because of its geochemical condition (higher salinity) in the groundwater and lower ambient temperature due to its shallower depth compared to NL and ZNO. On the other hand, JO has a shorter transport length upwards to the upper aquifer (Calcareous Dogger) than NL and ZNO (Malm aquifer). By contrast, NL has a slightly higher diffusion coefficient and a shorter transport length down to the Keuper aquifer than ZNO.

6.1.1.1 Jura Ost (JO)

Fig. 6-2 shows the total dose rate and nuclide-specific dose rates for those radionuclides with the highest contribution from the CRZ of an HLW repository in the JO siting region. The total dose rate reaches 1.3×10^{-4} mSv/a at 1 million years, which is about three orders of magnitude lower than the protection criterion of 0.1 mSv/a stipulated by ENSI G03 (ENSI 2023), indicating a large safety margin. The dose rate continues to increase slightly thereafter, reaching a maximum of about 2×10^{-4} mSv/a at 4.7 million years and about 4 orders of magnitude lower than the lower bounding value of the typical natural radiological exposures in Switzerland (BAG 2021). Significant dose rates, defined as dose rates above 10^{-7} mSv/a, occur only after 10^5 years, which demonstrates the retention capacity of the repository in the siting region.

The radionuclide with the greatest contribution to the dose rate at all calculated times is I-129, which has a long half-life (15,700,000 years) and is non-sorbing and non-solubility-limited. Cl-36 and Se-79 also make significant contributions to dose rates, however both remain at least one order of magnitude below that of I-129 due to their shorter half-lives, meaning that they will decay more through the transport pathway. Se-79 comes mainly from the RP-HLW, whereas I-129 and Cl-36 come mainly from SF.

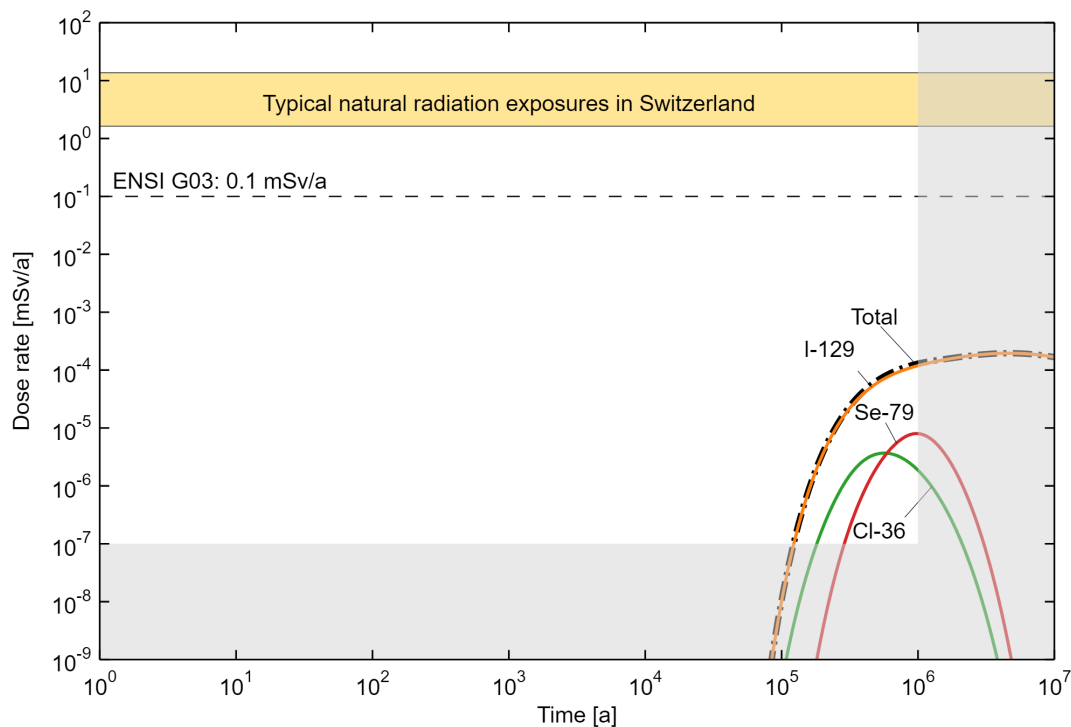


Fig. 6-2: Total and nuclide-specific dose rates due to SF and RP-HLW in the reference case for an HLW repository in the JO siting region.

Fig. 6-3 illustrates the contributions of releases across the three individual interfaces to the total dose rate. The dose rates due to releases from the Muschelkalk aquifer are much lower than via Calcareous Dogger and Keuper aquifer, and lie below the level of the significant dose rate (10^{-7} mSv/a). This is because of the relatively high flow rate assumed for the Keuper aquifer, which means that most radionuclides migrating downwards from the repository are captured by the Keuper aquifer, with only a relatively small amount migrating further down to the Dolomitic Muschelkalk. By contrast, the dose rates due to releases from the Calcareous Dogger and from the Keuper aquifer are comparable because of the similar transport length (see Tab. 6-1).

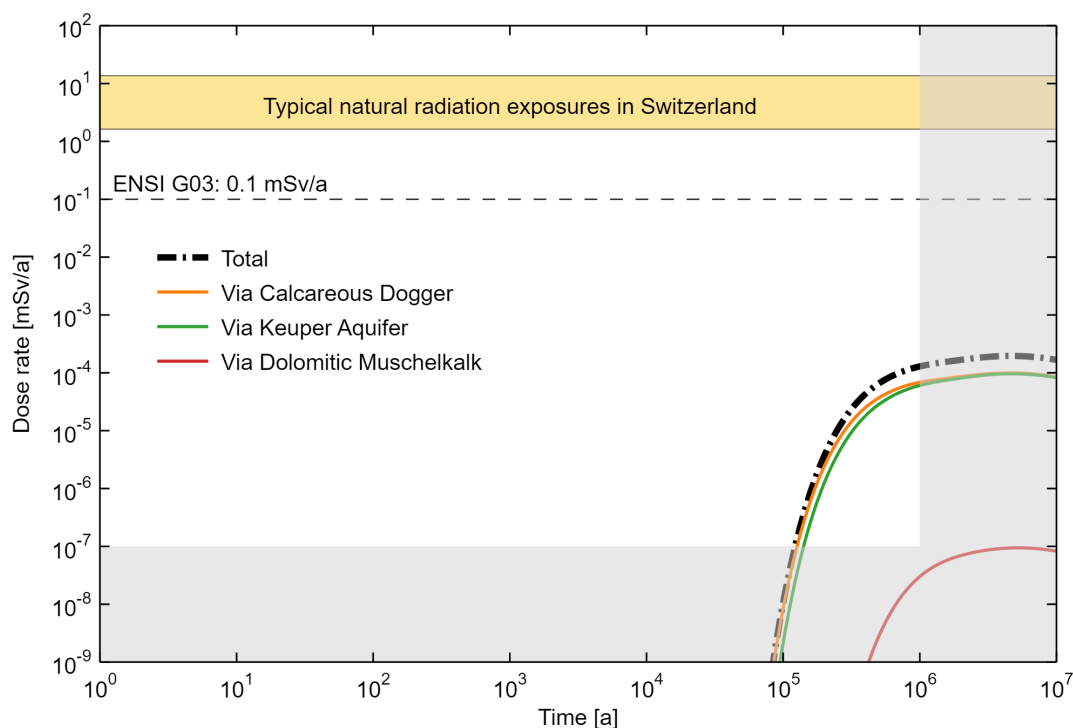


Fig. 6-3: Total dose rate due to SF and RP-HLW in the reference case for an HLW repository in the JO siting region, and the contributions to the total release from the Calcareous Dogger, the Keuper aquifer and the Dolomitic Muschelkalk

In Fig. 6-4, maximum dose rates are shown over one million years at different vertical distances from the repository. The figure illustrates how the maxima are attenuated as the radionuclides migrate through the barrier system. After 60 m (i.e., the upper and lower boundaries of the Opalinus Clay), the maximum dose rate dominated by I-129 is far below the protection criterion. This demonstrates the strong retention of many radionuclides in the main clay barriers (the bentonite buffer and the Opalinus Clay). Most attenuation occurs within the first 10 metres of the clay barrier due to the decay of the strongly sorbing radionuclides with high radioactivity.

Most of the radionuclides never reach the boundaries of the Opalinus Clay, and those that do are relatively long-lived and non-sorbing (e.g., I-129). The role of the confining unit aims at limiting the release maxima and delaying the release of long-lived, soluble anions over very long time periods.

The stepwise decrease in the maximum total dose rate at the Keuper aquifer, at a distance of about 117 m below the repository, is caused by a high radionuclide flow out of the model and not by retention, as in the case of the Opalinus Clay. The rock units beneath the Keuper aquifer show low maximum dose rates and provide essentially no additional attenuation because, as noted above, most radionuclides migrating downwards from the repository are captured by this aquifer, and never reach the underlying units.

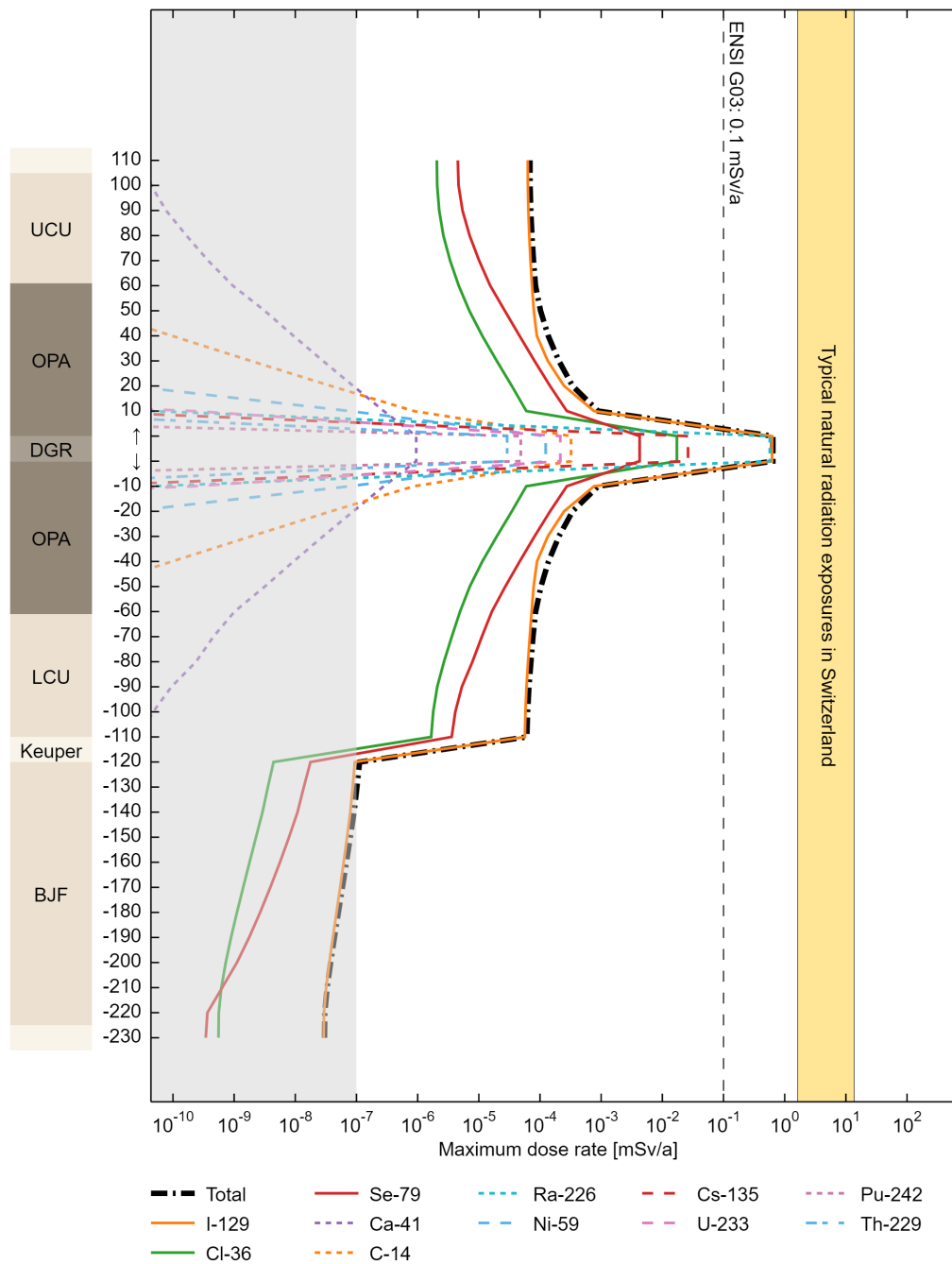


Fig. 6-4: Maximum dose rates calculated for an HLW repository in the JO siting region as a function of distance from the repository centre point

(only individual radionuclides with a maximum dose rate higher than 10^{-5} mSv/a anywhere or with a maximum dose rate higher than 10^{-7} mSv/a at a distance of 20 m or more from the repository centre are illustrated in the figure)

UCU = upper confining unit, OPA = Opalinus Clay, LCU = lower confining unit, BJJ = Bänkerjoch Formation. For each radionuclide, the line indicates the maximum dose rate contribution that would be captured as the maximum flux of that radionuclide at the given distance from the repository. For example, Cl-36 would contribute ca. 10^{-5} mSv/a for the maximum flux of Cl-36 at 30 m. Radionuclides with dashed lines would contribute less than the level of significance (10^{-7} mSv/a) to the hypothetical dose rate if their flux were captured 50 m from the centre of the repository.

Fig. 6-5 illustrates the evolution of the radiotoxicity (RT) of different materials within the repository system. Throughout the first million years after repository closure, most of the RT is contained within the SF matrix and the vitrified waste body of the RP-HLW due to the robust stability of the waste matrix. However, after breaching of the HLW canister 10,000 years after repository closure, some radionuclides in the IRF are instantaneously transferred to the bentonite buffer and further into the Opalinus Clay, which causes the instantaneous breakthrough at 10,000 years shown by the violet, pink, blue and brown curves in Fig. 6-5. These radionuclides, however, are effectively retarded in the Opalinus Clay and confining geological units. After the IRF release phase, the radionuclides from the SF matrix and vitrified waste are released congruently (CRF: congruent release fraction). These radionuclides (e.g., Th, Np, U) are mostly sorbed or precipitated in the bentonite buffer and the Opalinus Clay. Therefore, the strong retention of radionuclides within the buffer and the Opalinus Clay results in an RT in the confining units which is orders of magnitude lower. Consistent with Fig. 6-4, the RT that reaches the confining geological units and beyond is dominated by the long-lived, non-sorbing and non-solubility-limited I-129.

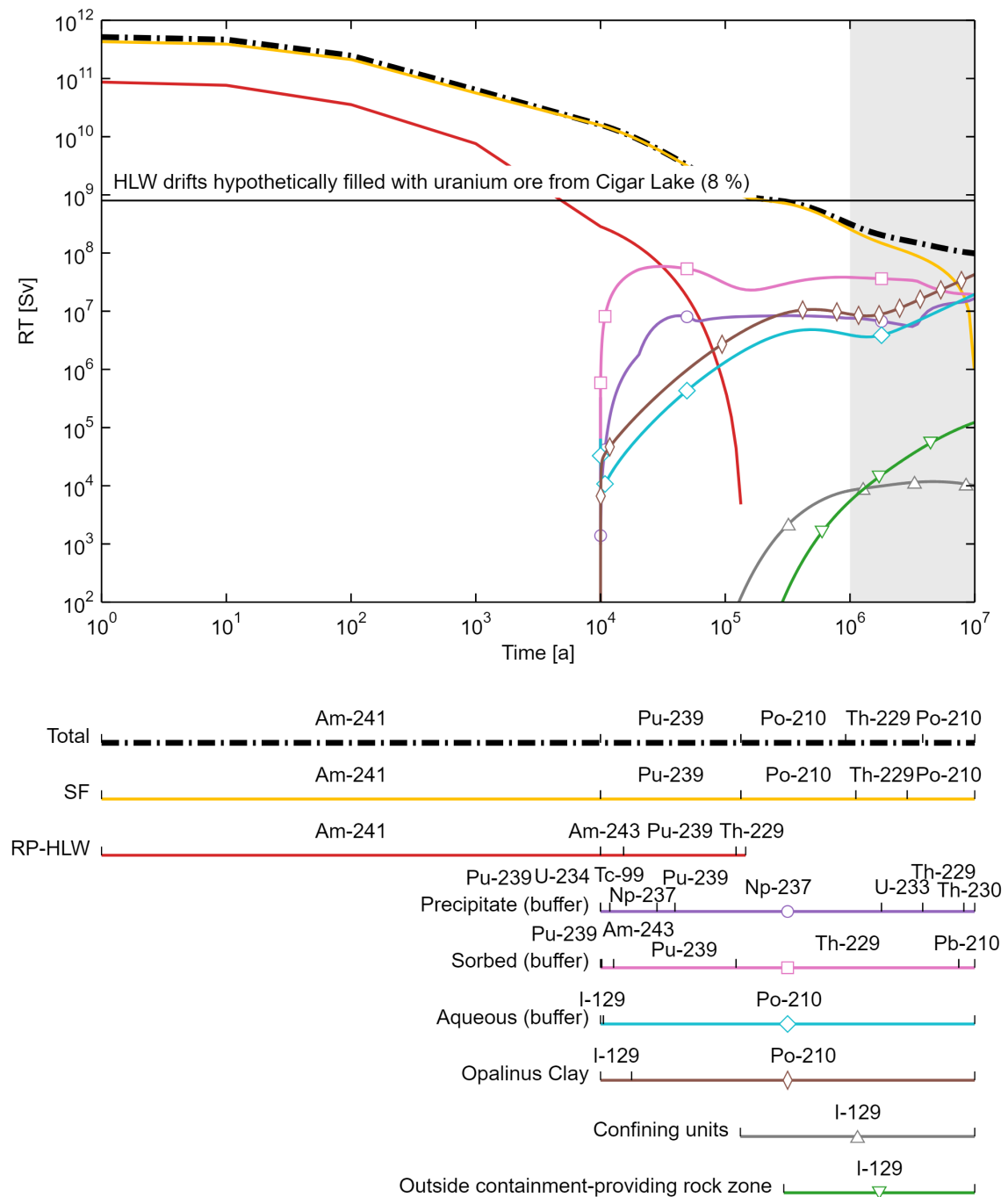


Fig. 6-5: Evolution and distribution of radiotoxicity over time in SF, RP-HLW, the bentonite buffer, the Opalinus Clay, its confining geological units and outside the containment-providing rock zone for an HLW repository in the JO siting region. For comparison of the radiotoxicity, all 20 HLW emplacement drifts are shown to be hypothetically filled with uranium ore (8%)

The reference case uses BDCFs for a reference biosphere based on present-day climatic conditions. Three additional deterministic calculation cases are defined using different BDCFs, which assume different, though still steady-state, climatic and surface conditions:

- RS-BIOS/WARM_DRY, based on a warmer and drier climate;
- RS-BIOS/COLD, based on a colder climate; and
- RS-BIOS/DRAINED_FARMLAND, which assumes a drained farmland.

The highest BDCFs are given in the “WARM_DRY” variation because the dilution effect is the smallest among the assumptions in the biosphere models.

The evolution of the dose rate in each of these cases is shown in Fig. 6-6. A warmer and drier climate is found to result in a maximum dose rate of 1.15×10^{-3} mSv/a at 10^6 years, which is about a factor of ten higher than that of the reference case. However, a large safety margin of several orders of magnitude compared to the protection criteria can be obtained.

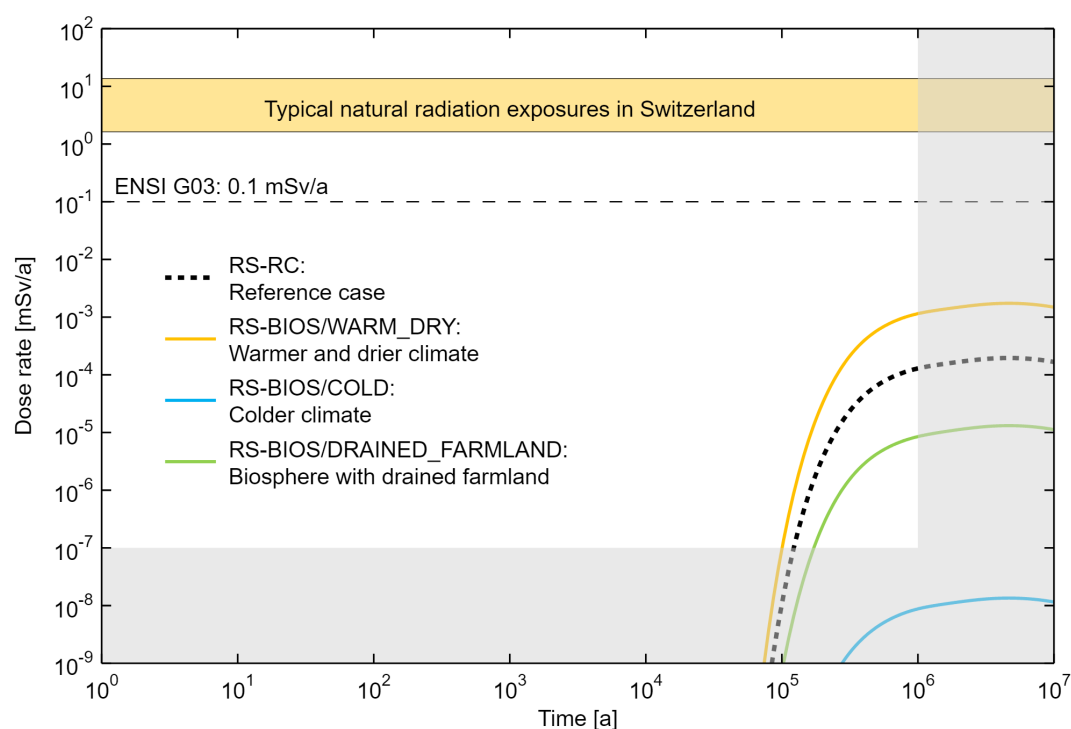


Fig. 6-6: Total dose rates resulting from SF and RP-HLW for an HLW repository in the JO siting region in the reference case and in cases assuming different climatic and surface conditions

6.1.1.2 Nördlich Lägern (NL)

For the NL siting region, analyses have been done that are identical to those for JO mentioned above. Fig. 6-7 shows the total dose rates and nuclide-specific dose rates for the nuclides with the highest contributions in the reference case of an HLW repository in the NL siting region. It also shows the dose rates for a variant of the reference safety scenario in which the Keuper aquifer below the repository is assumed to be hydraulically inactive. As noted in Section 4.1, this variant is only considered for a repository in NL.

The contributions of the different radionuclides are similar to the performance shown in the reference case for JO in Fig. 6-2. The total dose rate reaches 1.5×10^{-4} mSv/a at 1 million years, which is about 3 orders of magnitude lower than the protection criterion of 0.1 mSv/a given by (ENSI 2023), indicating a large safety margin. The dose rate continues to increase slightly thereafter, reaching a maximum of around 2×10^{-4} mSv/a at approximately 4.5 million years, which is about 4 orders of magnitude lower than the lower bound value of the typical natural radiological exposures in Switzerland (BAG 2021). Significant dose rates, defined as dose rates higher than 10^{-7} mSv/a, occur only after about 8×10^4 years, which demonstrates the retention capacity of the repository in the siting region. Compared to JO, the breakthrough is earlier because of the higher local temperature in NL which leads to a higher effective diffusion coefficient. However, the earlier breakthrough does not cause a significant increase in the maximum dose rate.

The assumption that the Keuper aquifer below the repository is hydraulically inactive reduces the dose rate at 1 million years, which is dominated by I-129, by a factor of about 2.5. Significant dose rates occur only after about 10^5 years in this variant.

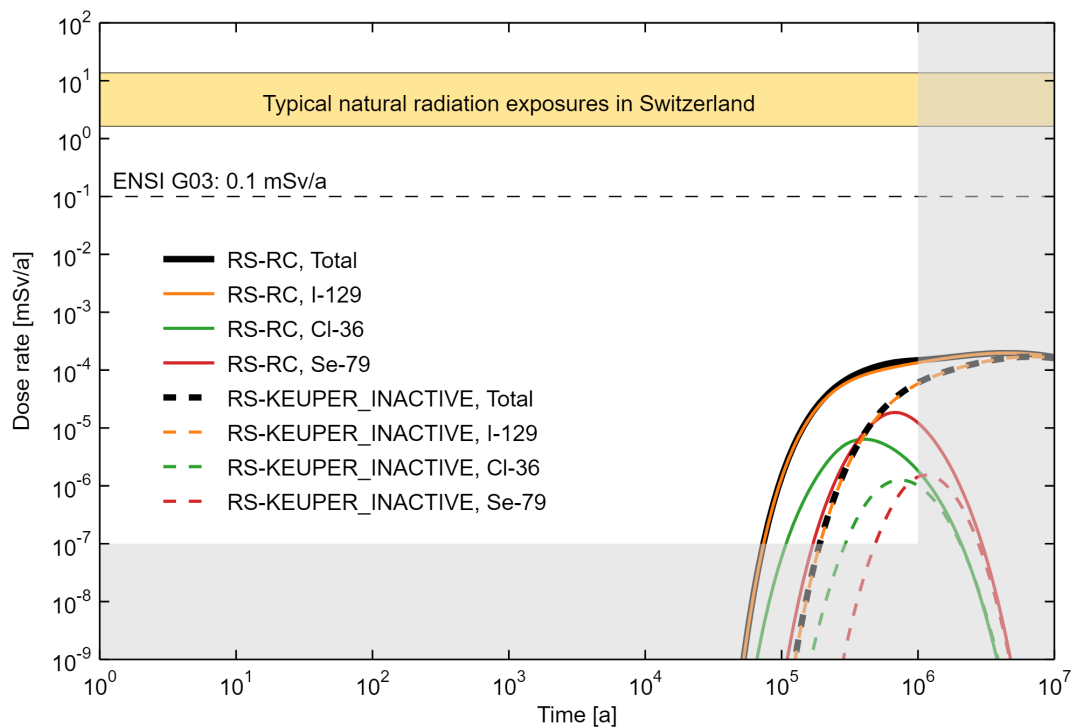


Fig. 6-7: Total and nuclide-specific dose rates due to SF and RP-HLW in the reference case for an HLW repository in the NL siting region, and for a variant of the reference safety scenario in which the Keuper aquifer below the repository is hydraulically inactive

Fig. 6-8 illustrates the contributions to the total dose rates in the reference case from releases across the three individual interfaces with the biosphere: 1) Malm aquifer (the upper model boundary), 2) Keuper aquifer (first deep aquifer below the repository) and 3) Dolomitic Muschelkalk (the lower model boundary). The dose rates due to releases from the Keuper aquifer dominate the total, with the release from the Malm aquifer being somewhat lower because of the difference in the transport length (see Tab. 6-1). As in the case of JO, the dose rates due to releases from the Muschelkalk aquifer are much smaller than those due to release from the other aquifers. They lie just barely above the level of the significant dose rate (10^{-7} mSv/a). This is because, as noted above, most radionuclides migrating downwards from the repository are captured by this aquifer, and never reach the underlying units. In the variant with the inactive Keuper aquifer, the Dolomitic Muschelkalk becomes the dominating pathway.

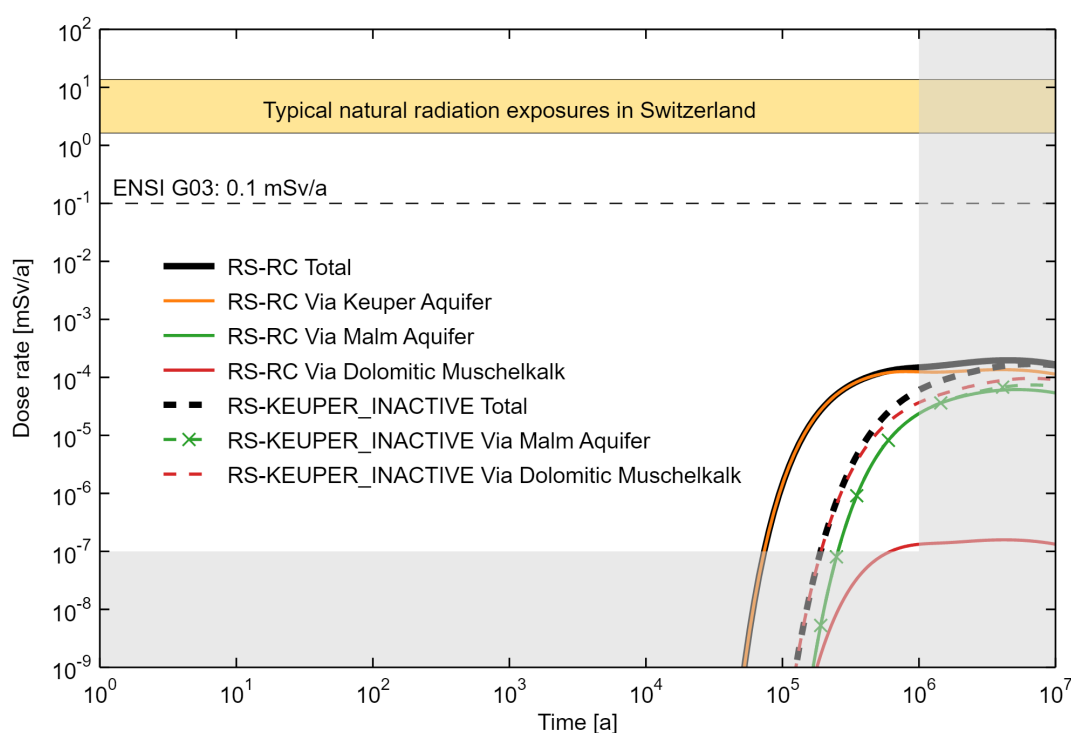


Fig. 6-8: Total dose rates due to SF and RP-HLW in the reference case for an HLW repository in the NL siting region, and for a variant of the reference safety scenario in which the Keuper aquifer below the repository is hydraulically inactive. For both cases, the contributions to the total dose rate due to releases via the Malm aquifer, the Keuper aquifer and the Dolomitic Muschelkalk are also displayed

In Fig. 6-9, maximum dose rates over 1 million years are shown at different vertical distances from the repository. The figure illustrates how the maxima are attenuated as the radionuclides migrate through the barrier system. The results are very similar to those for JO, due to the similarity in the geometry and properties of the repository near-field and the Opalinus Clay host rock. After 50 m of transport, the maximum dose rate is reduced to a level far below the regulatory protection criterion. This demonstrates the strong retention of many radionuclides in the main clay barriers (the bentonite buffer and the Opalinus Clay). Most attenuation occurs within the first 10 metres of the clay barrier due to the decay of the strongly sorbing radionuclides with high radioactivity. Similar to those for JO, most radionuclides never reach the boundaries of the Opalinus Clay, and those that do are relatively long-lived and non-sorbing (e.g. I-129).

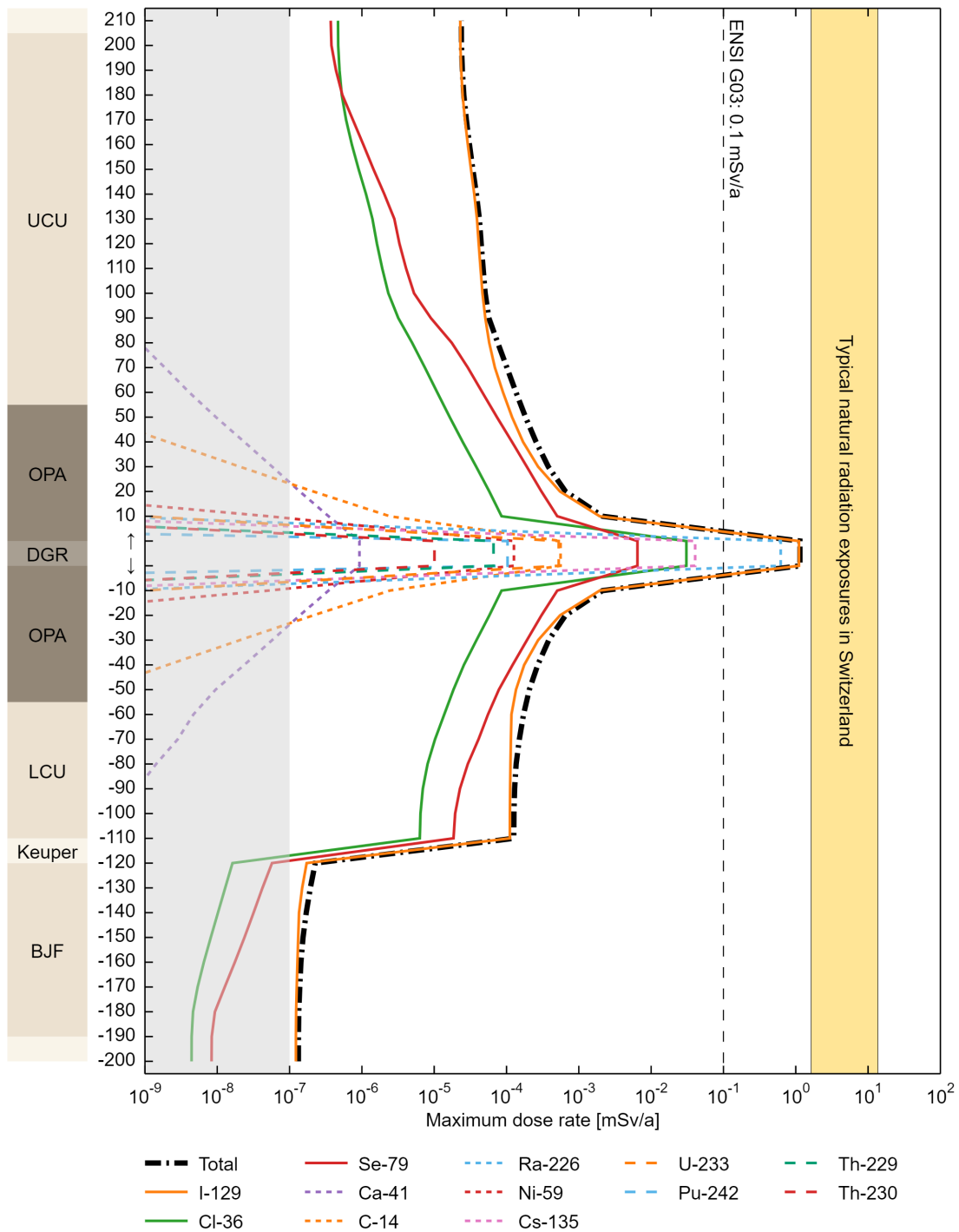


Fig. 6-9: Maximum dose rates obtained by applying BDCFs to radionuclide transport rates calculated for an HLW repository in the NL siting region as a function of distance from the repository centre

(only individual radionuclides with a maximum dose rate higher than 10^{-5} mSv/a anywhere or with a maximum dose rate higher than 10^{-7} mSv/a at a distance of 20 m or more from the repository centre are illustrated in the figure)

Fig. 6-10 illustrates the evolution of the total radiotoxicity (RT) in different materials within the repository system. Because of the similarity in the geometry and properties of the repository near-field and the Opalinus Clay host rock, the results are very similar to those shown in Fig. 6-5 for JO.

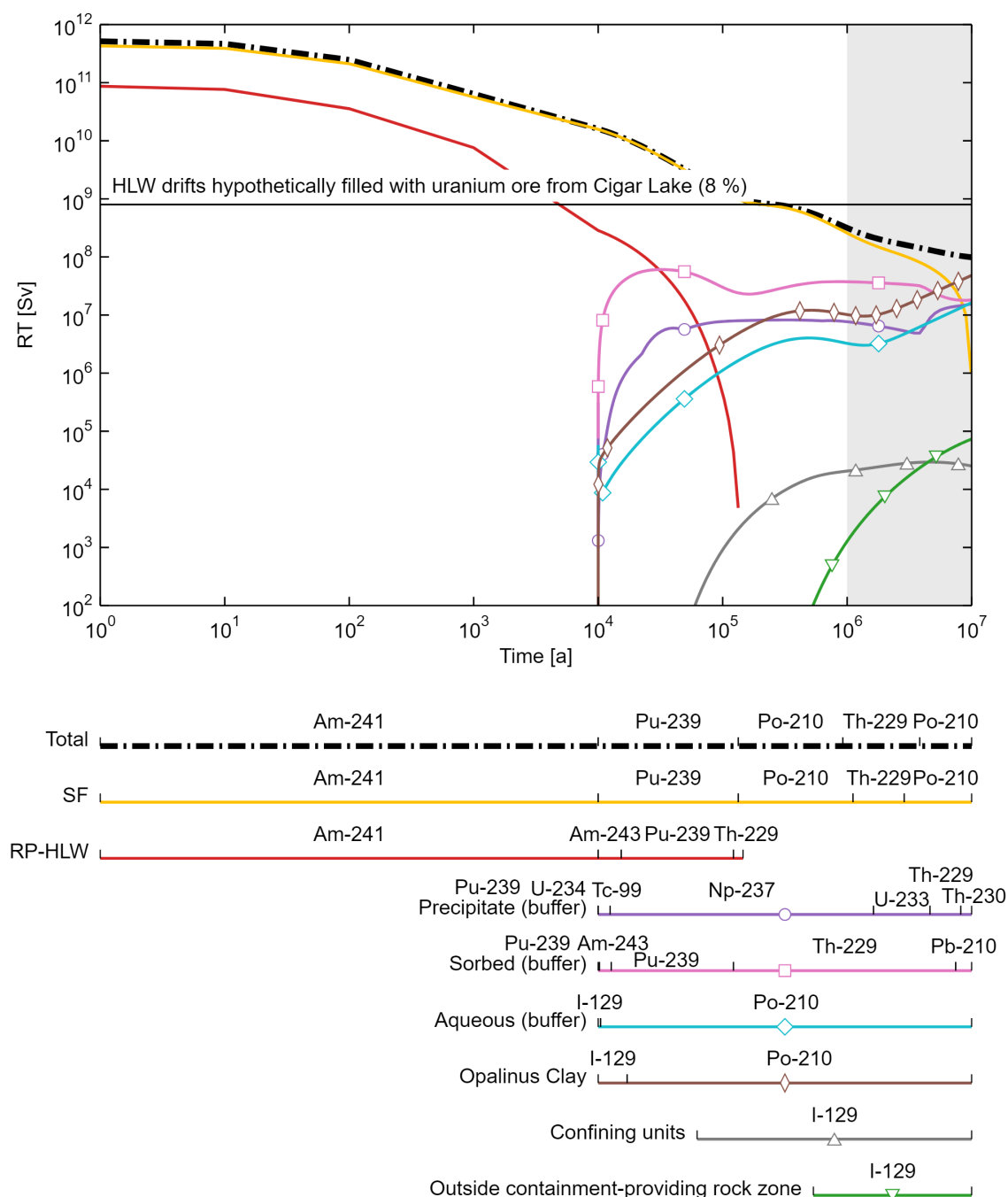


Fig. 6-10: Evolution and distribution of the radiotoxicity over time in SF, RP-HLW, the bentonite buffer, the Opalinus Clay, its confining geological units and outside the containment-providing rock zone for an HLW repository in the NL siting region. For comparison of the radiotoxicity, all 20 HLW emplacement drifts are shown to be hypothetically filled with uranium ore (8%)

As in the case of JO, three additional deterministic calculation cases concerning uncertainty in biosphere are performed. Using the same BDCFs considered for JO, the evolution of the dose rates in each of these cases is shown in Fig. 6-11. A warmer and drier climate is found to result in a maximum dose rate of 1.32×10^{-3} mSv/a at 10^6 years, which is about a factor of ten higher than that of the reference case. Other climatic and surface conditions result in lower dose rates showing the impact of the BDCFs at the site.

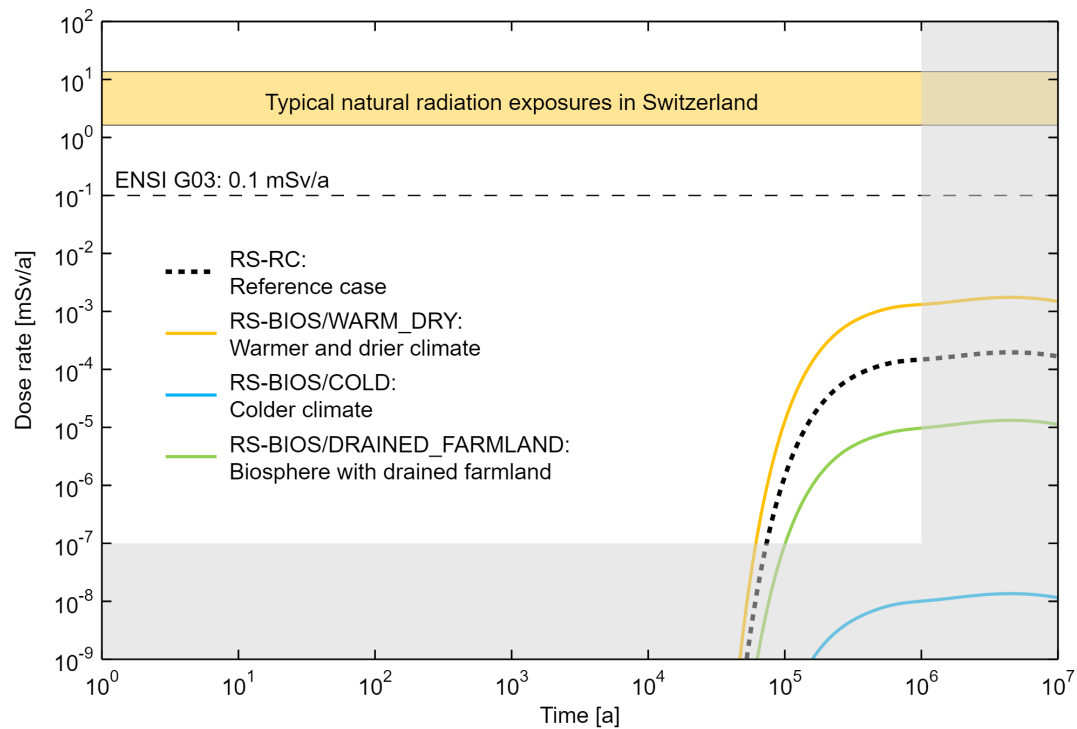


Fig. 6-11: Total dose rates due to SF and RP-HLW for an HLW repository in the NL siting region in the reference case and in cases assuming different climatic and surface conditions

6.1.1.3 Zürich Nordost (ZNO)

Fig. 6-12 shows the total dose rates and nuclide-specific dose rates of nuclides with the highest contributions in the reference case for an HLW repository in the ZNO siting region.

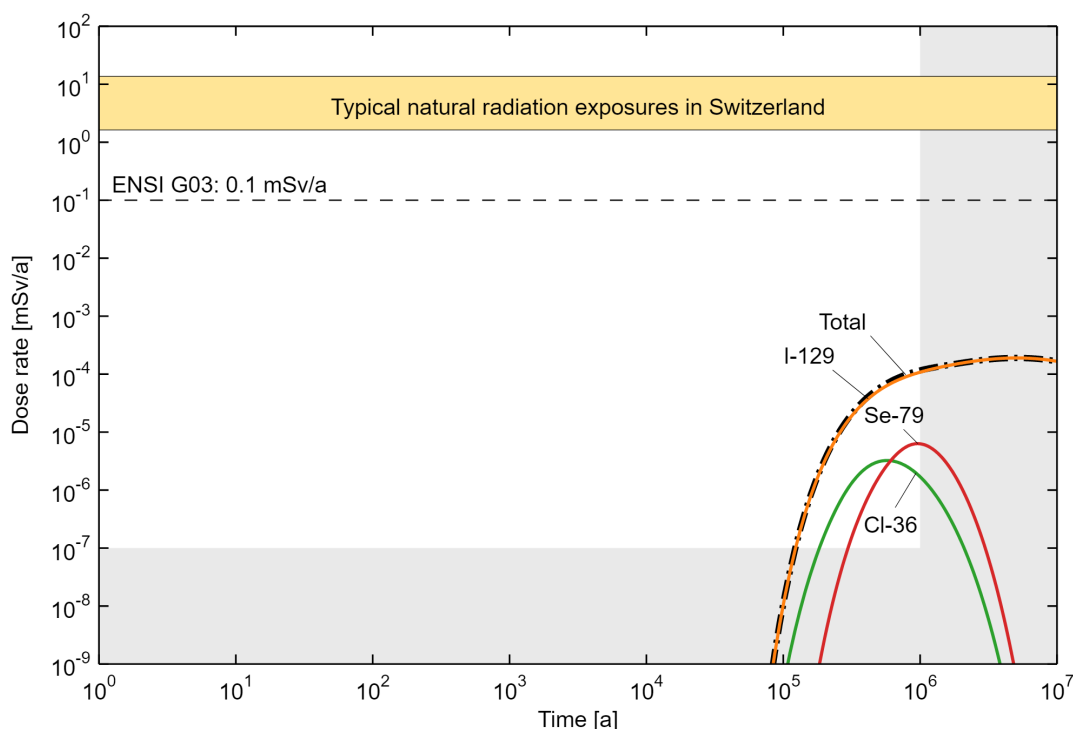


Fig. 6-12: Total and nuclide-specific dose rates due to SF and RP-HLW in the reference case for an HLW repository in the ZNO siting region

The results for the reference case are similar to those for the other two siting regions. The total dose rate reaches 1.16×10^{-4} mSv/a at 1 million years, which is about three orders of magnitude lower than the protection criterion of 0.1 mSv/a stipulated by (ENSI 2023), indicating a large safety margin. The dose rate continues to increase slightly thereafter, reaching a maximum of about 1.9×10^{-4} mSv/a at 5 million years, which is about 4 orders of magnitude lower than the lower bound value of the typical natural radiological exposures in Switzerland (BAG 2021). Significant dose rates, defined as dose rates above 10^{-7} mSv/a, occur only after about 10^5 years, which demonstrates the retention capacity of the repository in the siting region. Due to the similarity between the disposal system in the three siting regions, the radionuclide constricting most to the dose rate at all calculated times is I-129, which has a long half-life and is non-sorbing and non-solubility-limited. Cl-36 from SF and Se-79 from RP-HLW also give significant dose rates, though these are lower than the dose rates of I-129 at all calculated times.

Fig. 6-13 illustrates the contributions to the total dose rates in the reference case from releases from three individual interfaces with the biosphere: 1) Malm aquifer (the upper model boundary), 2) Keuper aquifer (first deep aquifer below the repository) and 3) Dolomitic Muschelkalk (the lower model boundary). The dose rates due to releases from the Keuper aquifer dominate the total, with the release from the Malm aquifer being somewhat lower, although both reach similar values after a million years. However, compared to NL, the dominance of the Keuper aquifer to the total transport is not as strong in ZNO as in NL because of the difference of the transport length listed in Tab. 6-1.

As in the cases of JO and NL, the dose rates due to releases from the Muschelkalk aquifer are much smaller than those due to the release from the other aquifers, and, for ZNO, lie below the level of the significant dose rate (10^{-7} mSv/a).

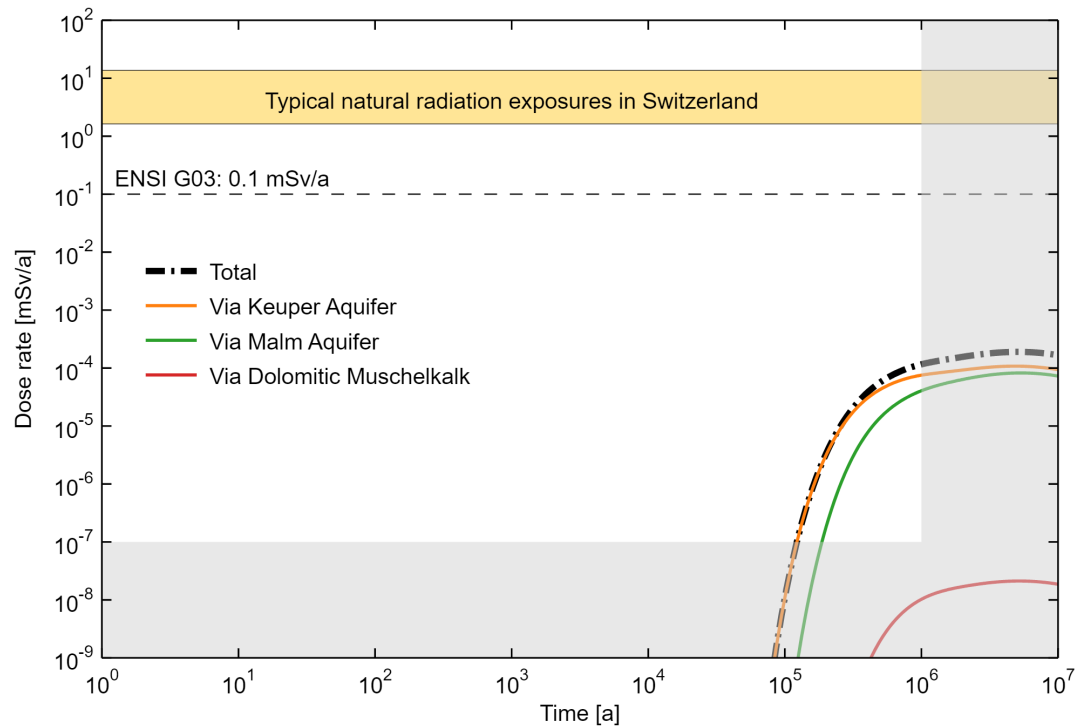


Fig. 6-13: Total dose rates due to SF and RP-HLW in the reference case for an HLW repository in the ZNO siting region, and the contributions to the total due to releases from the Malm aquifer, the Keuper aquifer and the Dolomitic Muschelkalk

In Fig. 6-14, maximum dose rates over 1 million years are shown at different vertical distances from the repository. The figure illustrates how the maxima are attenuated as the radionuclides migrate through the barrier system. The results are very similar to those for both JO and NL, due to the similarity in the geometry and properties of the repository near-field and the Opalinus Clay host rock. After 50 m of transport, the maximum dose rate is reduced to a level far below the protection criterion. This demonstrates the strong retention of many radionuclides in the main clay barriers (the bentonite buffer and the Opalinus Clay). Most attenuation occurs within the first 10 metres of the clay barrier, due to the decay of the strongly sorbing radionuclides with high radioactivity.

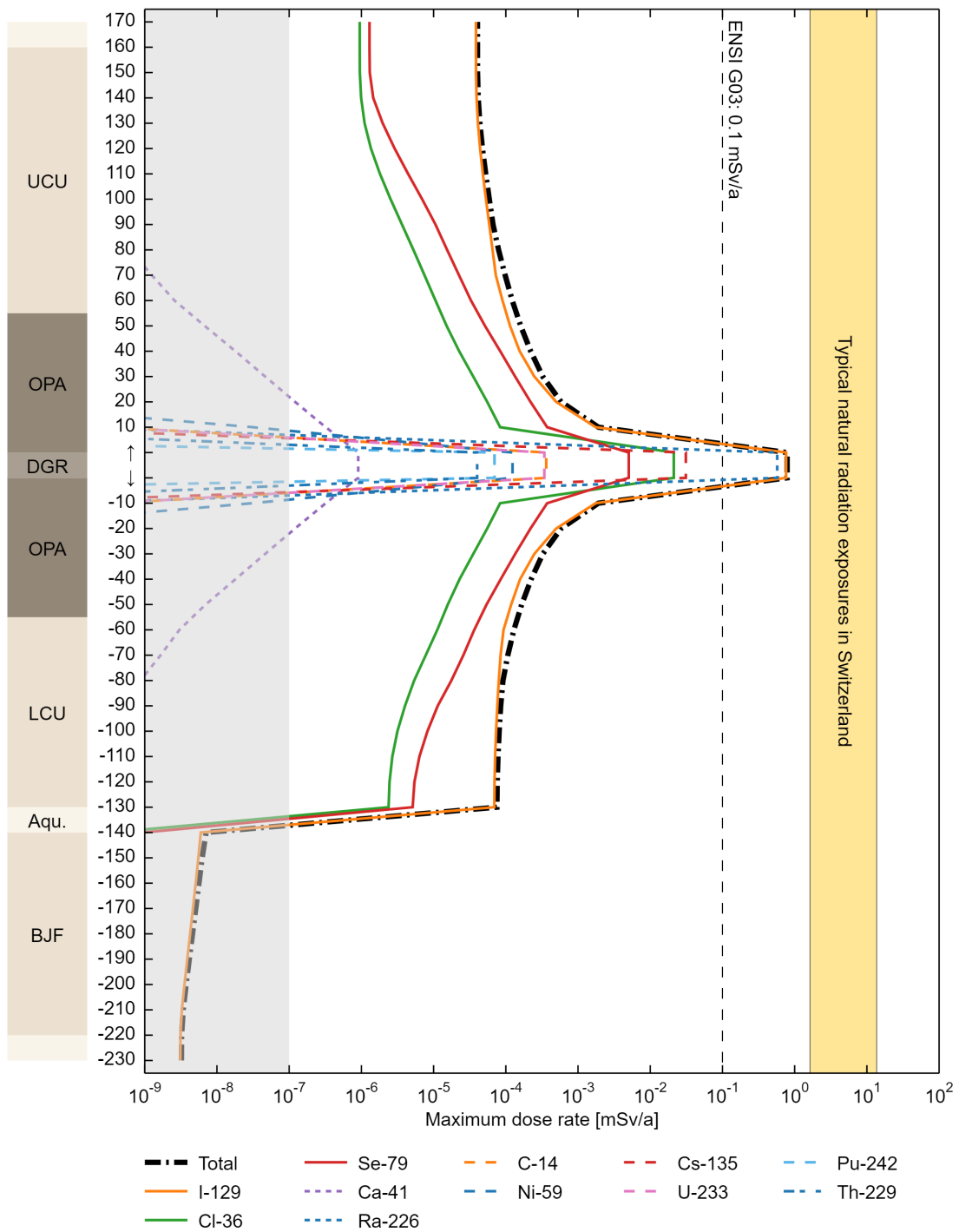


Fig. 6-14: Maximum dose rates obtained by applying BDCFs to radionuclide transport rates calculated for an HLW repository in the ZNO siting region as a function of distance from the centre of the repository

(only individual radionuclides with a maximum dose rate above 10^{-5} mSv/a anywhere or with a maximum dose rate higher than 10^{-7} mSv/a at a distance of 20 m or more from the repository centre are illustrated in the figure)

Fig. 6-15 illustrates the overall evolution of the RT in different materials within the repository system. Because of the similarity in the geometry and properties of the repository near-field and the Opalinus Clay host rock, the results are very similar to those shown in Fig. 6-5 for JO and in Fig. 6-10 for NL.

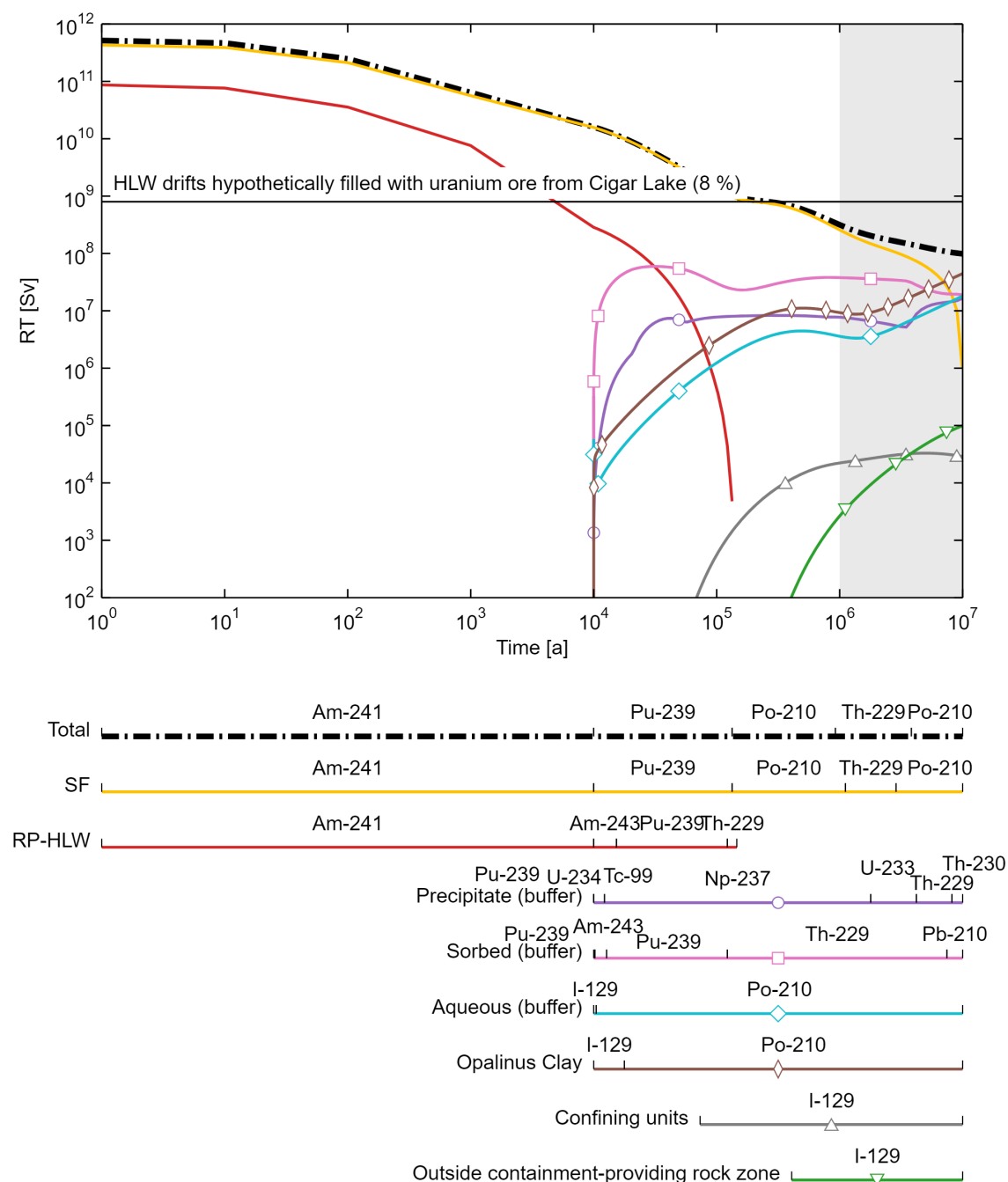


Fig. 6-15: Evolution and distribution of the radiotoxicity over time in SF, RP-HLW, the bentonite buffer, the Opalinus Clay, its confining geological units and outside the containment-providing rock zone for an HLW repository in the ZNO siting region. For comparison of the radiotoxicity, all 20 HLW emplacement drifts are shown to be hypothetically filled with uranium ore (8%).

As in the cases of JO and NL, three additional deterministic calculation cases concerning uncertainty in biosphere are performed. The evolution of the dose rates in each of these cases is shown in Fig. 6-16. A warmer and drier climate is found to result in a maximum dose rate of 1.03×10^{-3} mSv/a at 10^6 years, which is about a factor of ten higher than that of the reference case. Other climatic and surface conditions result in lower dose rates.

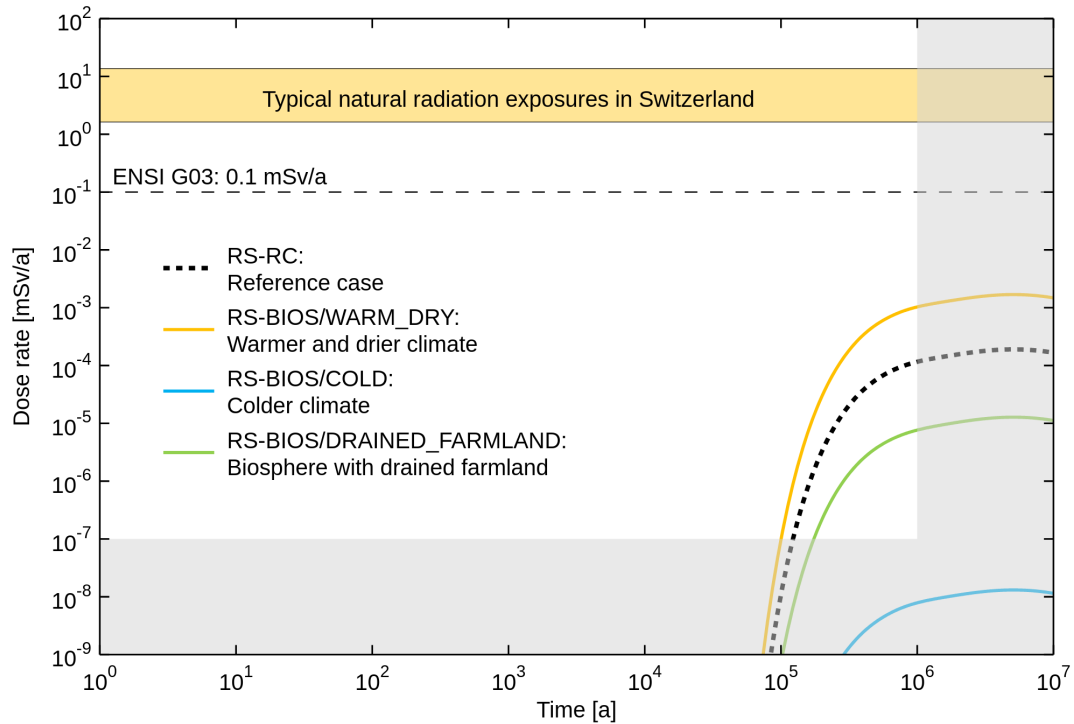


Fig. 6-16: Total dose rates due to SF and RP-HLW for an HLW repository in the ZNO siting region in the reference case and in cases assuming different climatic and surface conditions

6.1.2 Probabilistic and deterministic analysis covering parameter uncertainty

In accordance with the workflow described at the start of this chapter, probabilistic analysis of the reference safety scenario is performed for each site-specific model, along with deterministic analysis of pessimistic cases, in which those parameters identified as the most sensitive in the probabilistic analysis are set to pessimistic, bounding values. This also includes a deterministic case that combines the pessimistic bounding values of all the most sensitive parameters. The results of these probabilistic and deterministic analysis are presented for each siting region in the following sections. Details of the Monte-Carlo simulation approach and of the sensitivity analysis methods used in the probabilistic analyses are given in App. G.

6.1.2.1 Jura Ost (JO)

Fig. 6-17 shows statistical percentiles calculated from 4,000 Monte-Carlo simulations of the dose rate evolution of an HLW repository in the JO siting region, with each simulation realisation carried out by sampling input parameters from probability distribution functions representing parameter uncertainty. The bandwidth of the maximum dose rates due to uncertainty in the input

parameter values spans less than 2 orders of magnitude. The maximum calculated dose rate within the time frame of 10^6 years is 1.50×10^{-3} mSv/a, which still includes a safety margin of about 2 orders of magnitude. The dose rate after the time period for assessment is several orders of magnitude below that of the lower bound values of the typical natural radiological exposures in Switzerland (BAG 2021).

Sensitivity analyses have been performed based on the results of the Monte-Carlo simulations. The first step is a graphical analysis using scatter plots showing the maximum dose within the one-million-year time period for assessment against individual input parameter values sampled in the Monte-Carlo simulations. Some selected examples of such scatter plots are shown in Fig. 6-18 to Fig. 6-20.

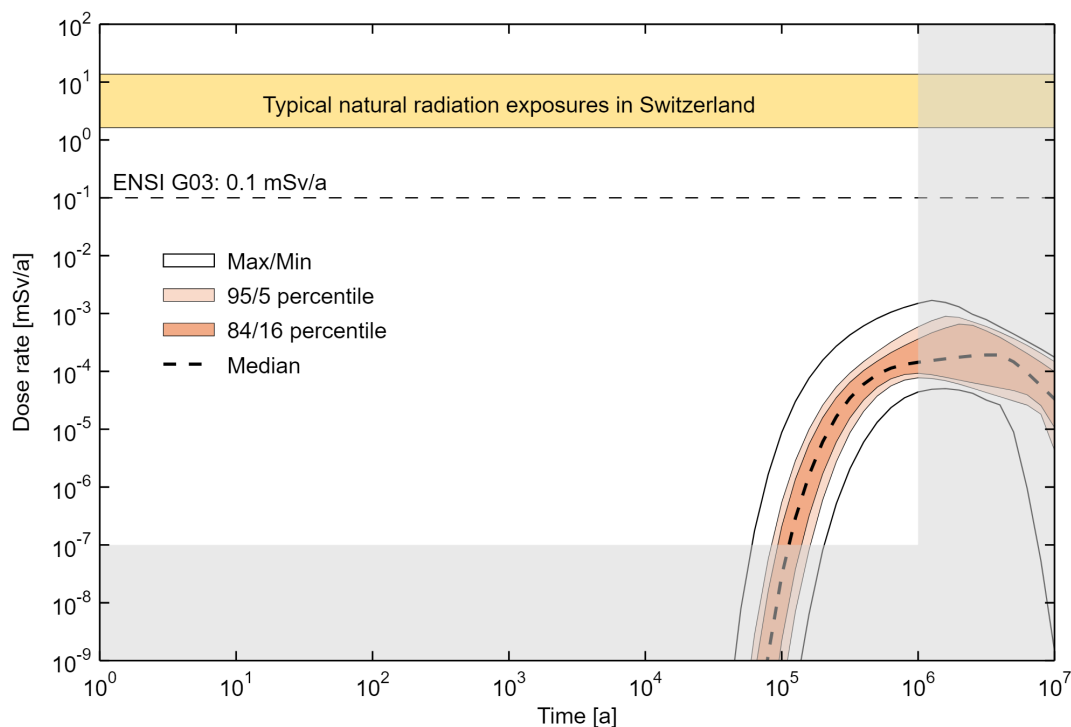


Fig. 6-17: Statistical percentiles calculated from 4,000 Monte-Carlo simulations of the dose rate evolution of an HLW repository in the JO siting region

Fig. 6-18 shows a clear and monotonic relationship between the maximum dose rate and the fractional release rate from the SF matrix. This arises because the maximum dose rate is dominated by the long-lived radionuclide I-129, which, in addition to an instant release fraction, is released continuously as the fuel matrix dissolves. Because I-129 (half-life: 1.57×10^7 years) behaves like a conservative tracer in the first one million years, I-129 can reach the biosphere in all of the simulations despite the long transport time. A higher radionuclide release rate from the spent fuel matrix to the bentonite buffer leads to a higher release rate of I-129 from the geosphere to the biosphere, and hence to the maximum dose rate. The correlation between the maximum dose rate and the fractional release rate is more pronounced at higher release rates, because, in these cases, the contribution of the SF matrix release (congruent release fraction) to the maximum dose rate is more likely to dominate over the contribution of the instant release fraction (note that both axes in the scatter plot are logarithmic).

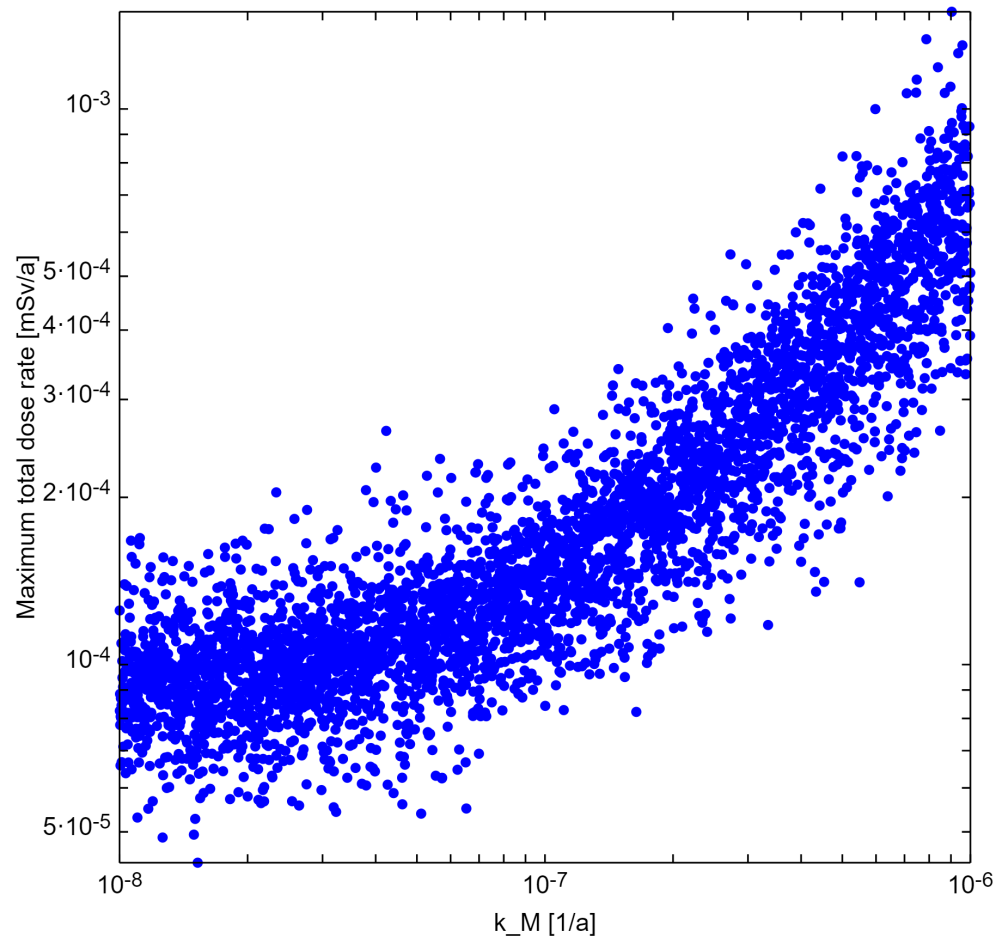


Fig. 6-18: Scatter plot showing the maximum dose rate for an HLW repository in the JO siting region within the one-million-year time period for assessment against the fractional release rate of radionuclides from SF due to dissolution of the SF matrix, sampled in Monte-Carlo simulations

Fig. 6-19 illustrates another correlation between the effective diffusion coefficients of the halogens Cl-36 and I-129 in the Opalinus Clay, which are varied using an identical scaling factor because of their strong correlation, and the maximum dose rates from an HLW repository in JO siting region. The “scaling factor” is a normalised factor used in the sampling to vary the effective diffusion coefficient between its lower and higher boundary values. Fig. 6-19 shows a limited effect of the effective diffusion coefficient of halogens in the Opalinus Clay on the maximum total dose rates as its main impact is on the timing of the maximum dose rate. The higher the diffusion in the Opalinus Clay, the sooner the maximum total dose rate is reached, the higher is the maximum dose rate in frame of the time period for assessment.

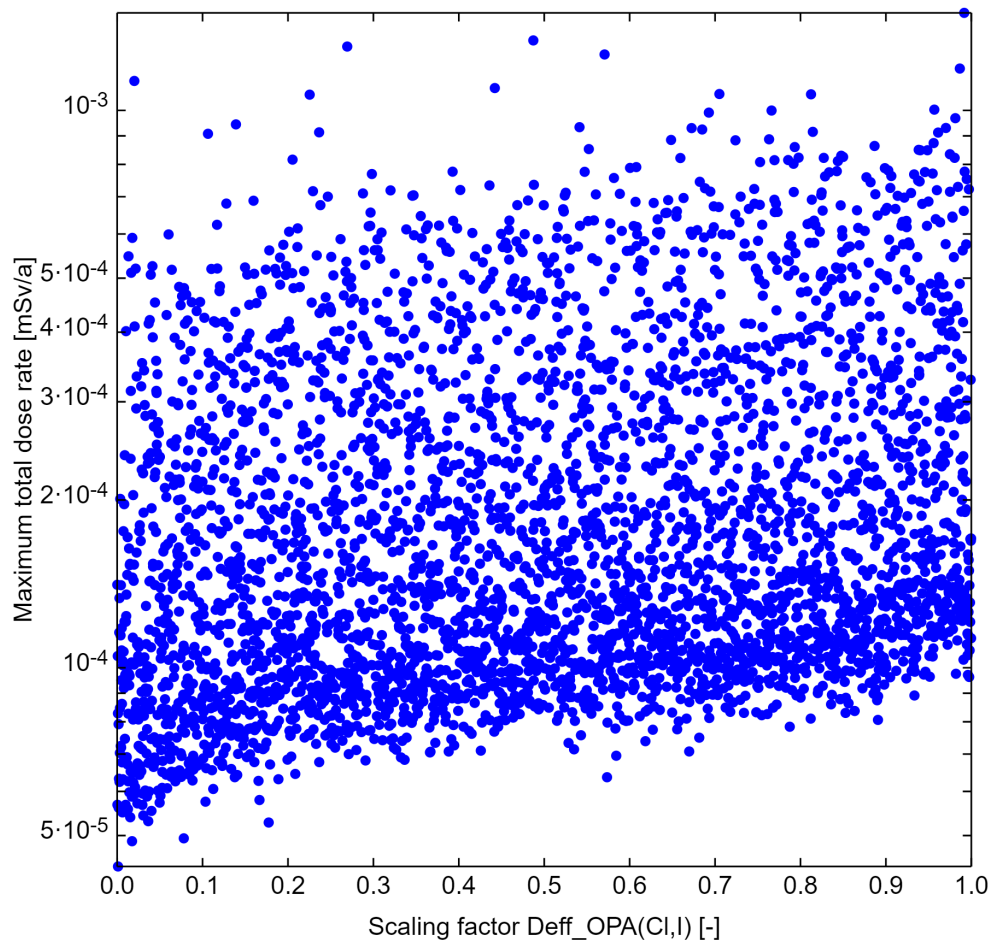


Fig. 6-19: Scatter plot showing the maximum dose rate for an HLW repository in the JO siting region within the one-million-year time period for assessment against the effective diffusion coefficient of Cl-36 and I-129 in the Opalinus Clay, which is varied using a scaling factor, sampled in Monte-Carlo simulations

It is, nonetheless, still of interest to examine the sensitivity of the maximum dose rate to the parameters that control advective transport. A correlation can be seen in the scatter plot in Fig. 6-20 between the maximum dose rate and the vertical Darcy flow rate through the geological formations of the Opalinus Clay and the confining units. The relationship is, however, not monotonic. This is because the Darcy flow is varied between negative (downward) and positive (upward) values. More specifically, the vertical hydraulic head difference between the upper and lower model boundaries is varied between -1 and 1 m/m, thus changing the flow direction. The correlation is more significant at higher Darcy flow rates, where the dominance of diffusion over advection is less pronounced. At lower Darcy flows of between about -1×10^{-14} and 1×10^{-14} m/s, the maximum dose rate shows little sensitivity to this parameter.

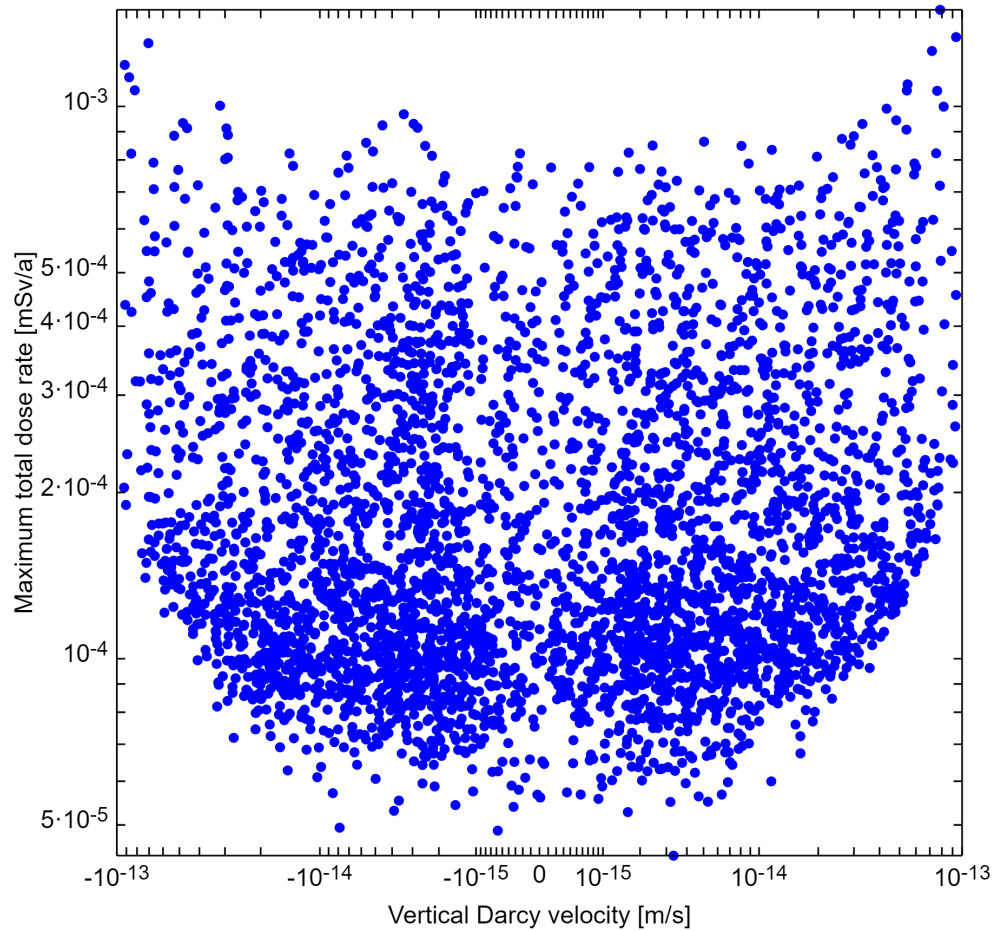


Fig. 6-20: Scatter plot showing the maximum dose rate for an HLW repository in the JO siting region within the one-million-year time period for assessment against the vertical Darcy flow velocity

Quantitative sensitivity measures are calculated to evaluate parameter sensitivity. The sensitivity measures used here are the Pearson correlation coefficient and the Spearman correlation coefficient. Moreover, according to the methodology of sensitivity analysis introduced in App. G.2, if a non-monotonic relationship is detected, variance-based sensitivity indices are needed. In this case with a non-monotonic relationship shown in Fig. 6-20, a modified EASI first-order sensitivity index, which belongs to variance-based sensitivity indices, is calculated.

Tab. 6-2 shows these sensitivity measures calculated for the parameters varied in the probabilistic analyses. Consistent with the scatterplots discussed above, the most sensitive parameters, according to all three sensitivity measures, are:

- the fractional release rate of spent fuel (k_M);
- the effective diffusion coefficient of Cl-36 and I-129 in the Opalinus Clay ($Deff_OPA(Cl_I)$); and
- the vertical hydraulic conductivity of the Opalinus Clay ($K_{v,OPA}$).

The vertical hydraulic gradient (i_v), which is multiplied by the vertical hydraulic conductivity to give the Darcy velocity, yields Pearson and Spearman correlation coefficients that are below the threshold of significance (marked in red in Tab. 6-2). However, these correlation coefficients are not suited to non-monotonic relationships, such as that shown by the hydraulic gradient. The sensitivity index obtained using the modified EASI method, which is better suited to such parameters, is above the threshold of significance.

The effective diffusion coefficient of Cl-36 and I-129 in the KEU formation ($Deff_KEU(Cl,I)$), which is near to the Keuper aquifer, also shows a marked sensitivity, indicating its influence on the rate of diffusive transport towards the aquifer, which was shown in the reference case to provide a significant release path to the biosphere (see Fig. 6-3).

Under the current modelling assumptions, the porosities of the confining geological units provide a “reservoir volume” for the released radionuclides, which reduces radionuclide concentrations and hence the release rates to the biosphere, explaining why these porosities show a negative correlation with the maximum dose rate. Furthermore, there is some sensitivity to the thickness of the Opalinus Clay (hOPA), due to its impact on the radionuclide attenuation capacity of the disposal system.

For this diffusion-dominated transport system, the transport properties of rock formations with a higher thickness (e.g., the Opalinus Clay) show higher sensitivity.

Tab. 6-2: Sensitivity measures for the parameters of the probabilistic analyses with at least one significant correlation for an HLW repository in the JO siting region

Values above the calculated “threshold of significance” are marked in blue. See main text for explanation of the combined pessimistic case. Signs of the Pearson and Spearman correlations indicate positive or negative correlation between the input and output parameters. Values marked in red are unreliable because the scatterplot shows the relationship to be non-monotonic. (+) or (-) indicates the selected bounding value for the individual and combined pessimistic calculations.

Parameter	Description	Pearson correlation coefficient	Spearman correlation coefficient	Modified EASI sensitivity index
	<i>Significance threshold</i>	<i>0.034</i>	<i>0.039</i>	<i>0.0037</i>
$k_M (+)$ $1 \times 10^{-8} - 1 \times 10^{-6} a^{-1}$	Fractional dissolution rate of SF matrix	0.90	0.90	0.80
$Deff_OPA(Cl,I) (+)$ $6.7 \times 10^{-13} - 2.9 \times 10^{-12} m^2/s (Cl)$ $6.6 \times 10^{-13} - 2.9 \times 10^{-12} m^2/s (I)$	Effective diffusion coefficient of halogens in the Opalinus Clay	0.18	0.24	0.035
$K_{v,OPA} (+)$ $2 \times 10^{-15} - 1 \times 10^{-13} m/s$	Hydraulic conductivity of the Opalinus Clay	0.16	0.15	0.028
$Deff_KEU(Cl,I) (+)$ $8.5 \times 10^{-13} - 5.3 \times 10^{-12} m^2/s (Cl)$ $8.3 \times 10^{-13} - 5.3 \times 10^{-12} m^2/s (I)$	Effective diffusion coefficient of halogens in the KEU	0.11	0.13	0.013

Tab. 6-2: continued

Parameter	Description	Pearson correlation coefficient	Spearman correlation coefficient	Modified EASI sensitivity index
	<i>Significance threshold</i>	<i>0.034</i>	<i>0.039</i>	<i>0.0037</i>
h_OPA (-) 117 - 129 m	Thickness of the Opalinus Clay	-0.055	-0.08	0.0056
Deff_SCAD(Cl,I) (+) 1.1×10^{-12} - 7.8×10^{-12} m ² /s (Cl) 1.1×10^{-12} - 7.7×10^{-12} m ² /s (I)	Effective diffusion coefficient of halogens in the SCAD+SCD	0.041	0.049	0.0026
Phi_OPA(Ag,C,Ca,Hg,Se,C _{org}) (-) 0.1 - 0.16 (Ag, Ca, Hg, Se) 0.03 - 0.05 (C, C _{org})	Radionuclide-accessible porosity (except halogens) of the Opalinus Clay	-0.035	-0.036	0.0034
Deff_CAD(Cl,I) (+) 1.2×10^{-12} - 9.4×10^{-12} m ² /s (Cl) 1.2×10^{-12} - 9.2×10^{-12} m ² /s (I)	Effective diffusion coefficient of halogens in the CAD	0.035	0.022	0.0053
K_d_KEU(C) (-) 8.3×10^{-5} - 6.2×10^{-3} m ³ /kg	Sorption coefficient of inorganic C-14 in the KEU	-0.034	-0.032	0.0025
Phi_OPA(Cl,I) (-) 0.02 - 0.03 (Cl, I)	Radionuclide-accessible porosity of halogens of the Opalinus Clay	-0.031	-0.043	0.0024
i_v (+) -1 - 1 m/m	Hydraulic gradient along the geological formations	0.031	0.035	0.0049
Deff_OPA(Se) (+) 2.1×10^{-12} - 6.7×10^{-12} m ² /s	Effective diffusion coefficient of selenium in the Opalinus Clay	0.028	0.049	0.0028
Deff_KAK(Cl,I) (+) 2.3×10^{-13} - 4.0×10^{-12} m ² /s (Cl) 2.3×10^{-13} - 3.9×10^{-12} m ² /s (I)	Effective diffusion coefficient of halogens in the KAK	0.017	0.039	0.0017

In order to provide a better understanding of the impact of various parameters, additional deterministic cases have been analysed, switching each of the individual sensitive parameters to their most pessimistic, bounding values. These deterministic cases can give the significance of the impact of the individual parameters without considering its interaction with the other parameters (global effect), which can be investigated in the probabilistic sensitivity analysis. (+) indicates the most pessimistic upper bound values and (-) indicates the most pessimistic lower bound values in accordance with Tab. 6-2.

Fig. 6-21 shows some individual deterministic cases where the most sensitive parameter and various effective diffusion coefficients are set to their most pessimistic (generally upper) bounding values. Consistent with the sensitivity measures given in Tab. 6-2, assigning high values to the diffusion coefficient of Cl-36 and I-129 in the Opalinus Clay is found to increase the maximum dose rate because of the dominant contribution of these radionuclides, especially I-129, to the total dose. By contrast, assigning high values to the diffusion coefficients of other radionuclides and of other geological formations only slightly affects the total dose rate, which is generally consistent with the sensitivity measures given in Tab. 6-2.

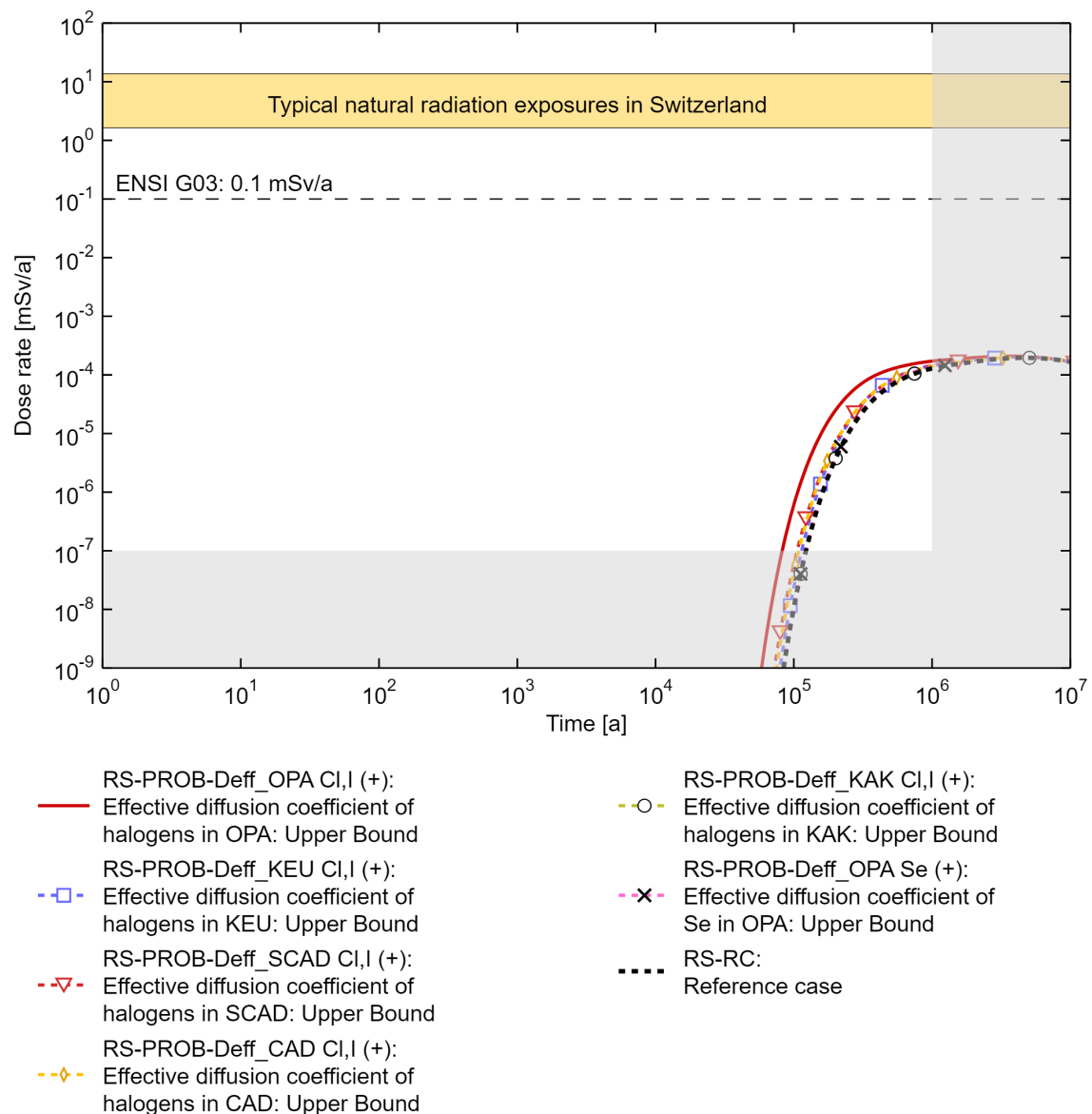


Fig. 6-21: Total dose rates due to SF and RP-HLW in the reference case for an HLW repository in the JO siting region, and in cases where various effective diffusion coefficients are set to their most pessimistic, bounding values. (SCAD = SCAD + SCD)

In addition to the effective diffusion coefficients, several other Opalinus Clay properties show sensitivity, according to Tab. 6-2. Fig. 6-22 shows these individual deterministic cases where various Opalinus Clay properties, excluding the effective diffusion coefficients, are set to their most pessimistic, bounding values.

Fig. 6-22 shows that assigning low values to the accessible porosity for I-129 and Cl-36 of the Opalinus Clay can slightly increase the maximum dose rate, while the accessible porosity for other radionuclides has no significant impact on the maximum dose rate, which is consistent to the dominant contribution to the dose rate of these radionuclides, especially I-129. Assigning a lower bounding value to the thickness of the Opalinus Clay leads to no significant increase in the dose rate.

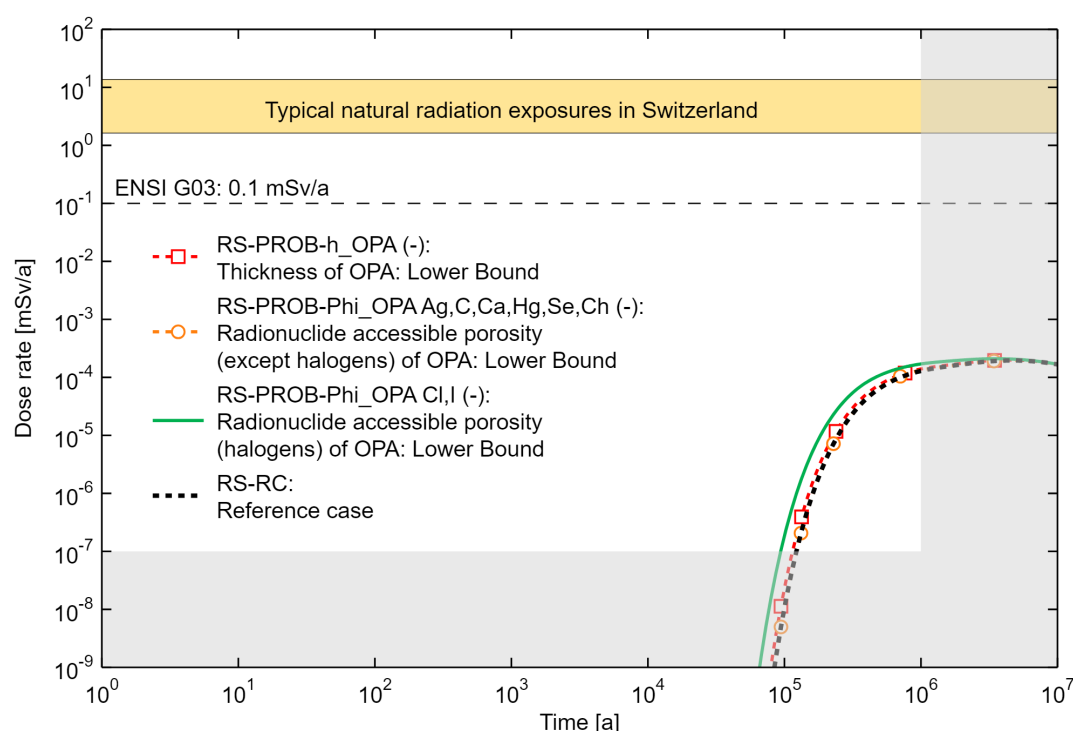


Fig. 6-22: Total dose rates due to SF and RP-HLW in the reference case for an HLW repository in the JO siting region, and in cases where various Opalinus Clay properties, excluding the effective diffusion coefficients, are set to their most pessimistic, bounding values.

Fig. 6-23 shows the results of two further deterministic cases concerning the rest of the parameters with correlations identified in Tab. 6-2. Setting the fractional release rate from the SF matrix (k_M) to its upper bound value leads to a significant increase in the dose rate, consistent with the sensitivity measures in Tab. 6-2, although the early part of the release curve, including the time when a significant dose rate (i.e., a dose rate higher than 10^{-7} mSv/a) first occurs, is unaffected. This time point is determined mainly by transport processes in the CRZ, and not by the release rate from the waste packages. Thus, for example, setting the Darcy velocity through the CRZ to its upper bound value (by setting the vertical hydraulic gradient and the conductivity of OPA to their upper bound value) results in slightly earlier releases and a higher dose rate.

The case concerning sorption capacity of the inorganic C-14 in the KEU does not impact the dose rate evolution. This is in agreement with the negligibly weak sensitivity shown in Tab. 6-2 and the system understanding.

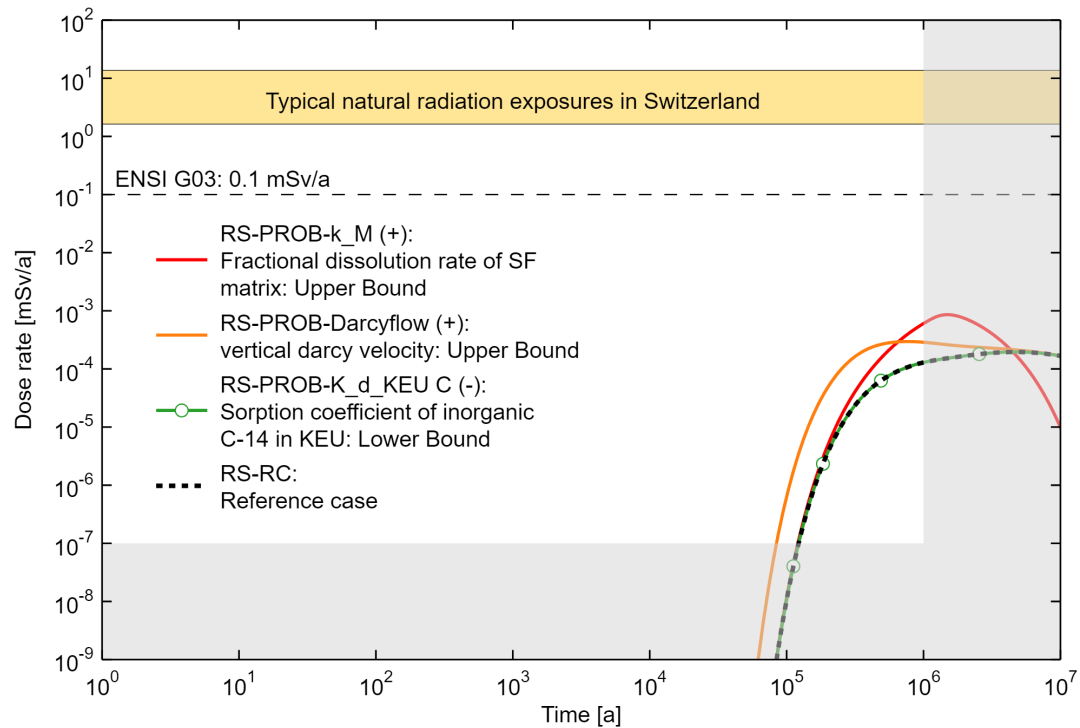


Fig. 6-23: Total dose rates due to SF and RP-HLW in the reference case for an HLW repository in the JO siting region, and in cases where various individual parameters are set to their most pessimistic, bounding values.

Fig. 6-24 shows a case in which pessimistic bounding values are set for all the above-mentioned parameters. The maximum dose rate is increased by about one order of magnitude and occurs earlier, around one million years after repository closure, compared with the reference case. It remains, however, still almost two orders of magnitude below that of the protection criterion of 0.1 mSv/a given by (ENSI 2023) in the time period for assessment and several orders of magnitude below the lower bound value of typical natural radiological exposures in Switzerland (BAG 2021) after 1 million years. Although the likelihood of pessimistic bounding values occurring together in this way is low, the combined pessimistic case further demonstrates the robustness of the repository from a post-closure safety perspective.

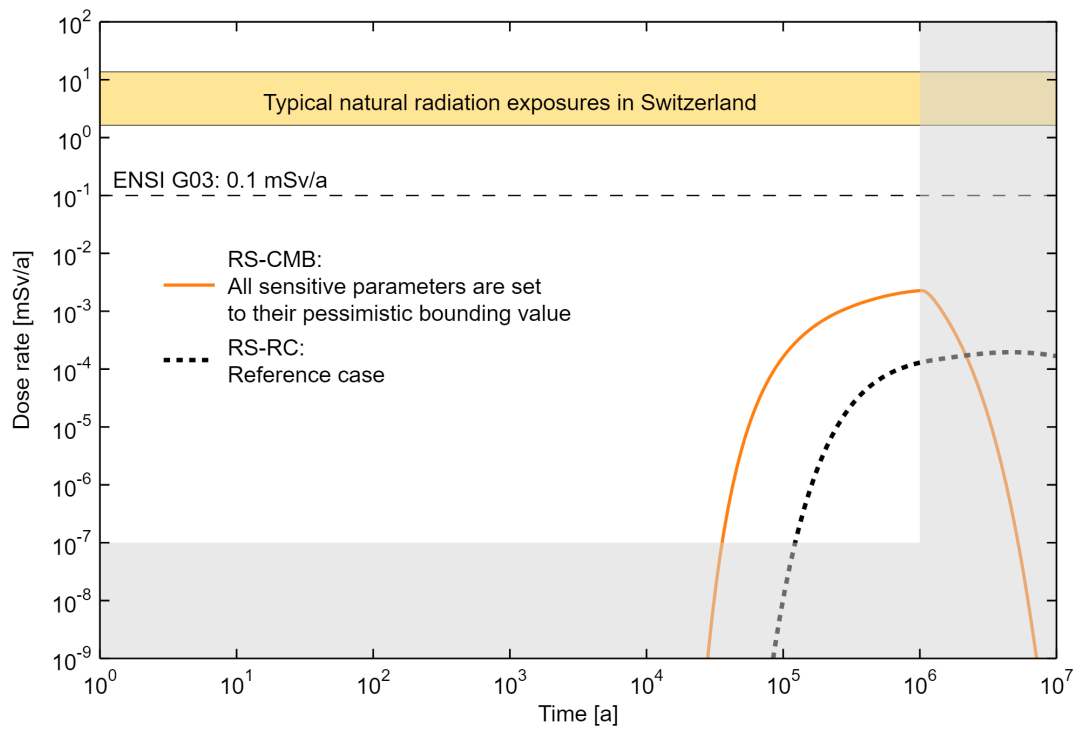


Fig. 6-24: Total dose rates due to SF and RP-HLW in the reference case for an HLW repository in the JO siting region, and in a case in which pessimistic bounding values are set for all sensitive parameters

6.1.2.2 Nördlich Lägern (NL)

Fig. 6-25 shows statistical percentiles calculated from 4,000 Monte-Carlo simulations of the dose rate evolution of an HLW repository in the NL siting region. The bandwidth of the maximum dose rate due to uncertainty in the input parameter values spans about 1.5 orders of magnitude. The evolution of the dose rate is very similar to that shown in Fig. 6-17, which confirms the similarity of the system behaviour between the JO and NL siting regions. A similar maximum calculated dose rate within the time frame of 10^6 years (1.10×10^{-3} mSv/a), as in the case for JO, can be obtained. The dose rate after the time period for assessment is several orders of magnitude lower than the lower bound value of the typical natural radiological exposures in Switzerland (BAG 2021).

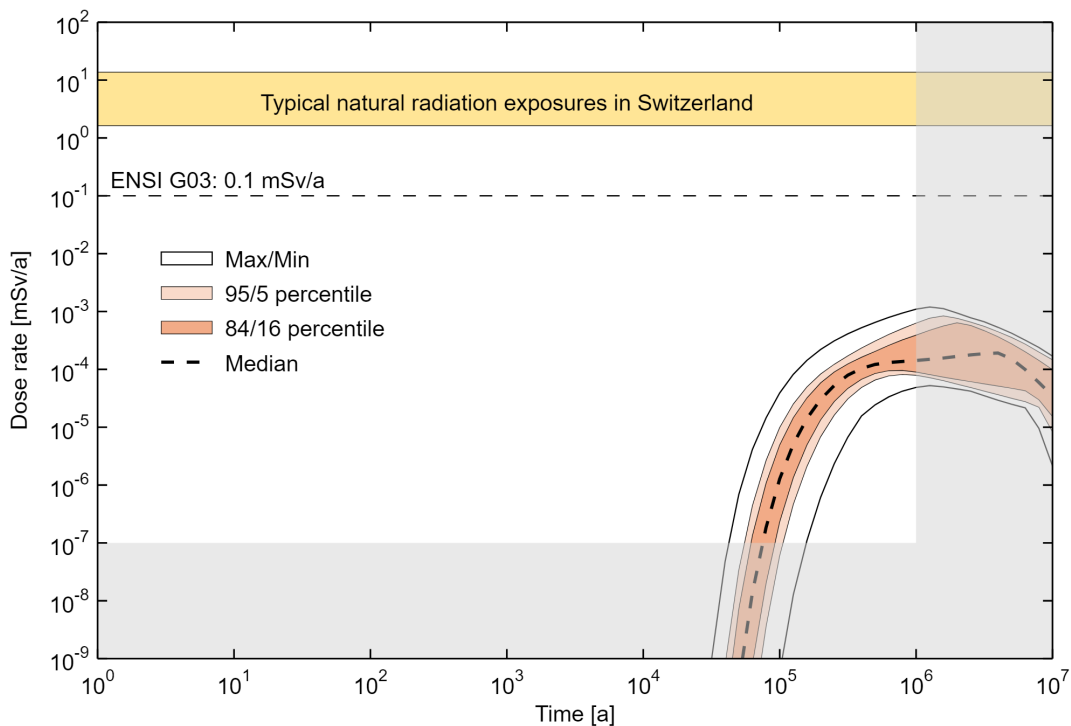


Fig. 6-25: Statistical percentiles calculated from 4,000 Monte-Carlo simulations of the dose rate evolution of an HLW repository in the NL siting region

With the same workflow as for JO, sensitivity analyses have been performed based on the results of the Monte-Carlo simulations. The first step is a graphical analysis using scatter plots showing the maximum dose rates within the one-million-year time period for assessment against individual input parameter values sampled in the Monte-Carlo simulations for selected parameters. Some examples of such scatter plots are shown in Fig. 6-26 to Fig. 6-29.

Fig. 6-26 shows a clear and monotonic relationship between the maximum dose rate and the fractional release rate from the SF matrix. As in the case of JO, the dissolution rate of the SF matrix determines the rate of the I-129 release, which is the main driver of the variation of the maximum dose rate from the HLW repository. The correlation between the maximum dose rate and the fractional release rate is more pronounced at higher release rates, in particular when the fractional release rate exceeds 10^{-7} per year.

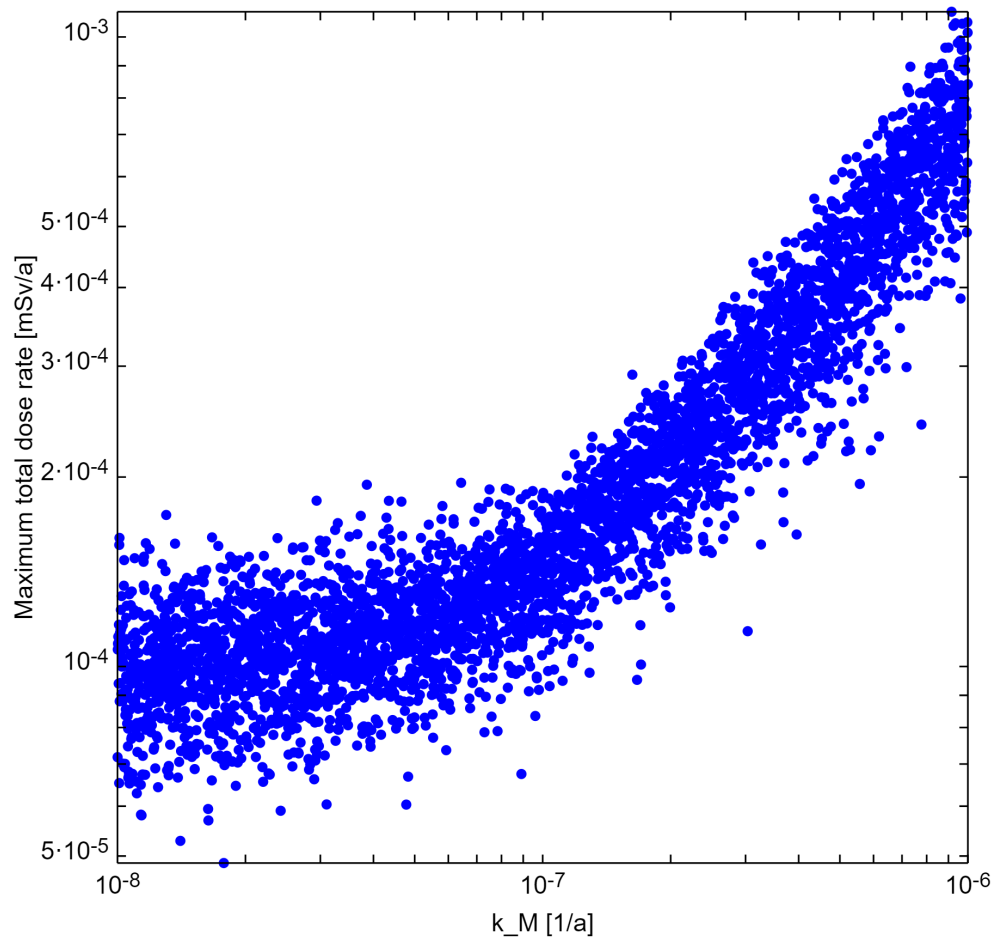


Fig. 6-26: Scatter plot showing the maximum dose rate for an HLW repository in the NL siting region within the one-million-year time period for assessment against the fractional release rate of radionuclides from SF due to dissolution of the SF matrix, sampled in Monte-Carlo simulations.

Fig. 6-27 illustrates another correlation between the effective diffusion coefficients of the halogens Cl-36 and I-129 in the Opalinus Clay, which are varied using a normalised scaling factor, and the maximum dose rates due to these halogens. The correlation shown in Fig. 6-27 is a little weaker than that shown in Fig. 6-19 for the JO siting region. This can be attributed to the higher thickness of the Opalinus Clay in JO compared with NL, resulting in greater sensitivity to the parameters controlling the transport process in JO compared with NL.

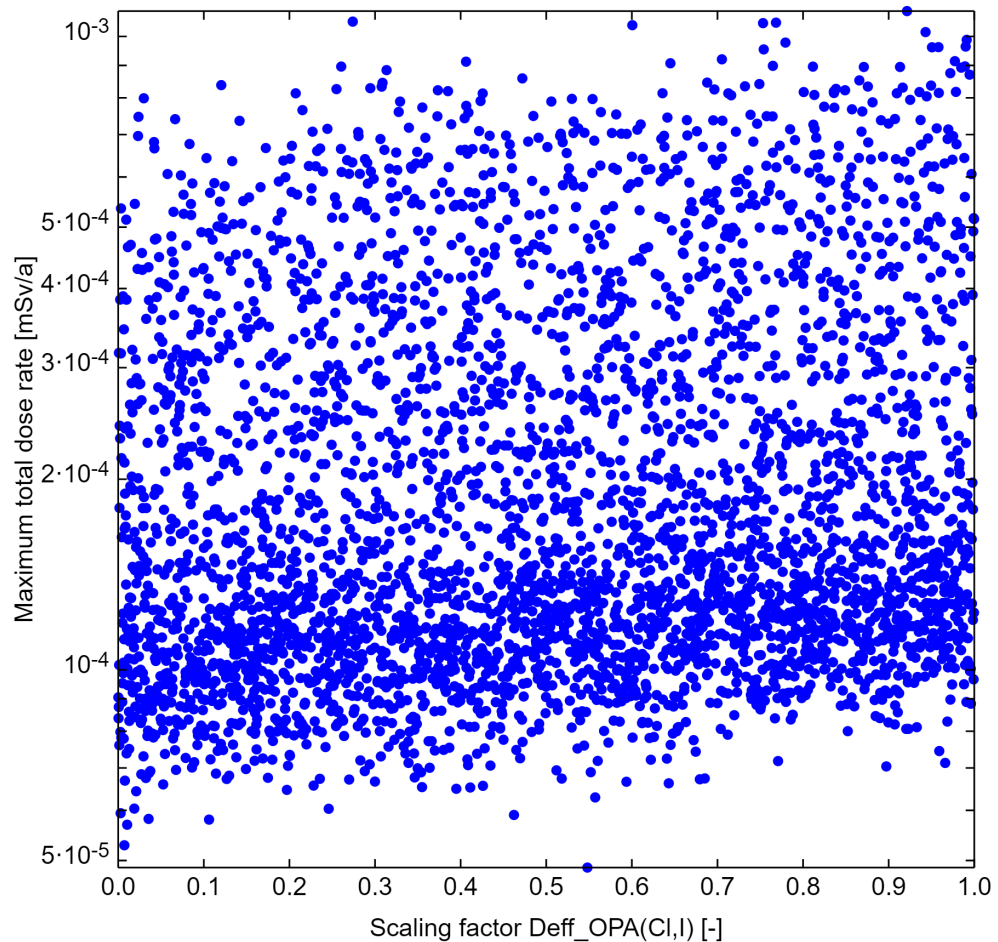


Fig. 6-27: Scatter plot showing the maximum dose rate for an HLW repository in the NL siting region within the one-million-year time period for assessment against the effective diffusion coefficient of the halogens Cl-36 and I-129 in the Opalinus Clay, which is varied using a scaling factor, sampled in Monte-Carlo simulations

Fig. 6-28 shows another monotonic relationship between the maximum dose rate and the activation energy for diffusion in the pore water, which is a key parameter used when accounting for the temperature dependence of effective diffusion coefficient (see App. C.1). It is used when adjusting the effective diffusion coefficient at a reference temperature of 25 °C to the ambient temperature at repository depth. In JO, the ambient temperature is taken to be 28 °C, which is rather similar to the reference temperature. Thus, the temperature correction is small, and the activation energy has little impact on diffusion through the rock. By contrast, in NL, because of the greater repository depth, the ambient temperature is higher, and is taken to be 48 °C. Thus, the temperature correction is larger and, as shown in Fig. 6-28, the activation energy is positively correlated with the dose rate.

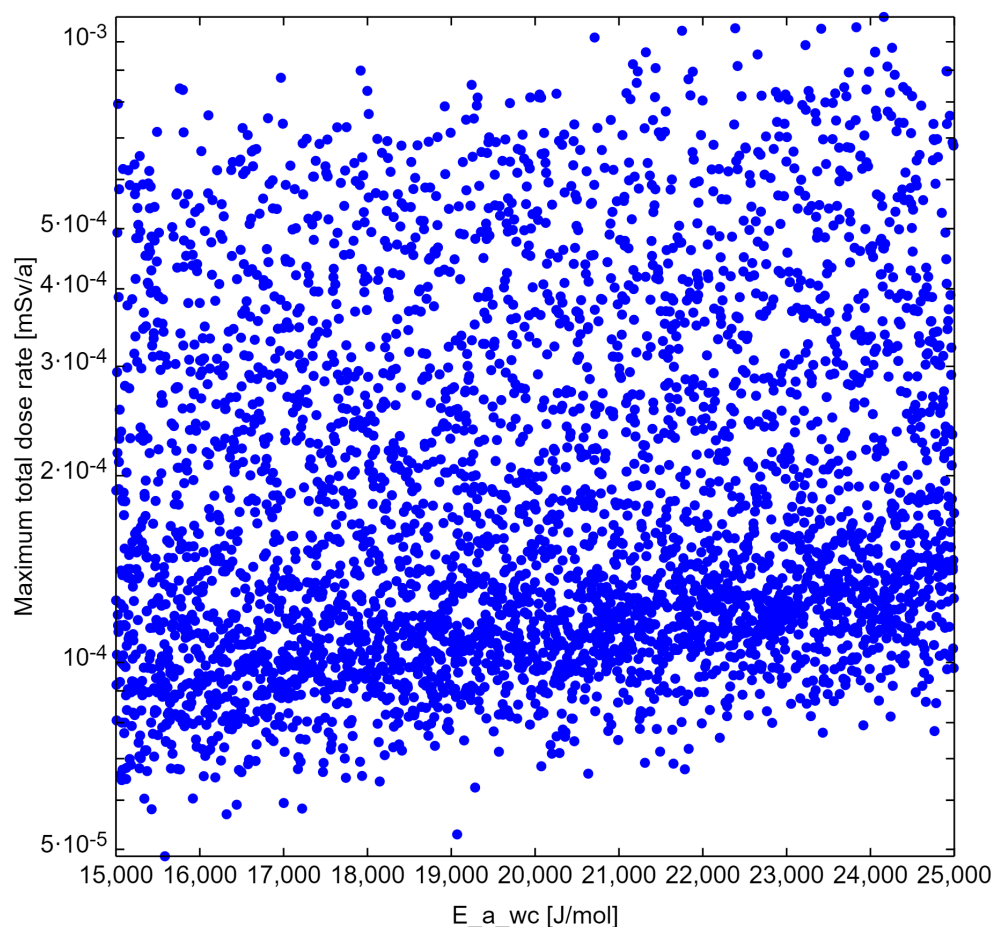


Fig. 6-28: Scatter plot showing the maximum dose rate for an HLW repository in the NL siting region within the one-million-year time period for assessment against the activation energy used when adjusting the effective diffusion coefficient to the ambient rock temperature

It is of interest to examine the sensitivity of the maximum dose rate to the parameters that control advective transport. Some correlation can be seen in the scatter plot in Fig. 6-29 between the maximum dose rate and the vertical Darcy flow rate through the geological units of the Opalinus Clay and the confining units. The relationship is, however, weaker for NL than for JO (cf. Fig. 6-20) and, unlike JO, it is negative and monotonic. The bandwidth of Darcy flow in NL is smaller (-5×10^{-14} to 5×10^{-14} m/s in NL compared to -1×10^{-13} to 1×10^{-13} m/s in JO) and can

thus not cause a significant correlation. Since the dominant transport pathway in the model for NL is downwards to the Keuper aquifer (see Fig. 6-8), a negative (downward) Darcy flow slightly increases the dose rate, while a positive (upward) Darcy flow slightly reduces the dose rate.

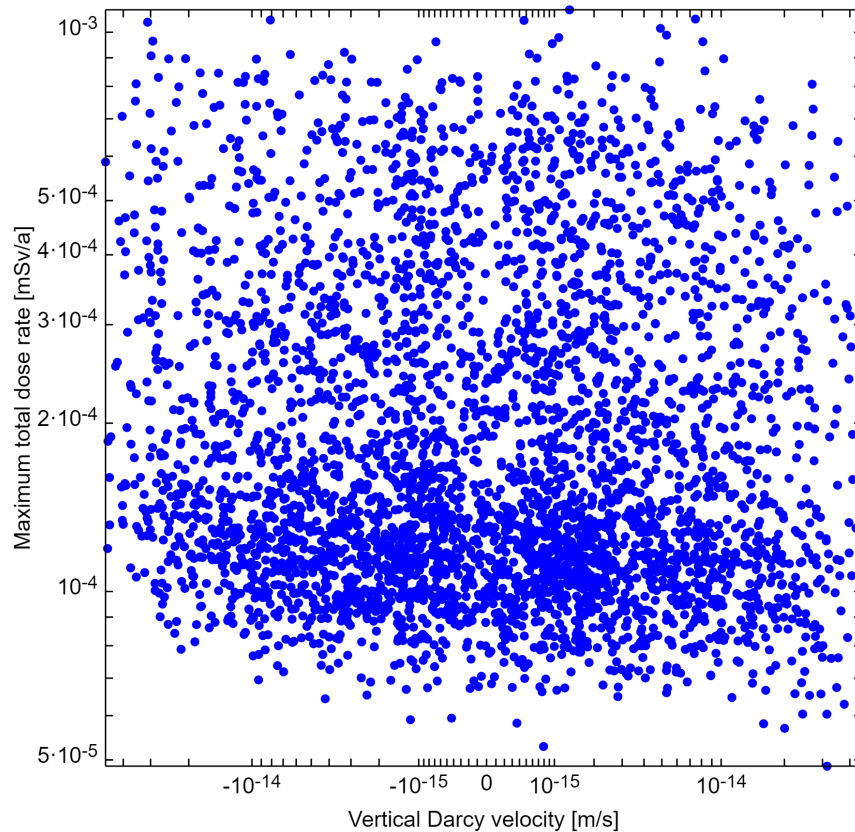


Fig. 6-29: Scatter plot showing the maximum dose rate for an HLW repository in the NL siting region within the one-million-year time period for assessment against the vertical Darcy flow velocity

For the quantitative sensitivity measures calculated for the NL siting region, Tab. 6-3 shows three sensitivity measures: the Pearson correlation coefficient, the Spearman correlation coefficient and the modified EASI first-order sensitivity index, calculated for the parameters considered in the probabilistic analyses for the HLW repository in the NL siting region.

The most sensitive parameters are the same as for JO, except that, as discussed above, the maximum dose is also sensitive to activation energy.

Furthermore, consistent to the system understanding discussed in Section 6.1.1.2 that the dominant transport pathway in NL, unlike JO, is downwards to the Keuper aquifer, the transport properties of the Opalinus Clay and the formations in lower confining geological units mainly show sensitivity.

Tab. 6-3: Sensitivity measures for the parameters of the probabilistic analyses with at least one significant correlation for an HLW repository in the NL siting region

Values above the calculated “threshold of significance” are marked in blue. Signs of the Pearson and Spearman correlation coefficients indicate positive or negative correlation between the input and output parameters. (+) or (-) indicates the selected bounding value for the individual and combined pessimistic calculations.

Parameter	Description	Pearson correlation coefficient	Spearman correlation coefficient	Modified EASI sensitivity index
	<i>Significance threshold</i>	<i>0.036</i>	<i>0.041</i>	<i>0.0045</i>
k_M (+) 1×10^{-8} - 1×10^{-6} a ⁻¹	Fractional dissolution rate of the SF matrix	0.95	0.91	0.90
E_a,wc (+) 1.5×10^4 - 2.5×10^4 J/mol	Activation energy for diffusion in the porewater	0.11	0.17	0.014
Deff_OPA(Cl,I) (+) 1.2×10^{-12} - 5.6×10^{-12} m ² /s (Cl) 1.2×10^{-12} - 5.5×10^{-12} m ² /s (I)	Effective diffusion coefficient of halogens in the Opalinus Clay	0.12	0.15	0.015
Deff_KEU(Cl,I) (+) 1.6×10^{-12} - 8.7×10^{-12} m ² /s (Cl) 1.5×10^{-12} - 8.6×10^{-12} m ² /s (I)	Effective diffusion coefficient of halogens in the KEU	0.11	0.14	0.014
h_OPA (-) 100 - 115 m	Thickness of the Opalinus Clay	-0.039	-0.074	0.0025
i_v (-) -0.5 - 0.5 m/m	Hydraulic gradient along the geological formations	-0.029	-0.06	0.0031
K_KAL (+) 1.0×10^{-9} - 1.0×10^{-5} m/s	Hydraulic conductivity of the KAL (Keuper aquifer)	0.025	0.059	0.0046
Deff_CD(Cl,I) (+) 9.1×10^{-13} - 9.9×10^{-12} m ² /s (Cl) 9.0×10^{-13} - 9.8×10^{-12} m ² /s (I)	Effective diffusion coefficient of halogens in the CD («Herrenwis Unit»)	0.045	0.052	0.0027
Phi_KAU(Ag,C,Ca,Hg,Se,C _{org}) (-) 0.03 - 0.11 (Ag,Ca,Hg,Se) 0.02 - 0.07 (C, C _{org})	Radionuclide-accessible porosity (except halogens) of the KAU	-0.044	-0.049	0.0033
DissRate_HLW_1 (+) 2.0×10^{-5} - 9.0×10^{-2} g/m ² /d	Fractional dissolution rate of RP-HLW Type 1 ⁸	0.0046	0.047	0.0015

⁸ There are two types of RP-HLW. Type 1 is the vitrified RP-HLW from Areva named “J-Z-005000” in MIRAM

Tab. 6-3: continued

Parameter	Description	Pearson correlation coefficient	Spearman correlation coefficient	Modified EASI sensitivity index
	<i>Significance threshold</i>	<i>0.036</i>	<i>0.041</i>	<i>0.0045</i>
K_d_OPA(C) (-) 3.0×10 ⁻⁴ - 3.0×10 ⁻³ m ³ /kg	Sorption coefficient of inorganic C-14 in the Opalinus Clay	-0.041	-0.031	0.0029
Deff_ML(C _{org}) (+) 2.2×10 ⁻¹² - 1.2×10 ⁻¹¹ m ² /s	Effective diffusion coefficient of organic C-14 in the ML	0.036	0.021	0.0029
K_d_AAK(C) (-) 1.3×10 ⁻⁴ - 2.2×10 ⁻³ m ³ /kg	Sorption coefficient of inorganic C-14 in the AAK	-0.0076	-0.01	0.0057

As in the process performed for JO, additional deterministic cases have been analysed by switching each of the individual sensitive parameters to their most pessimistic, bounding values, in order to provide a better understanding of the impact of the various parameters. It should be noted that these deterministic cases can merely show the impact of the individual parameters without considering their interaction with the other parameters (global effect), which can be investigated in the probabilistic sensitivity analysis. In the figures shown below in this section, (+) indicates the most pessimistic upper bound values and (-) indicates the most pessimistic lower bound values, according to Tab. 6-3.

Fig. 6-30 shows some individual deterministic cases where various effective diffusion coefficients and the activation energy are set to their most pessimistic (generally upper) bounding values. Consistent with the sensitivity measures given in Tab. 6-3, assigning higher boundary values to the diffusion coefficient of Cl-36 and I-129 in the Opalinus Clay and in the KEU formation is found to increase the maximum dose rate, as is assigning the higher boundary value to the activation energy⁹. The diffusion coefficient of Cl-36 and I-129 in the KEU formation shows stronger sensitivity in the NL than in the JO siting region because the dominant transport pathway in NL, unlike JO, is downwards to the Keuper aquifer. This increases the importance of rock formations, especially the KEU, in the lower confining geological units.

Assigning high values to the diffusion coefficients of other radionuclides and of other geological formations does not show any effect on the total dose rate.

⁹ The line for the case of pessimistic (high) activation energy for diffusion (E_{awc}) largely coincides with the line for the case of pessimistic (high) effective diffusion coefficients for the halogens (Deff_{KEU} (halogens)).

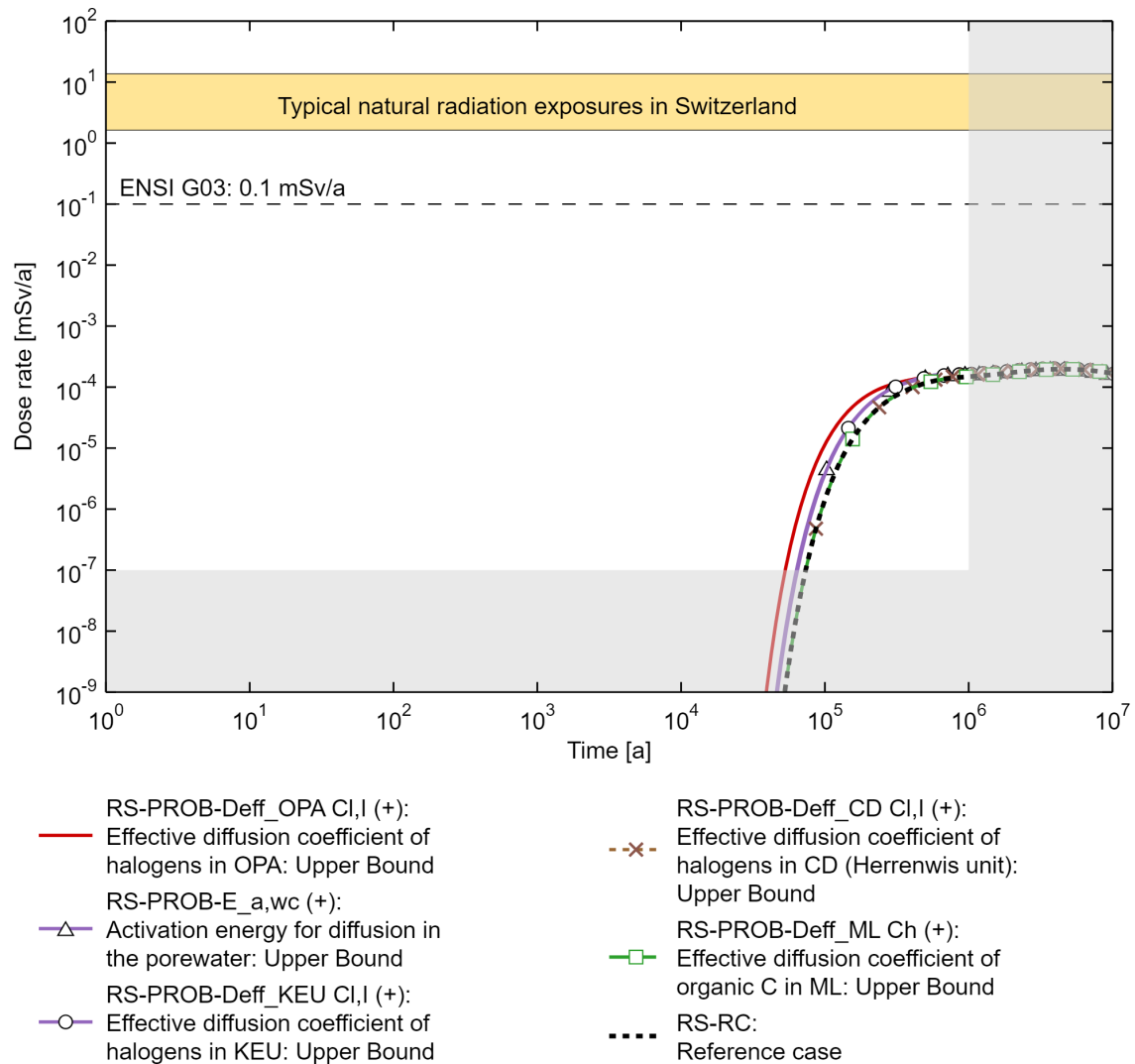


Fig. 6-30: Total dose rates due to SF and RP-HLW in the reference case for an HLW repository in the NL siting region, and in cases where various effective diffusion coefficients and the activation energy are set to their most pessimistic, bounding values

Fig. 6-31 shows cases where the dissolution rates of SF (k_M) and RP-HLW (DissRate_HLW_1) are set to their pessimistic, upper-bound values. As in the case of JO, setting the fractional release rate from the SF matrix to its upper bound value leads to a significant increase in the dose rate, consistent with the sensitivity measures in Tab. 6-3. The dissolution rate of RP-HLW has no significant impact on the dose rates for NL, which is consistent as well with the performance of this parameter in Tab. 6-3, i.e., it is only slightly above the “threshold of significance” in the case of the Spearman correlation coefficient.

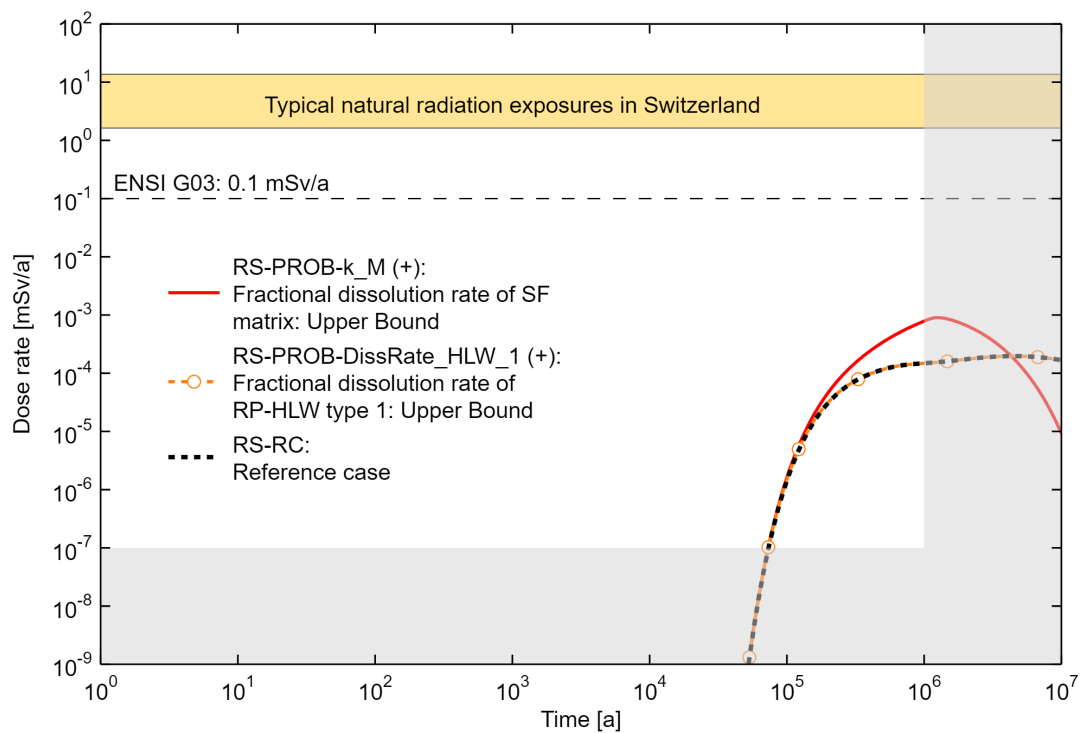


Fig. 6-31: Total dose rates due to SF and RP-HLW in the reference case for an HLW repository in the NL siting region, and in cases where the dissolution rate of the SF and RP-HLW matrices are set to their most pessimistic, bounding values

Fig. 6-32 shows additional, individual deterministic cases where various Opalinus Clay properties, excluding the effective diffusion coefficients, namely its thickness and its sorption coefficient for inorganic C (C-14), are set to their most pessimistic, bounding values. Both parameters have only a negligible impact on the dose rate, as expected from the relatively weak sensitivity measures in Tab. 6-3.

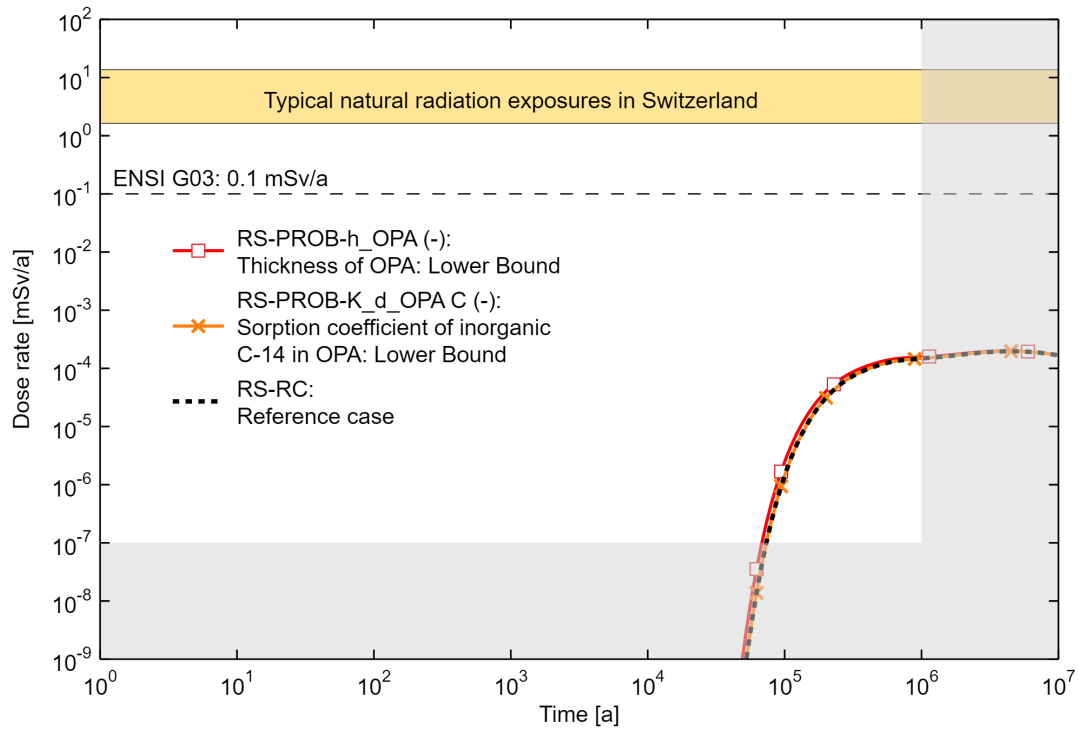


Fig. 6-32: Total dose rates due to SF and RP-HLW in the reference case for an HLW repository in the NL siting region, and in cases where various Opalinus Clay properties, excluding the effective diffusion coefficients, are set to their most pessimistic, bounding values

Fig. 6-33 shows the results of some further deterministic cases concerning the rest of the parameters with correlations identified in Tab. 6-3. A pessimistic Darcy flow increases the dose rate slightly. However, the impact is much lower than in the JO siting region (see Fig. 6-23), which indicates that NL has a more diffusion-dominated transport system than JO because of the lower boundary value of the vertical hydraulic gradient. The horizontal hydraulic conductivity of the Keuper aquifer (K_KAL) alone does not show any significant impact on the dose rate, because the water flow in the Keuper aquifer in all simulation cases is large enough for this aquifer to provide the dominant release route for radionuclides transported downwards from the repository to the biosphere. As expected, varying other parameters does not have a significant impact on dose rate evolution, either, which is consistent with their weak sensitivity measures shown in Tab. 6-3.

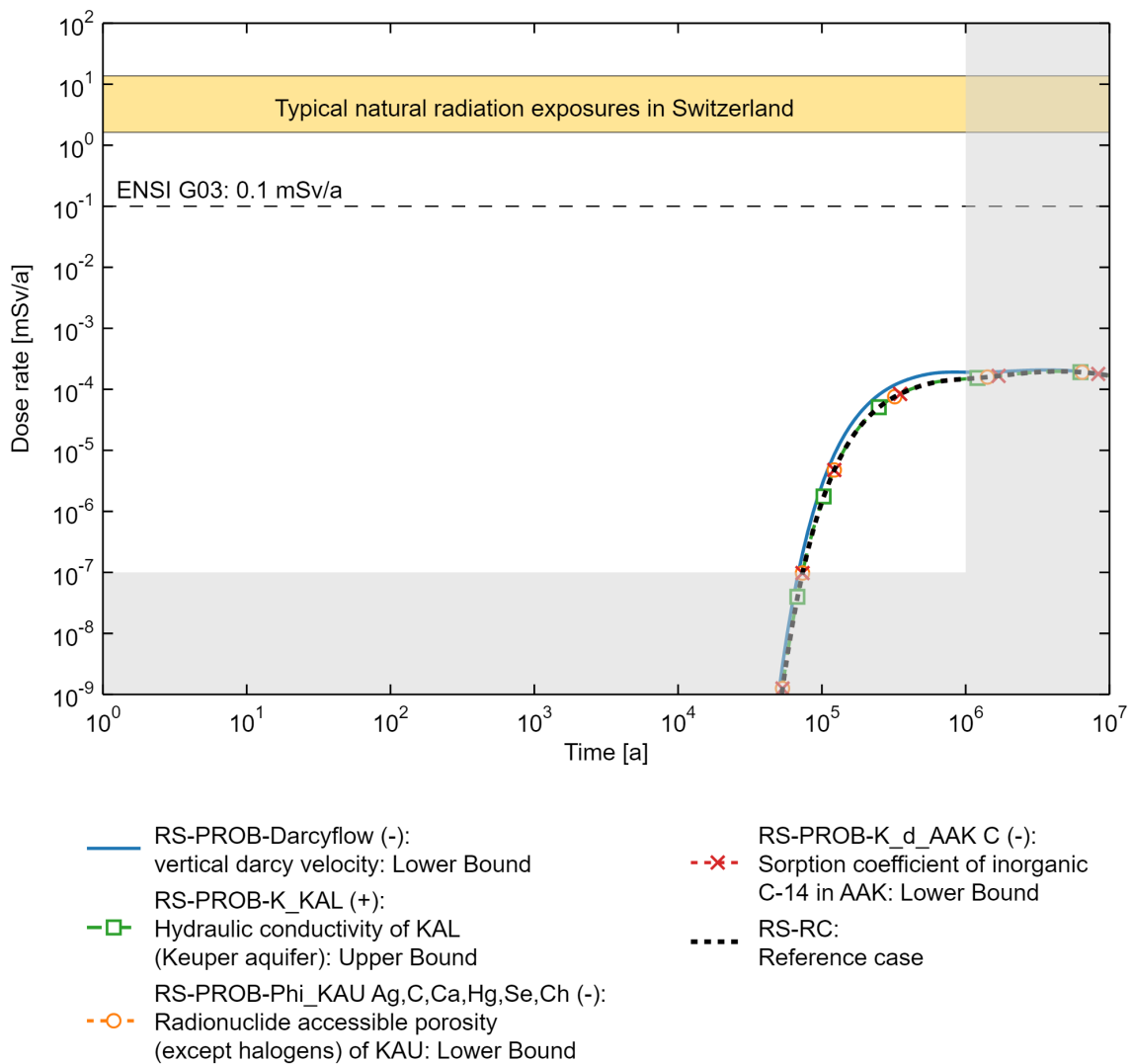


Fig. 6-33: Total dose rates due to SF and RP-HLW in the reference case for an HLW repository in the NL siting region, and in cases where other parameters identified as sensitive in Tab. 6-3 are set to their most pessimistic, bounding values

Fig. 6-34 shows a case in which pessimistic bounding values are set for all the above-mentioned parameters. As in the case of JO, the maximum dose rate is increased by about an order of magnitude compared with the reference case and occurs earlier, around one million years after repository closure. It remains, however, almost two orders of magnitude lower than the protection criterion of 0.1 mSv/a stipulated in ENSI (2023) and always several orders of magnitude below the lower bound value of the typical natural radiological exposures in Switzerland (BAG 2021) after 1 million years. Although the likelihood of pessimistic bound values occurring together in this way is low, the combined pessimistic case further demonstrates the robustness of the repository from a post-closure safety perspective.

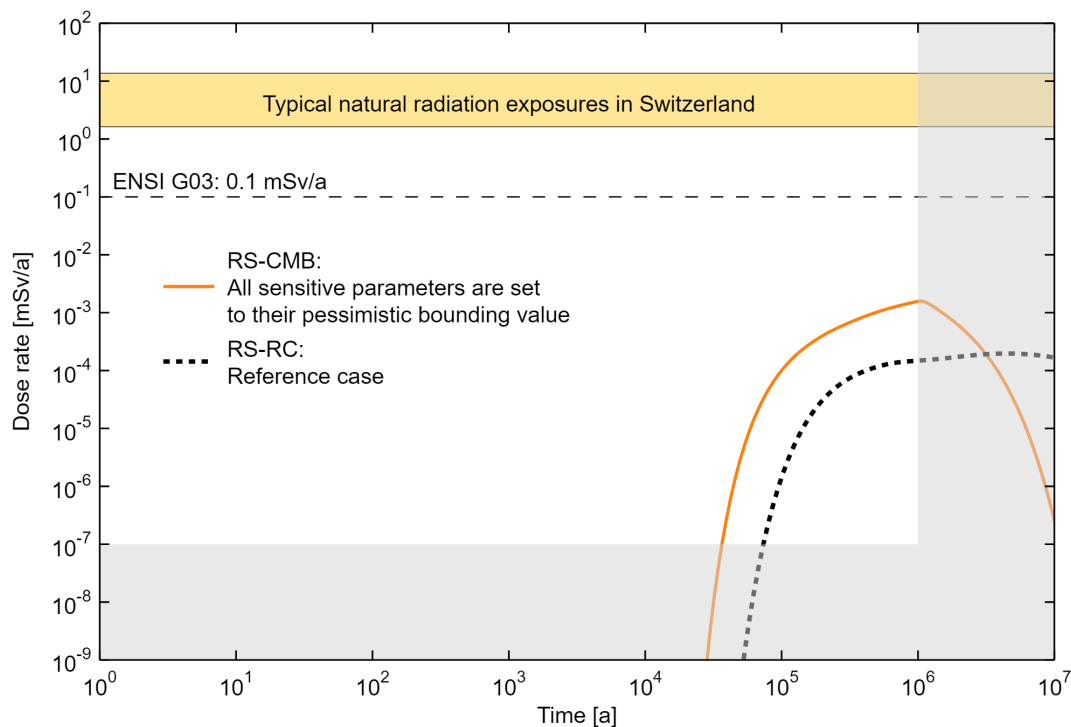


Fig. 6-34: Total dose rates due to SF and RP-HLW in the reference case for an HLW repository in the NL siting region, and in a case in which pessimistic bounding values are set for all sensitive parameters

6.1.2.3 Zürich Nordost (ZNO)

Fig. 6-35 shows statistical percentiles calculated from 4,000 Monte-Carlo simulations of the dose rate evolution of an HLW repository in the ZNO siting region. The bandwidth of the maximum dose rate due to uncertainty in the input parameter values spans about 1.5 orders of magnitude. The maximum calculated dose rate within the time frame of 10^6 years has a safety margin of about 2 orders of magnitude. The dose rate after the time period for assessment is several orders of magnitude below that of the lower bound value of the typical natural radiological exposures in Switzerland (BAG 2021).

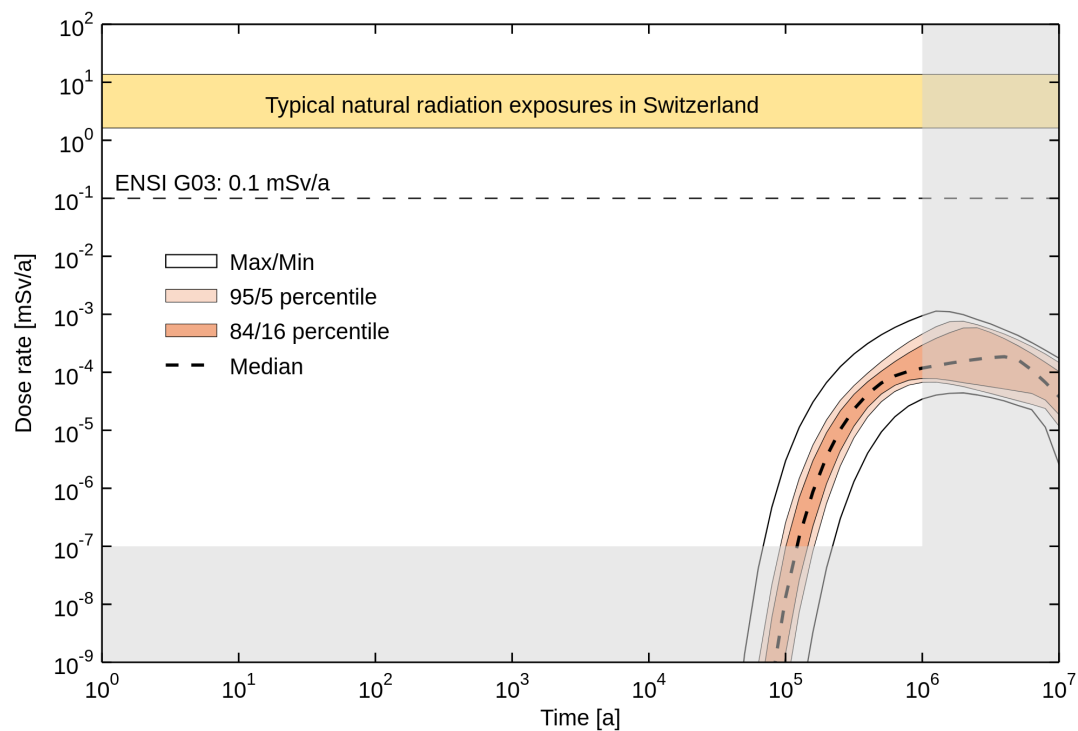


Fig. 6-35: Statistical percentiles calculated from 4,000 Monte-Carlo simulations of the dose rate evolution of an HLW repository in the ZNO siting region

Sensitivity analyses have been performed based on the results of the Monte-Carlo simulations. Some examples of scatter plots showing the maximum dose rates within the one-million-year time period for assessment against individual input parameter values sampled in the Monte-Carlo simulations for selected parameters are shown in Fig. 6-36 to Fig. 6-39.

Fig. 6-36 shows a clear and monotonic relationship between the maximum dose rate and the fractional release rate from the SF matrix, similar to the correlations found in the other siting regions, which becomes more pronounced at higher release rates.

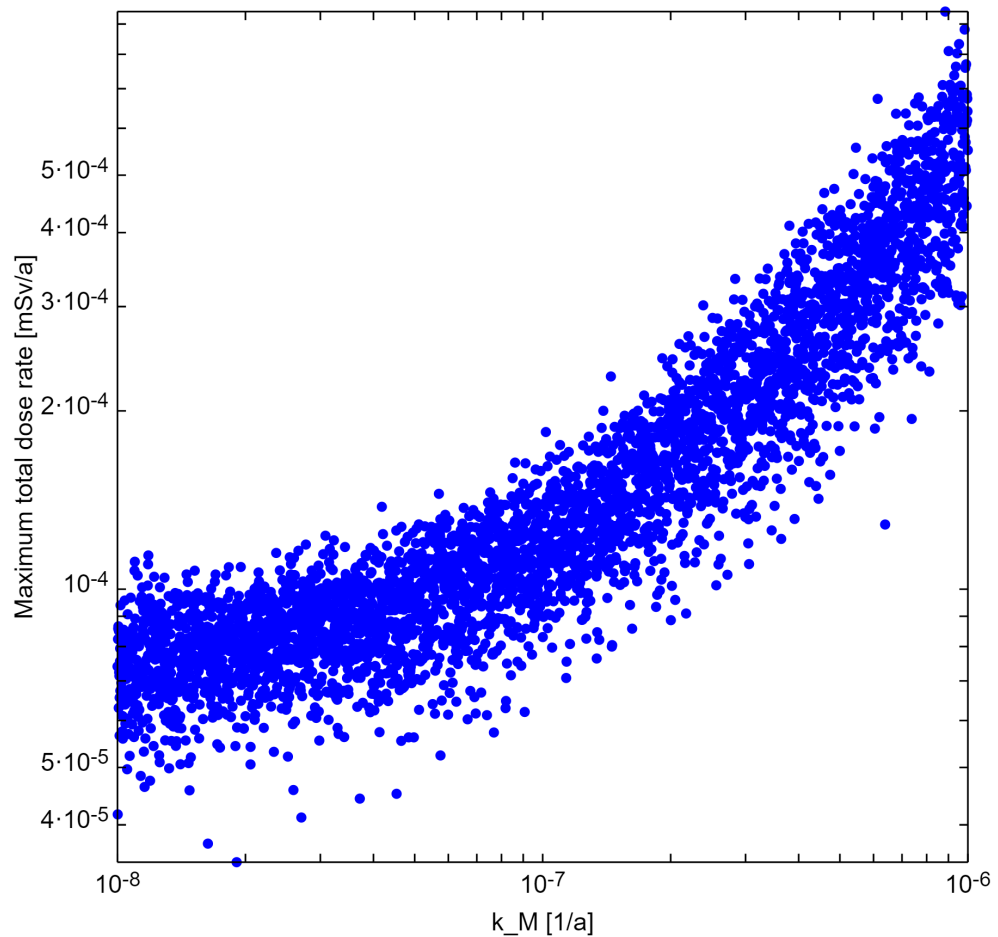


Fig. 6-36: Scatter plot showing the maximum dose rate for an HLW repository in the ZNO siting region within the one-million-year time period for assessment against the fractional release rate of radionuclides from SF due to dissolution of the SF matrix, sampled in Monte-Carlo simulations

Fig. 6-37 and Fig. 6-38 show the expected positive, monotonic relationship between the maximum dose rate and the effective diffusion coefficient for I-129 and Cl-36 in the KEU formation of the lower confining unit, which is adjacent to the Keuper aquifer as the main release path from the geosphere to the biosphere in ZNO (see Fig. 6-13), and in the Opalinus Clay host rock.

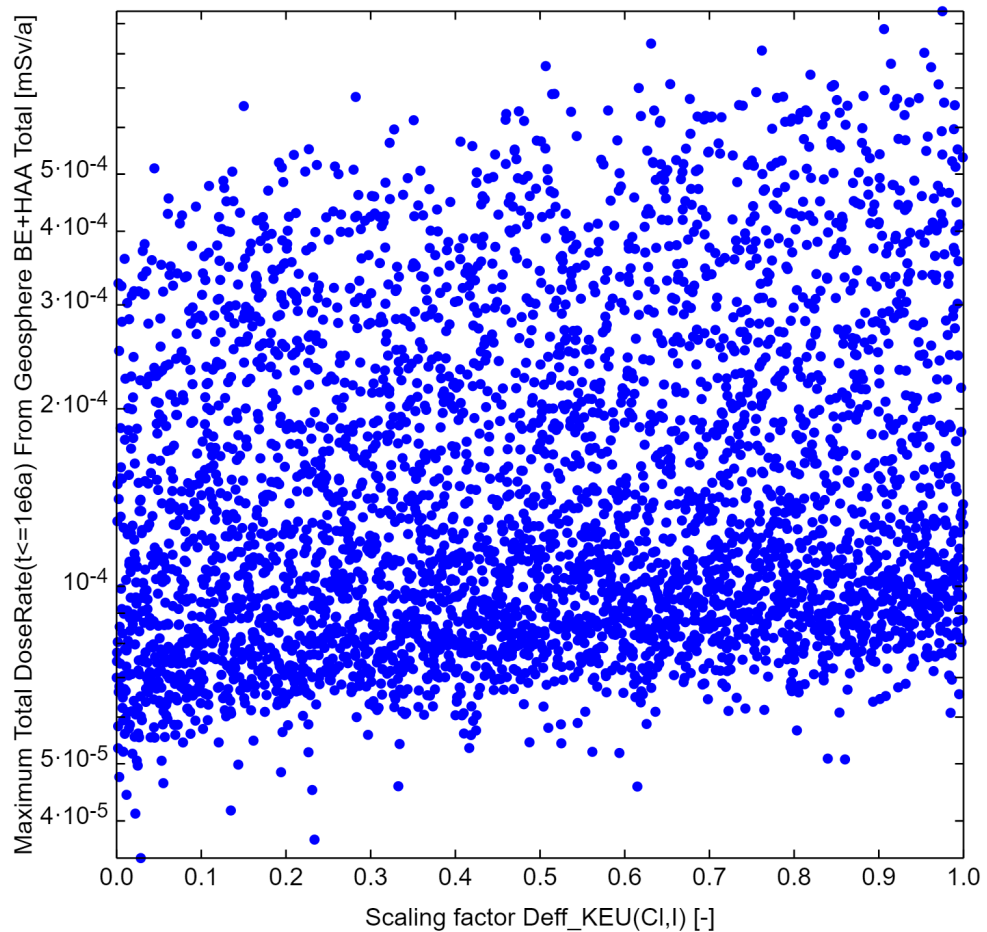


Fig. 6-37: Scatter plot showing the maximum dose rate for an HLW repository in the ZNO siting region within the one-million-year time period for assessment against the effective diffusion coefficient of the halogens Cl-36 and I-129 in the KEU formation of the lower confining units, which is varied using a scaling factor, sampled in Monte-Carlo simulations

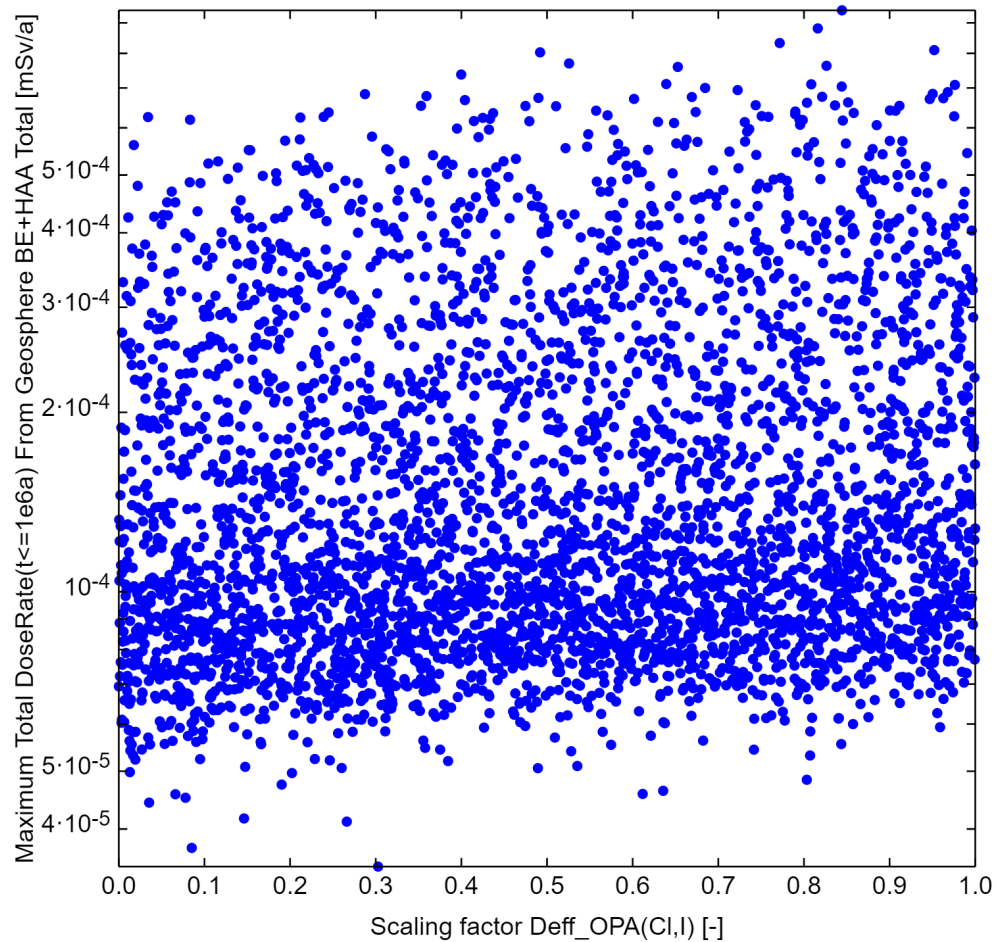


Fig. 6-38: Scatter plot showing the maximum dose rate for an HLW repository in the ZNO siting region within the one-million-year time period for assessment against the effective diffusion coefficient of the halogens Cl-36 and I-129 in the Opalinus Clay, which is varied using a scaling factor, sampled in Monte-Carlo simulations

It is of interest to examine the sensitivity of maximum dose rate to the parameters that control advective transport. Some correlation can be seen in the scatter plot in Fig. 6-39 between the maximum dose rate and the vertical Darcy flow rate through the geological formations of the Opalinus Clay and the confining units. The correlation is much weaker for ZNO than for JO (cf. Fig. 6-20) and is rather similar to that seen in the case of NL (Fig. 6-29).

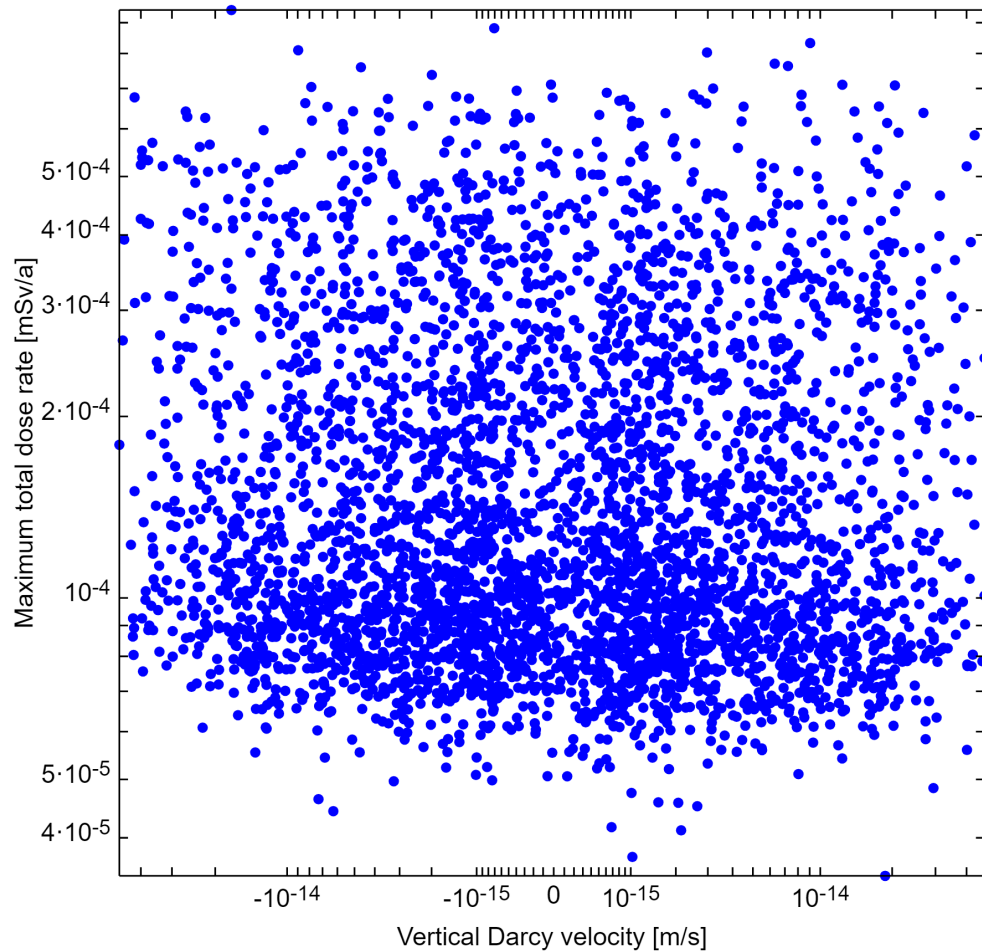


Fig. 6-39: Scatter plot showing the maximum dose rate for an HLW repository in the ZNO siting region within the one-million-year time period for assessment against the vertical Darcy flow velocity

Tab. 6-4 shows three sensitivity measures, the Pearson correlation coefficient, the Spearman correlation coefficient and the modified EASI first-order sensitivity index, calculated for the parameters considered in the probabilistic analyses for the HLW repository in the ZNO siting region.

The most sensitive parameters are similar to those for NL, including the effective diffusion coefficients for Cl-36 and I-129 in the Opalinus Clay and in other geological units with relatively large thicknesses, indicating their influence on the rate of diffusive transport in the system as a whole. Like NL, but unlike JO, including the activation energy, which is used to adjust effective diffusion coefficients to the ambient temperature, is also among the sensitive parameters, because the ambient temperature of 36 °C is significantly higher than the reference temperature of 25 °C.

The Spearman coefficients for the porosity of the Opalinus Clay and the ML rock formation in the lower confining geological units show weak negative correlation. Furthermore, there are low, but still detectable, correlations with parameters such as the hydraulic conductivity of the Keuper aquifer, and with the thickness of the Opalinus Clay and the rock formation AD in the upper confining geological units (h_{OPA} , h_{AD}).

Tab. 6-4: Sensitivity measures for the parameters of the probabilistic analyses with at least one significant correlation for an HLW repository in the ZNO siting region

Values above the calculated “threshold of significance” are marked in blue. Signs of the Pearson and Spearman correlation coefficients indicate positive or negative correlation between the input and output parameters. (+) or (-) indicates the selected bounding value for the individual and combined pessimistic calculations.

Parameter	Description	Pearson correlation coefficient	Spearman correlation coefficient	Modified EASI sensitivity index
	<i>Significance threshold</i>	<i>0.039</i>	<i>0.035</i>	<i>0.0048</i>
k_M (+) 1×10^{-8} - 1×10^{-6} a ⁻¹	Fractional dissolution rate of the SF matrix	0.93	0.92	0.86
Deff_KEU(Cl,I) (+) 1.6×10^{-12} - 9.3×10^{-12} m ² /s (Cl) 1.6×10^{-12} - 9.2×10^{-12} m ² /s (I)	Effective diffusion coefficient of halogens in the KEU	0.15	0.17	0.026
Deff_AD(Cl,I) (+) 1.7×10^{-12} - 9.2×10^{-12} m ² /s (Cl) 1.7×10^{-12} - 9.0×10^{-12} m ² /s (I)	Effective diffusion coefficient of halogens in the AD	0.10	0.14	0.016
Deff_OPA(Cl,I) (+) 1.5×10^{-12} - 7.1×10^{-12} m ² /s (Cl) 1.4×10^{-12} - 7.0×10^{-12} m ² /s (I)	Effective diffusion coefficient of halogens in the Opalinus Clay	0.10	0.12	0.011
E_a,wc(+) 1.5×10^4 - 2.5×10^4 J/mol	Activation energy for diffusion in the porewater	0.071	0.087	0.0054
h_OPA(-) 100.4 - 120.3 m	Thickness of the Opalinus Clay	-0.070	-0.084	0.0060
K_d_KAU(C) 2.6×10^{-4} - 2.2×10^{-3} kg/m ³	Sorption coefficient inorganic C-14 in the KAU	-0.052	-0.04	0.0054
Deff_OPA(C) (+) 1.7×10^{-12} - 6.6×10^{-12} m ² /s	Effective diffusion coefficient of inorganic C-14 in the Opalinus Clay	0.049	0.045	0.0033
Deff_AL(Cl,I) (+) 1.3×10^{-12} - 5.8×10^{-12} m ² /s (Cl,I)	Effective diffusion coefficient of halogens in the AL	0.045	0.039	0.0027
i_v (-) -0.5 - 0.5 m/m	Hydraulic gradient along the geological formations	-0.038	-0.059	0.0017
Phi_OPA(Cl,I) (-) 0.03 - 0.07 (Cl,I)	Radionuclide-accessible porosity for halogens in the Opalinus Clay	-0.035	-0.044	0.0035

Tab. 6-4: continued

Parameter	Description	Pearson correlation coefficient	Spearman correlation coefficient	Modified EASI sensitivity index
	<i>Significance threshold</i>	<i>0.039</i>	<i>0.035</i>	<i>0.0048</i>
Phi_ML(Cl,I) (-) 0.02 - 0.08 (Cl,I)	Radionuclide-accessible porosity for halogens in the ML	-0.032	-0.037	0.0029
h_AD (-) 42 - 51 m	Thickness of the AD	-0.025	-0.044	0.0028
K_KAU (+) 1×10^{-9} - 1×10^{-4} m/s	Hydraulic conductivity of the KAU (Keuper)	0.014	0.084	0.010

In order to provide a better understanding of the impact of various parameters, additional deterministic cases have been analysed, switching each of the individual sensitive parameters to their most pessimistic, bounding values. (+) indicates the most pessimistic upper bound values are most pessimistic and (-) indicates the most pessimistic lower bounding, according to Tab. 6-4.

Fig. 6-40 shows some individual deterministic cases where various effective diffusion coefficients and the activation energy are set to their most pessimistic, upper bound values. The figure shows that there is a visible impact on the dose rate from varying the diffusion coefficients of the Cl-36 and I-129 in the Opalinus Clay and in the KEU formation in the lower confining geological units, consistent with the sensitivity measures for these parameters shown in Tab. 6-4. There is little impact from varying other diffusion coefficients, which is again generally consistent with the sensitivity performance shown in Tab. 6-4.

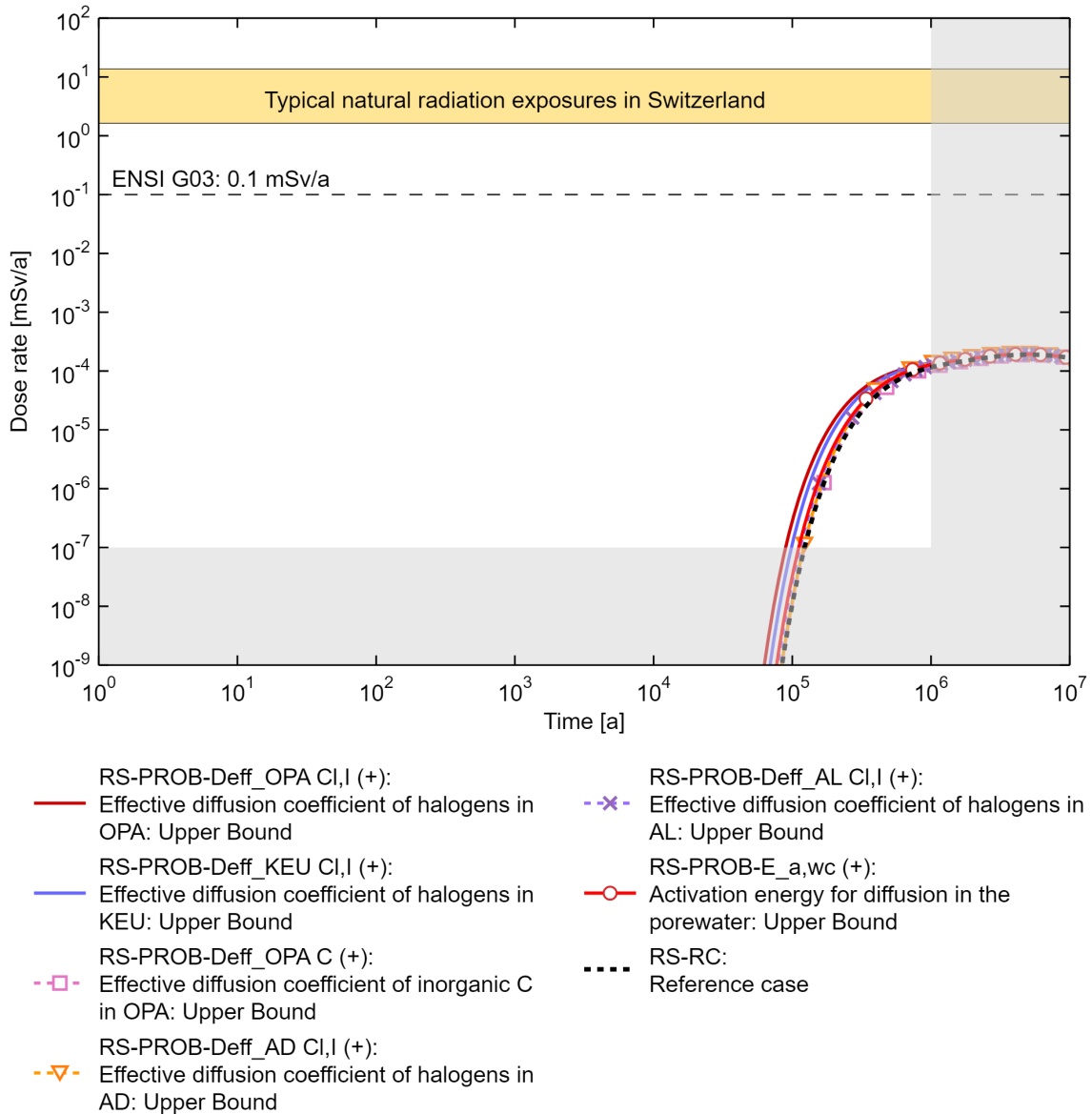


Fig. 6-40: Total dose rates due to SF and RP-HLW in the reference case for an HLW repository in the ZNO siting region, and in cases where various effective diffusion coefficients and the activation energy are set to their most pessimistic, bounding values

Fig. 6-41 shows further individual deterministic cases where various Opalinus Clay properties excluding the effective diffusion coefficients, namely its thickness and the accessible porosity for Cl-36 and I-129, are set to their most pessimistic, bounding values. Both parameters have relatively low impact on the dose rate evolution, as expected from the weak sensitivity measures in Tab. 6-4; however, the pessimistic accessible porosity of the Opalinus Clay can slightly increase the dose rate.

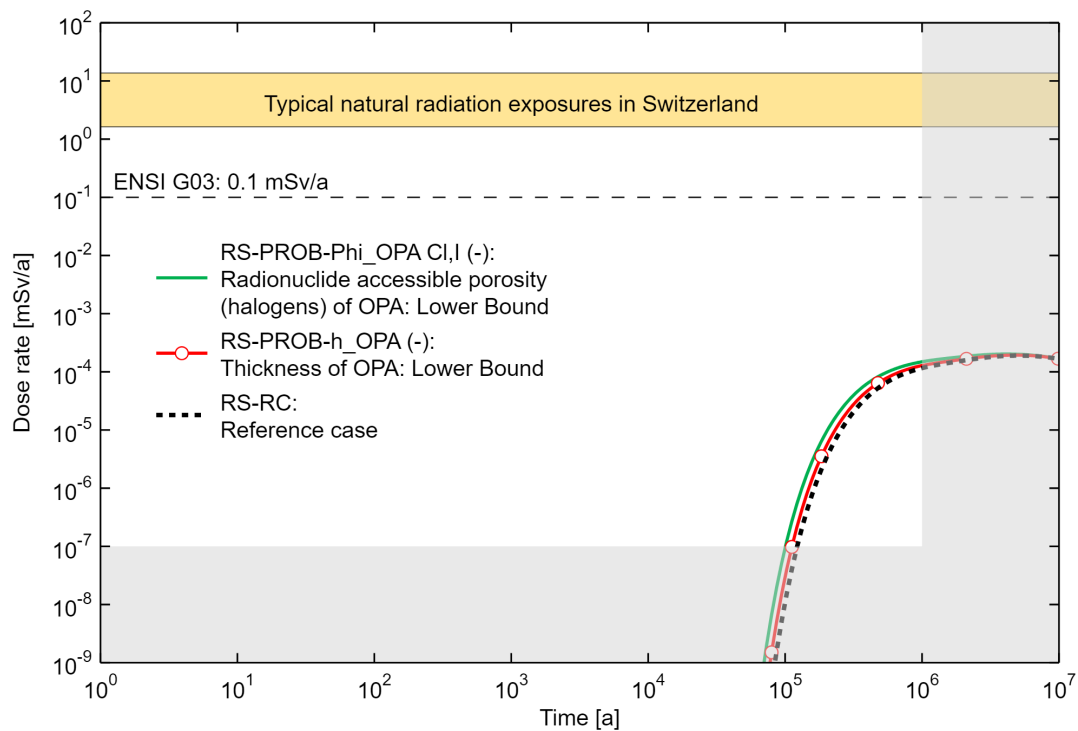


Fig. 6-41: Total dose rates due to SF and RP-HLW in the reference case for an HLW repository in the ZNO siting region, and in cases where various Opalinus Clay properties, excluding the effective diffusion coefficients, are set to their most pessimistic, bounding values

Fig. 6-42 shows the results of some further deterministic cases concerning the rest of the parameters with correlations identified in Tab. 6-4. The behaviour is broadly consistent with the other two siting regions, with the dissolution rate of the SF matrix (k_M) showing the most significant impact on the maximum dose rate. Other parameter variations case only have a slight or non-significant increase on the dose rate, as expected from the sensitivity measures presented in Tab. 6-4.

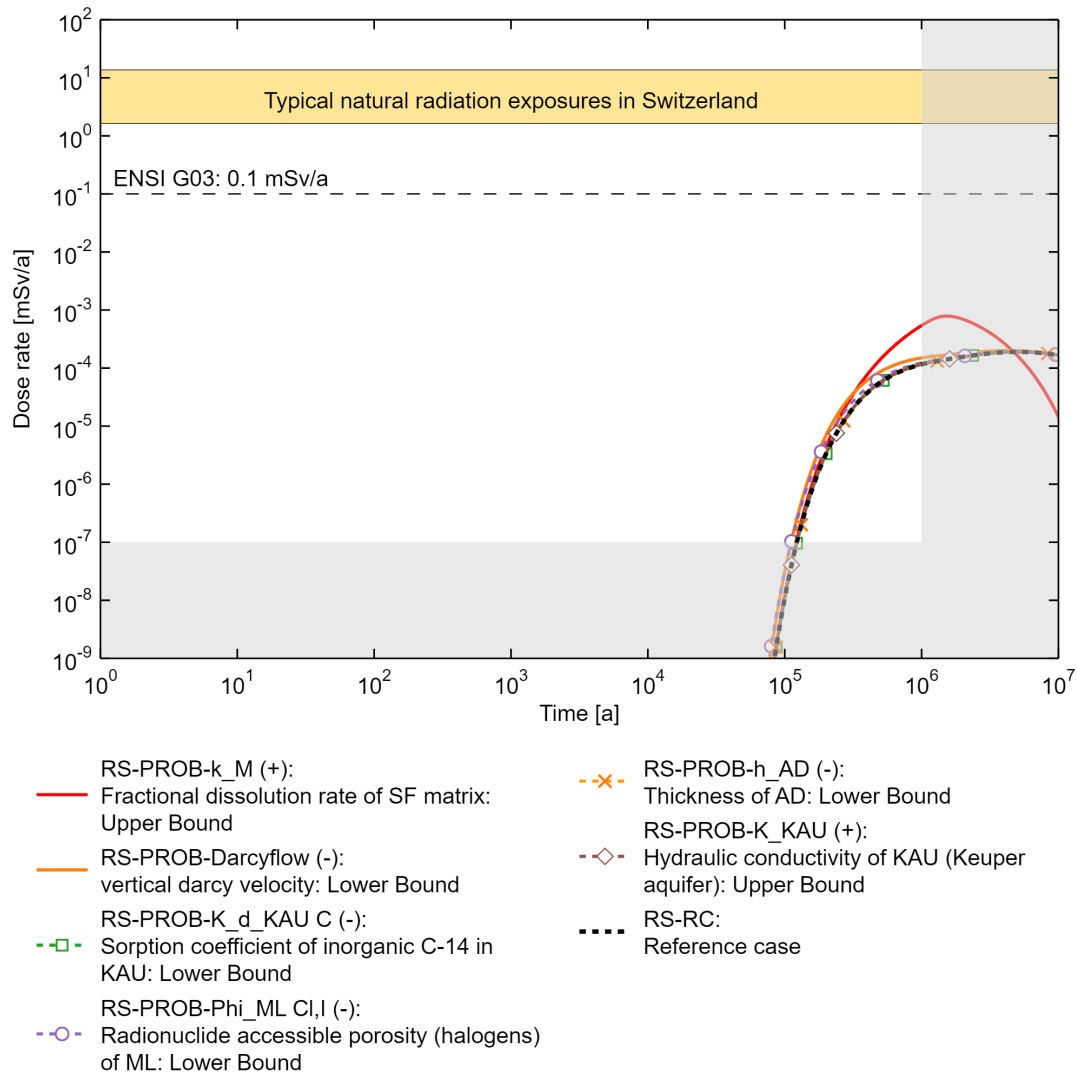


Fig. 6-42: Total dose rates due to SF and RP-HLW in the reference case for an HLW repository in the ZNO siting region, and in cases where other parameters identified as sensitive in Tab. 6-4 are set to their most pessimistic, bounding values

Finally, Fig. 6-43 shows a case in which pessimistic bounding values are set for all the above-mentioned parameters. As in the cases of both JO and NL, the maximum dose rate is increased by about an order of magnitude compared with the reference case and occurs earlier, around one million years after repository closure. It remains, however, almost two orders of magnitude below the protection criterion of 0.1 mSv/a stipulated by (ENSI 2023) and several orders of magnitude lower than the lower bound values of the typical natural radiological exposures in Switzerland (BAG 2021). Although the likelihood of pessimistic bounding values occurring together in this way is low, the combined pessimistic case further demonstrates the robustness of the repository from a post-closure safety perspective.

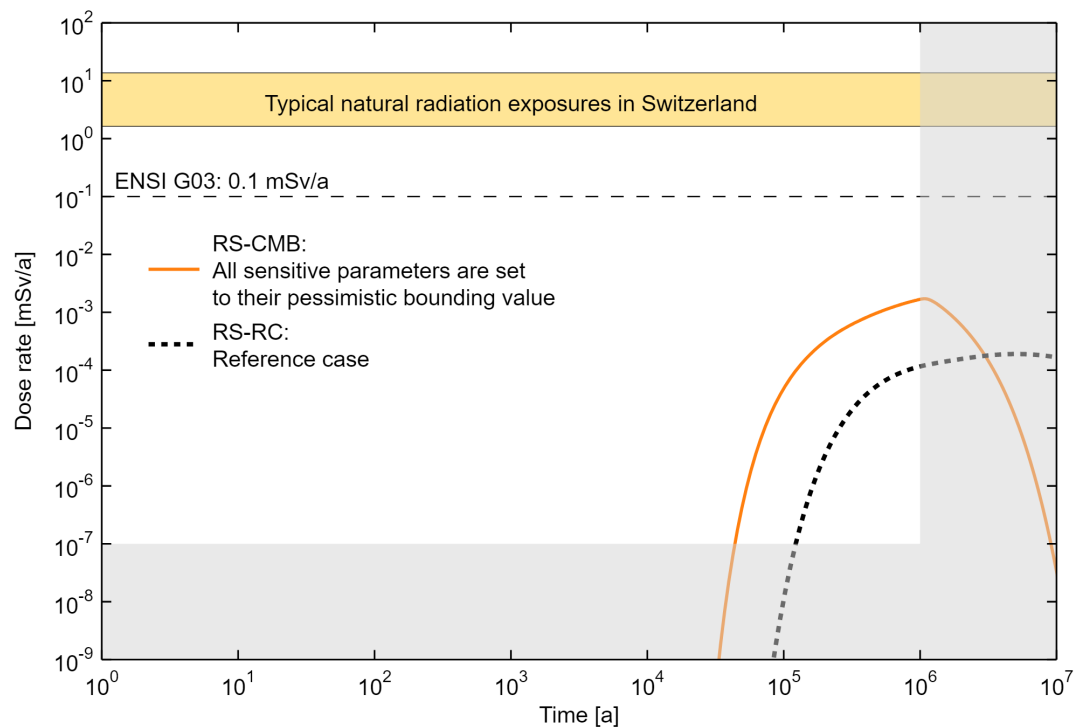


Fig. 6-43: Total dose rates due to SF and RP-HLW in the reference case for an HLW repository in the ZNO siting region, and in a case in which pessimistic bounding values are set for all sensitive parameters

6.1.3 Radiological consequence analysis for the alternative safety scenarios

In addition to the reference safety scenario, alternative safety scenarios are also considered in the site comparison, and are evaluated deterministically, with the results for each siting region presented in the following sections.

As described in Nagra (2024b) and summarised in Section 4.2, specific uncertainties flagged for further consideration as alternative safety scenarios concern uncertainties in geological characterisation, and, specifically, the possibility that there could be:

- a hydraulically active confining unit above or below the Opalinus Clay; or
- an undetected fault in the vicinity of the repository emplacement rooms.

The variants and calculation cases for these two safety scenarios are summarised in Tab. 4-2 and Tab. 4-3, respectively.

The concepts and models for analysing radionuclide migration in the liquid phase in these alternative safety scenarios are described in App. B.1. In cases concerning an undetected fault, the Darcy flow rate through the fault is taken from a 2D hydraulic simulation described in Nagra (2024g), where the two-dimensional impact of the fault on the hydraulic flow field in the surrounding rock is taken into account.

6.1.3.1 Jura Ost (JO)

As illustrated in Fig. 2-5, there are two potentially hydraulically active confining units considered in the JO siting region: one is the SCD within the upper confining geological units, and the other is the KEU within the lower confining geological units. The impact of these is analysed in two deterministic calculation cases (see also Tab. 4-2):

- AS-HA/SCD, where the SCD is assumed to be hydraulically active; and
- AS-HA/KEU, where the KEU is assumed to be hydraulically active.

It is to note that for the case concerning the KEU as the hydraulically active unit, the whole thickness of the KEU, including the Argillaceous Keuper (AK2/3) and Calcareous Lias (CL) (see Fig. 2-5), is conservatively assumed to be hydraulically active with the conductivity of CL.

The evolution of the dose rate in these two cases is compared with the reference case in Fig. 6-44, which shows only a slight increase in the dose rate maximum caused by either of these units, which are hydraulically active. This is because the hydraulically active units (hard beds) can shorten the transport pathway in the upper or lower confining units, leading to an earlier breakthrough of radionuclides into the biosphere. However, thanks to the excellent retention capacity of the Opalinus Clay, the confining units can merely contribute a limited reduction of the maximum dose rate as shown in Fig. 6-4, and the confining units can only contribute a limited reduction of the maximum dose rate. Therefore, shortening the transport length in the confining unit due to “hard beds” will not cause a significant increase in the maximum dose rate. This shows the robustness of the results with regard to uncertainty in hydrogeological characterisation.

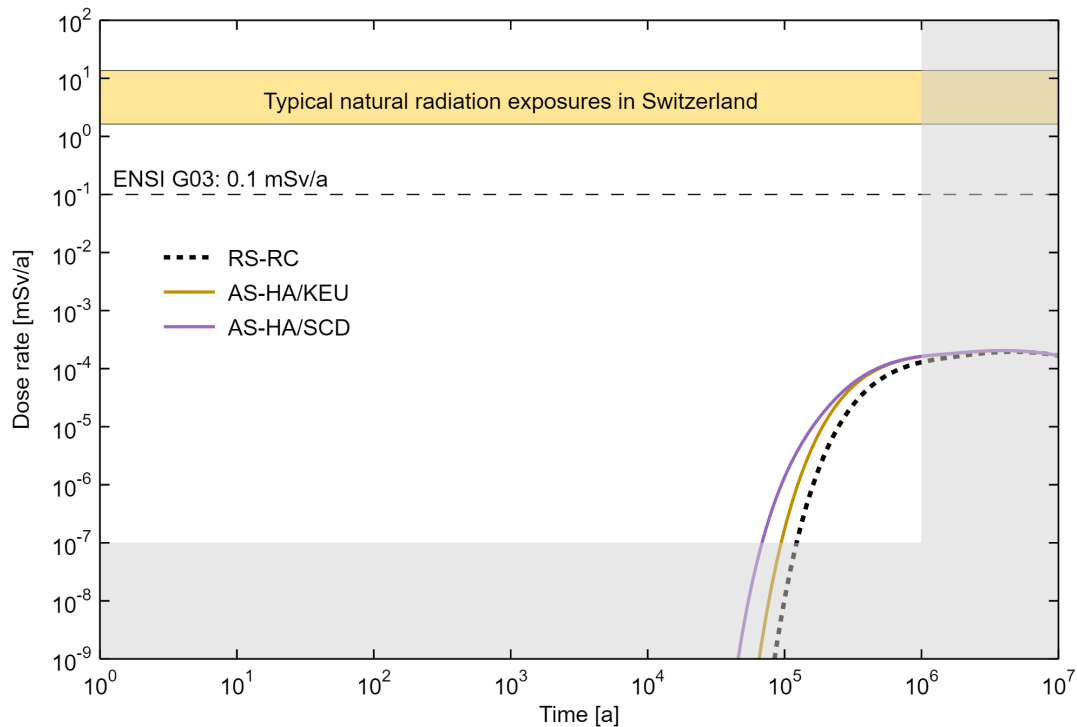


Fig. 6-44: Total dose rates due to SF and RP-HLW in the reference case for an HLW repository in the JO siting region, and for two cases of hydraulically active confining units above and below the Opalinus Clay

Two calculation cases are defined for the HLW repository for the safety scenario considering an undetected fault (see Tab. 4-3):

- AS-FLT-HLW-Along, where the fault passes along one of the HLW emplacement drifts; and
- AS-FLT-HLW-Across, where the fault passes through all the HLW emplacement drifts, perpendicular to their axes.

These cases concerning undetected faults are modelled with extremely conservative assumptions:

- The fault extends across the whole CRZ, permanently connecting two aquifers above and below the repository.
- The fault impacts either a part of all the emplacement rooms or a whole emplacement room, which can be easily detected and avoided.
- The fault transmissivity is set to $10^{-10} \text{ m}^2/\text{s}$, which has not been observed in the geological investigations of the potential repository fields (Nagra 2024e).

The evolution of the dose rate in these two cases is compared with the reference case in Fig. 6-45. In this safety scenario, the assumption is made that the HLW canister lifetime is unaffected, and hence the canisters will remain intact for 10,000 years, as in the reference case. Furthermore, the expected release behaviour of the SF, including the IRF, CRF (congruent release fraction) and the sorption capacity of the CRZ, will not be impacted by the fault.

Radionuclide transport due to advective release of the IRF along the fault begins almost immediately following canister breaching, which leads to an immediate breakthrough at 10,000 years. Transport along the fault does not, however, greatly increase the maximum dose rate. There are basically two reasons why the system behaves like this:

- Only a limited number of HLW disposal canisters are affected by the fault ($20 \times 3 = 60$ canisters in the AS-FLT-HLW-Across case and 97 canisters in the AS-FLT-HLW-Along case). Therefore, a small part of the total IRF inventory can be released more quickly into the biosphere.
- The Darcy velocity in the fault (transmissivity = $10^{-10} \text{ m}^2/\text{s}$) is set to be about $7 \times 10^{-12} \text{ m/s}$ by considering the water availability in the Keuper aquifer. This can limit the speed of the advective transport in the fault.

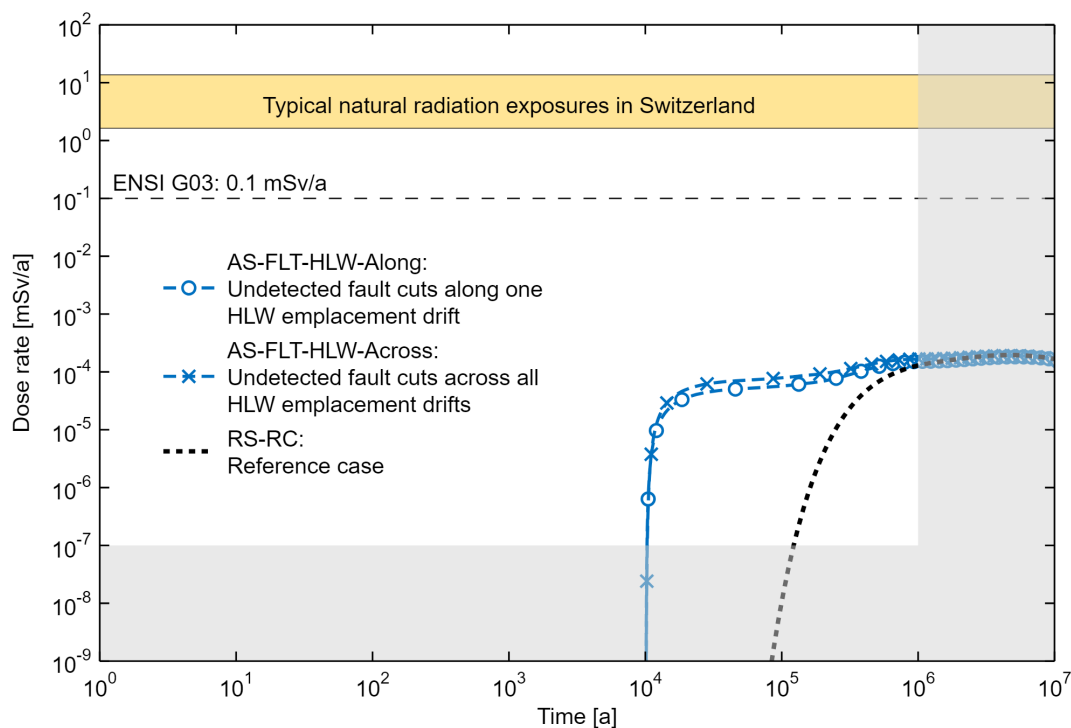


Fig. 6-45: Total dose rates due to SF and RP-HLW in the reference case for an HLW repository in the JO siting region, and for two cases of an undetected fault intersecting the emplacement drifts

6.1.3.2 Nördlich Lägern (NL)

As illustrated in Fig. 2-5, there are five potentially hydraulically active confining units considered in the NL siting region: SCD, CD, and CM in the upper confining geological units, and KEU and KAU in the lower confining geological units. The impact of these is analysed in five deterministic calculation cases (see also Tab. 4-2):

- AS-HA/SCD, where the SCD is assumed to be hydraulically active;
- AS-HA/CD, where the CD is assumed to be hydraulically active;
- AS-HA/CM, where the CM is assumed to be hydraulically active;
- AS-HA/KEU, where the KEU is assumed to be hydraulically active; and
- AS-HA/KAU, where the KAU is assumed to be hydraulically active.

The evolution of the dose rate in these five cases is compared with the reference case in Fig. 6-46, which shows only a slight increase in the dose rate caused by any of these units being hydraulically active. This performance is similar to the case for JO (see opening paragraphs in Section 6.1.3.1) and demonstrates the robustness of the system with regard to uncertainties in the hydrogeological characterisation.

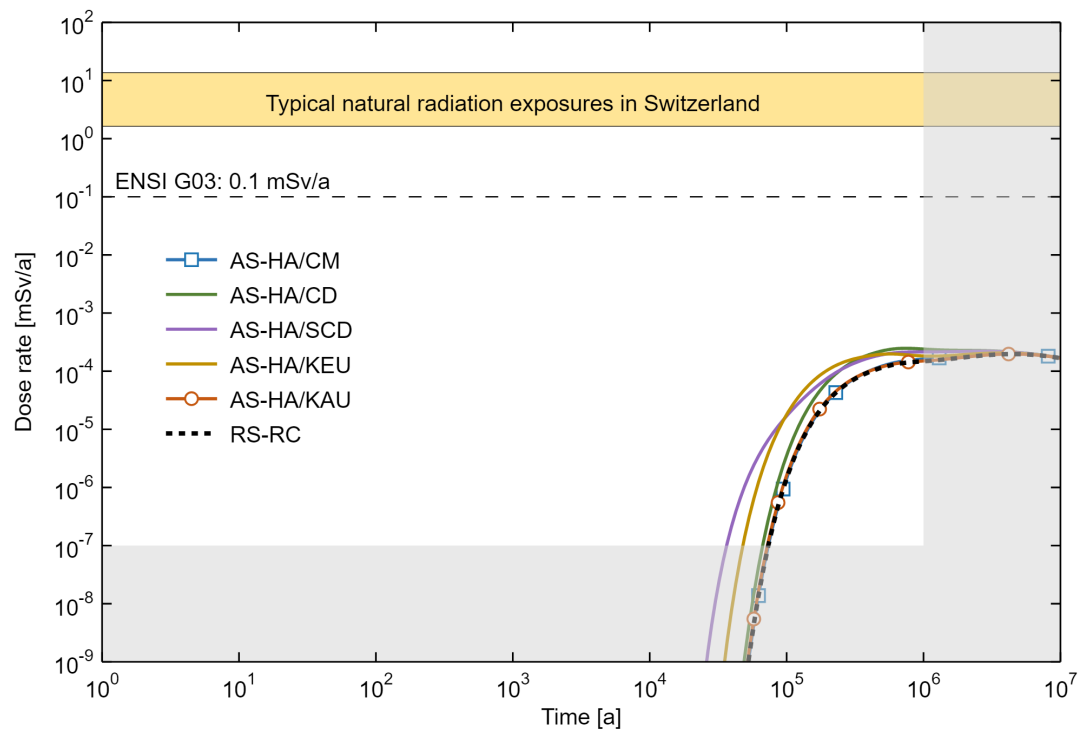


Fig. 6-46: Total dose rates due to SF and RP-HLW in the reference case for an HLW repository in the NL siting region, and for five cases of hydraulically active confining units above and below the Opalinus Clay

Generally, the closer the hydraulically active unit is located to the repository, the higher its impact. Thus, units such as the CM and KAU, which are at the greatest distance from the repository, do not have a significant impact on the radionuclide release. One exception is the CD (the «Herrenwis Unit»), which, when assumed to be hydraulic active, gives rise to a higher dose rate than the SCD unit, even though the SCD unit is closer to the repository. The reason is the greater thickness of the CD, which combined with the higher hydraulic conductivity leads to a higher water flow than the SCD unit, and thus has a greater potential to capture radionuclides migrating vertically through the geosphere.

The evolution of dose rates in the reference case and in the two cases defined for the safety scenario with an undetected fault is shown in Fig. 6-47. As in the case of JO, transport along the fault does not greatly increase the maximum dose rate, because of the same points discussed in Section 6.1.3.1 for the JO siting region.

In all siting regions, the vertical hydraulic gradient in the fault and in the rock matrix is taken to be upwardly directed. As discussed in Section 6.1.1, dose rates in the reference case due to releases from the top boundary of the model and from the Keuper aquifer are comparable to the case of JO, with the release from the top boundary (the Calcareous Dogger) being slightly higher. By contrast, the Keuper aquifer releases dominate in NL. Thus, advective flow along the fault works to reinforce the dominant pathway in the case of JO, but works against it in the case of NL.

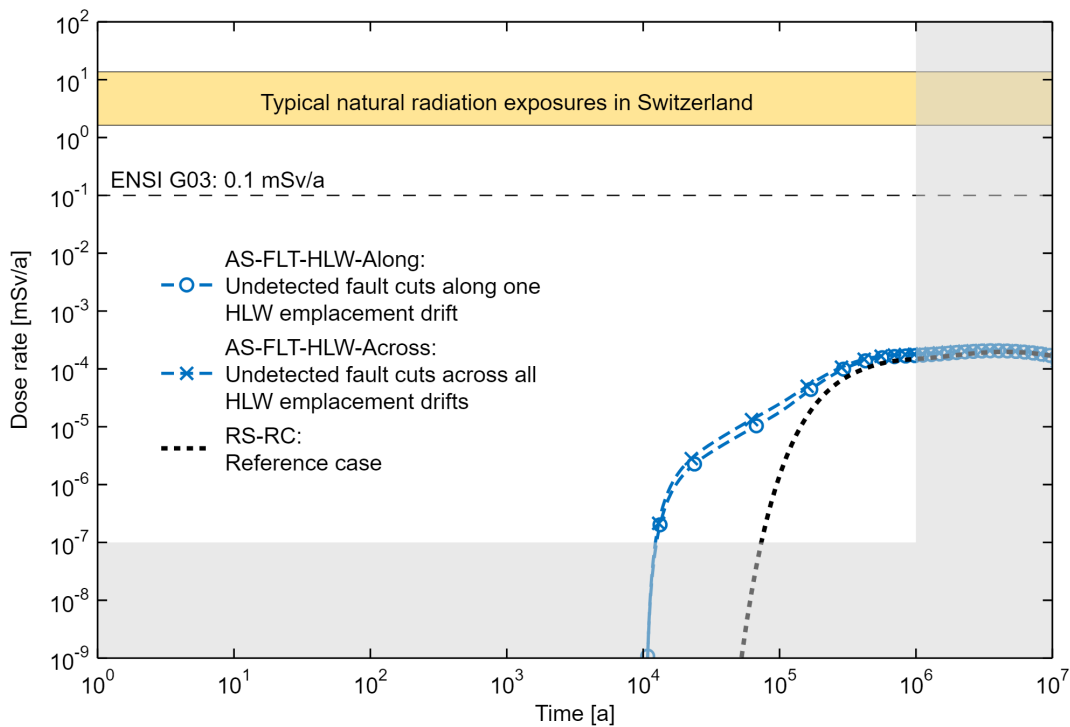


Fig. 6-47: Total dose rates due to SF and RP-HLW in the reference case for an HLW repository in the NL siting region, and for two cases of an undetected fault intersecting the emplacement drifts

6.1.3.3 Zürich Nordost (ZNO)

As in the case of JO, there are two potentially hydraulically active confining units considered in the ZNO siting region: one is the SCD unit in the upper confining geological units, and the other is the KEU in the lower confining geological units. The impact of these is analysed in two deterministic calculation cases (see also Tab. 4-2):

- AS-HA/SCD, where SCD is assumed to be hydraulically active; and
- AS-HA/KEU, where KEU is assumed to be hydraulically active.

The result of the two cases is shown in the following figure, in comparison with the reference case. The result is similar to the cases shown in JO and NL (see opening paragraphs in Sections 6.1.3.1 and 6.1.3.2) because of the similar behaviour of the system in the siting regions.

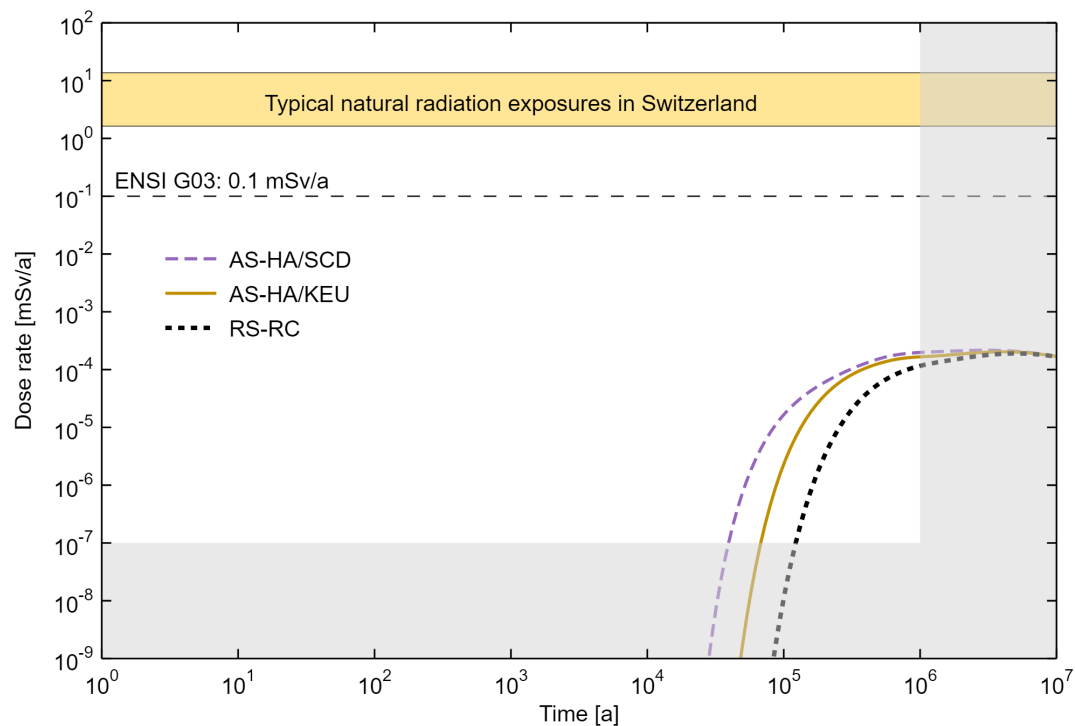


Fig. 6-48: Total dose rates due to SF and RP-HLW in the reference case for an HLW repository in the ZNO siting region, and for two cases of hydraulically active confining units above and below the Opalinus Clay

The evolution of the dose rates in the reference case and in the two cases defined for the safety scenario with an undetected fault is shown in Fig. 6-49. As in the case of the other two siting regions, dose rates due to the release of the IRF radionuclides by advection along the fault begin almost following canister breaching. Transport along the fault does not, however, greatly increase the maximum dose rate.

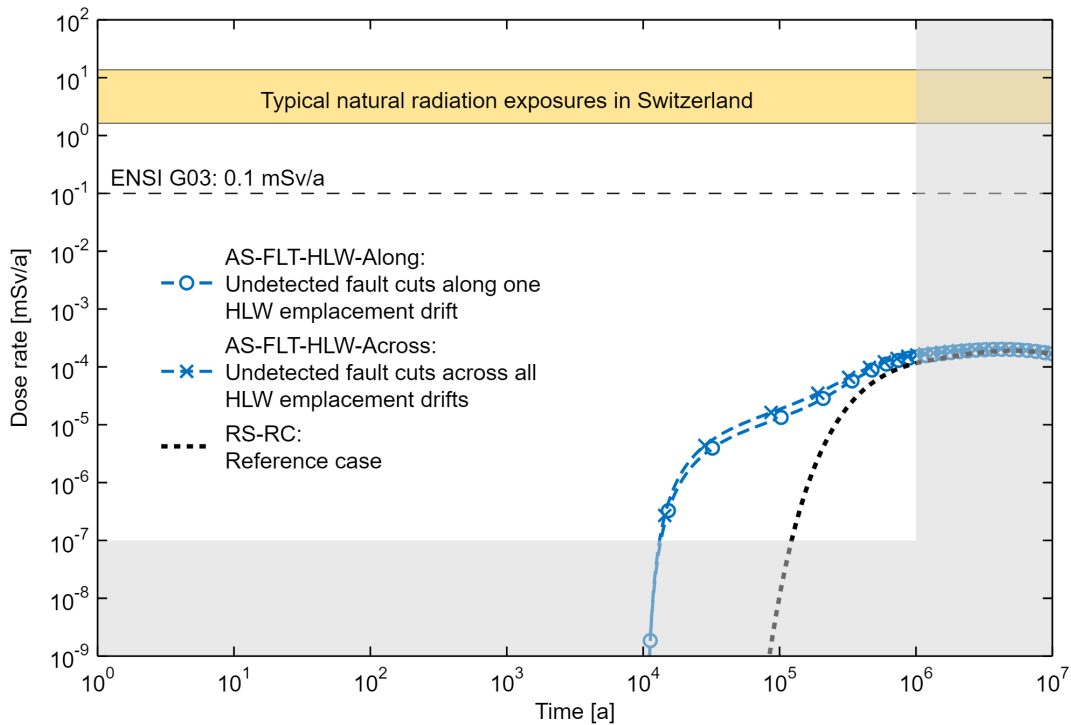


Fig. 6-49: Total dose rates due to SF and RP-HLW in the reference case for an HLW repository in the ZNO siting region, and for two cases of an undetected fault intersecting the emplacement drifts

Because the dominant transport pathway from the HLW repository in the ZNO siting region, as in the case of NL, is downwards to the Keuper aquifer (see the discussion in Section 6.1.1.3), the behaviour of the dose rate evolution in response to the presence of the fault is similar in NL and ZNO.

6.1.4 Comparison between the siting regions

The calculation cases performed for the three siting regions covering the reference and alternative safety scenarios show similar results because of the similarities between the near-field (e.g., the radionuclide release behaviour of the waste) and geosphere (transport properties in the CRZ) in the three siting regions. The slight differences can readily be understood.

Consistent with the radiological consequence analysis in Stage 2 of the SGT process (Nagra 2014b), 0.01 mSv/a can be considered as a threshold dose rate below which the potential siting regions should be considered equivalent from a post-closure safety perspective (see Fig. 2.1-3 in Nagra (2014c)).

It should also be kept in mind that, in the NL siting region, there is a variant conceptualisation of the reference safety scenario in which the Keuper aquifer is assumed to be hydraulically inactive (case RS-KEUPER_INACTIVE in Fig. 6-50), which gives a dose rate that is lower than that for the reference case in any of the siting regions.

The dose rate evolution in the reference case for the three siting regions is illustrated in Fig. 6-50. For all siting regions, the HLW repository shows a robust safety margin of almost 3 orders of magnitude compared with the protection criterion of 0.1 mSv/a (ENSI 2023).

The maximum dose rate and the dose rate evolution are similar in all three siting regions. In this sense, the radiological consequences in the reference case for the three siting regions can be considered essentially equivalent.

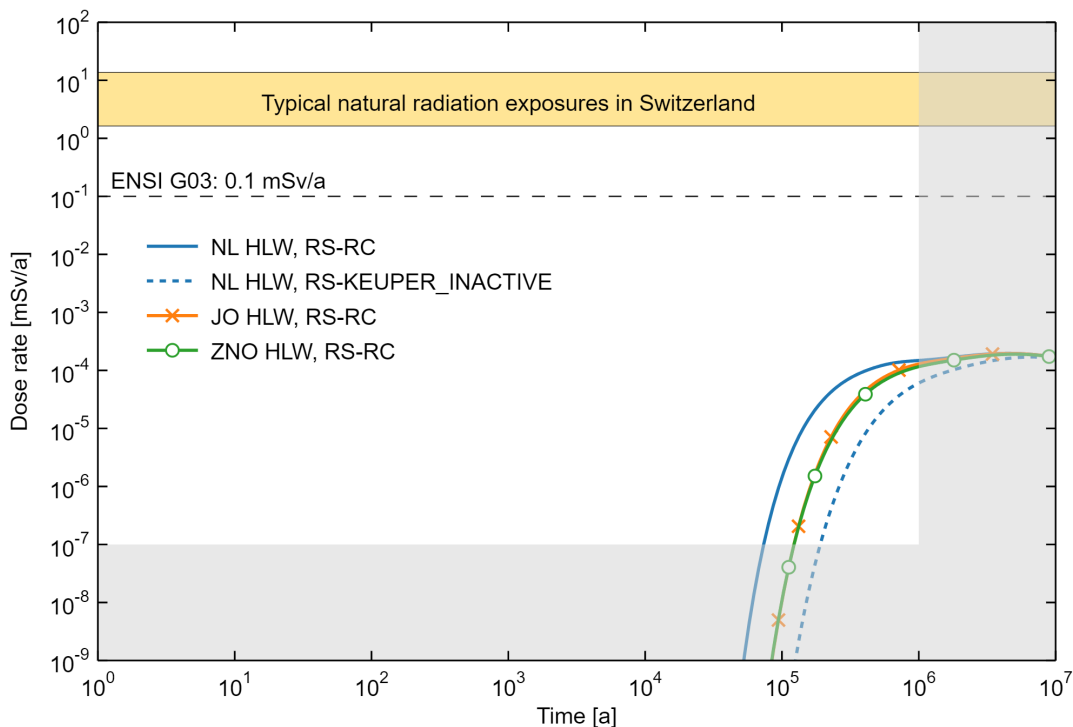


Fig. 6-50: Total dose rates due to SF and RP-HLW in the reference case for an HLW repository in all three siting regions

Fig. 6-51 shows the range of the maximum dose rates calculated from the 4,000 probabilistic simulations carried out for each siting region, as well as various percentiles of the maximum dose rates. The resulting bands are the so-called “characteristic dose intervals”. In each siting region, the characteristic dose intervals are rather similar, and lie 2 to 3 orders of magnitude below the protection criterion (ENSI 2020b) of 0.1 mSv/a. The three siting regions can be considered equivalent in terms of radiological consequences.

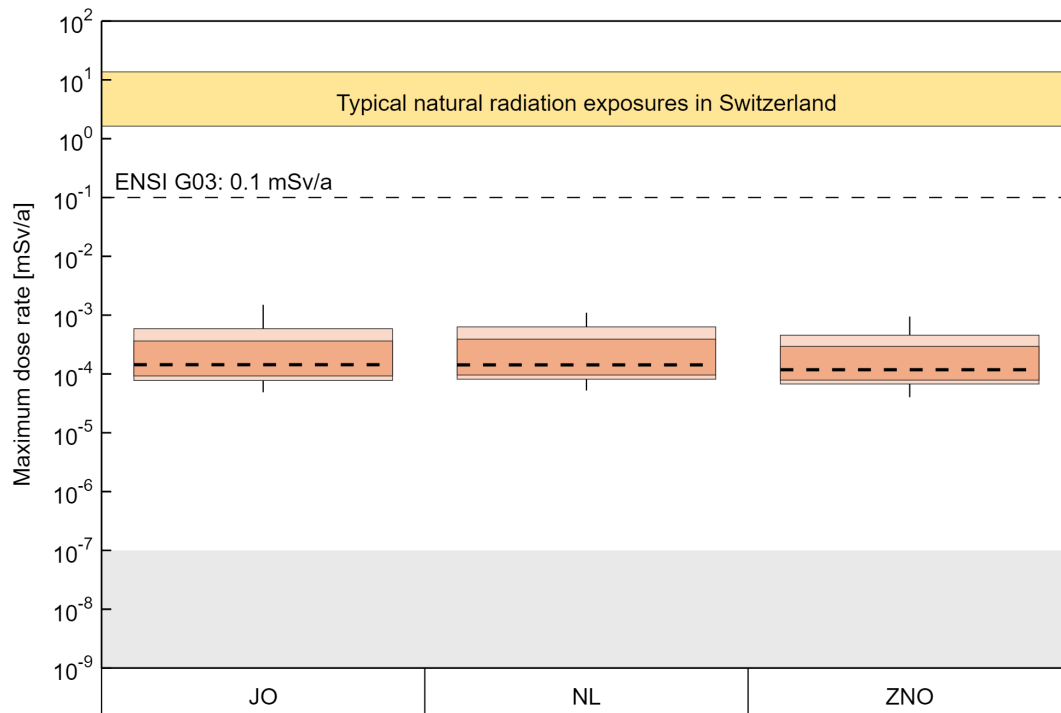


Fig. 6-51: Characteristic dose intervals based on the results of the probabilistic dose calculations carried out for an HLW repository in the three siting regions. The box plots show the 0%, 5%, 16%, 50%, 84%, 95% and 100% percentiles of the maximum dose rates of the probabilistic calculations within one million years

To facilitate comparison, the Keuper aquifer was assumed to be active in the probabilistic dose calculations. If the aquifer were inactive, the dose rates would be lower, as shown in the deterministic calculations (see Fig. 6-50).

Fig. 6-52 shows the characteristic dose intervals for each siting region based on the results of the deterministic calculations carried out for the reference safety scenario and for the alternative safety scenarios (excluding biosphere variations). Most dose maxima are clustered in a narrow band around the reference case. On the other hand, the cases combining pessimistic bounding values for sensitive parameters show significantly higher dose rates, though still almost two orders of magnitude below the protection criterion of 0.1 mSv/a in all three siting regions, which shows a robust safety margin. As in the probabilistic analyses, the characteristic dose intervals are rather similar in all three siting regions and can be considered as equivalent.

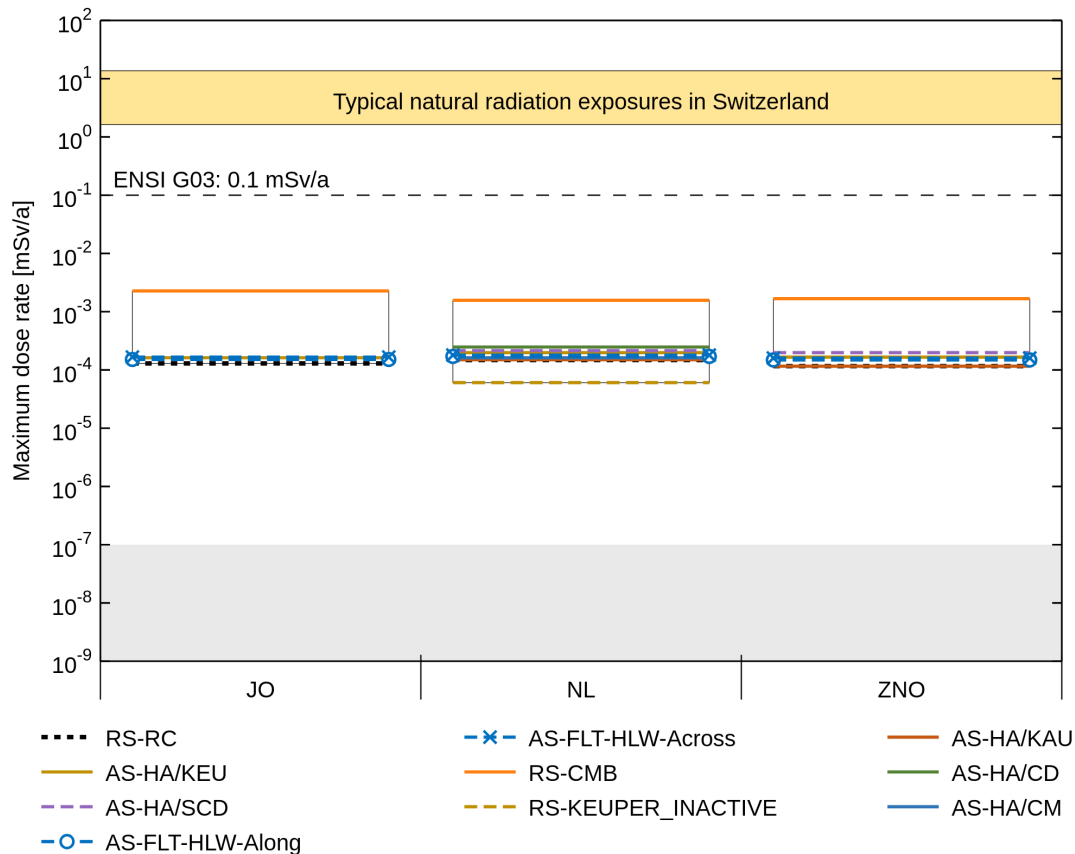


Fig. 6-52: Characteristic dose intervals based on deterministic calculations carried out for the reference safety scenario and for the alternative safety scenarios for an HLW repository in the three siting regions. The dashed brown line is for a variant conceptualisation of the reference safety scenario in which the Keuper aquifer is assumed to be hydraulically inactive in the NL siting region

Characteristic dose intervals for the deterministic cases examining different assumptions in the biosphere model are shown in Fig. 6-53. The ranges obtained for the maximum dose rate are larger than those shown in Figs. 6-51 and 6-52, which address uncertainties in the near-field and geosphere, but are still rather similar in the three siting regions. Furthermore, the maximum dose rate, even in the least favourable climatic variation, is still about two orders of magnitude below the protection criterion of 0.1 mSv/a. The characteristic dose rate interval can again be considered equivalent.

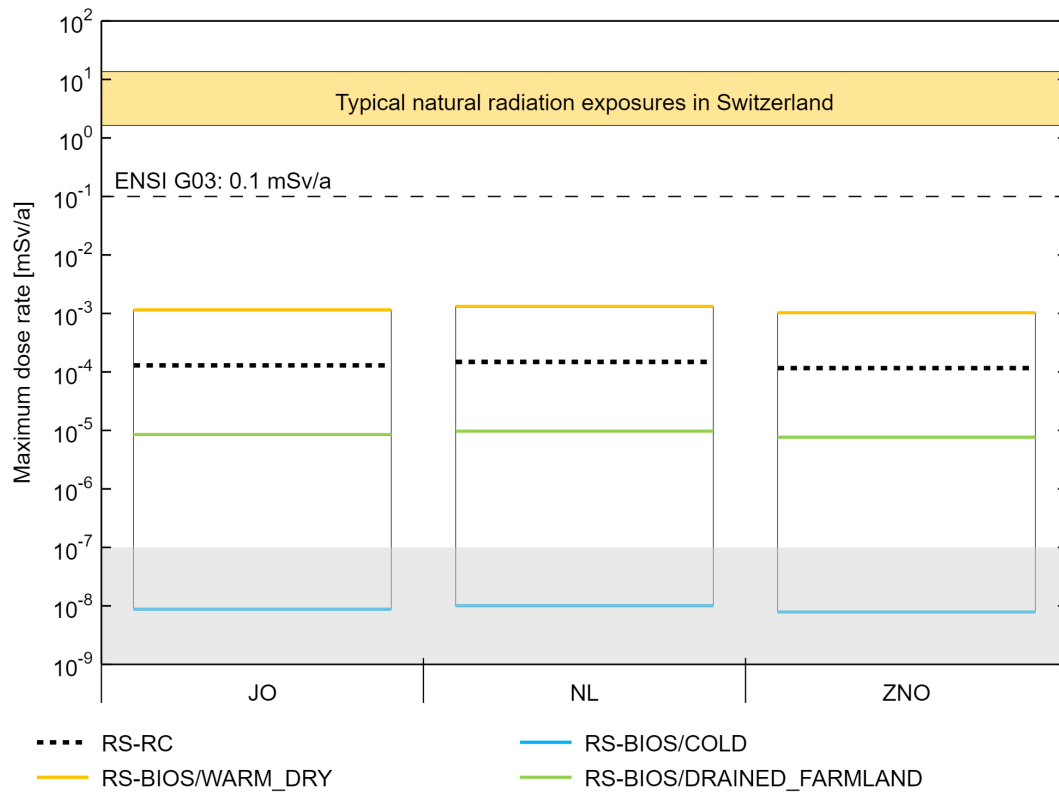


Fig. 6-53: Characteristic dose intervals for deterministic cases examining different assumptions for the climate and surface conditions for an HLW repository in the three siting regions

The calculation cases in the radiological consequence analysis confirm the results from Stage 2 of the SGT process (Nagra 2014c) where all the three siting regions can be considered as equally safe and suitable for an HLW repository from a post-closure safety perspective. Furthermore, in all the simulation cases, the dose rate after the time period for assessment is also far below the lower bound value of the typical natural radiological exposures in Switzerland (BAG 2021).

6.2 Radiological consequence analysis considering radionuclide migration in the liquid phase for site comparison for the L/ILW repository

The site comparison for the L/ILW repository takes place after the selection of the site for the HLW repository. Although the NL siting region has been selected as the site for the HLW repository, a separate L/ILW repository in NL is assumed for the safety-based comparison.

In all the simulations done in this chapter, in line with the description in Section 4.1, the radionuclides in L/ILW are assumed to be instantaneously released into the cementitious near-field directly after repository closure. One exception is the organic C-14 in the activated metals which will follow the corrosion rate of the metals in the modelling.

6.2.1 Reference safety scenario analysis including barrier performance and dose rates

The reference safety scenario, including the reference case and several additional calculation cases exploring the impact of assumptions regarding climatic and surface conditions, is described in Nagra (2024b) and summarised in Section 4.1 of this report. A fixed assumption of a hydraulically active Keuper aquifer in all three siting regions is made in the analyses for an L/ILW repository.

As in the case of the HLW repository, a site-specific deterministic reference calculation case provides a baseline for comparison with other calculation cases. It is analysed in the greatest detail to develop an understanding of the modelled system, including the efficiency of the different barriers. The reference calculation case uses a combination of reference values for all parameters; some of the reference parameter values are set to their best-estimate values, while others are set conservatively; see App. C.2. The reference case considers the BDCFs based on present-day climatic conditions in Switzerland; see Section 3.3. However, as noted above, additional deterministic calculation cases are defined that assume different, though still steady-state, climatic and surface conditions.

The concepts and models for analysing radionuclide migration in the liquid phase in the reference safety scenario are described in App. B.1.

Tab. 6-5: Comparison of the most important parameters related to diffusive transport between the siting regions for the L/ILW repository

	Unit	JO	NL	ZNO
Effective diffusion coefficient of chlorine (Cl) in the Opalinus Clay	m ² /s	1.47×10^{-12}	2.69×10^{-12}	3.21×10^{-12}
Transport length to the Malm aquifer (Calcareous Dogger in JO)	m	100	203	153
Transport length to the Keuper aquifer	m	116	122	132
Ambient temperature at the centre of the Opalinus Clay	°C	32	44	36
Effective diffusion coefficient of chlorine (Cl) in the Opalinus Clay after temperature correction	m ² /s	1.79×10^{-12}	4.37×10^{-12}	4.25×10^{-12}

Similar to the situation in HLW discussed in Tab. 6-1, one can see from Tab. 6-5 that JO exhibits a lower diffusion coefficient because of its geochemical condition (salinity) and the lower ambient temperature due to its depth compared to NL and ZNO. Nevertheless, JO has a relatively shorter transport distance to the overlying aquifer (Calcareous Dogger) compared with NL and ZNO (Malm aquifer). By contrast, NL has a slightly higher diffusion coefficient and a shorter transport distance to the underlying Keuper aquifer compared with ZNO.

6.2.1.1 Jura Ost (JO)

Fig. 6-54 shows the total dose rates and nuclide-specific dose rates for dominant nuclides for an L/ILW repository in the JO siting region. The calculated dose rate remains below the level of the significant dose rate, defined as 10^{-7} mSv/a, throughout the 100,000-year time period for assessment defined for the L/ILW repository, with the dose rate at 100,000 years being 4.4×10^{-8} mSv/a. This is more than 6 orders of magnitude below the protection criterion of 0.1 mSv/a given by (ENSI 2023). The dose rate continues to increase after 100,000 years, reaching a maximum of 1.9×10^{-6} mSv/a after 4.6×10^5 years, which is more than 5 orders of magnitude below the bounding value of the typical natural radiological exposures in Switzerland (BAG 2021), indicating a large safety margin. The radionuclide contributing most to the dose rate at all calculated times is Cl-36, which has a long half-life (301,300 years), with more minor contributions from I-129 and Se-79. This is in contrast with the HLW repository, where I-129 makes the dominant contribution, due to the difference in the waste inventory.

As in the case of the HLW repository, the calculated dose rate is obtained by applying the reference BDCFs to the sum of the release rates from all three interfaces with the biosphere: 1) Calcareous Dogger (the upper model boundary), 2) Keuper aquifer (first deep aquifer below the repository) and 3) Dolomitic Muschelkalk (the lower model boundary). Fig. 6-55 illustrates the contributions of releases across the three individual interfaces to the total dose rate. The dose rates due to releases from the Calcareous Dogger dominate. The dose rates due to releases from the Muschelkalk aquifer are much smaller, and lie well below the level of significant dose rate of 10^{-7} mSv/a.

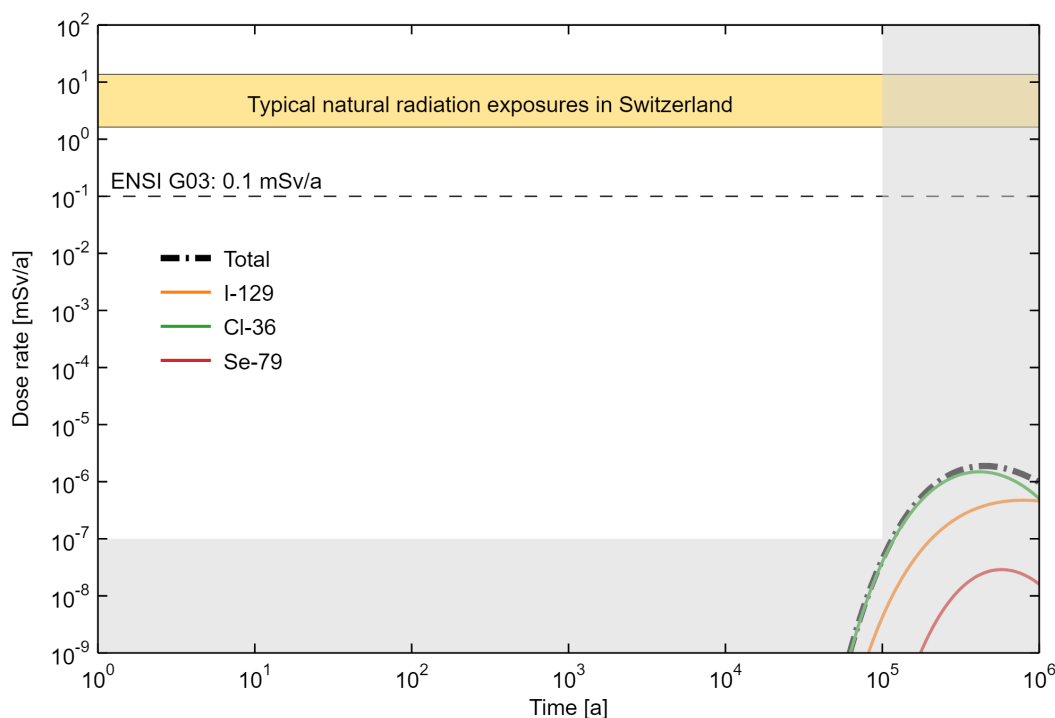


Fig. 6-54: Total and nuclide-specific dose rates in the reference case for an L/ILW repository in the JO siting region

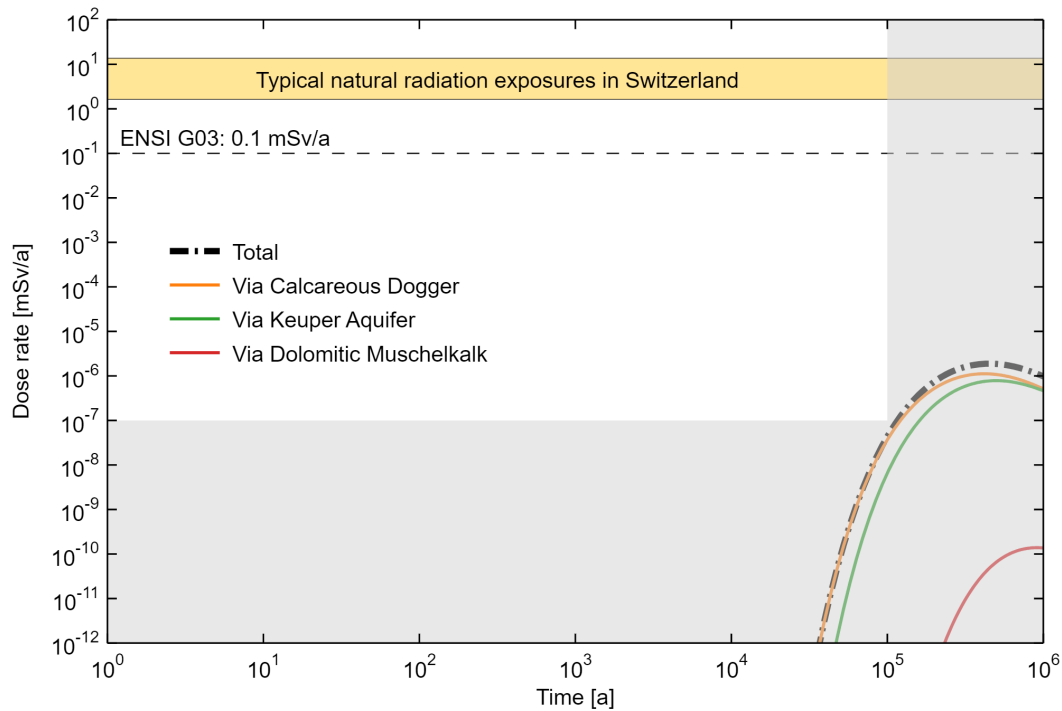


Fig. 6-55: Total dose rates in the reference case for an L/ILW repository in the JO siting region, and the contributions to the total due to releases from the Calcareous Dogger, the Keuper aquifer and the Dolomitic Muschelkalk¹⁰

In Fig. 6-56, maximum dose rates are shown at different vertical distances from the repository. In contrast to the HLW repository, because of the greater size of the L/ILW emplacement cavern, the maximum dose rate curves take longer until they are reduced to values below the protection criterion of 0.1 mSv/a. However, after transport in the Opalinus Clay, the maximum dose rate is well below the protection criterion of 0.1 mSv/a. This demonstrates the strong retention of many radionuclides in the Opalinus Clay. The rock formations of the confining geological units further reduce the maximum dose rate. After about 100 m of transport within the confining geological units, the maximum dose rate is decreased below the level of significance, taken to be 10^{-7} mSv/a. In fact, the dose rates due to most of the radionuclides are reduced below this level in just the first few tens of metres of transport in the Opalinus Clay. Only non-sorbing and longer-lived radionuclides, such as I-129 and Cl-36, migrate to any degree beyond the host rock, and these are attenuated to below 10^{-7} mSv/a within the confining units.

¹⁰ The y-axis is extended to 10^{-12} mSv/a, so that the release curve from the Muschelkalk aquifer is visible.

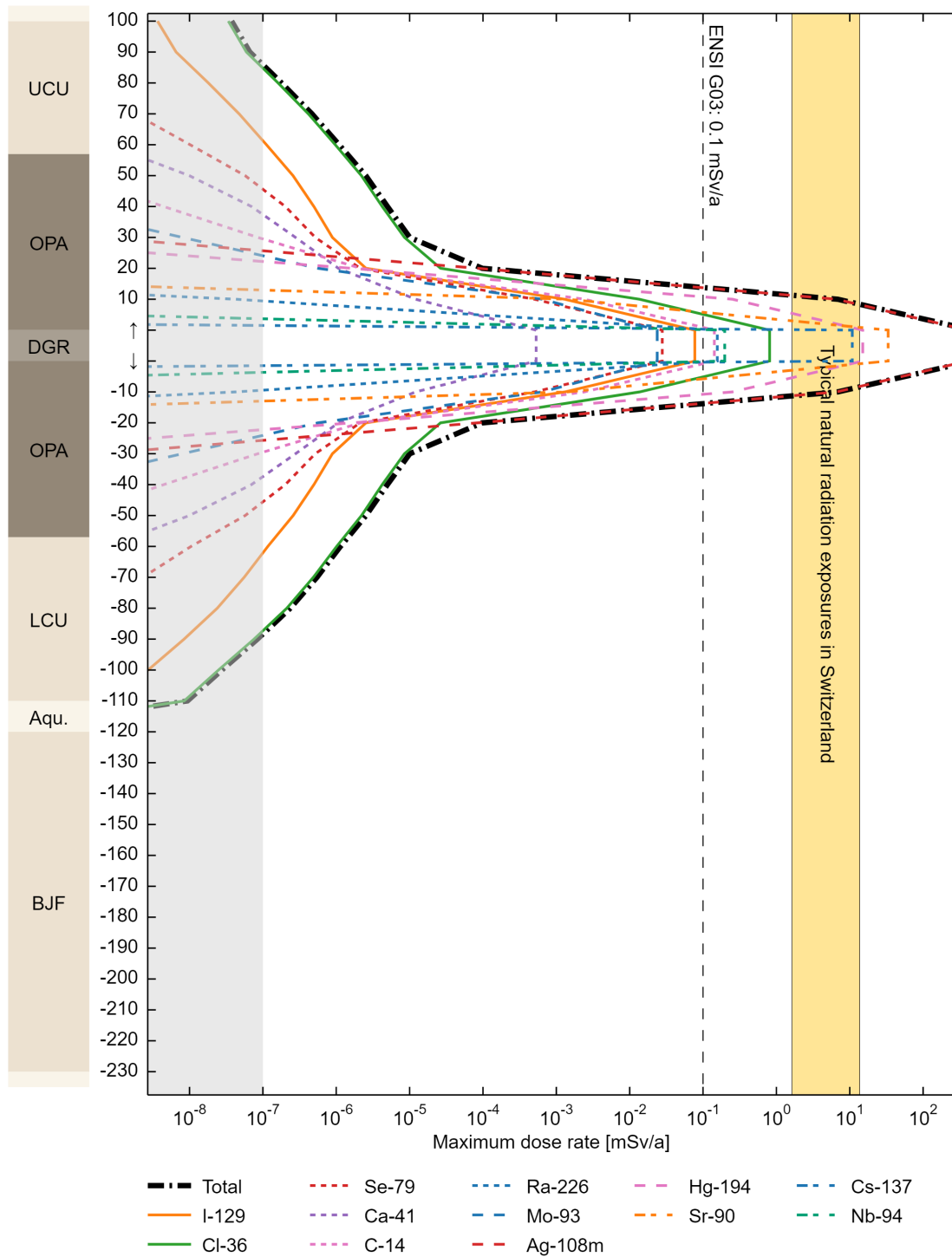


Fig. 6-56: Maximum dose rates obtained by applying BDCFs to radionuclide transport rates calculated for an L/ILW repository in the JO siting region as a function of distance from the repository centre point

(only individual radionuclides with a maximum dose rate exceeding 10⁻¹ mSv/a anywhere or with a maximum dose rate higher than 10⁻⁷ mSv/a at a distance of 20 m or more from the repository centre are illustrated in the figure)

Fig. 6-57 illustrates the evolution of the total RT (radiotoxicity) in different materials within the repository system. RT, which is defined in Section 3.1, is a measure of the relative potential hazard of radioactive material.

The initial RT of L/ILW is much lower than that of HLW and is an order of magnitude or more below that associated with the L/ILW being hypothetically filled with uranium ore from the Cigar Lake deposit in Canada. As mentioned in Section 4.1.1, after repository closure, the radionuclides are assumed to be released into the cementitious near-field without any containment of the containers. Throughout that 10^5 -year time period for assessment, most of the RT is sorbed in the cementitious near-field, where it decreases by more than two orders of magnitude during this period, which shows a good retention capacity of cementitious near-field against the release of radionuclides. Thanks to the excellent retention capacity of Opalinus Clay against the radionuclides, a large amount of RT is kept in Opalinus Clay, so that very little RT ever migrates into the confining units or beyond.

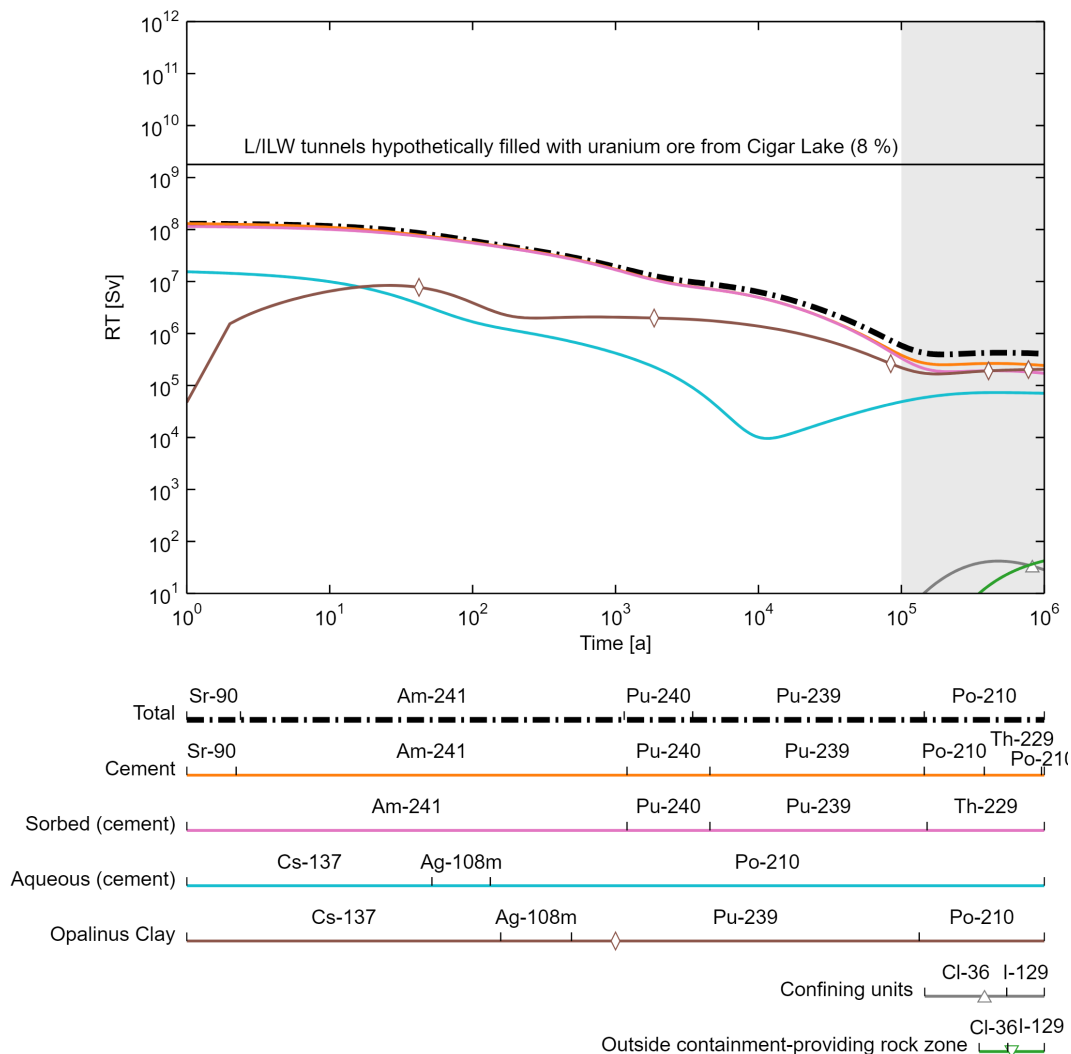


Fig. 6-57: Evolution and distribution of the radiotoxicity over time in the cementitious near-field (in aqueous and in sorbed form, and in total), the Opalinus Clay, its confining units and outside the containment-providing rock zone for an L/ILW repository in the JO siting region. The hypothetical radiotoxicity of all L/ILW emplacement caverns filled with uranium ore (8%) is shown for comparison of the radiotoxicity

The reference case uses BDCFs for a reference biosphere based on present-day climatic conditions. As in the case of HLW, three additional deterministic calculation cases are defined that assume different, though still steady-state, climatic and surface conditions:

- RS-BIOS/WARM_DRY, based on a warmer and drier climate
- RS-BIOS/COLD, based on a colder climate and
- RS-BIOS/DRAINED_FARMLAND, which assumes a drained farmland.

The evolution of the dose rate in each of these cases is shown in Fig. 6-58. A warmer and drier climate is found to result in a maximum dose rate of 4.36×10^{-7} mSv/a at 10^5 years, which is about a factor of ten higher than that of the reference case. Other climatic and surface conditions result in lower dose rates.

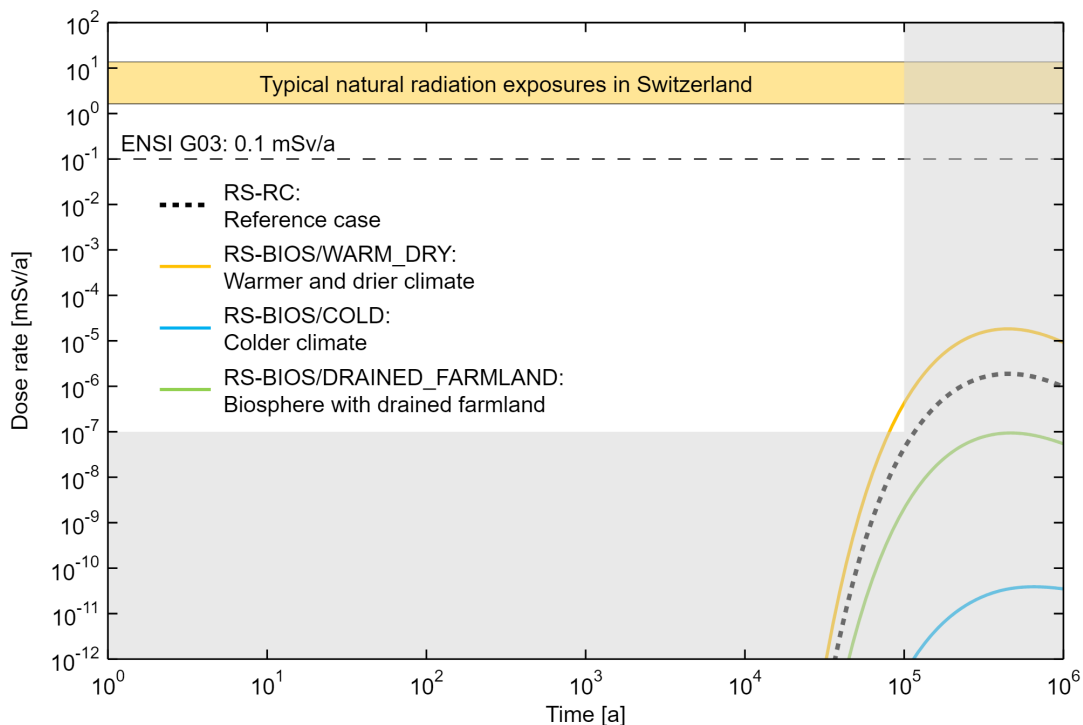


Fig. 6-58: Total dose rates for an L/ILW repository in the JO siting region in the reference case and in cases assuming different climatic and surface conditions¹¹

¹¹ The y-axis is extended to 10^{-12} mSv/a, so that the release curve of the colder climate is visible.

6.2.1.2 Nördlich Lägern (NL)

Fig. 6-59 shows the total dose rates and nuclide-specific dose rates for dominant nuclides for an L/ILW repository in the NL siting region. The calculated dose rate evolves in a very similar way to JO, remaining below the level of significant dose rate, defined as 10^{-7} mSv/a, throughout the 100,000-year time period for assessment.

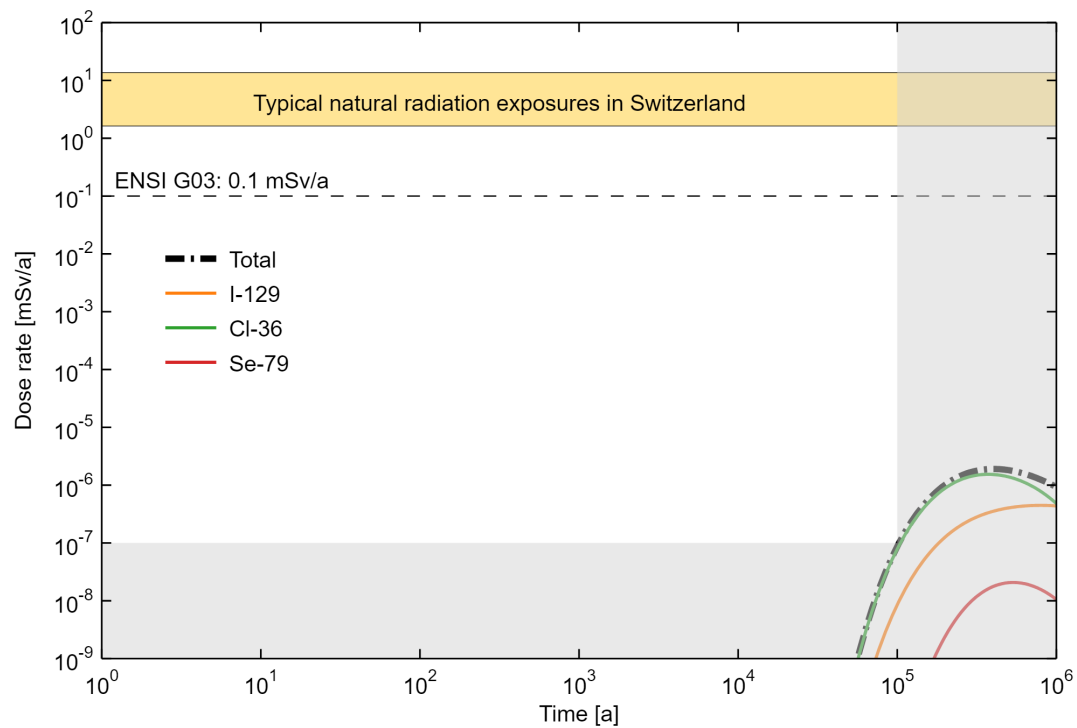


Fig. 6-59: Total and nuclide-specific dose rates in the reference case for an L/ILW repository in the NL siting region

Fig. 6-60 illustrates the contributions to the total dose rate of releases across the three individual interfaces with the biosphere: 1) Malm aquifer (upper model boundary), 2) Keuper aquifer (first deep aquifer below the repository) and 3) dolomitic Muschelkalk (lower model boundary). Similarly to the results for HLW in this siting region, the dose rates due to releases from the Keuper aquifer dominate the total, while the release from the Malm aquifer is much lower. The dose rates due to releases from the Muschelkalk aquifer are much smaller than those due to release from the other aquifers.

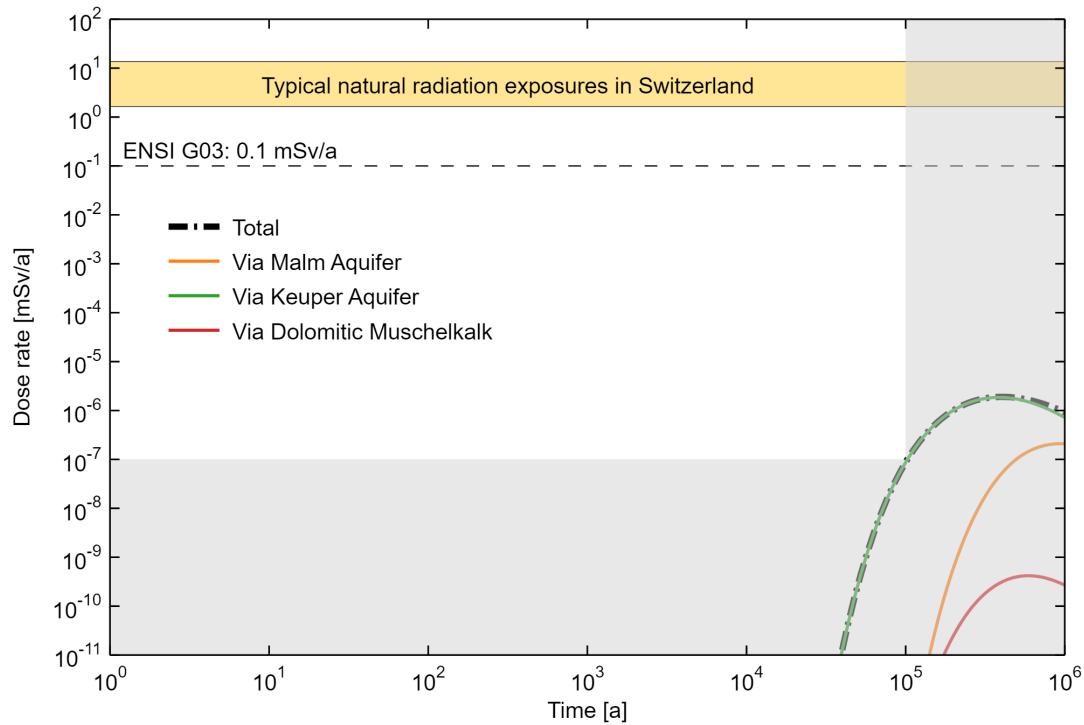


Fig. 6-60: Radionuclide-specific dose rates due to L/ILW releases from the Malm aquifer, the Keuper aquifer and the Dolomitic Muschelkalk to the biosphere model in the reference case for the NL siting region¹²

Fig. 6-61 shows how the maximum dose rates are attenuated as the radionuclides migrate through the barrier system in NL. Compared with Fig. 6-56, the results are broadly similar to those for JO due to the similarity in the geometry and properties of the repository near-field and the Opalinus Clay host rock. The dose rates for most of the radionuclides are reduced to below the level of the significant dose rate 10^{-7} mSv/a after just a few tens of metres of transport. Furthermore, other than the behaviour in JO, because of the greater thickness of the upper confining geological units, the maximum dose rate up to the upper confining units drops below 10^{-9} mSv/a at about 140 m in the figure.

¹² The y-axis is extended to 10^{-11} mSv/a, so that the release curve from the Muschelkalk aquifer is visible.

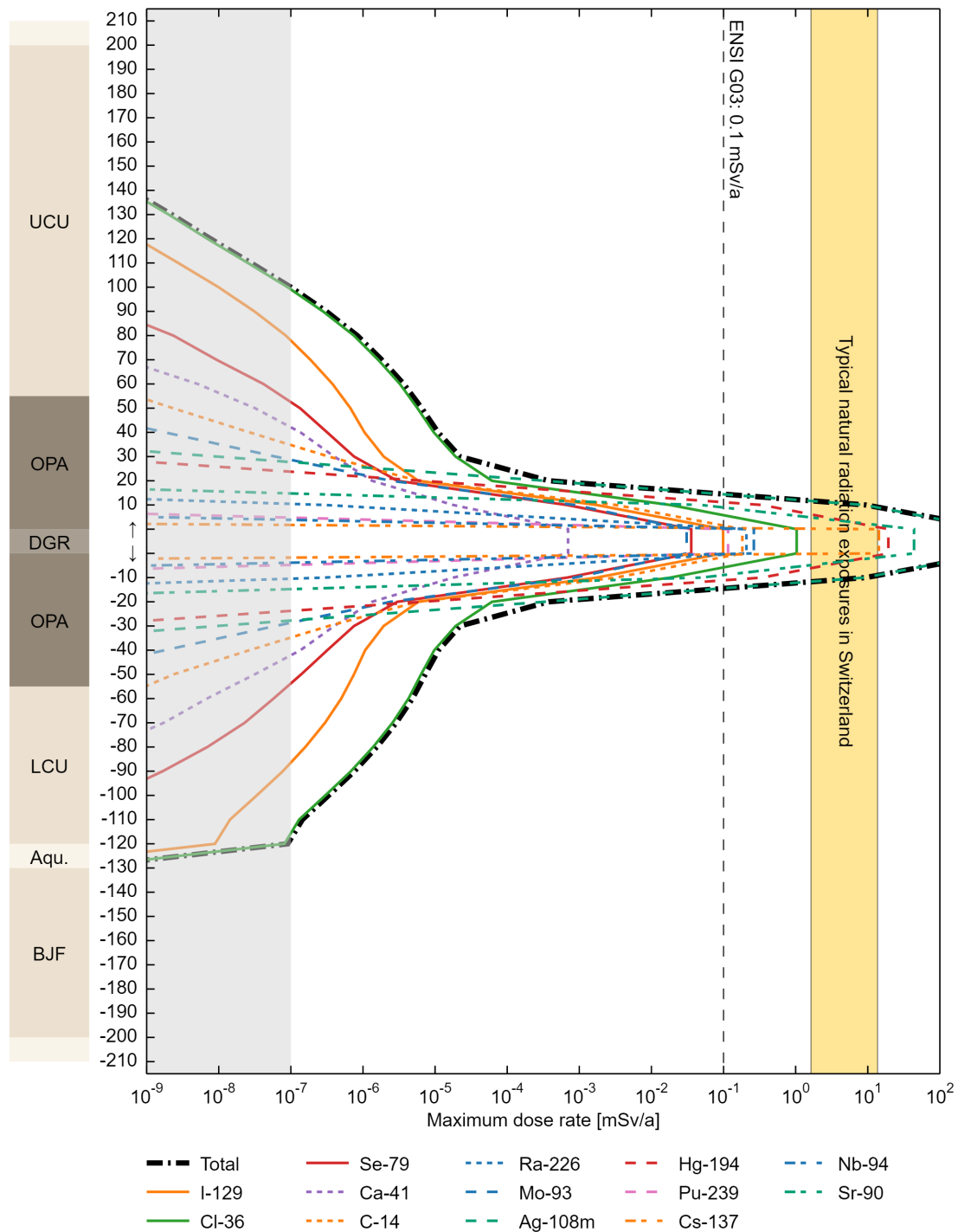


Fig. 6-61: Maximum dose rates obtained by applying BDCFs to radionuclide transport rates calculated for an L/ILW repository in the NL siting region as a function of distance from the repository centre point

(only individual radionuclides with a maximum dose rate exceeding 10^{-1} mSv/a anywhere or with a maximum dose rate higher than 10^{-7} mSv/a at a distance of 20 m or more from the repository centre are illustrated in the figure)

Fig. 6-62 illustrates the evolution of the overall RT in different materials within the repository system. The results are very similar to those shown in Fig. 6-57 for the JO siting region. Due to the thicker confining units in NL compared to JO, more RT can be retarded in them, therefore, the RT outside of the CRZ is not visible in this figure for NL.

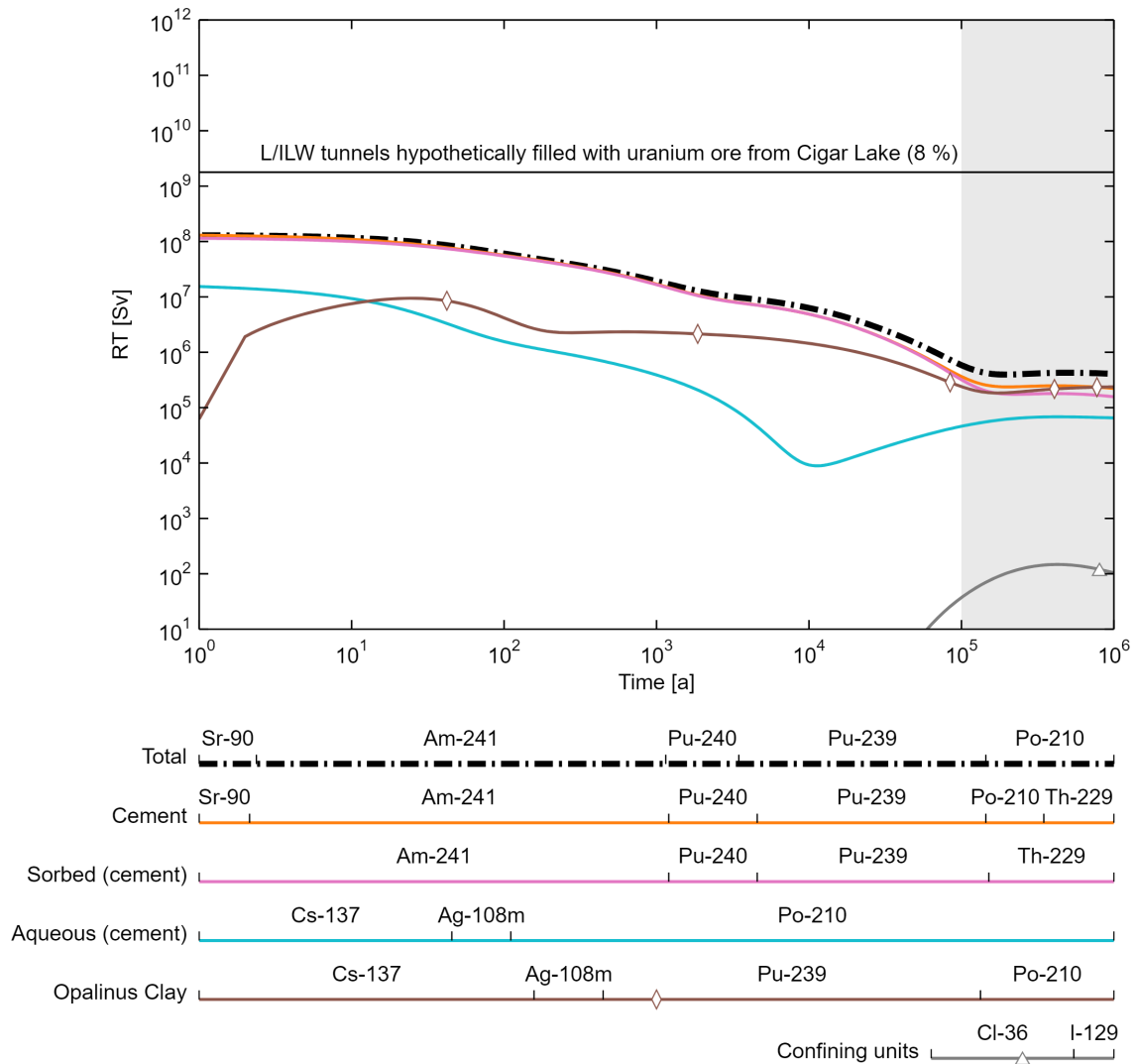


Fig. 6-62: Evolution and distribution of the radiotoxicity over time in the cementitious near-field (in aqueous and in sorbed form, and in total), the Opalinus Clay, its confining geological units and outside the containment-providing rock zone for an L/ILW repository in the NL siting region. For comparison of the radiotoxicity, all L/ILW emplacement caverns are shown to be hypothetically filled with uranium ore (8%)

As in the case of JO, the reference case for NL uses BDCFs for a reference biosphere based on present-day climatic conditions. Three additional deterministic calculation cases concerning uncertainty in biosphere are performed.

The evolution of the dose rates in each of these cases is shown in Fig. 6-63. A warmer and drier climate is found to result in a maximum dose rate of 8.7×10^{-7} mSv/a at 10^5 years, which is about a factor of ten higher than that of the reference case. Other climatic and surface conditions result in lower dose rates.

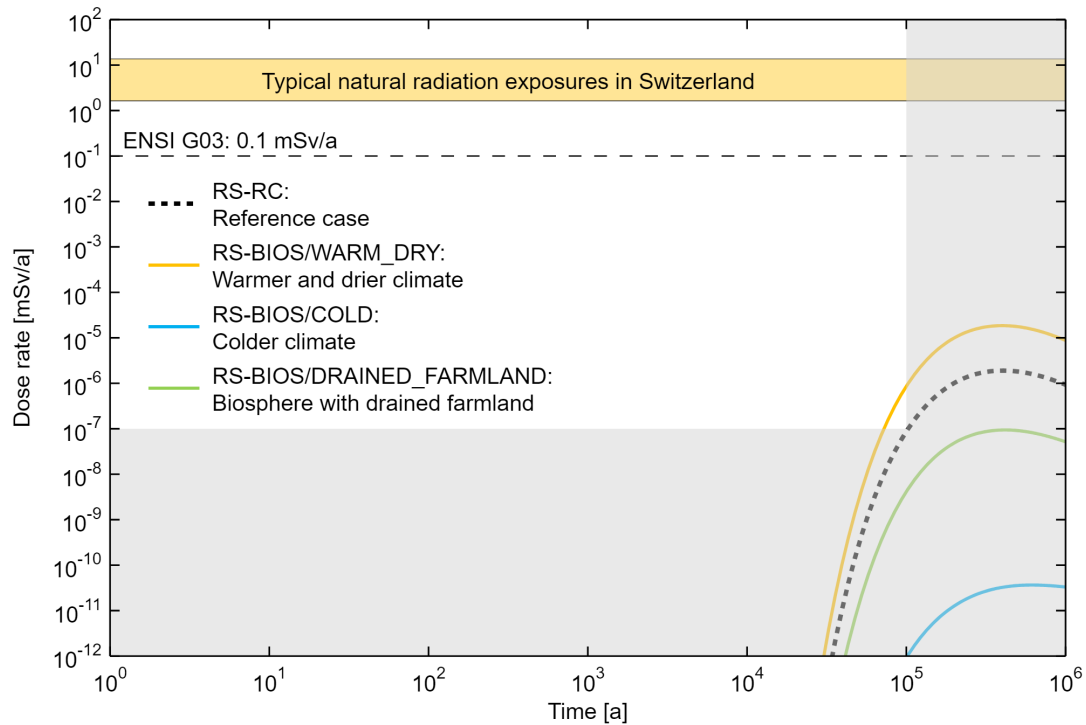


Fig. 6-63: Total dose rates for an L/ILW repository in the NL siting region in the reference case and in cases assuming different climatic and surface conditions¹³

¹³ The y-axis is extended to 10^{-12} mSv/a, so that the release curve of the colder climate is visible.

6.2.1.3 Zürich Nordost (ZNO)

Fig. 6-64 shows the total dose rates and nuclide-specific dose rates for dominant nuclides for an L/ILW repository in the ZNO siting region. The calculated dose rate evolves in a similar way to that for the other siting regions, remaining below the level of the significant dose rate, defined as 10^{-7} mSv/a, throughout the 100,000-year time period for assessment.

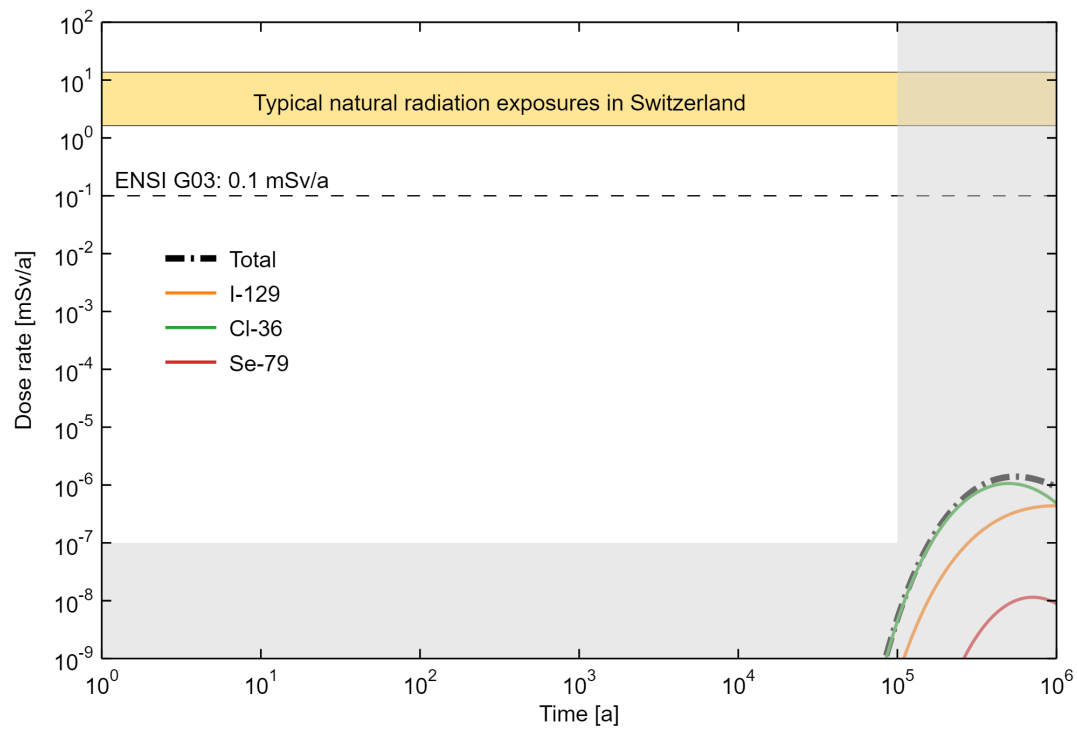


Fig. 6-64: Total and nuclide-specific dose rates in the reference case for an L/ILW repository in the ZNO siting region

Fig. 6-65 illustrates the contributions to the total dose rate of releases in the reference case across the three individual interfaces with the biosphere: 1) Malm aquifer (upper model boundary), 2) Keuper aquifer (first deep aquifer below the repository) and 3) Dolomitic Muschelkalk (lower model boundary). As in the case of the NL siting region (Fig. 6-60), radionuclide release from the geosphere is dominated by the Keuper aquifer. The Malm aquifer, which provides the upper boundary to the geosphere model, plays a secondary role. The release rate from the Muschelkalk aquifer at the lower boundary is negligibly low.

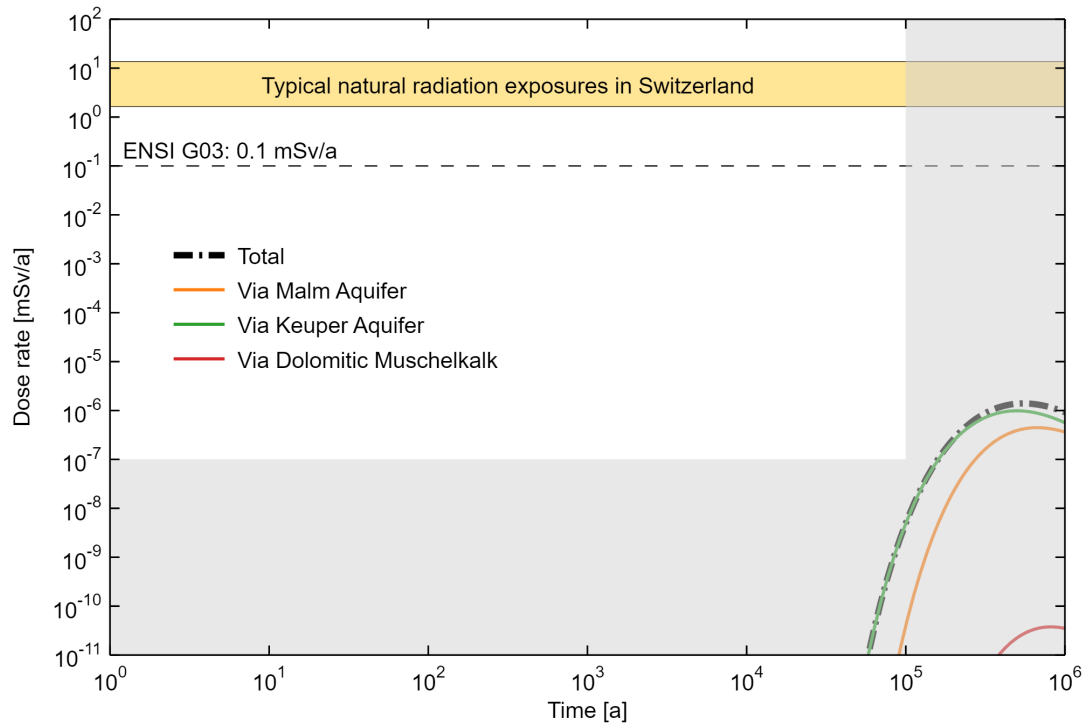


Fig. 6-65: Radionuclide-specific dose rates due to L/ILW releases from the Malm aquifer, the Keuper aquifer and the Dolomitic Muschelkalk to the biosphere model in the reference case for the ZNO siting region¹⁴

In Fig. 6-66, the maximum dose rates are shown at different vertical distances from the repository. Compared with Fig. 6-56 and Fig. 6-61, the results are broadly similar to those for JO and NL due to the similarity in the geometry and properties of the repository near-field and the Opalinus Clay host rock.

¹⁴ The y-axis is extended to 10^{-11} mSv/a, so that the release curve from the Muschelkalk aquifer is visible.

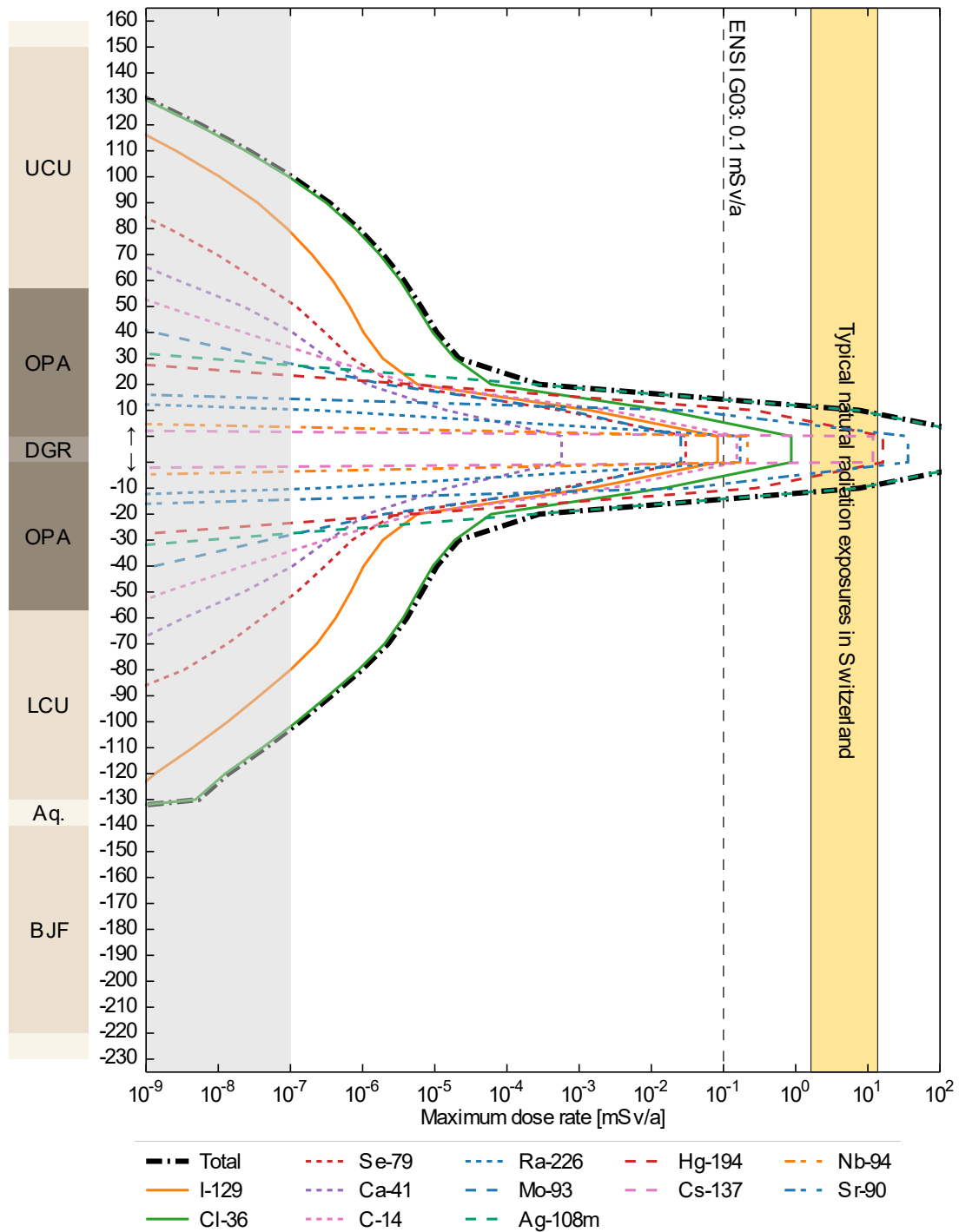


Fig. 6-66: Maximum dose rates obtained by applying BDCFs to radionuclide transport rates calculated for an L/ILW repository in the ZNO siting region as a function of distance from the repository centre point

(only individual radionuclides with a maximum dose rate exceeding 10^{-1} mSv/a anywhere or with a maximum dose rate higher than 10^{-7} mSv/a at a distance of 20 m or more from the repository centre are illustrated in the figure)

Fig. 6-67 illustrates the evolution of the overall RT in different materials within the repository system. The results are very similar to those shown in Fig. 6-57 for the JO siting region and to those shown in Fig. 6-62 for NL.

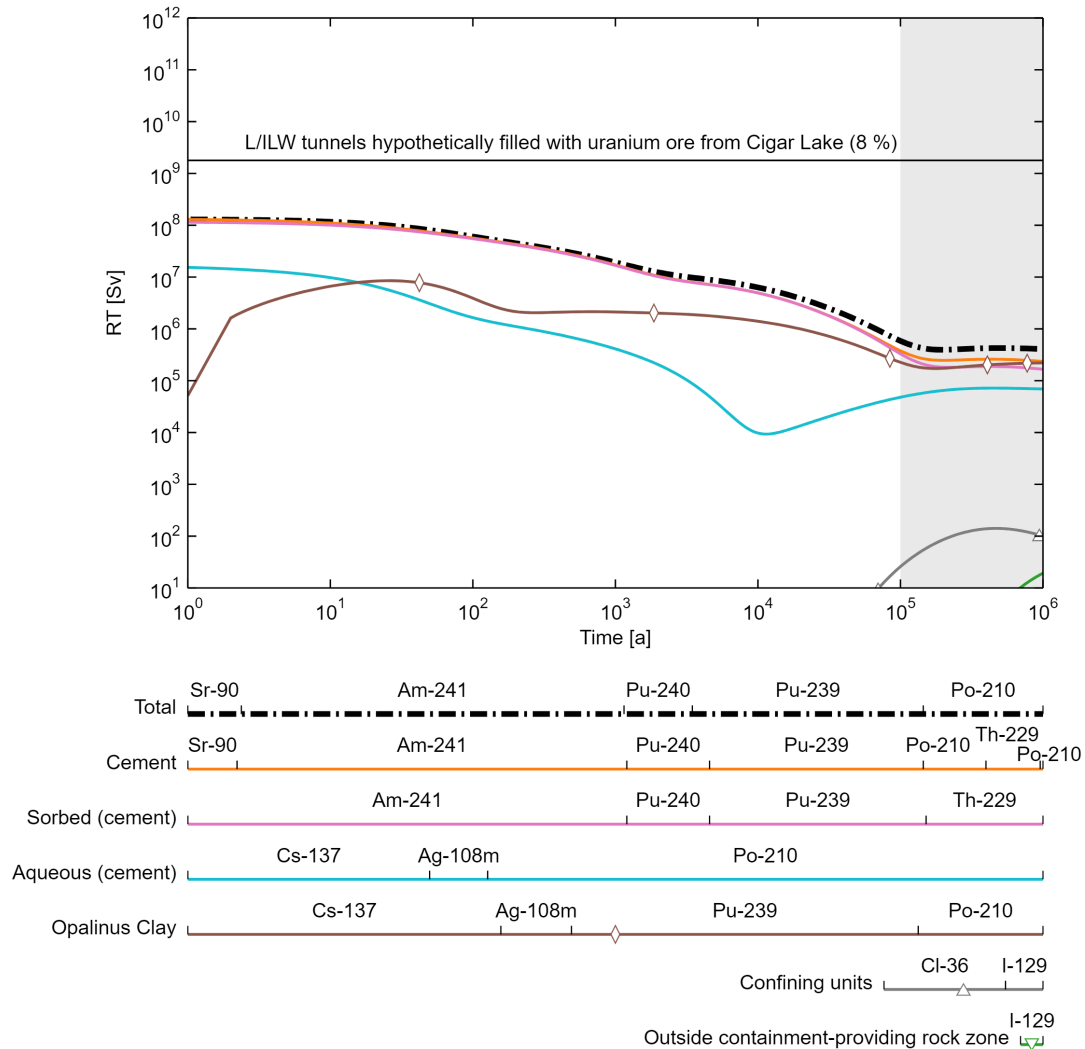


Fig. 6-67: Evolution and distribution of the radiotoxicity over time in the cementitious near-field (in aqueous and in sorbed form, and in total), the Opalinus Clay, its confining geological units and outside the containment-providing rock zone for an L/ILW repository in the ZNO siting region. For comparison of the radiotoxicity, all L/ILW emplacement caverns are shown to be hypothetically filled with uranium ore (8%)

As with the other two siting regions, the reference case for ZNO uses BDCFs for a reference biosphere based on present-day climatic conditions. Three additional deterministic calculation cases concerning uncertainty in the biosphere are calculated.

The evolution of the dose rates in each of these cases is shown in Fig. 6-68. A warmer and drier climate is found to result in a maximum dose rate of 5.04×10^{-8} mSv/a at 10^5 years, which is about a factor of ten higher than that of the reference case. Other climatic and surface conditions result in lower dose rates.

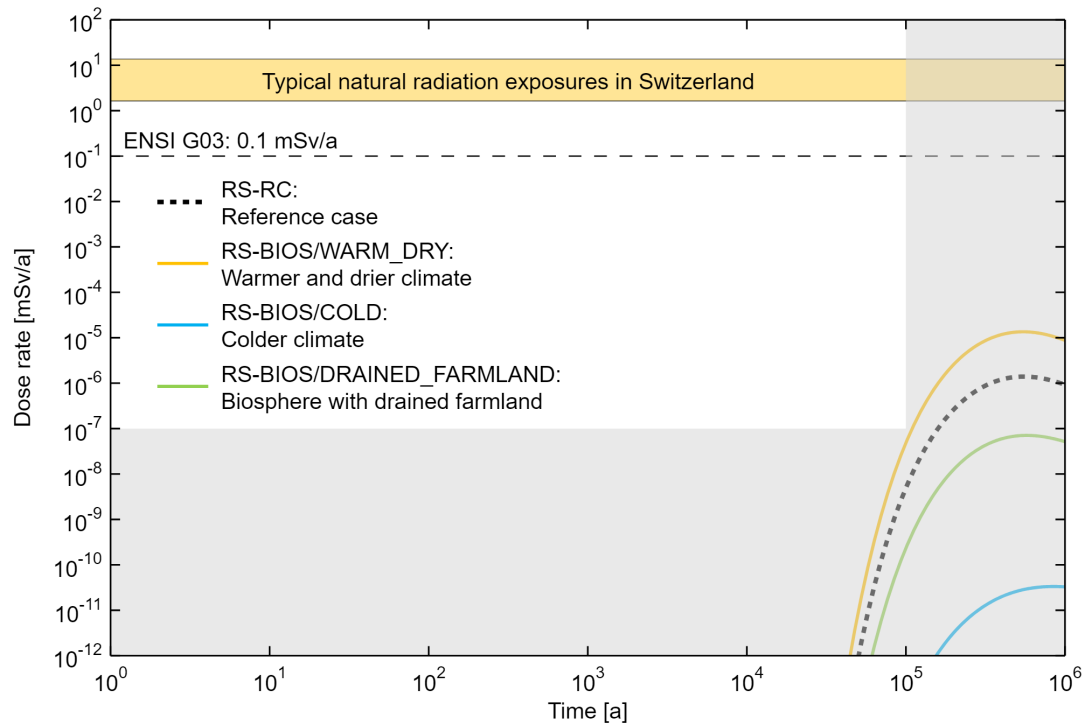


Fig. 6-68: Total dose rates for an L/ILW repository in the ZNO siting region in the reference case and in cases assuming different climatic and surface conditions¹⁵

¹⁵ The y-axis is extended to 10^{-12} mSv/a, so that the release curve of the colder climate is visible.

6.2.2 Probabilistic and deterministic analysis covering parameter uncertainty

As in the analysis of the HLW repository, and in accordance with the workflow described at the start of this chapter, probabilistic analyses of the reference safety scenario are performed for each site-specific model, along with deterministic analyses of pessimistic cases, in which those parameters identified to be the most sensitive in the probabilistic analyses are set to pessimistic, bounding values. This includes a deterministic case that combines the pessimistic bounding values of all the most sensitive parameters. The results of these probabilistic and deterministic analyses are presented for each siting region in the following sections.

6.2.2.1 Jura Ost (JO)

Fig. 6-69 shows statistical percentiles calculated for Monte-Carlo simulations of the dose rate evolution of an L/ILW repository in the JO siting region, where each simulation was carried out by sampling input parameters from probability distribution functions representing parameter uncertainty. The significance level of the dose rates, defined as dose rates higher than 10^{-7} mSv/a, occur, at the earliest, only after about 6×10^4 years, and, at the latest, after about 2×10^5 years. This demonstrates the retention capacity of the repository in the siting region. In all cases, the maximum dose rate appears after 10^5 years. The highest calculated dose rate within the first 10^5 years is 1.5×10^{-6} mSv/a. Although the dose rates increase after the time period for assessment, they remain several orders of magnitude below the lower bound value of the typical natural radiological exposures in Switzerland (BAG 2021).

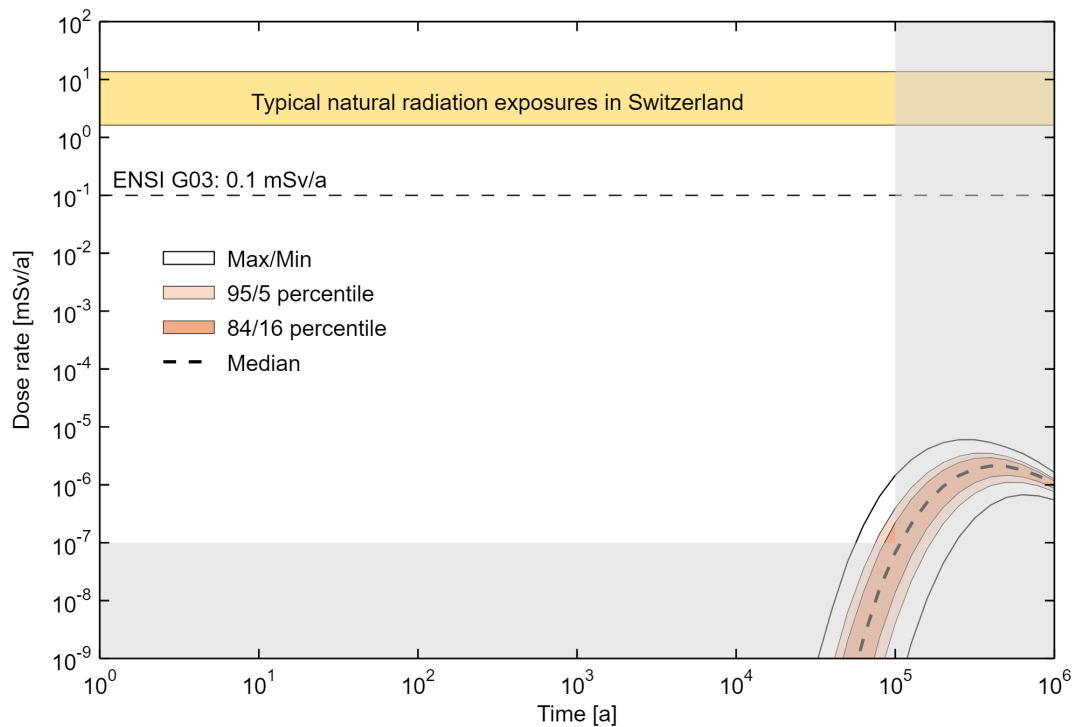


Fig. 6-69: Statistical percentiles calculated from 4,000 Monte-Carlo simulations of the dose rate evolution of an L/ILW repository in the JO siting region

As in the analysis of an HLW repository, sensitivity analyses have been performed based on the results from the Monte-Carlo simulations. The first step is a graphical analysis using scatter plots showing the maximum dose rate within the one-hundred-thousand-year time period for assessment against individual input parameter values sampled in the Monte-Carlo simulations. Some examples of such scatter plots are shown in Figs. 6-70 to Fig. 6-72.

Fig. 6-70 shows the monotonic relationship between the maximum dose rate and the effective diffusion coefficient of halogens in the Opalinus Clay. Unlike the HLW repository, where the maximum dose rate is always dominated by I-129, the maximum dose rate for the L/ILW repository is mainly dominated by Cl-36. However, all the parameters that are varied for I-129 are linked to the parameter variations for Cl-36, as both are halogens. This leads to the maximum dose rate being sensitive to multiple parameters describing the properties of halogens.

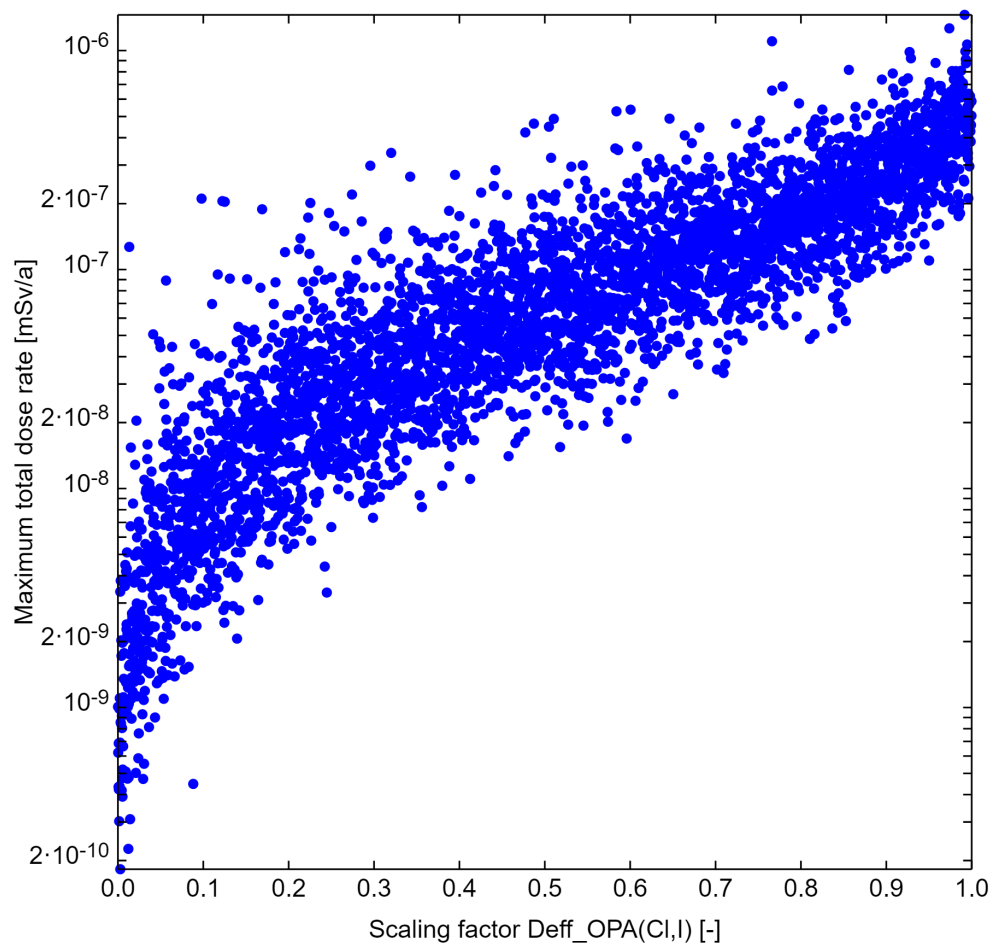


Fig. 6-70: Scatter plot showing the maximum dose rate for an L/ILW repository in the JO siting region within the one-hundred-thousand-year time period for assessment against the effective diffusion coefficient of the halogens in the Opalinus Clay, which is varied using a normalised scaling factor, sampled in Monte-Carlo simulations

Fig. 6-71 shows a negative correlation between the maximum dose rate and the thickness of the Opalinus Clay. The diffusive transport length controlled by the rock thickness shows more importance in L/ILW than in HLW.

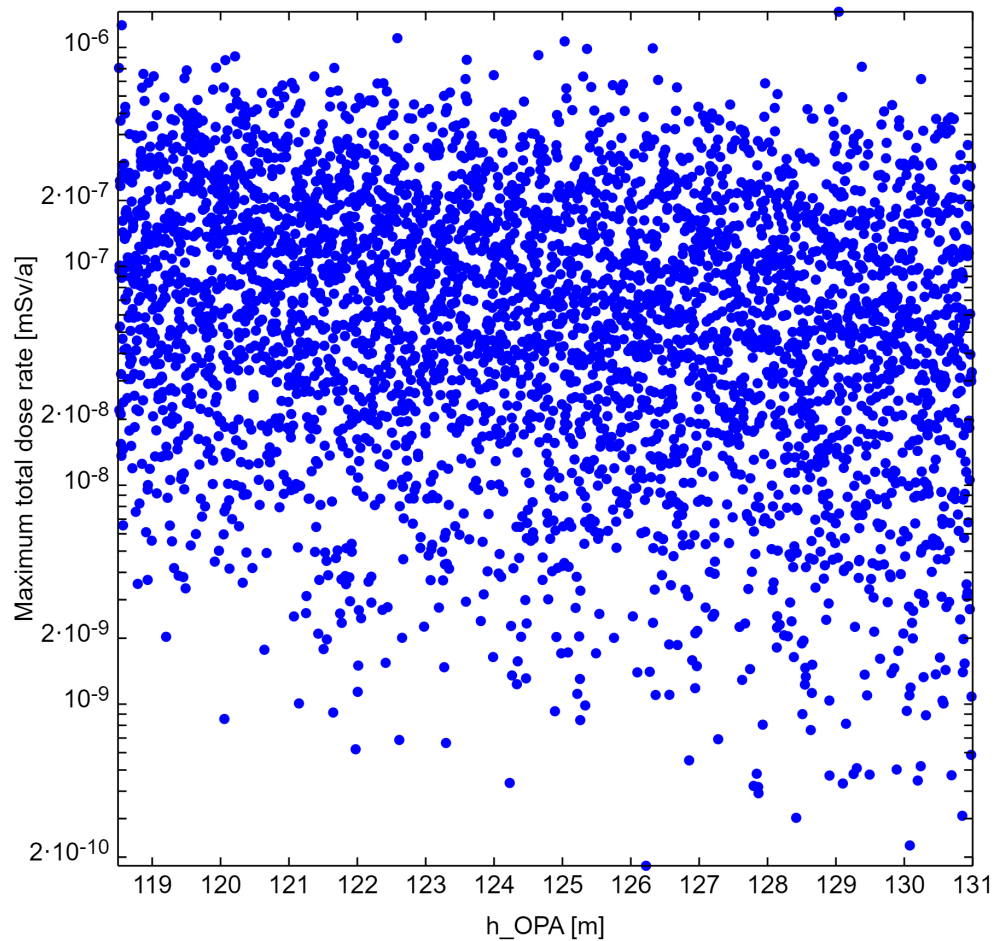


Fig. 6-71: Scatter plot showing the maximum dose rate for an L/ILW repository in the JO siting region within the one-hundred-thousand-year time period for assessment against the thickness of the Opalinus Clay formation

The monotonic relationship between the maximum dose rate and the effective diffusion coefficient of halogens over the whole parameter value range indicates the dominant role of diffusive transport of radionuclides in the Opalinus Clay host rock over advective transport. It is, nonetheless, still of interest to examine the sensitivity of the maximum dose rate to the parameters that control advective transport. A correlation can be seen in the scatter plot in Fig. 6-72 between the maximum dose rate and the vertical Darcy flow rate through the Opalinus Clay and the confining geological units. As in the corresponding results for HLW (Fig. 6-20), the relationship is not monotonic. This is because the Darcy flow is varied between negative (downward) and positive (upward) values. More specifically, the vertical hydraulic head difference between the upper and lower model boundaries is varied between -1 and 1 m/m, thus changing the flow direction. The maximum dose rate is affected predominantly by the magnitude of flow, rather than by its direction. The correlation is more significant at higher Darcy flow rates, where the dominance of diffusion over advection is less pronounced. At low Darcy flows of between about -1×10^{-14} and 1×10^{-14} m/s, the maximum dose rate shows little sensitivity to this parameter. There is, however, some difference related to the direction of flow, with a stronger correlation observed between maximum dose rate and upwardly directed (positive) flow, compared with downwardly directed (negative) flow. This is consistent with the observation made from the

reference case analysis that the dose rates due to releases from the Calcareous Dogger at the top of the geosphere model dominate over releases in the downward direction (see Fig. 6-55). An increased positive Darcy flow increases the releases via this dominant pathway.

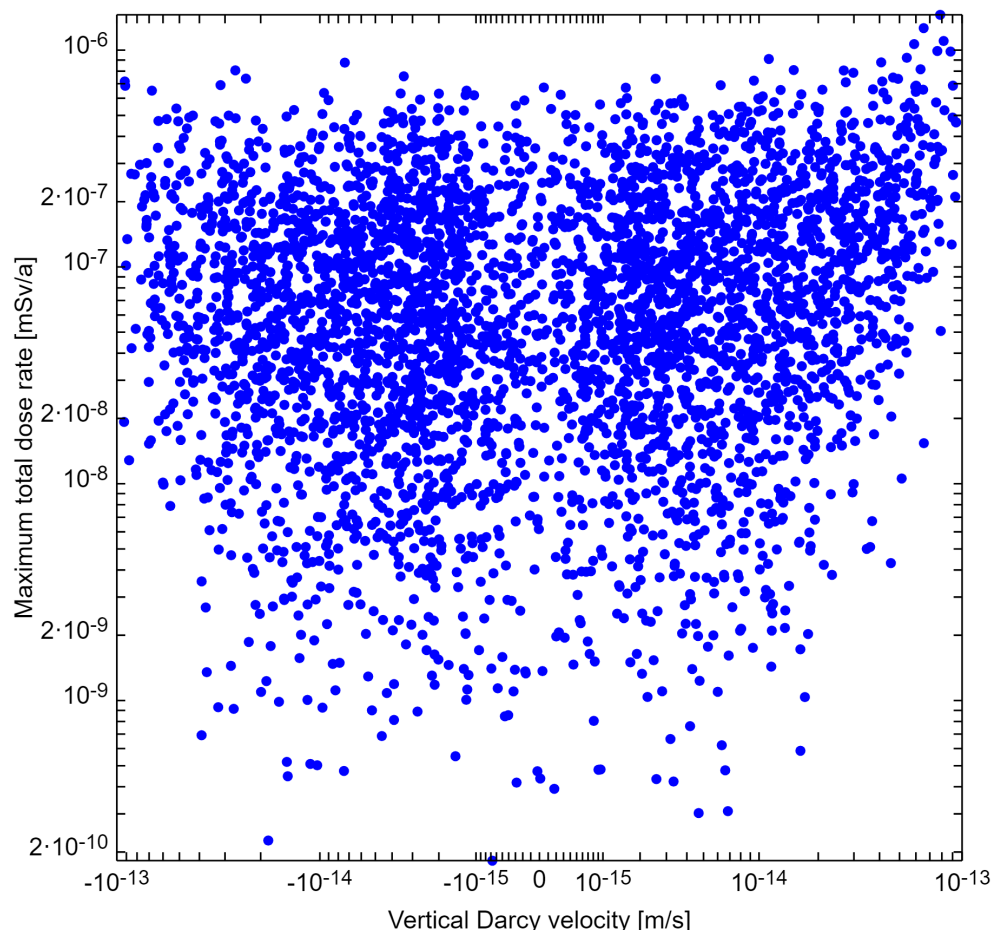


Fig. 6-72: Scatter plot showing the maximum dose rate for an L/ILW repository in the JO siting region within the one-hundred-thousand-year time period for assessment against the vertical Darcy flow velocity

As in the case of the HLW repository, the sensitivity of the variance in maximum dose rate to the variance in the input parameters can also be evaluated in terms of sensitivity measures using non-graphical statistical methods. Most of Monte-Carlo realisations give dose rates below 10^{-7} mSv/a, which are below the assumed level of the significant dose rate. Nonetheless, the full set of the 4,000 Monte-Carlo realisations is considered in the sensitivity analysis, in order to ensure comprehensive system understanding.

The sensitivity measures used here are the Pearson correlation coefficient, the Spearman correlation coefficient and the modified EASI first-order sensitivity index, the latter being variance-based and, unlike the other measures, suitable where relationship is not monotonic, as in the above example of vertical Darcy flow. Tab. 6-6 shows these sensitivity measures calculated for the parameters considered in the probabilistic analyses. No significance should be assigned to sensitivity measures with magnitudes below the threshold of significance shown in the table. Sensitivities are calculated for the maximum dose rates occurring over the first 10^5 years following repository closure.

Tab. 6-6: Sensitivity measures for the parameters with at least one significant correlation of the JO probabilistic analyses for an L/ILW repository

Values above the calculated “threshold of significance” are marked in blue. (+) or (-) indicates the selected bounding value for the individual and combined pessimistic calculations.

Parameter	Description	Pearson correlation coefficient	Spearman correlation coefficient	Modified EASI sensitivity index
	<i>Significance threshold</i>	<i>0.031</i>	<i>0.031</i>	<i>0.0052</i>
Deff_OPA(Cl,I) (+) 6.7×10^{-13} - 2.9×10^{-12} m ² /s (Cl) 6.6×10^{-13} - 2.9×10^{-12} m ² /s (I)	Effective diffusion coefficient of halogens in the Opalinus Clay	0.74	0.9	0.67
h_OPA (-) 119 - 131 m	Thickness of the Opalinus Clay	-0.16	-0.19	0.028
Deff_SCAD(Cl,I) (+) 1.1×10^{-12} - 7.8×10^{-12} m ² /s (Cl) 1.1×10^{-12} - 7.7×10^{-12} m ² /s (I)	Effective diffusion coefficient of halogens in the SCAD+SCD	0.15	0.14	0.023
K_v,OPA (+) 2.0×10^{-15} - 1.0×10^{-13} m/s	Hydraulic conductivity of the Opalinus Clay	0.16	0.13	0.026
Deff_KEU(Cl,I) (+) 8.5×10^{-13} - 5.3×10^{-12} m ² /s (Cl) 8.3×10^{-13} - 5.3×10^{-12} m ² /s (I)	Effective diffusion coefficient of halogens in the KEU	0.11	0.11	0.014
i_v (+) -1.0 - 1.0 m/m	Hydraulic gradient along the geological formations	0.12	0.1	0.022
E_a,wc (+) 1.5×10^4 - 2.5×10^4 J/mol	Activation energy for diffusion in the porewater	0.082	0.0-93	0.0073
Phi_OPA(Cl,I) (-) 0.015 - 0.035 (Cl,I)	Radionuclide accessible porosity of halogens of the Opalinus Clay	-0.089	-0.081	0.0097
h_CAD (-) 16.5 - 17.9 m	Thickness of the CAD	-0.077	-0.076	0.0071
h_SCAD(-) 14.7 - 17.9 m	Thickness of the SCAD within the SCAD+SCD	-0.082	-0.071	0.010
Deff_CAD(Cl,I) (+) 1.2×10^{-12} - 9.4×10^{-12} m ² /s (Cl) 1.2×10^{-12} - 9.2×10^{-12} m ² /s (I)	Effective diffusion coefficient of halogen in the CAD	0.045	0.053	0.0040
Phi_KEU(Cl,I) (-) 0.01 - 0.04 (Cl, I)	Radionuclide accessible porosity of halogens in the KEU	-0.053	-0.05	0.0047
h_KAK(-) 11.5 - 11.9 m	Thickness of the KAK	-0.042	-0.04	0.0038

Tab. 6-6: continued

Parameter	Description	Pearson correlation coefficient	Spearman correlation coefficient	Modified EASI sensitivity index
	<i>Significance threshold</i>	<i>0.031</i>	<i>0.031</i>	<i>0.0052</i>
Deff_SCAD(Ca) (+) $4.3 \times 10^{-11} - 8.9 \times 10^{-11} \text{ m}^2/\text{s}$	Effective diffusion coefficient of Ca in the SCAD+SCD	0.041	0.034	0.0039
Deff_AAK(C _{org}) (+) $1.1 \times 10^{-12} - 6.7 \times 10^{-12} \text{ m}^2/\text{s}$	Effective diffusion coefficient of organic C-14 in the AAK	0.038	0.031	0.0040

Consistent with the scatterplots discussed above, the most sensitive parameter, according to all three sensitivity measures, is the effective diffusion coefficient of halogens in the Opalinus Clay (Deff_Opa(Cl_I)). The second most sensitive parameter is the thickness of the Opalinus Clay. Other sensitive parameters are the thicknesses of the confining units and their effective diffusion coefficients, mostly for halogens. The activation energy ($E_{a,wc}$), which is used to adjust the effective diffusion coefficient to ambient temperature, also shows some sensitivity. All these parameters control the rate of diffusive transport both upwards and downwards through the host rock and confining geological units.

Parameters that control the rate of advective transport, notably the hydraulic conductivity of the Opalinus Clay and the vertical hydraulic gradient (i_v), show sensitivities, since they provide the advective path in the upper, shorter confining geological units (however, the Pearson and Spearman correlation coefficients are unsuited for non-monotonic relationships, such as that shown by the hydraulic gradient; see Fig. 6-72).

As in the case of the HLW repository, in order to provide a better understanding of the impact of various parameters, additional deterministic cases have been analysed, switching each of the individual sensitive parameters to their most pessimistic, bounding values. These deterministic cases can provide the significance of the impact of the individual parameters without considering their interaction with the other parameters (global effect) which can be investigated in the probabilistic sensitivity analysis.

Fig. 6-73 shows dose rate histories for some individual deterministic cases where various effective diffusion coefficients, as well as the activation energy, are set to their most pessimistic (generally upper) bounding values.

Consistent with the results of the sensitivity analyses in Tab. 6-6, the high value of the effective diffusion coefficient of halogens in the Opalinus Clay is found to be able to potentially increase the dose rate. The impact of the other rock units is not well visible. In addition, increasing the activation energy alone, however, which is used in the temperature correction of the effective diffusion coefficients, has no significant impact on the dose rate because the ambient temperature near the L/ILW repository in the JO siting region (32 °C) is still similar to the reference temperature (25 °C), so the temperature correction is also minor.

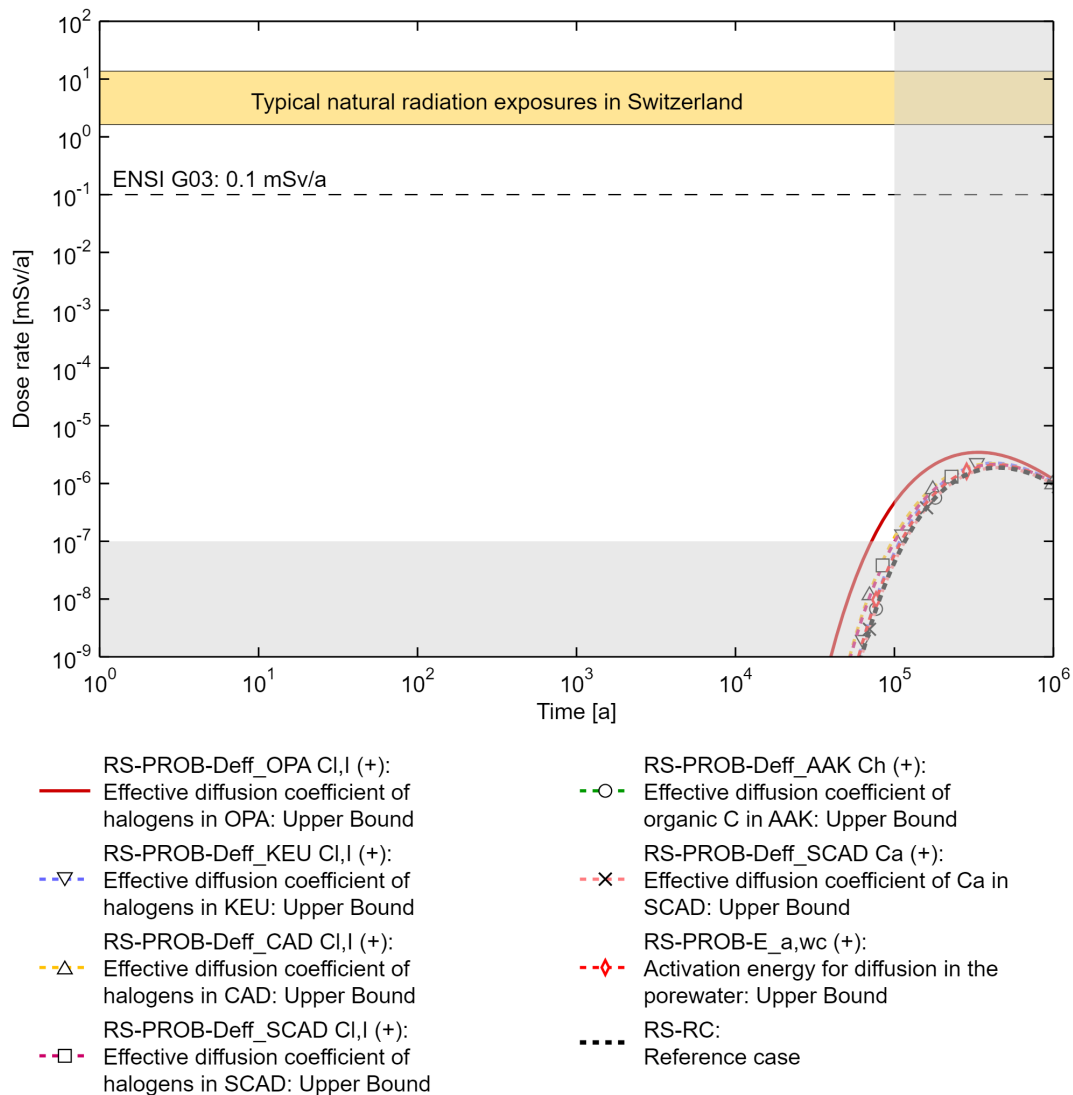


Fig. 6-73: Total dose rates in the reference case for an L/ILW repository in the JO siting region, and in cases where various effective diffusion coefficients and the activation energy used in temperature correction are set to their most pessimistic, bounding values. (+) indicates the most pessimistic upper bound values and (-) indicates the most pessimistic lower bound values, according to Tab. 6-6. (SCAD = SCAD+SCD)

Fig. 6-74 shows some further individual deterministic cases where various Opalinus Clay properties, excluding the effective diffusion coefficients, are set to their most pessimistic, bounding values. Setting the Opalinus Clay thickness (hOPA) to its lower bound value increases the total dose rate slightly, since it shortens the transport paths both upwards and downwards from the repository. Setting the accessible porosity for halogens to its lower bound value also slightly increases the total dose rate, since it results in less dilution of radionuclides within the Opalinus Clay formation.

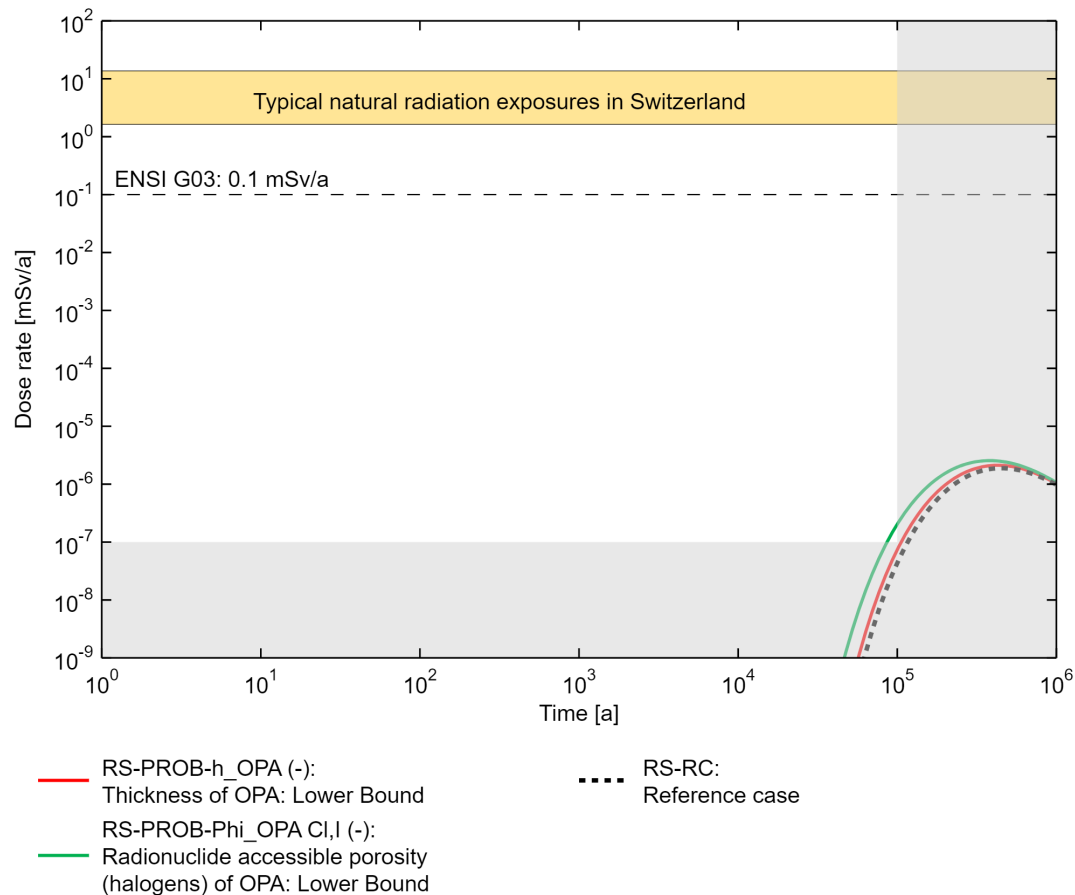


Fig. 6-74: Total dose rates in the reference case for an L/ILW repository in the JO siting region, and in cases where various Opalinus Clay properties, excluding the effective diffusion coefficients, are set to their most pessimistic, bounding values. (+) indicates the most pessimistic upper bound values and (-) indicates the most pessimistic lower bound values, according to Tab. 6-6

Fig. 6-75 shows the results of further deterministic cases addressing the remaining parameters with correlations identified in Tab. 6-6. Setting the upward Darcy flow to its upper bound value has a significant impact on the dose rates, as it enhances advective transport through the upper confining units. By contrast, uncertainty of the thicknesses of the confining geological units does not, in itself, have significant impact on the dose rate compared with the reference case. Low sensitivity to the porosity of halogens in the KEU rock unit ($\Phi_{\text{KEU Cl,I}}$) is also consistent with the relatively low values of sensitivity measures shown in Tab. 6-6.

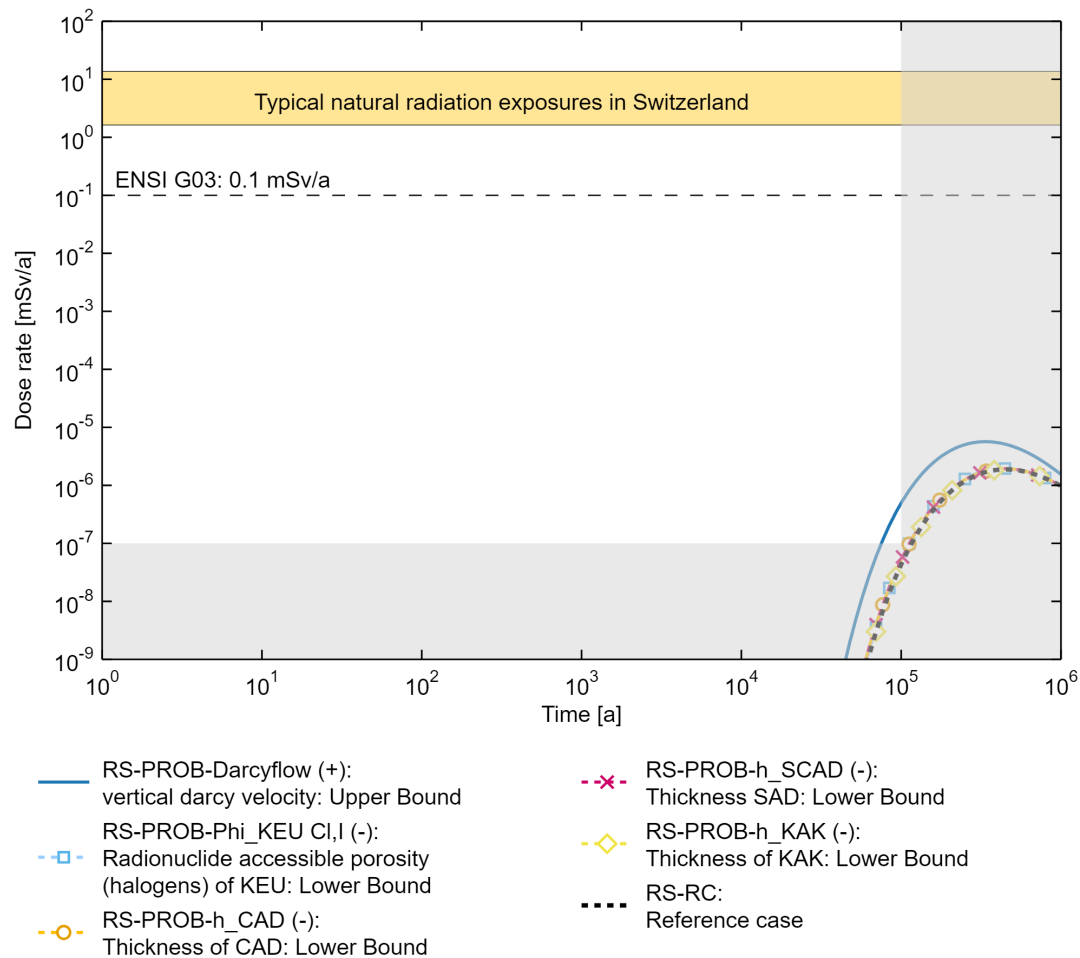


Fig. 6-75: Total dose rates in the reference case for an L/ILW repository in the JO siting region, and in cases where various individual parameters are set to their most pessimistic, bounding values. (+) indicates the most pessimistic upper bound values and (-) indicates the most pessimistic lower bound values, according to Tab. 6-6

Fig. 6-76 shows a case in which sensitive parameters are set to their pessimistic bounding value. The maximum dose rate calculated for the first 10^5 years is increased by a factor of about 300 compared with the reference case, resulting in a value of 1.25×10^{-5} mSv/a, compared with 4.4×10^{-8} mSv/a in the reference case. The dose rate of the “combined pessimistic case” continues to increase at later times, reaching a maximum of 1.46×10^{-5} mSv/a after one hundred thousand years, which is several orders of magnitude lower than the bounding value of the typical natural radiological exposure in Switzerland (BAG 2021), indicating a large safety margin. Although the likelihood of pessimistic bounding values occurring together in this way is low, the combined pessimistic case further demonstrates the robustness of the repository from a post-closure safety perspective.

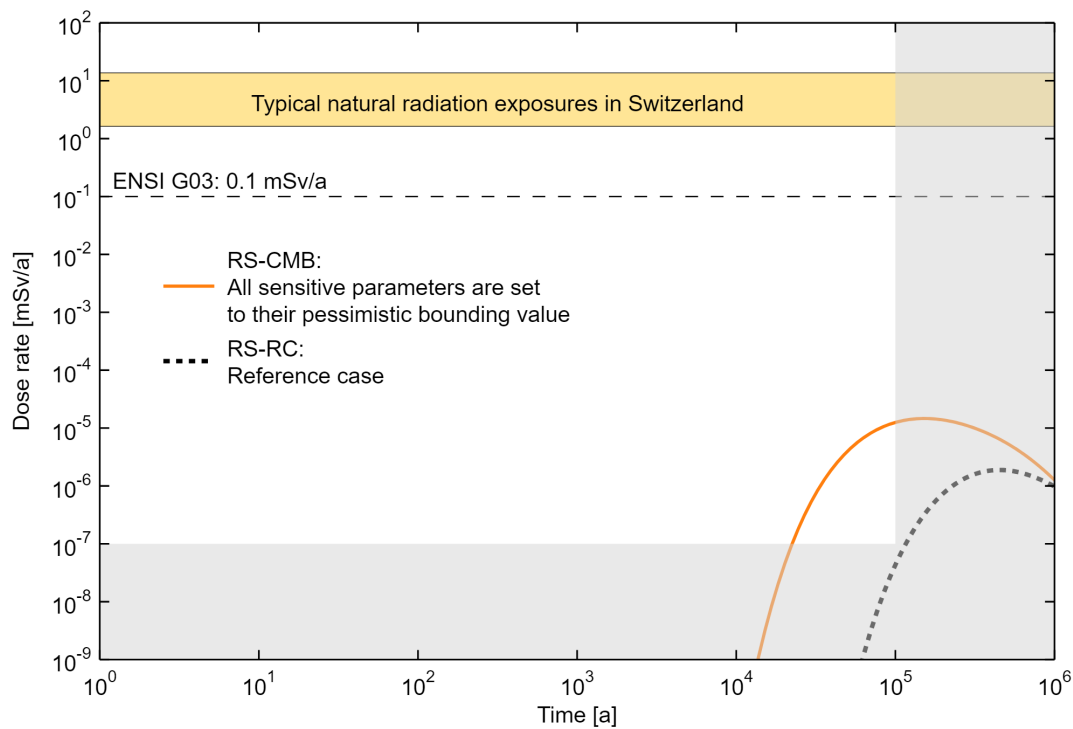


Fig. 6-76: Total dose rates in the reference case for an L/ILW repository in the JO siting region, and in a case in which pessimistic bounding values are set for all sensitive parameters

6.2.2.2 Nördlich Lägern (NL)

Fig. 6-77 shows statistical percentiles calculated from 4,000 Monte-Carlo simulations of the dose rate evolution of an L/ILW repository in the NL siting region. Significant dose rates, defined as dose rates higher than 10^{-7} mSv/a, occur, at the earliest, only after about 5.4×10^4 years, and, at the latest, after about 2.4×10^5 years, which demonstrates the retention capacity of the repository in the siting region. The highest calculated dose rate within the first 10^5 years is 1.5×10^{-6} mSv/a. In all cases, the maximum dose rate appears after 10^5 years. However, the dose rate after the time period for assessment is several orders of magnitude below the lower bound value of the typical natural radiological exposures in Switzerland (BAG 2021).

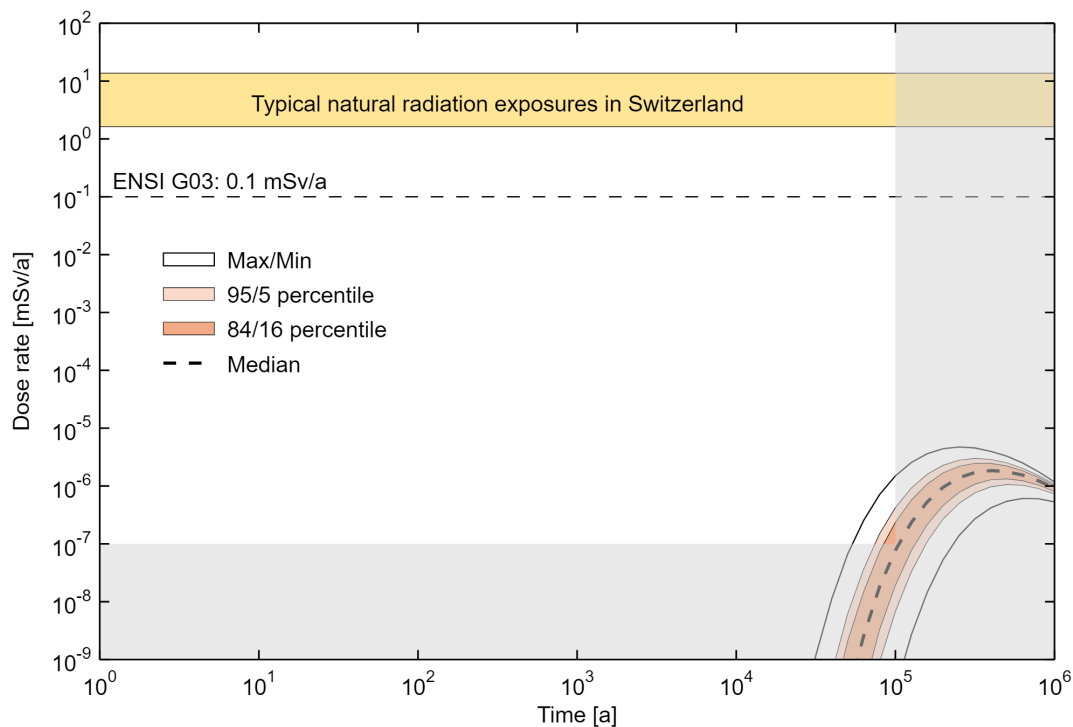


Fig. 6-77: Statistical percentiles calculated from 4,000 Monte-Carlo simulations of the dose rate evolution of an L/ILW repository in the NL siting region

Sensitivity analyses have been performed based on the results from the Monte-Carlo simulations. The first step is a graphical analysis using scatter plots showing the maximum dose within the one-hundred-thousand-year time period for assessment against individual input parameter values sampled in the Monte-Carlo simulations for selected parameters. Some examples of such scatter plots are shown in Figs. 6-78 to Fig. 6-80.

Fig. 6-78 shows the monotonic relationship between the maximum dose rate and the effective diffusion coefficient of halogens in the Opalinus Clay, similar to the situation in siting region JO.

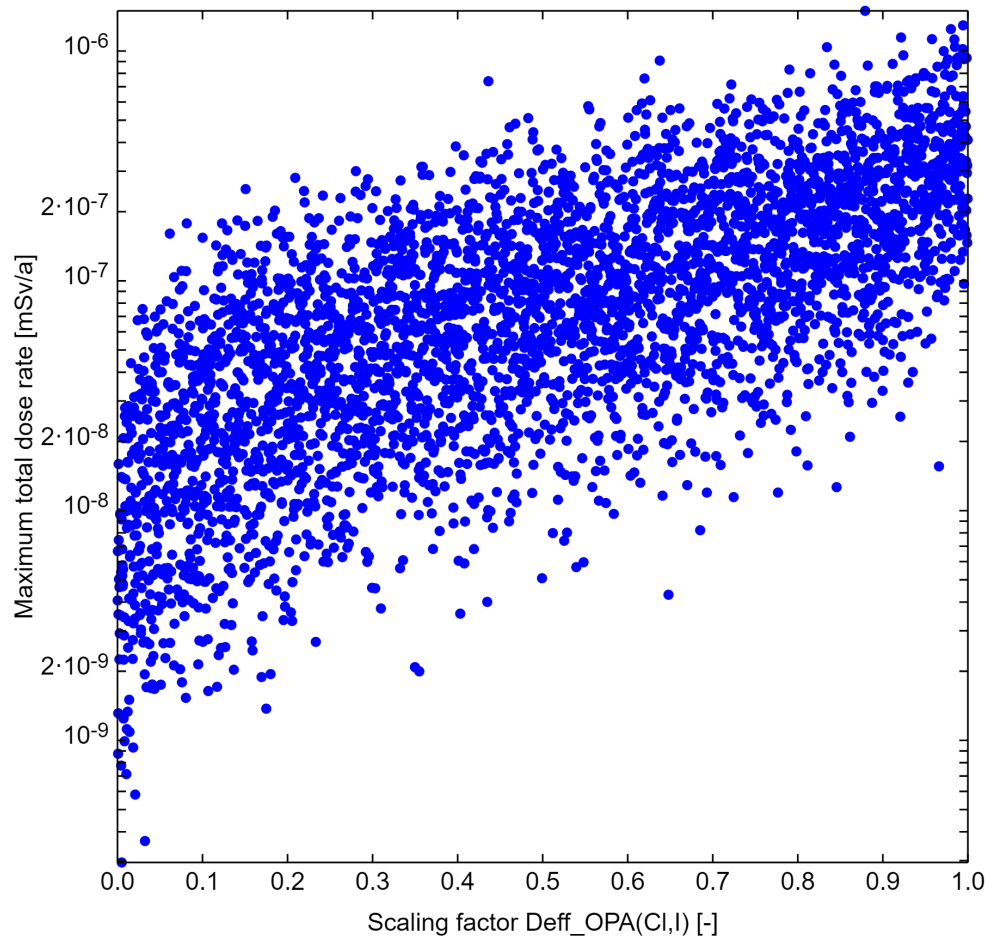


Fig. 6-78: Scatter plot showing the maximum dose rate for an L/ILW repository in the NL siting region within the one-hundred-thousand-year time period for assessment against the effective diffusion coefficient of the halogens in the Opalinus Clay, which is varied using a scaling factor, sampled in Monte-Carlo simulations

Fig. 6-79 shows another clear positive correlation between the total dose rate and the activation energy used when adjusting the effective diffusion coefficients due to the ambient temperature. Similarly to the behaviour shown in the HLW repository discussed in Section 6.1.2.2, the sensitivity of the activation energy is more significant in NL than in JO. This is because the temperature around the L/ILW emplacement caverns, at 44 °C, is higher than in JO, where it is 32 °C, and the correction of the effective diffusion coefficients from the reference temperature of 25 °C is thus larger. This higher temperature strengthens the impact of the activation energy on the effective diffusion coefficients which dominate the transport process.

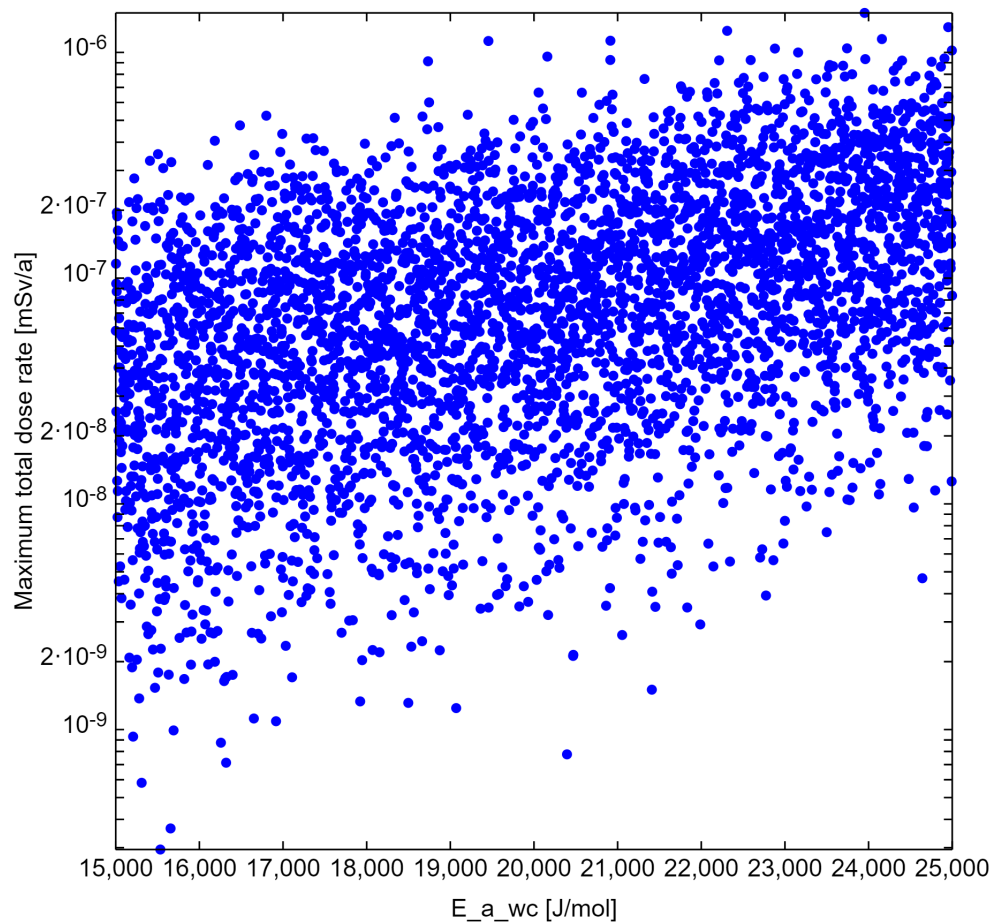


Fig. 6-79: Scatter plot showing the maximum dose rate for an L/ILW repository in the NL siting region within the one-hundred-thousand-year time period for assessment against the activation energy used in the temperature correction of the effective diffusion coefficients, sampled in Monte-Carlo simulations

The scatter plot in Fig. 6-80 does not show a strong correlation between vertical Darcy flow and the maximum dose rate, unlike the clear correlation found for JO, but is similar to the findings for HLW in NL discussed in Section 6.1.2.2. The range of the Darcy flow is smaller because of the smaller bandwidth of the given vertical hydraulic gradient.

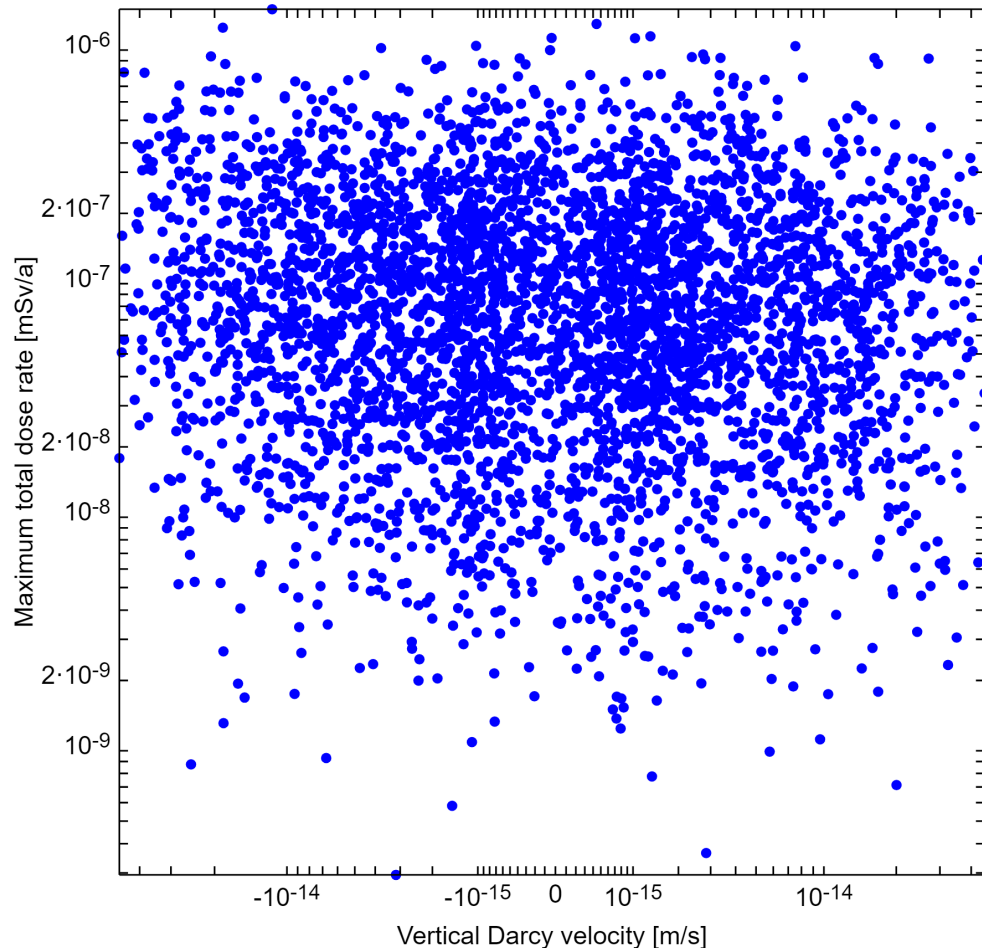


Fig. 6-80: Scatter plot showing the maximum dose rate for an L/ILW repository in the NL siting region within the one-hundred-thousand-year time period for assessment against the vertical Darcy flow velocity

Although no significant non-monotonic relationship is detected in the scatter plots, a modified EASI first-order sensitivity index is calculated anyway to avoid unnecessarily missing sensitive parameters. The sensitivity of the variance between the maximum dose rate over the first 10^5 years and the variance in the input parameters is evaluated in terms of the Pearson correlation coefficient, the Spearman correlation coefficient and the modified EASI first-order sensitivity index; the results are shown in Tab. 6-7.

Tab. 6-7: Sensitivity measures for the parameters with at least one significant correlation of the NL probabilistic analyses for an L/ILW repository

Values above the calculated “threshold of significance” are marked in blue. (+) or (-) indicates the selected bounding value for the individual and combined pessimistic calculations.

Parameter	Description	Pearson correlation coefficient	Spearman correlation coefficient	Modified EASI sensitivity index
	<i>Significance threshold</i>	<i>0.029</i>	<i>0.029</i>	<i>0.0046</i>
Deff_OPA(Cl,I) (+) 1.2×10^{-12} - 5.6×10^{-12} m ² /s (Cl) 1.2×10^{-12} - 5.5×10^{-12} m ² /s (I)	Effective diffusion coefficient of halogens in the Opalinus Clay	0.58	0.7	0.37
E_a,wc(+) 1.5×10^4 - 2.5×10^4 J/mol	Activation energy for diffusion in the porewater	0.39	0.43	0.16
Deff_KEU(Cl,I) (+) 1.6×10^{-12} - 8.7×10^{-12} m ² /s (Cl) 1.5×10^{-12} - 8.6×10^{-12} m ² /s (I)	Effective diffusion coefficient of halogens in the KEU	0.29	0.34	0.093
h_OPA(-) 100 - 115 m	Thickness of the Opalinus Clay	-0.23	-0.26	0.054
Deff_AL(Cl,I) (+) 1.8×10^{-12} - 1.1×10^{-11} m ² /s (Cl) 1.8×10^{-12} - 1.0×10^{-11} m ² /s (I)	Effective diffusion coefficient of halogens in the AL	0.16	0.15	0.031
Deff_KAU(Cl,I) (+) 1.6×10^{-12} - 1.4×10^{-11} m ² /s (CL,I)	Effective diffusion coefficient of halogens in the KAU	0.12	0.1	0.015
Phi_OPA(Cl,I) (-) 0.03 - 0.06 (Cl, I)	Radionuclide-accessible porosity of halogens of the Opalinus Clay	-0.089	-0.1	0.0087
Deff_ML(Cl,I) (+) 2.0×10^{-12} - 1.5×10^{-11} m ² /s (Cl,I)	Effective diffusion coefficient of halogens in the ML	0.068	0.084	0.0072
h_ML (-) 17.8 - 19.3 m	Thickness of the ML	-0.063	-0.065	0.0047
Phi_ML(Cl,I) (-) 0.02 - 0.08 (Cl, I)	Radionuclide-accessible porosity of halogens in the ML	-0.064	-0.055	0.0059
Phi_KEU(Cl,I) (-) 0.02 - 0.07 (Cl, I)	Radionuclide-accessible porosity of halogens in the KEU	-0.054	-0.063	0.0045
i_v(-) -0.5 - 0.5 m/m	Hydraulic gradient along the geological formations	-0.052	-0.043	0.0055

Tab. 6-7: continued

Parameter	Description	Pearson correlation coefficient	Spearman correlation coefficient	Modified EASI sensitivity index
	<i>Significance threshold</i>	<i>0.029</i>	<i>0.029</i>	<i>0.0046</i>
i_h,KAL(+) 0.01 - 0.1 m/m	Horizontal hydraulic gradient along the Keuper aquifer	0.049	0.048	0.0037
h_KEU (-) 18.9 - 20.5 m	Thickness of the KEU	-0.041	-0.043	0.0022
Phi_KAU(Cl,I) (-) 0.01 - 0.06 (Cl, I)	Radionuclide-accessible porosity of halogens in the KAU	-0.041	-0.035	0.0025
Deff_KAU(Se) (+) 2.2×10^{-12} - 1.1×10^{-11} m ² /s	Effective diffusion coefficient of Se-79 in the KAU	0.041	0.029	0.0033
Deff_CD(C) (+) 1.6×10^{-12} - 1.1×10^{-11} m ² /s	Effective diffusion coefficient of inorganic C-14 in the CD	0.036	0.034	0.0040
Deff_SCAD(Ca) (+) 2.1×10^{-11} - 4.0×10^{-11} m ² /s	Effective diffusion coefficient of inorganic Ca-41 in the SCAD+SCD	0.036	0.031	0.0031
$\rho_{\text{Grain,OPA}}$ (-) 2669 - 2760 kg/m ³	Grain density of the Opalinus Clay	-0.033	-0.034	0.0033
K_d_Z(Se) (-) 3.0×10^{-5} - 3.3×10^{-4} m ³ /kg	Sorption coefficient of cementitious near-field against Se-79	-0.029	-0.031	0.0017

As in the case of JO, diffusion is the dominant transport process, with several diffusion-related parameters in the Opalinus Clay and in the confining geological units as far as the main exfiltration layers showing sensitivity. The diffusion coefficients for halogens in the Opalinus Clay and in the geological formation KEU show relatively significant sensitivity, which is consistent with the general observation that the effective diffusion coefficients of the thickest transport media in the dominant pathway usually show significant sensitivity.

Also as expected, there is a negative correlation with the thickness of the Opalinus Clay (h_{OPA}). The accessible porosity and the thicknesses of several geological formations, mainly in the lower confining geological units (such as ML and KEU), show sensitivity. This is consistent with the observation that the transport pathway downward to the Keuper aquifer is dominant (see Fig. 6-60). The vertical hydraulic gradient (i_v) shows some correlation, even though this is not particularly apparent in the scatter plot for the Darcy flow (Fig. 6-80).

In order to provide a better understanding of the impact of various parameters, additional deterministic cases have been analysed, switching each of the individual sensitive parameters to their most pessimistic, bounding values.

Fig. 6-81 shows dose rate histories for some individual deterministic cases where various effective diffusion coefficients, as well as the activation energy, are set to their most pessimistic (generally upper) bounding values. The effects are largely consistent with the results of the sensitivity analyses in Tab. 6-7, in that, for example, assigning high values to the effective diffusion coefficients of halogens in the Opalinus Clay and the activation energy for the diffusion slightly increases the dose rate. The effective diffusion coefficient of geological units in the lower confining units (such as KEU, AL) can also slightly increase the dose rate. This is consistent with the system understanding that the diffusive transport down to the Keuper is the dominating transport pathway in the NL siting region.

Fig. 6-82 shows some further individual deterministic cases where various Opalinus Clay properties, excluding the effective diffusion coefficients, are set to their most pessimistic, bounding values. A visible impact on the dose rate occurs when a lower bound value is set for the accessible porosity for halogens in the Opalinus Clay ($\Phi_{OPA\ Cl,I}$), resulting in less dilution within the Opalinus Clay. The total dose rate is also slightly increased when setting a lower bound value to the thickness of the Opalinus Clay, which shortens the transport pathway through the host rock.

Fig. 6-83 shows the results of several further deterministic cases addressing the remaining parameters with correlations identified in Tab. 6-7. The vertical Darcy velocity gives rise to a slight increase in the dose rate. Setting the accessible porosities for the halogens in the ML and KEU units ($\Phi_{ML\ Cl,I}$ and $\Phi_{KEU\ Cl,I}$) to their lower bound values also causes a slight increase in the total dose rate, consistent with the correlations shown in Tab. 6-7, since reducing the accessible porosity also reduces the degree of dilution in these units. Variations in the thicknesses of the formations in the lower confining geological units, such as ML (h_{ML}) and KEU (h_{KEU}), and in the accessible porosity for halogens in KAU ($\Phi_{KAU\ Cl,I}$), do not, on their own, give rise to any significant impact.

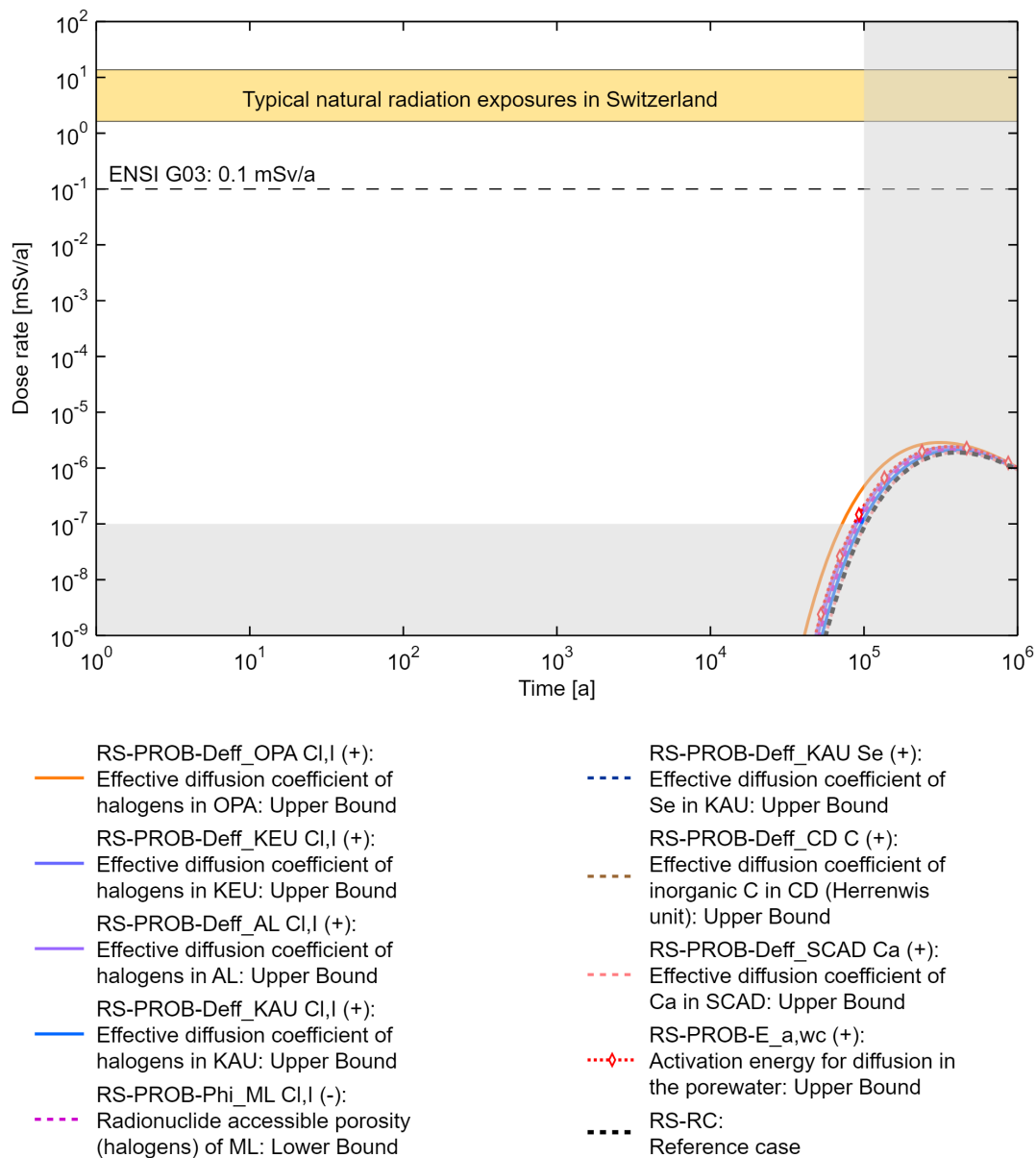


Fig. 6-81: Total dose rates in the reference case for an L/ILW repository in the NL siting region, and in cases where various effective diffusion coefficients and the activation energy used in temperature correction are set to their most pessimistic, bounding values. (+) indicates the most pessimistic upper bound values and (-) indicates the most pessimistic lower bound values, according to Tab. 6-7. (SCAD = SCAD + SCD)

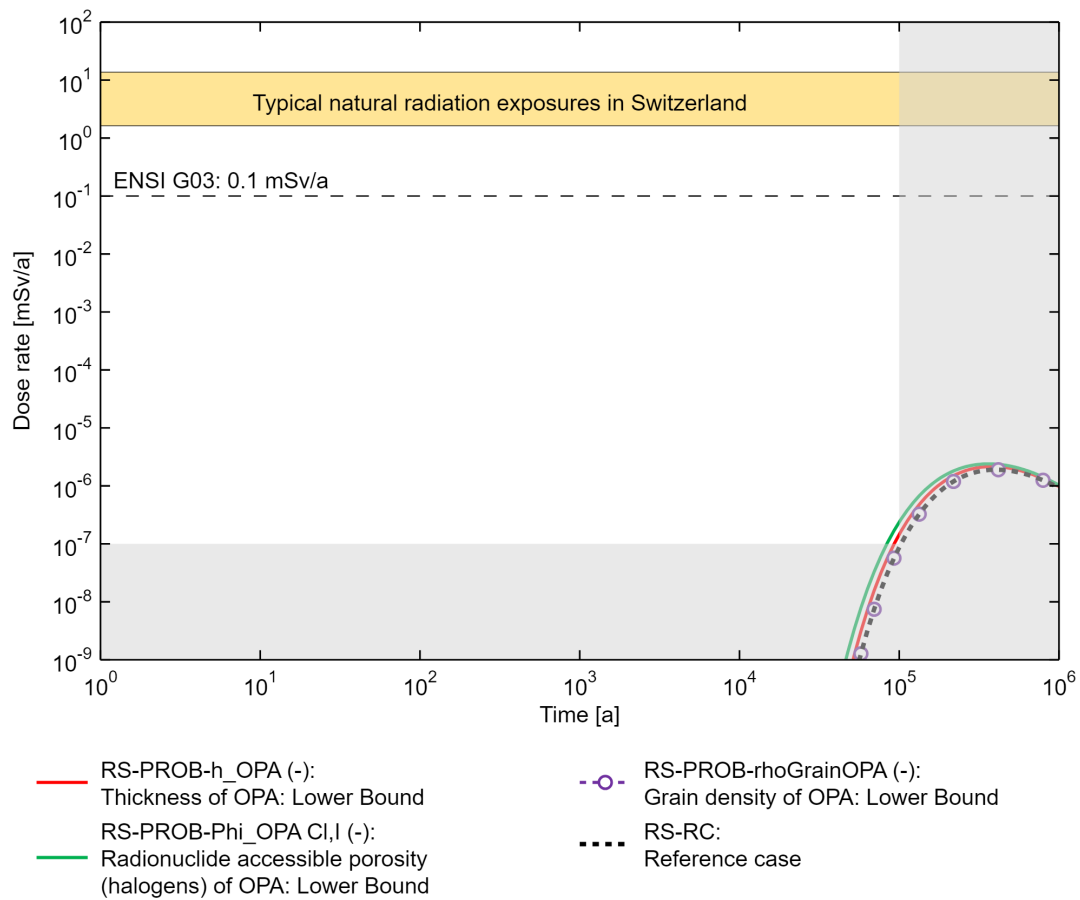


Fig. 6-82: Total dose rates due in the reference case for an L/ILW repository in the NL siting region, and in cases where various Opalinus Clay properties, excluding the effective diffusion coefficients, are set to their most pessimistic, bounding values. (+) indicates the most pessimistic upper bound values and (-) indicates the most pessimistic lower bound values, according to Tab. 6-7

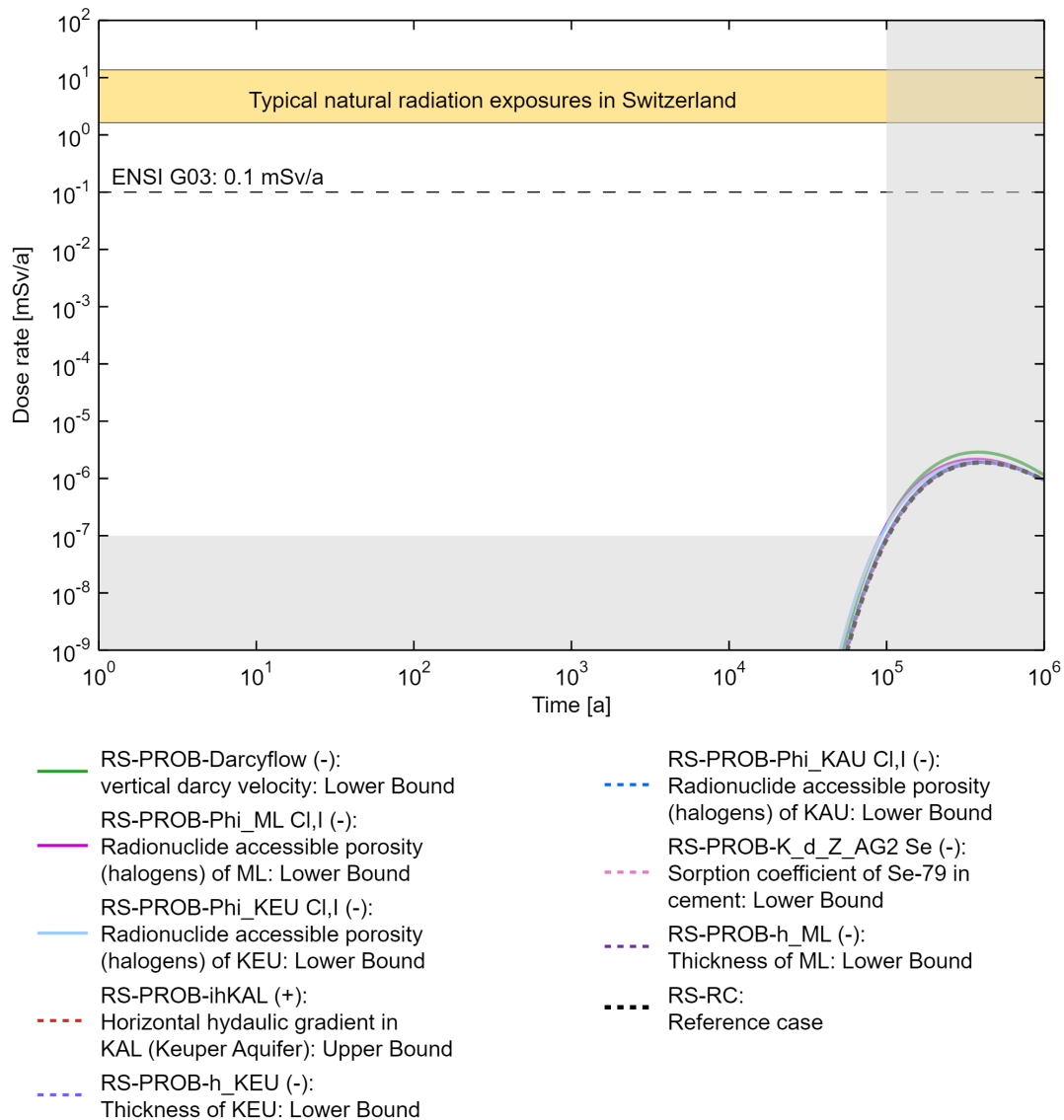


Fig. 6-83: Total dose rates in the reference case for an L/ILW repository in the NL siting region, and in cases where various individual parameters are set to their most pessimistic, bounding values. (+) indicates the most pessimistic upper bound values and (-) indicates the most pessimistic lower bound values, according to Tab. 6-7

Fig. 6-84 shows a case in which pessimistic bounding values are set for all the above-mentioned parameters. The maximum dose rate calculated for the first 10^5 years is increased by a factor of about 24 compared with the reference case, resulting in a value of 2.1×10^{-6} mSv/a, compared with 8.84×10^{-8} in the reference case. The dose rate continues to increase slightly at later times, reaching a maximum of 5.9×10^{-6} mSv/a after one hundred thousand years, which is several orders of magnitude lower than the bounding value of the typical natural radiological exposures in Switzerland (BAG 2021), thus indicating a large safety margin. Although the likelihood of pessimistic bounding values occurring together in this way is low, the combined pessimistic case further demonstrates the robustness of the repository from a post-closure safety perspective.

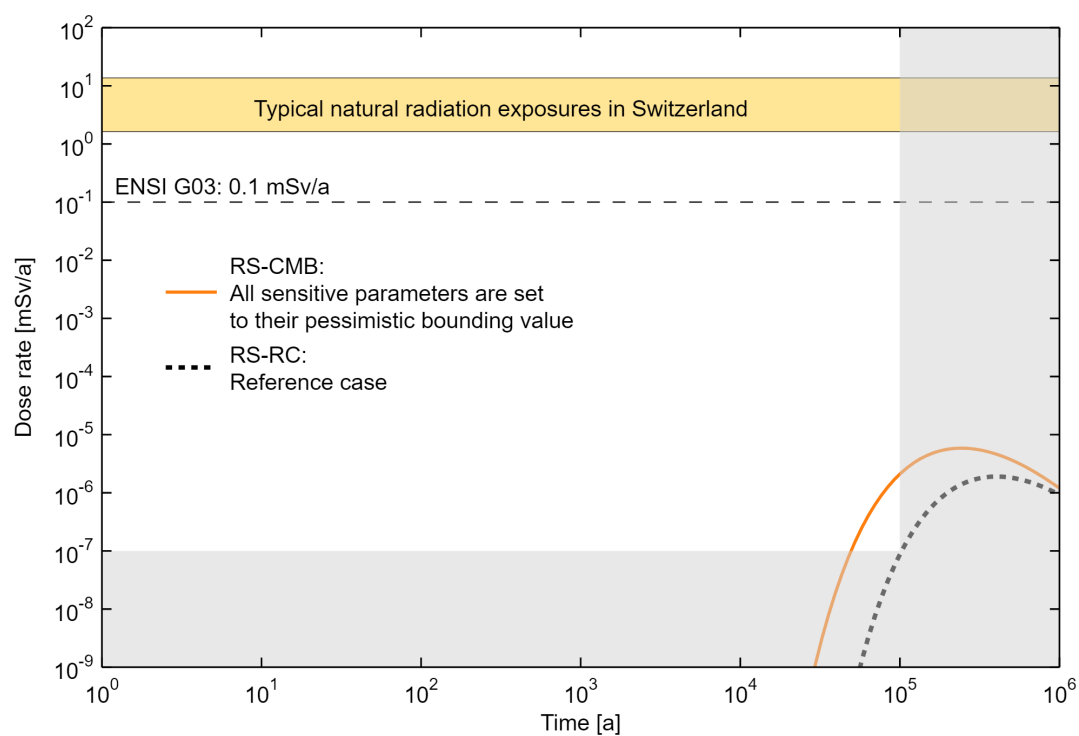


Fig. 6-84: Total dose rates in the reference case for an L/ILW repository in the NL siting region, and in a case in which pessimistic bounding values are set for all sensitive parameters

6.2.2.3 Zürich Nordost (ZNO)

Fig. 6-85 shows statistical percentiles calculated from 4,000 Monte-Carlo simulations of the dose rate evolution of an L/ILW repository in the ZNO siting region. In all cases, the maximum dose rate appears after 10^5 years, which demonstrates the retention capacity of the repository in the siting region. The highest calculated dose rate within the first 10^5 years is 3.4×10^{-7} mSv/a. As in the case for JO and NL, the maximum dose rate appears after 10^5 years. However, the dose rate after the time period for assessment is several orders of magnitude below the lower bound value of the typical natural radiological exposures in Switzerland (BAG 2021).

The transport length to the Keuper aquifer in ZNO is larger than in both JO and NL (see Tab. 6-5). Additionally, the ambient temperature in ZNO is not as high as in NL. These factors lead to a later breakthrough and lower maximum dose rate in ZNO than in the other two siting regions.

Sensitivity analyses have been performed based on the results from the Monte-Carlo simulations. The first step is a graphical analysis using scatter plots showing the maximum dose within the one-hundred-thousand-year time period for assessment against individual input parameter values sampled in the Monte-Carlo simulations. Some examples of such scatter plots are shown in Fig. 6-86 to Fig. 6-88.

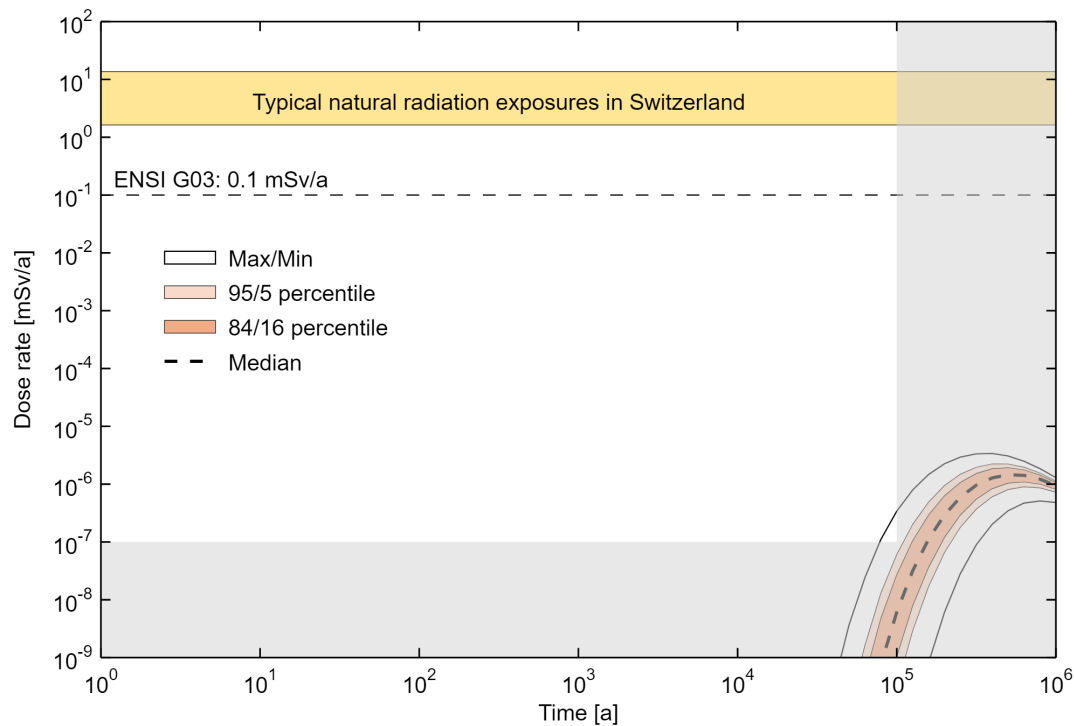


Fig. 6-85: Statistical percentiles calculated from 4,000 Monte-Carlo simulations of the dose rate evolution of an L/ILW repository in the ZNO siting region

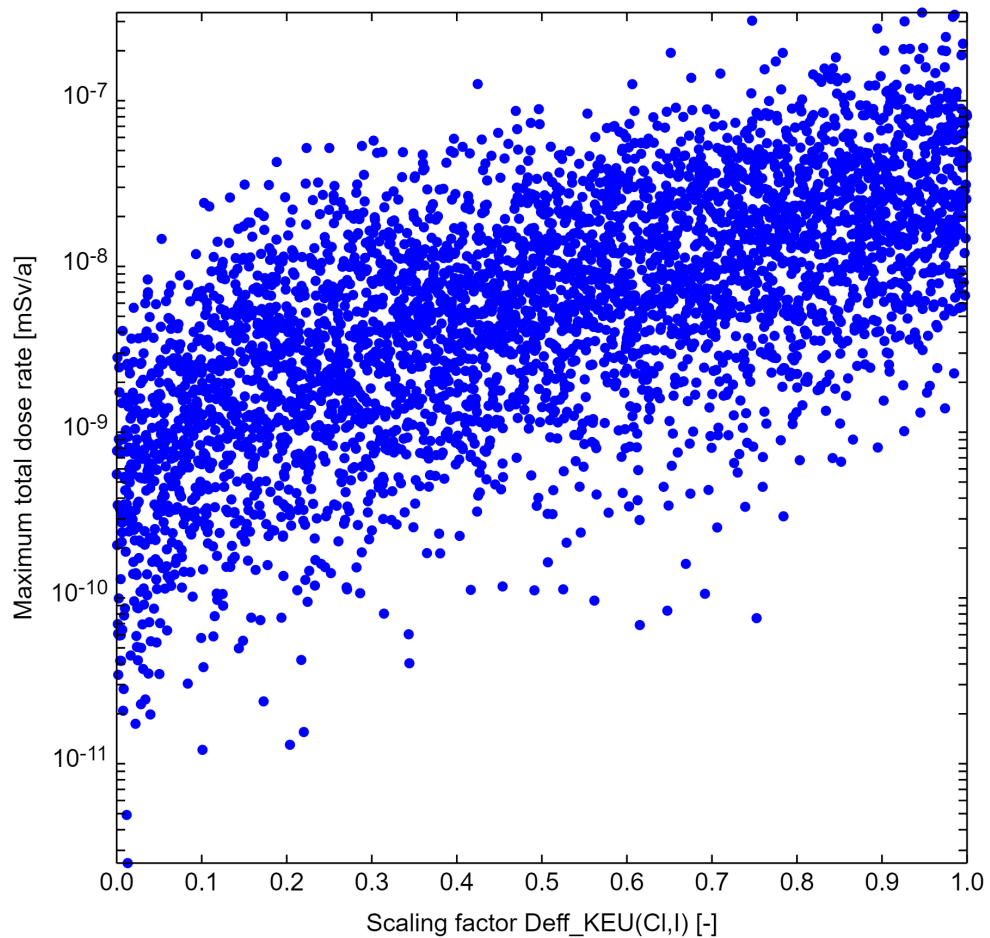


Fig. 6-86: Scatter plot showing the maximum dose rate for an L/ILW repository in the ZNO siting region within the one-hundred-thousand-year time period for assessment against the effective diffusion coefficient of the halogens in the KEU unit in the lower confining geological units, which is varied using a scaling factor, sampled in Monte-Carlo simulations

Figs. 6-86 and 6-87 show the strong monotonic relationship between the maximum dose rate and the effective diffusion coefficient of halogens in the KEU rock in the lower confining geological units and in the Opalinus Clay, respectively. This is, consistent with diffusion downwards to the Keuper aquifer being the dominant transport pathway through the rock, as observed in the deterministic analysis of the reference case (see Fig. 6-65).

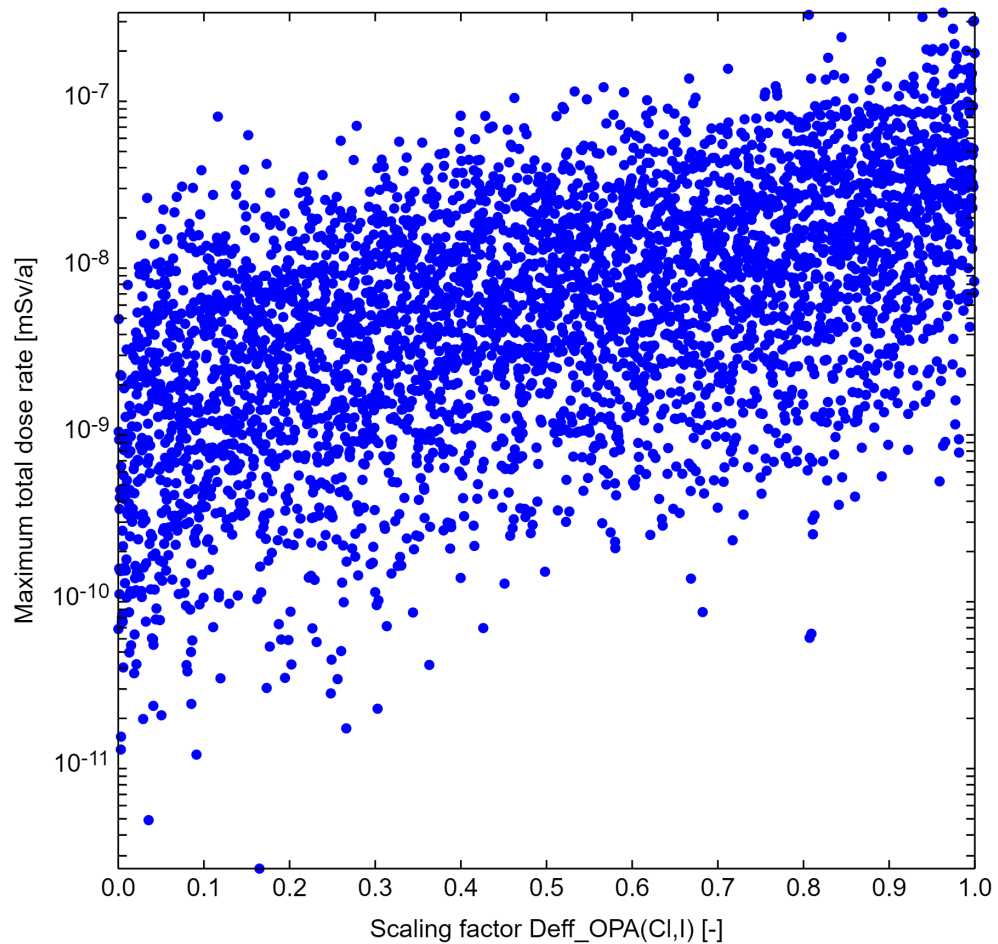


Fig. 6-87: Scatter plot showing the maximum dose rate for an L/ILW repository in the ZNO siting region within the one-hundred-thousand-year time period for assessment against the effective diffusion coefficient of the halogens in the Opalinus Clay, which is varied using a scaling factor, sampled in Monte-Carlo simulations

As observed for NL, the scatter plot in Fig. 6-88 does not show a strong correlation between the vertical Darcy flow and the maximum dose rate, unlike the clear correlation found for JO. The range of the Darcy flow is smaller because of the smaller bandwidth of the given vertical hydraulic gradient.

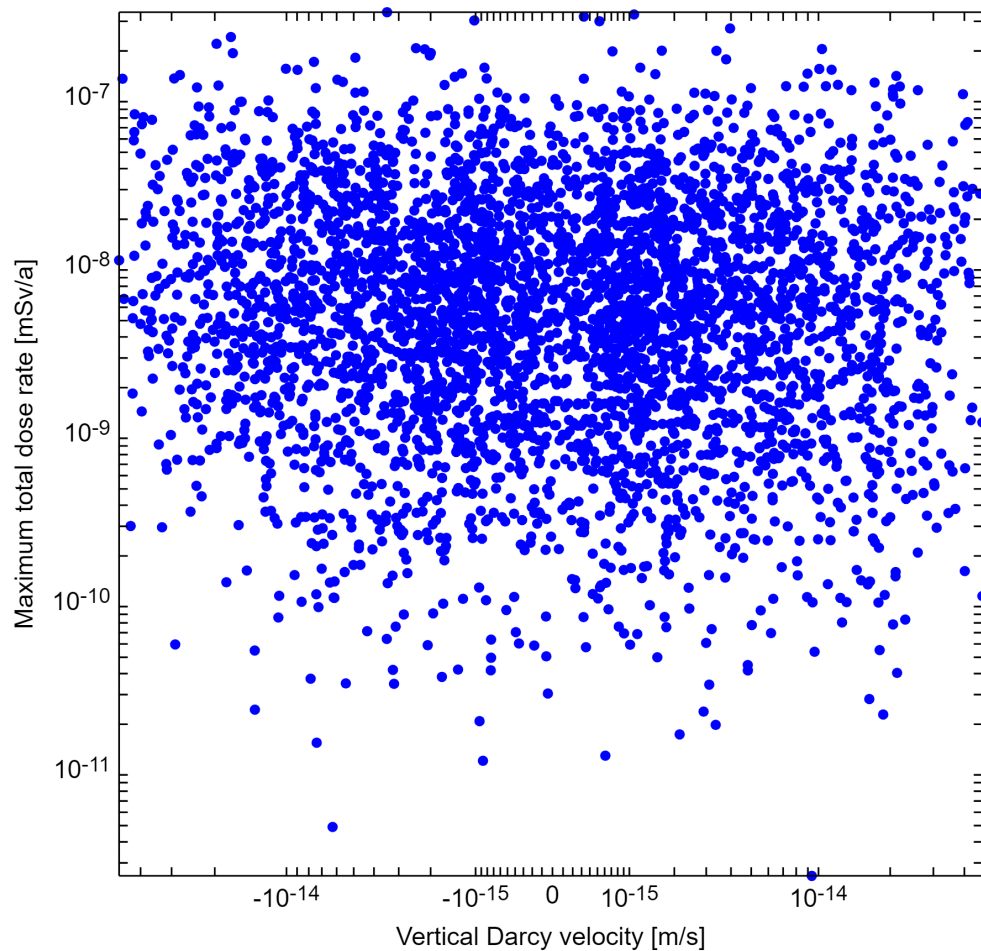


Fig. 6-88: Scatter plot showing the maximum dose rate for an L/ILW repository in the ZNO siting region within the one-hundred-thousand-year time period for assessment against the vertical Darcy flow velocity

Although there is no significant non-monotonic relationship detected in the scatter plots, a modified EASI first-order sensitivity index is calculated anyway to avoid unnecessarily missing sensitive parameters. The sensitivity of the maximum dose rate over the first 10^5 years to the variance in the input parameters is evaluated in terms of the Pearson correlation coefficient, the Spearman correlation coefficient and the modified EASI first-order sensitivity index; the results are shown in Tab. 6-8.

As in the cases of JO and NL, diffusion is the dominant transport process, with several diffusion-related parameters in the Opalinus Clay and in the confining geological units as far as the main exfiltration layers showing sensitivity. The diffusion coefficients for halogens in the Opalinus Clay and in the geological KEU formation close to the main release point (the Keuper aquifer) show particularly high sensitivity. This is consistent with the general observation that the effective diffusion coefficients of the thickest transport media in the dominant pathway usually show significant sensitivity. The activation energy used to correct the effective diffusion coefficients for temperature diffusion (E_{a_wc}) shows a degree of correlation. The two parameters affecting the vertical flow (K_{v_OPA} and i_v) show a relatively weak correlation, consistent with the scatter plot in Fig. 6-88.

Tab. 6-8: Sensitivity measures for the parameters with at least one significant correlation of the ZNO probabilistic analyses for an L/ILW repository

Values above the calculated “threshold of significance” are marked in blue. (+) or (-) indicates the selected bounding value for the individual and combined pessimistic calculations.

Parameter	Description	Pearson correlation coefficient	Spearman correlation coefficient	Modified EASI sensitivity index
	<i>Significance threshold</i>	<i>0.042</i>	<i>0.036</i>	<i>0.0041</i>
Deff_KEU(Cl,I) (+) $1.6 \times 10^{-12} - 9.3 \times 10^{-12} \text{ m}^2/\text{s}$ (Cl) $1.6 \times 10^{-12} - 9.2 \times 10^{-12} \text{ m}^2/\text{s}$ (I)	Effective diffusion coefficient of halogens in the KEU	0.45	0.65	0.23
Deff_OPA(Cl,I) (+) $1.5 \times 10^{-12} - 7.1 \times 10^{-12} \text{ m}^2/\text{s}$ (Cl) $1.4 \times 10^{-12} - 7.0 \times 10^{-12} \text{ m}^2/\text{s}$ (I)	Effective diffusion coefficient of halogens in the Opalinus Clay	0.41	0.52	0.20
h_OPA(-) 104 - 124 m	Thickness of the Opalinus Clay	-0.25	-0.3	0.065
E_a,wc (+) $1.5 \times 10^4 - 2.5 \times 10^4 \text{ J/mol}$	Activation energy for diffusion in the porewater	0.24	0.31	0.065
Deff_AL(Cl,I) (+) $1.3 \times 10^{-12} - 5.8 \times 10^{-12} \text{ m}^2/\text{s}$ (Cl,I)	Effective diffusion coefficient of halogens in the AL	0.12	0.12	0.015
Phi_KEU(Cl,I) (-) 0.02 - 0.07 (Cl,I)	Radionuclide-accessible porosity of halogens of the KEU	-0.098	-0.13	0.010
Deff_ML(Cl,I) (+) $2.0 \times 10^{-12} - 1.5 \times 10^{-11} \text{ m}^2/\text{s}$ (Cl,I)	Effective diffusion coefficient of halogens in the ML	0.081	0.079	0.0083
Phi_OPA(Cl,I) (-) 0.03 - 0.07 (Cl,I)	Radionuclide-accessible porosity of halogens of the Opalinus Clay	-0.062	-0.074	0.0059
h_ML (-) 21.3 - 22.6 m	Thickness of the ML	-0.05	-0.048	0.0058
K_v,OPA (+) $2 \times 10^{-15} - 1 \times 10^{-13} \text{ m/s}$	Hydraulic conductivity of the Opalinus Clay	0.049	0.039	0.0036
i_v (-) -0.5 - 0.5 m/m	Hydraulic gradient along the geological formations	-0.039	-0.055	0.0025
Phi_OPA(Ag,C,Ca,Hg,Se,C _{org}) (-) 0.09 - 0.15 (Ag,Ca,Hg,Se) 0.04 - 0.09 (C,C _{org})	Radionuclide-accessible porosity of the radionuclides except halogens of the Opalinus Clay	-0.032	-0.044	0.0027

Tab. 6-8: continued

Parameter	Description	Pearson correlation coefficient	Spearman correlation coefficient	Modified EASI sensitivity index
	<i>Significance threshold</i>	0.042	0.036	0.0041
h_MM(-) 11.9 - 14.5 m	Thickness of the MM	-0.026	-0.039	0.0042
h_KEU(-) 38.3 - 40.7 m	Thickness of the KEU	-0.024	-0.047	0.0016
K_KAU (+) 1×10^{-9} - 1×10^{-4} m/s	Hydraulic conductivity of the Keuper aquifer	0.026	0.1	0.014
Deff_AD(Cl,I) (+) 1.7×10^{-12} - 9.2×10^{-12} m ² /s (Cl) 1.7×10^{-12} - 9.0×10^{-12} m ² /s (I)	Effective diffusion coefficient of Halogens in the AD	0.013	0.045	0.0011

In order to provide a better understanding of the impact of various parameters, additional deterministic cases have been analysed, switching each of the individual sensitive parameters to their most pessimistic, bounding values.

Fig. 6-89 shows dose rate histories for some individual deterministic cases where various effective diffusion coefficients, as well as the activation energy, are set to their most pessimistic (generally upper) bounding values. The effects are largely consistent with the results of the sensitivity analyses in Tab. 6-8, in that, for example, assigning a high value to the effective diffusion coefficients of halogens in the Opalinus Clay (Deff_OPA Cl,I) and in the KEU rock unit (Deff_KEU Cl,I) increases the dose rate. A less increase in the dose rate is obtained by assigning high values to the effective diffusion coefficients of halogens in the rock units AL (Deff_AL Cl,I) and ML (Deff_ML Cl,I), as well as a high value to the activation energy (Eawc). Varying the effective diffusion coefficients of organic carbon in AD (Deff_AD Cl, I) has no discernible impact.

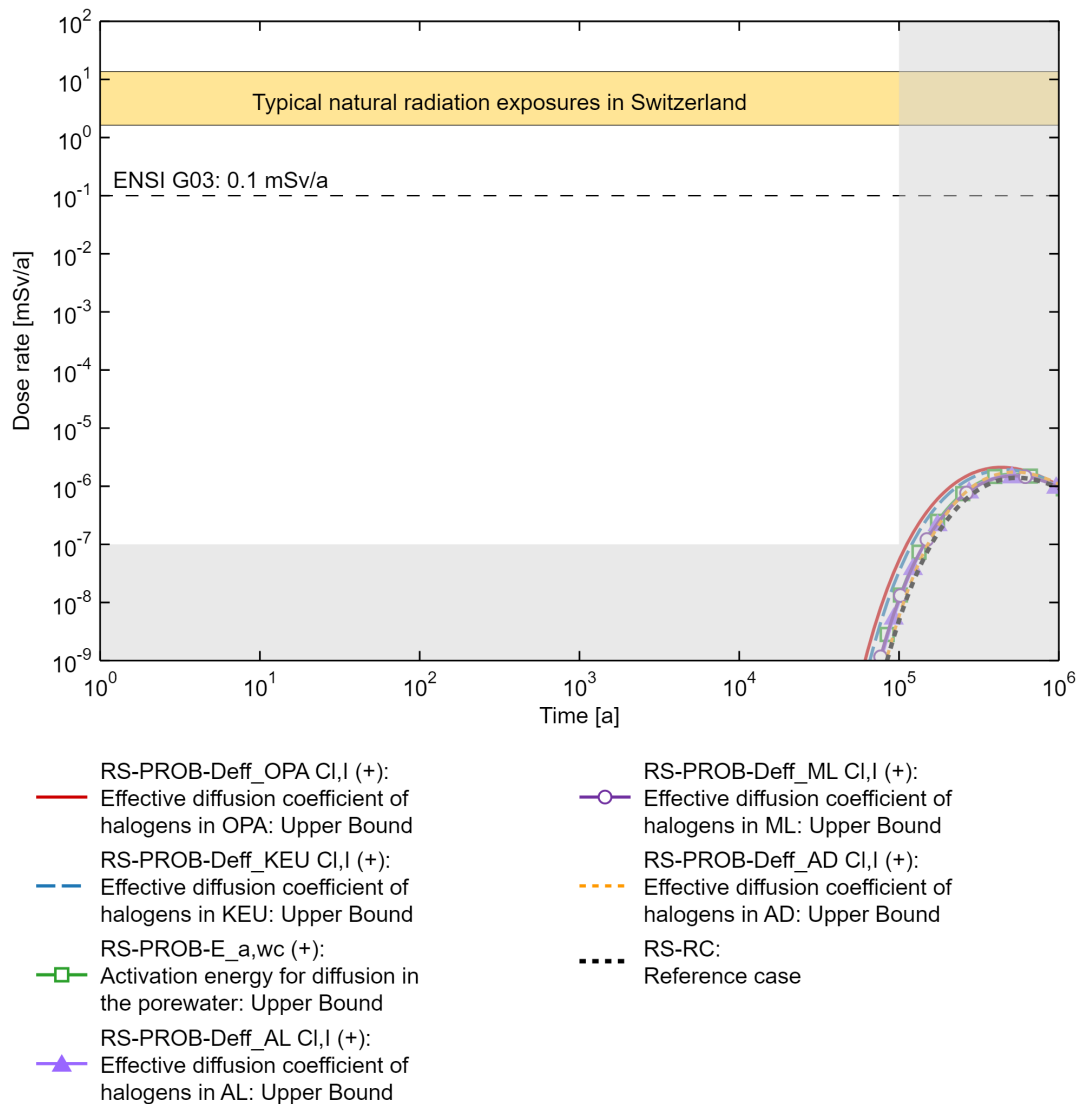


Fig. 6-89: Total dose rates in the reference case for an L/ILW repository in the ZNO siting region, and in cases where various effective diffusion coefficients and the activation energy used in temperature correction are set to their most pessimistic, bounding values. (+) indicates the most pessimistic upper bound values and (-) indicates the most pessimistic lower bound values, according to Tab. 6-8

Fig. 6-90 shows some further individual deterministic cases where various Opalinus Clay properties, excluding the effective diffusion coefficients, are set to their most pessimistic, bounding values. A visible impact on the dose rate occurs when a lower bound value is set for the accessible porosity for halogens in the Opalinus Clay (Phi_OPA Cl,I), resulting in less dilution within the Opalinus Clay. The total dose rate is also slightly increased by setting a lower bound value to the thickness of the Opalinus Clay (h_OPA), which shortens the transport pathway through the host rock. The other parameter variations, which concern non-halogens, do not show any significant impact on the dose rate, consistent with their sensitivity measures presented in Tab. 6-8 and the fact that it is the halogens that dominate the dose rate.

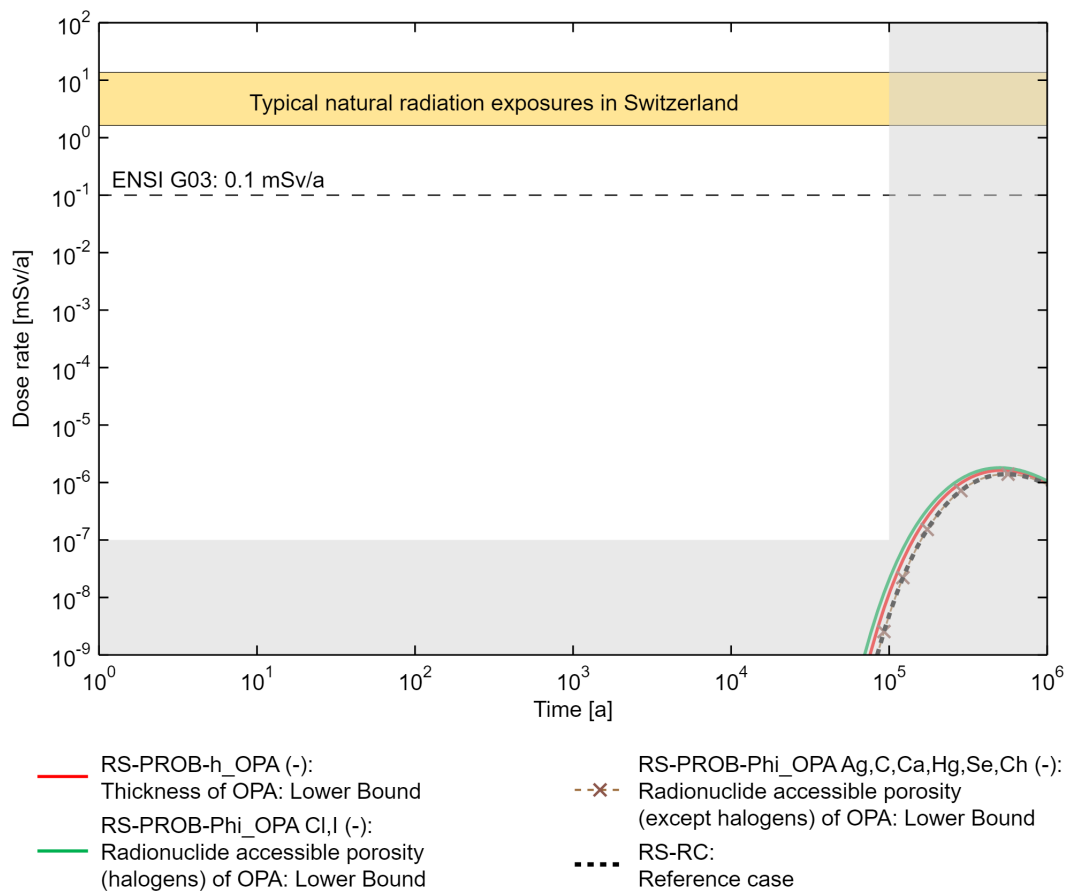


Fig. 6-90: Total dose rates in the reference case for an L/ILW repository in the ZNO siting region, and in cases where various Opalinus Clay properties, excluding the effective diffusion coefficients, are set to their most pessimistic, bounding values. (+) indicates the most pessimistic upper bound values and (-) indicates the most pessimistic lower bound values, according to Tab. 6-8

Fig. 6-91 shows the results of further deterministic cases addressing the remaining parameters with correlations identified in Tab. 6-8. Assigning lower bounds to the accessible porosity for halogens in the KEU unit ($\Phi_{KEU\ Cl,I}$) causes an increase in the total dose rate. Furthermore, setting a lower bound value to the vertical Darcy velocity causes a slight increase in the total dose rate. No significant sensitivity is shown to either the thicknesses of ML (h_{ML}), MM (h_{MM}) or KEU (h_{KEU}), or to the permeability of the Keuper aquifer (K_{KAU}), which is consistent with the low values calculated for the sensitivity measure in Tab. 6-8.

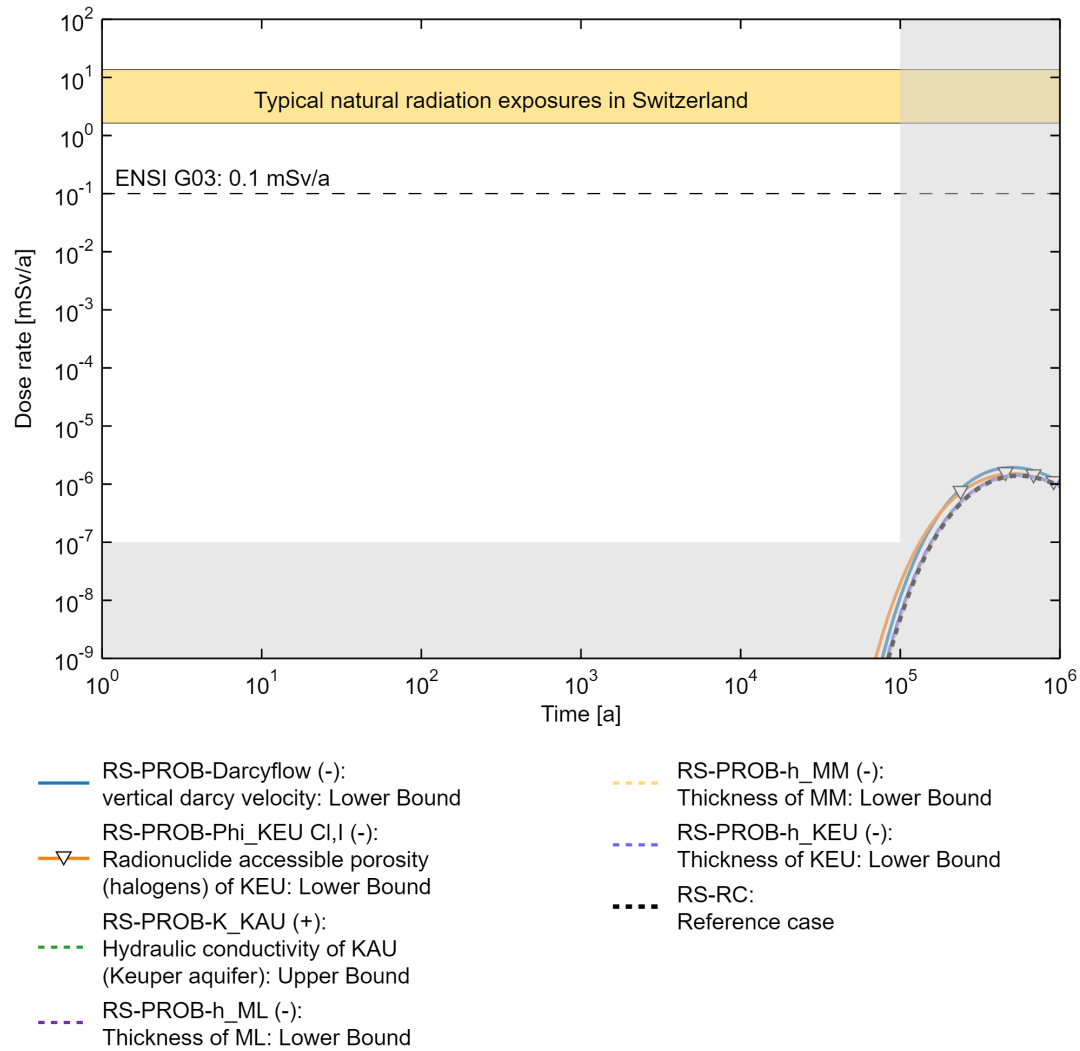


Fig. 6-91: Total dose rates in the reference case for an L/ILW repository in the ZNO siting region, and in cases where various individual parameters are set to their most pessimistic, bounding values. (+) indicates the most pessimistic upper bound values and (-) indicates the most pessimistic lower bound values, according to Tab. 6-8

A combined pessimistic case is evaluated that combines pessimistic bounding values of all the above-mentioned parameters. Fig. 6-92 shows that the maximum dose rate calculated for the first 10^5 years is increased by a factor of about 1,500 compared with the reference case, which is based on a value of 7.4×10^{-6} mSv/a. The dose rate continues to increase at later times, reaching a maximum of 1.07×10^{-5} mSv/a after one hundred thousand years. This is several orders of magnitude lower than the bounding value of the typical natural radiological exposures in Switzerland (BAG 2021), indicating a large safety margin. Although the likelihood of pessimistic bounding values occurring together in this way is low, the combined pessimistic case further demonstrates the robustness of the repository from a post-closure safety perspective.

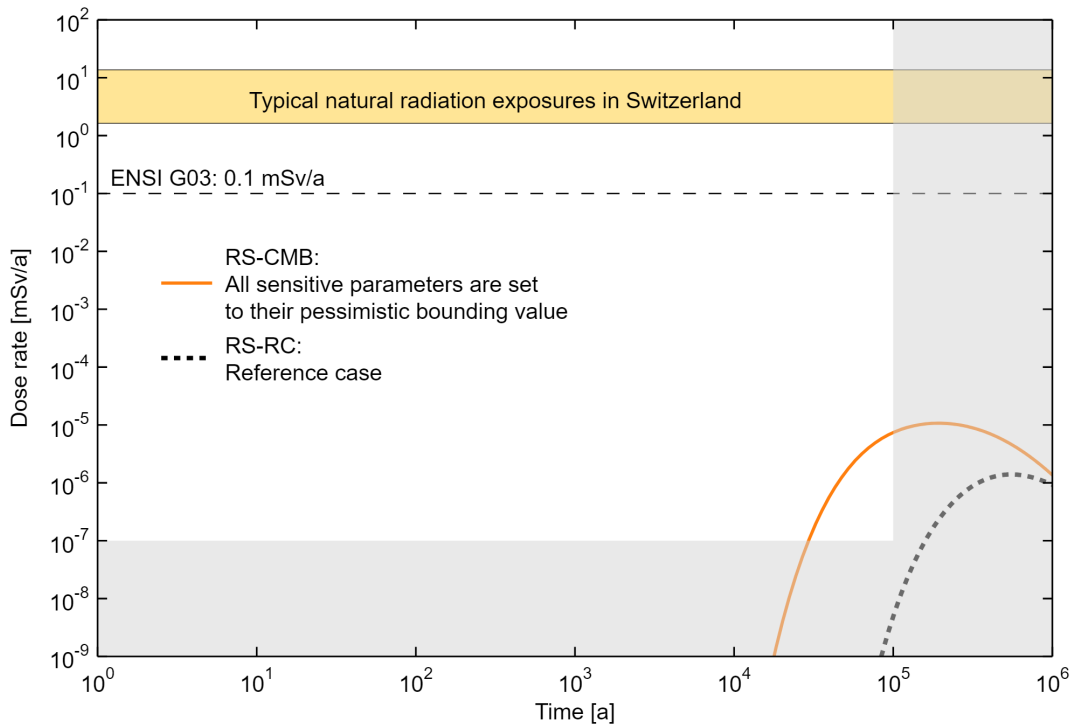


Fig. 6-92: Total dose rates in the reference case for an L/ILW repository in the ZNO siting region, and in a case in which pessimistic bounding values are set for all sensitive parameters

6.2.3 Radiological consequence analysis for alternative safety scenarios

As in the case of the HLW repository, in addition to the reference safety scenario, alternative safety scenarios are also considered in the site comparison, and are evaluated deterministically, with the results for each siting region presented in the following sections.

As described in Nagra (2024b) and summarised in Section 4.2, specific uncertainties flagged for further consideration as alternative safety scenarios concern uncertainties in geological characterisation, and, specifically, the possibility that there could be:

- hydraulically active confining units above or below the Opalinus Clay; or
- an undetected fault in the vicinity of the repository emplacement rooms.

The variants and calculation cases for these two safety scenarios are summarised in Tab. 4-2 and Tab. 4-3, respectively.

The concepts and models for analysing radionuclide migration in the liquid phase in these alternative safety scenarios are described in App. B.1. In cases concerning an undetected fault, the Darcy velocity in the fault (transmissivity = 10^{-10} m²/s) is set to be about 7×10^{-12} m/s where the two-dimension impact of the fault on the hydraulic flow field in the surrounding rock is taken into account (Nagra 2024g).

6.2.3.1 Jura Ost (JO)

Two potentially hydraulically active confining units are considered in the JO siting region: one is the SCD unit in the upper confining geological units, and the other is the KEU in the lower confining geological units. The impact of these is analysed in two deterministic calculation cases (see also Tab. 4-2):

- AS-HA/SCD, where the SCD is assumed to be hydraulically active; and
- AS-HA/KEU, where the KEU is assumed to be hydraulically active.

The evolution of the dose rate in these two cases is compared with the reference case in Fig. 6-93, which shows an increase in the dose rate maximum caused by either of these units being hydraulically active, with an increase at 10^5 years by about a factor of 10, bringing the dose rate at this time only slightly above the level of significance, defined as dose rates higher than 10^{-7} mSv/a. This is because the hydraulically active units (hard beds) can shorten the transport pathway in the upper or lower confining units, leading to an earlier breakthrough of radionuclides into the biosphere.

The assumption of a hydraulically active KEU unit in the lower confining unit has less impact than the assumption of a hydraulically active SCD unit in the upper confining units, because the SCD unit is closer to the Opalinus Clay formation and the dominating transport pathway in JO is upwards to the Calcareous Dogger rather than downwards to the Keuper aquifer according to the system understanding learnt from Fig. 6-55.

Two calculation cases are defined for the L/ILW repository for the safety scenario with an undetected fault (see Tab. 4-3):

- AS-FLT-L/ILW-Along, where the fault passes along one of the L/ILW emplacement caverns; and
- AS-FLT-L/ILW-Across, where the fault passes through all the L/ILW emplacement caverns, perpendicular to their axes.

Similar as the cases concerning undetected faults for the HLW repository, these cases are modelled based on extremely conservative assumptions:

- The fault is assumed to exist and connects the two deep aquifers (Keuper and Calcareous Dogger).
- The fault will either partly affect all the L/ILW emplacement caverns (AS-FLT-L/ILW-Across) or an entire emplacement cavern (AS-FLT-L/ILW-Along); the fault can be easily detected and avoided.
- Transmissivity of the fault is set to be 10^{-10} m²/s, which is not obtained in the investigation of the potential siting region (Nagra 2024e).

The evolution of the dose rate in these two cases is compared with the reference case in Fig. 6-94. The L/ILW near-field model assumes no containment time within the engineered barriers, and thus radionuclide release via the fault takes place relatively early. The transport along the fault increases the maximum dose rate in the first 10^5 years (time period for assessment) by a factor of about two orders of magnitude compared with the reference case, and also increases the cumulative release of radionuclides to the biosphere. However, thanks to the limited Darcy flow in the fault and the radiotoxicity in the liquid phase (see Fig. 6-57) in the L/ILW repository, a safety margin of several orders of magnitude remains between the dose maxima and the protection criterion of 0.1 mSv/a (ENSI 2023). Also, the dose rate after the time period for assessment is several orders of magnitude below the lower bound value of typical natural radiological exposure in Switzerland (BAG 2021).

The case of a fault passing along one of the L/ILW emplacement caverns gives rise to slightly lower dose rates than the case with the fault passing perpendicularly through all the caverns. This is because the total inventory in the emplacement caverns affected by the fault running along one cavern is lower than that of the fault passing perpendicularly through all the caverns, which leads to a lower radionuclide release rate through the fault.

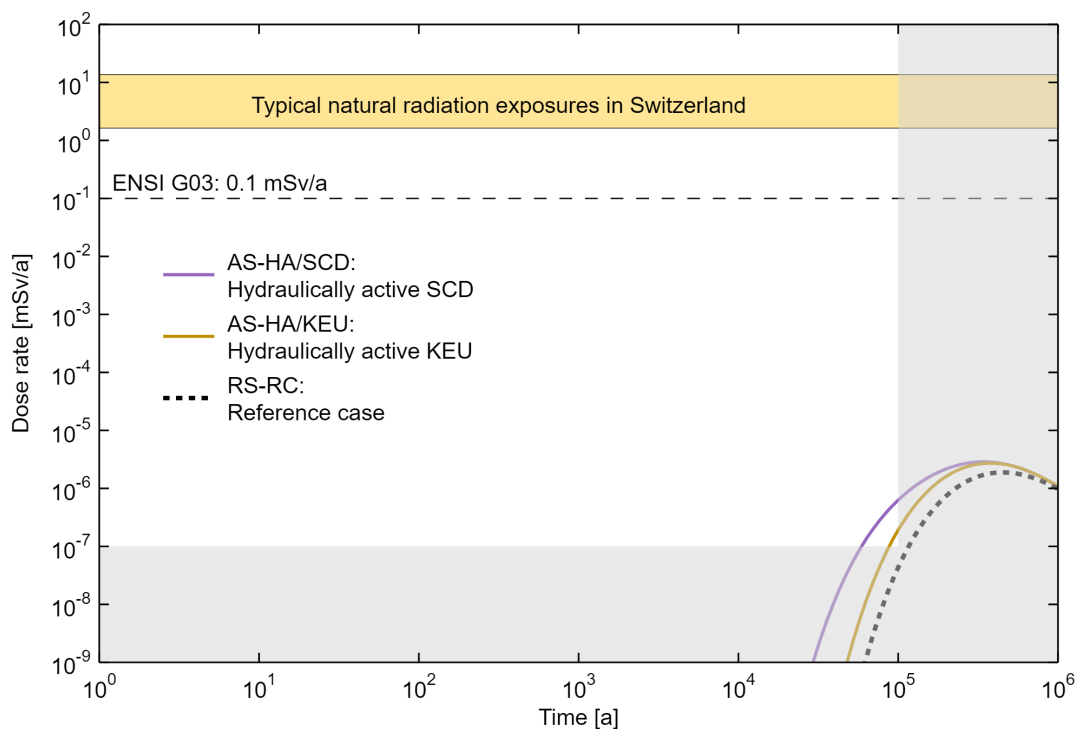


Fig. 6-93: Total dose rates in the reference case for an L/ILW repository in the JO siting region, and for two cases of hydraulically active confining units above and below the Opalinus Clay

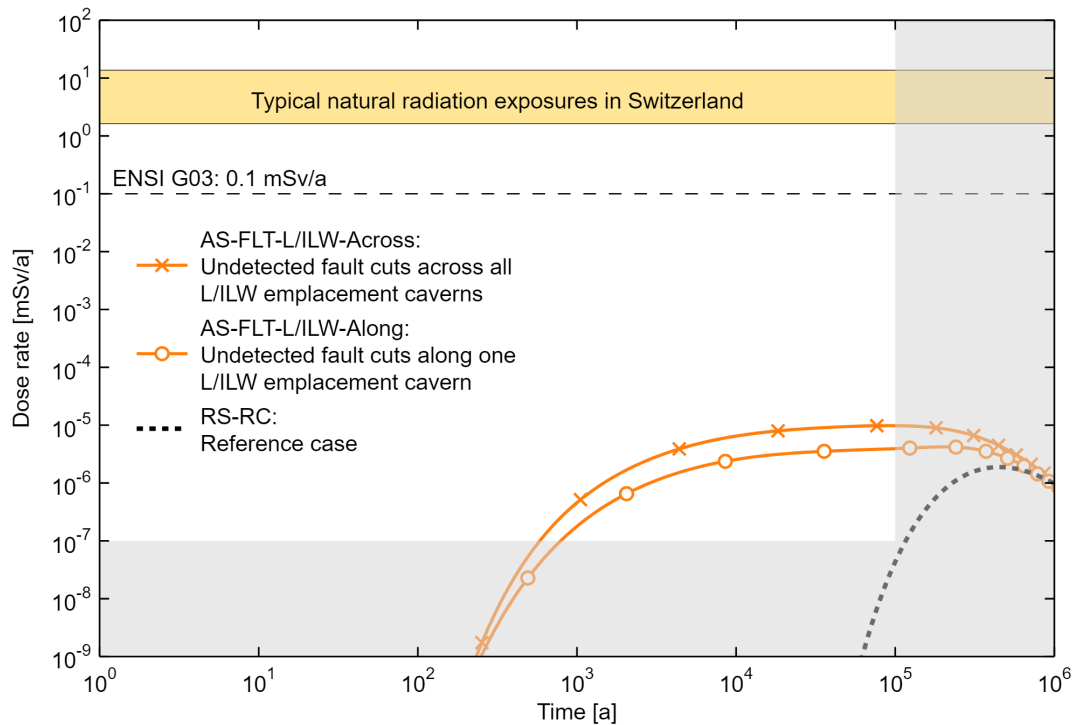


Fig. 6-94: Total dose rates in the reference case for an L/ILW repository in the JO siting region, and for two cases of an undetected fault intersecting the emplacement caverns

6.2.3.2 Nördlich Lägern (NL)

As illustrated in Fig. 2-5, there are five potentially hydraulically active confining units considered in the NL siting region: SCD, CD, and CM within the upper confining geological units, and KEU and KAU within the lower confining geological units. The impact of these is analysed in five deterministic calculation cases (see also Tab. 4-2):

- AS-HA/SCD, where SCD is assumed to be hydraulically active,
- AS-HA/CD, where CD is assumed to be hydraulically active,
- AS-HA/CM, where CM is assumed to be hydraulically active,
- AS-HA/KEU, where KEU is assumed to be hydraulically active,
- AS-HA/KAU, where KAU is assumed to be hydraulically active.

The evolution of the dose rate in these five cases is compared with the reference case in Fig. 6-95, which shows an increased dose rate caused by the cases concerning the SCD and CD units in the upper confining units and KEU being hydraulically active in the lower confining units. However, a safety margin of more than 4 orders of magnitude remains between the dose maxima and the protection criterion of 0.1 mSv/a (ENSI 2023). As in the case of the HLW repository, the closer the hydraulically active unit is to the repository, generally the higher the impact. Thus, units such as the CM and KAU, which are relatively far from the repository, do not have a significant impact on the radionuclide release when they are assumed to be hydraulically active.

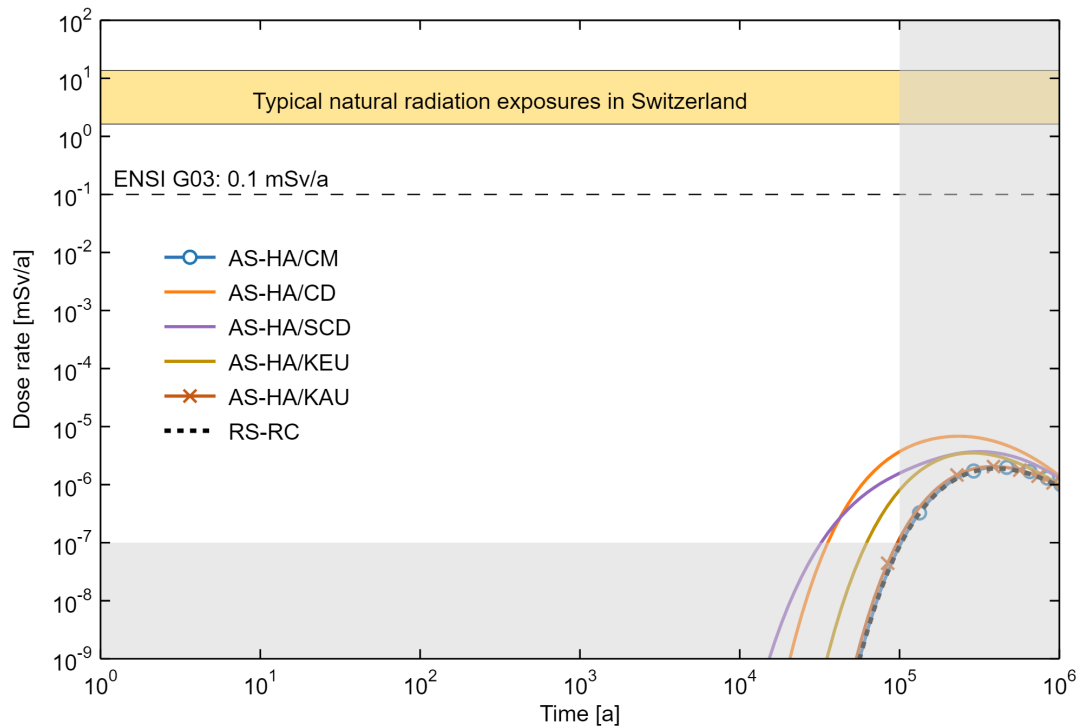


Fig. 6-95: Total dose rates in the reference case for an L/ILW repository in the NL siting region, and for five cases of hydraulically active confining units above and below the Opalinus Clay

The two cases illustrated in Fig. 6-96 show the impact of an undetected geological fault on the dose rate. The impact is qualitatively similar to that observed for the JO siting region. The transport along the fault increases the maximum dose rate compared with the reference case, and also increases the cumulative release of radionuclides to the biosphere. However, a safety margin of more than 4 orders of magnitude remains between the dose maxima and protection criterion of 0.1 mSv/a (ENSI 2023). Similar as the behaviour in HLW discussed in Section 6.1.3.2, the doses arise later, and the dose rate maximum is lower in NL compared with JO, because the transport length to the upper confining units is longer in NL than in JO.

Consistent with the observation in the results for JO, the case of a fault passing along one of the L/ILW emplacement caverns gives rise to slightly lower dose rates than the case with the fault passing perpendicularly through all the caverns.

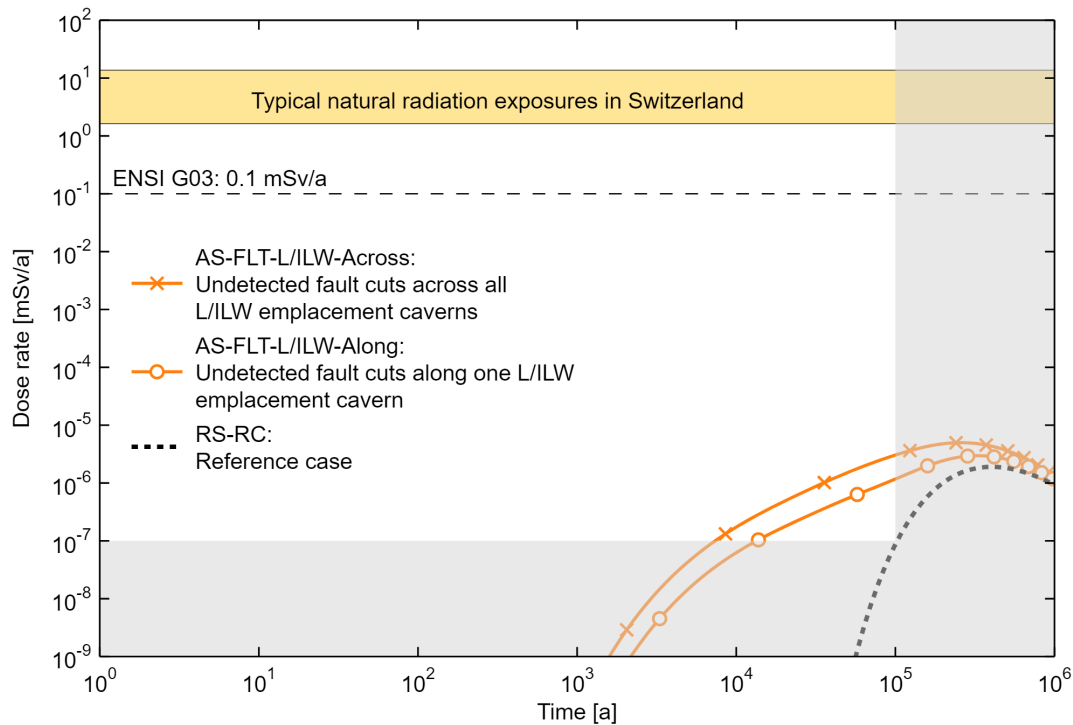


Fig. 6-96: Total dose rates in the reference case for an L/ILW repository in the NL siting region, and for two cases of an undetected fault intersecting the emplacement caverns

6.2.3.3 Zürich Nordost (ZNO)

As in the case of JO, as shown in Fig. 2-5, there are two potentially hydraulically active confining units considered in the ZNO siting region: one is the SCD unit in the upper confining geological units, and the other one is the KEU in the lower confining geological units. The impact of these is analysed in two deterministic calculation cases (see also Tab. 4-2):

- AS-HA/SCD, where the SCD is assumed to be hydraulically active; and
- AS-HA/KEU, where the KEU is assumed to be hydraulically active.

The evolution of the dose rate in these two cases is compared with the reference case in Fig. 6-97. The increase is up to about three orders of magnitude at 10^5 years. However, a safety margin of more than 4 orders of magnitude remains between the dose maxima and the protection criterion of 0.1 mSv/a (ENSI 2023). As with the other two siting regions, the geological barrier in ZNO shows a good level of robustness.

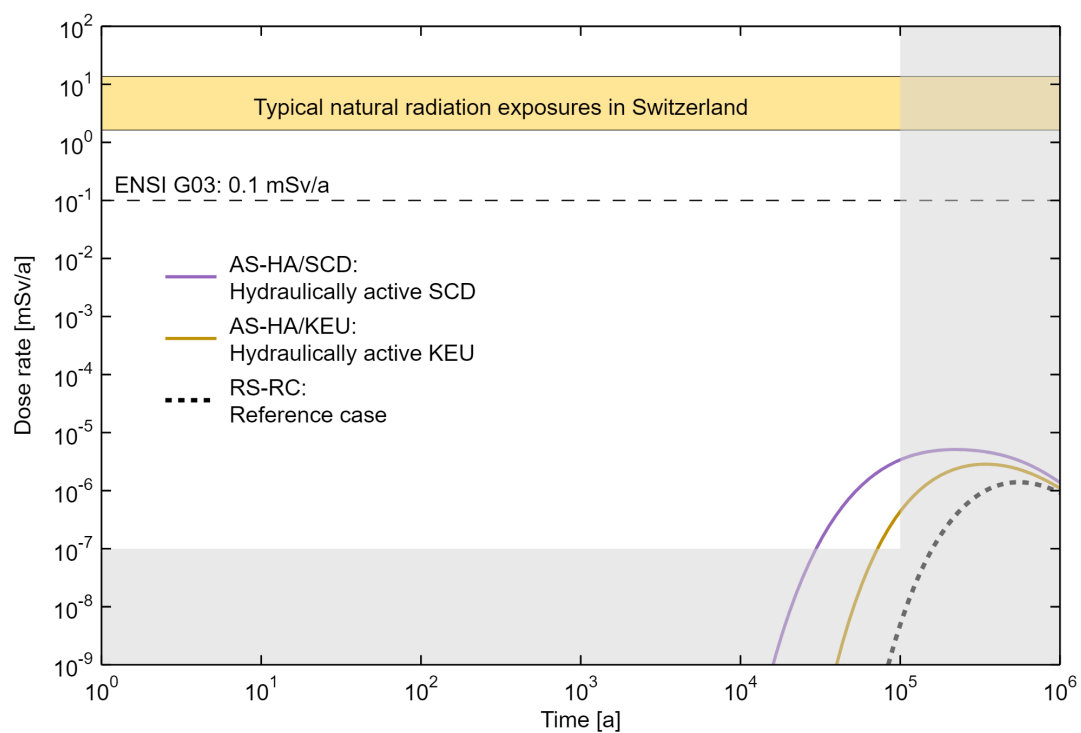


Fig. 6-97: Total dose rates in the reference case for an L/ILW repository in the ZNO siting region, and for two cases of hydraulically active confining units above and below the Opalinus Clay

The two cases illustrated in Fig. 6-98 show the impact of an undetected geological fault on the dose rate. The impact is qualitatively similar to that observed for the other siting regions. The transport along the fault increases the maximum dose rate by about 3 orders of magnitude compared with the reference case, which is a larger factor than observed for the other siting regions, mainly because the dose rate at 10^5 years in the reference case is relatively low. However, a safety margin of more than 4 orders of magnitude still remains between the dose maxima and the protection criterion of 0.1 mSv/a (ENSI 2023).

As observed in the results for the other siting regions, the case of a fault passing along one of the L/ILW emplacement caverns gives rise to slightly lower dose rates than the case with the fault passing perpendicularly through all the caverns.

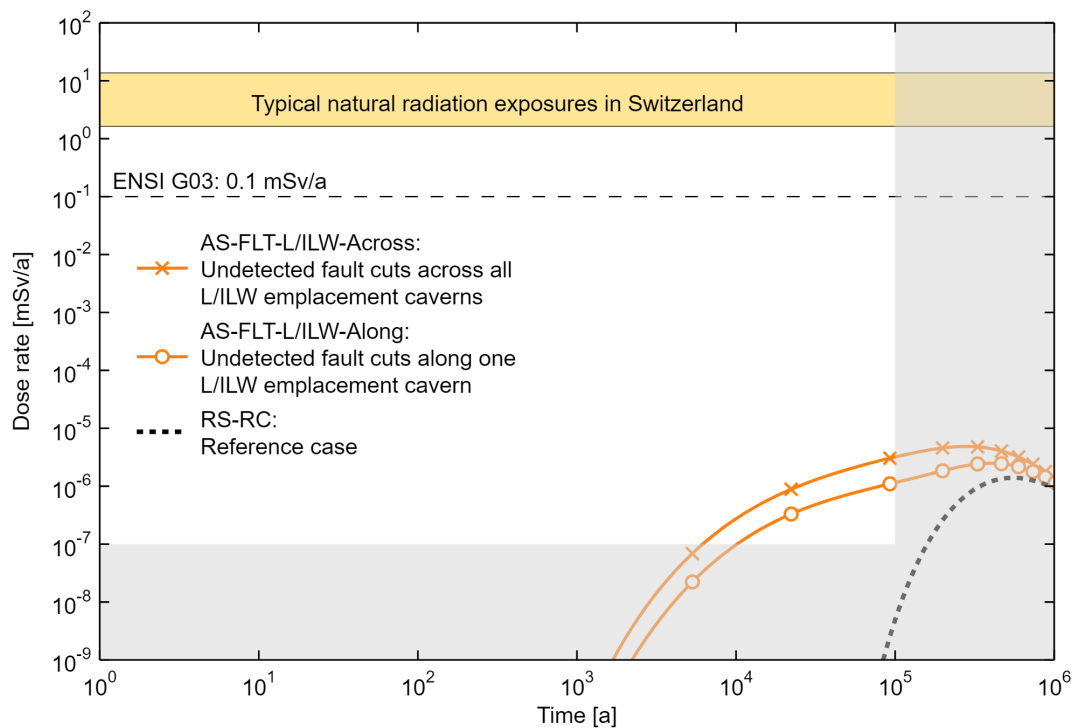


Fig. 6-98: Total dose rates in the reference case for an L/ILW repository in the ZNO siting region, and for two cases of an undetected fault intersecting the emplacement caverns

6.2.4 Comparison between the siting regions

The dose rate evolution in the reference case for the three siting regions is illustrated in Fig. 6-99. For all three siting regions, the L/ILW repository shows a robust safety margin, with dose rates above the significant dose rate 10^{-7} mSv/a arising only after the time period for assessment (10^5 years), and remaining several orders of magnitude below the protection criterion of 0.1 mSv/a (ENSI 2023) at all times.

Consistent with the radiological consequence analysis in Stage 2 of the SGT (Nagra 2014b), 0.01 mSv/a can be considered as a threshold dose rate below which the siting regions under consideration should be considered equivalent from a post-closure safety perspective (see Fig. 2.1-3 in Nagra (2014c)).

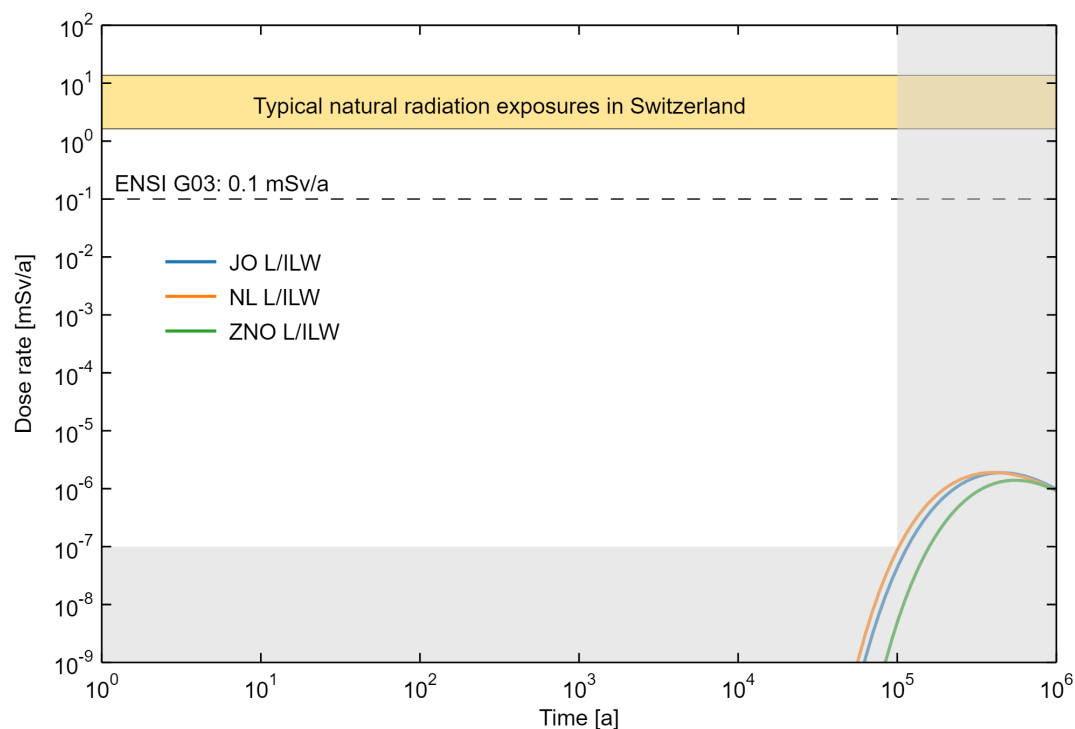


Fig. 6-99: Total dose rates in the reference cases for an L/ILW repository in all three siting regions

Fig. 6-100 shows the range of the maximum dose rates calculated from the 4,000 probabilistic simulations carried out for each siting region, as well as various percentiles of the maximum dose rates. The resulting bands are the so-called “characteristic dose intervals”¹⁶. In each siting region, the characteristic dose intervals are relatively similar and can be considered equivalent.

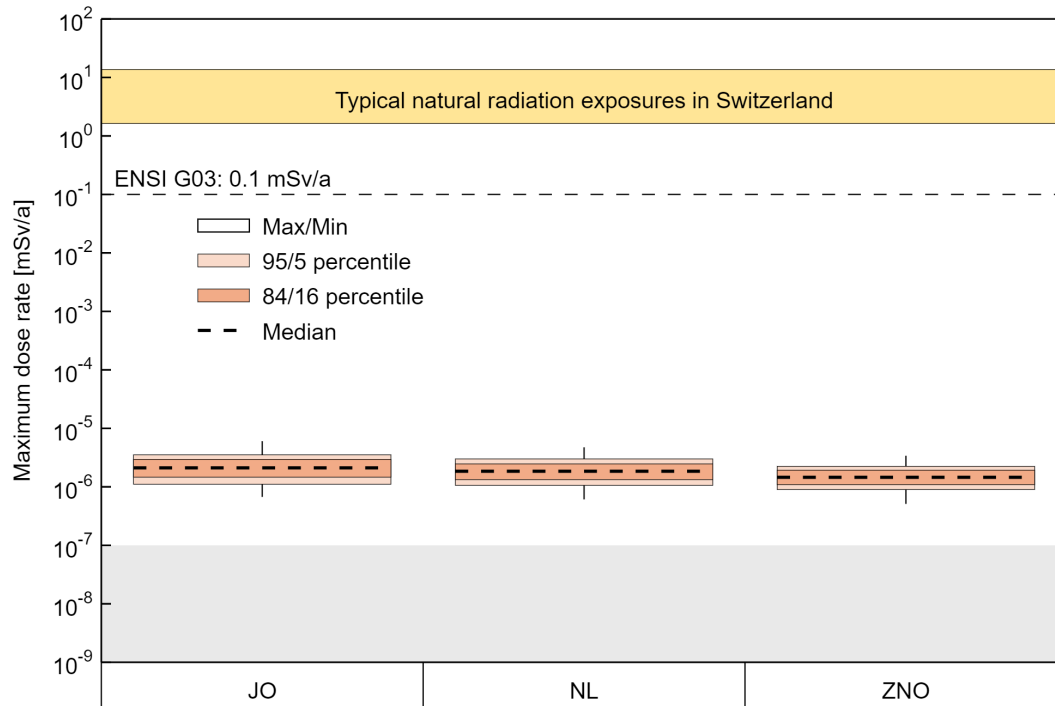


Fig. 6-100: Characteristic maximum dose intervals within 10^6 years based on the results of the probabilistic dose calculations carried out for an L/ILW repository in the three siting regions. The box plots show the 0%, 5%, 16%, 50%, 84%, 95% and 100% percentiles of the maximum dose rates of the probabilistic calculations

¹⁶ As it is usual to have a significant increase in dose rate after the time period of assessment (10^5 years) of L/ILW, the maximum dose rate within 10^6 years is considered to illustrate the “characteristic dose intervals”.

Fig. 6-101 shows the characteristic dose intervals for each siting region based on the results of the deterministic calculations carried out for the reference safety scenario and for the alternative safety scenarios (excluding biosphere variations). The cases combining pessimistic bounding values for sensitive parameters show significantly higher dose rates, though still several orders of magnitude below the protection criterion of 0.1 mSv/a in all three siting regions, which shows a robust safety margin. As in the probabilistic analyses, the characteristic dose intervals are rather similar in all three siting regions and can be considered as equivalent.

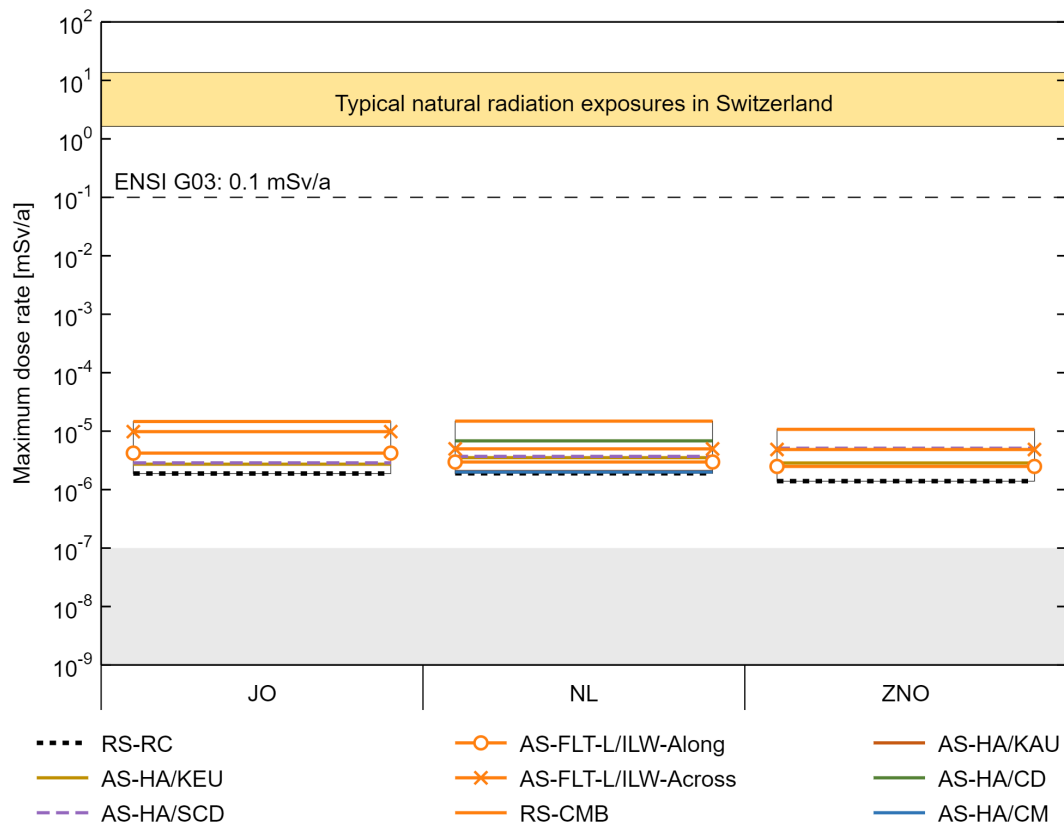


Fig. 6-101: Characteristic maximum dose intervals within 10^6 years based on deterministic calculations carried out for the reference safety scenario and for the alternative safety scenarios for an L/ILW repository in the three siting regions

Characteristic dose intervals for the deterministic cases examining different assumptions for the climate and surface conditions are shown in Fig. 6-102. The maximum dose rate, even with the least favourable climatic variation, is still about four orders of magnitude below the protection criterion of 0.1 mSv/a, which shows the robustness of the safety margin for the L/ILW repository. The characteristic dose intervals are rather similar in all three siting regions and can again be considered equivalent.

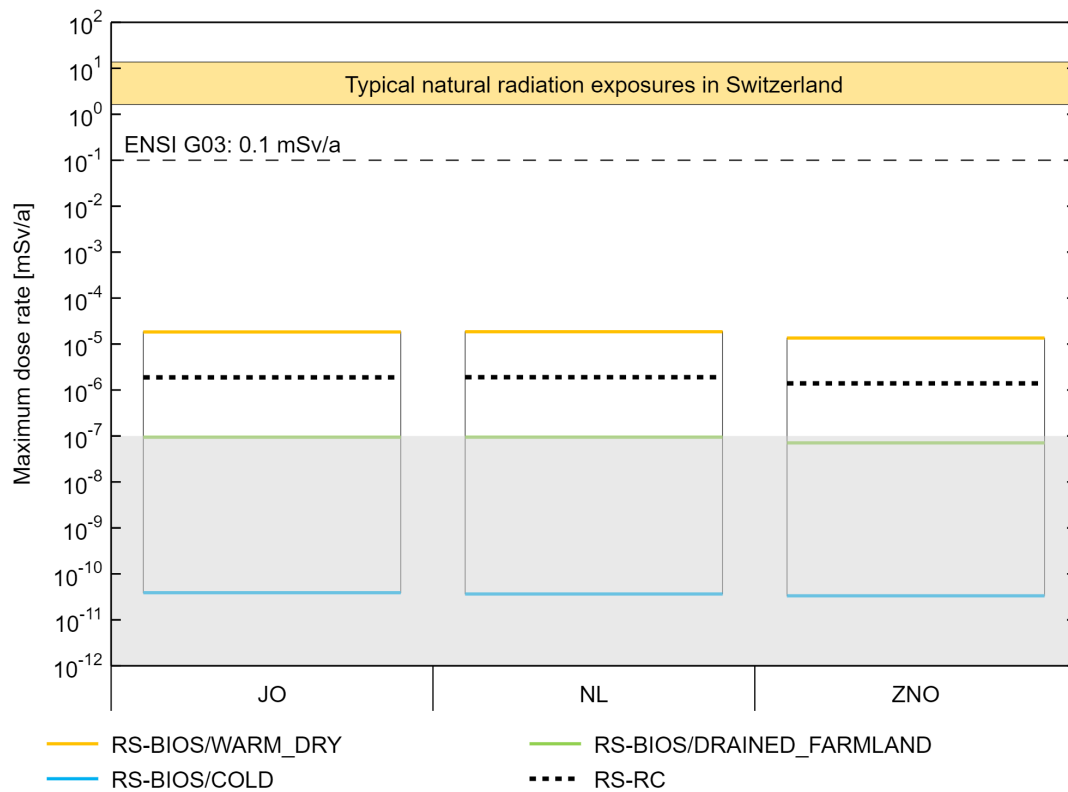


Fig. 6-102: Characteristic dose intervals within 10^6 years based on deterministic cases examining different assumptions for climate and surface conditions for an L/ILW repository in the three siting regions

The calculation cases in the radiological consequence analysis confirm the results from Stage 2 of the SGT (Nagra 2014c) where all the three siting regions can be considered as equally safe and suitable for an L/ILW repository from a post-closure safety perspective.

Furthermore, in all the calculation cases performed in this section, the dose rate after the time period for assessment is well far below the lower bound values of the typical natural radiological exposure in Switzerland (BAG 2021).

6.3 Radiological consequence analysis considering the two-phase migration of C-14 methane

As discussed in Nagra (2024r), C-14 is the only relevant gaseous radionuclide to be considered in the radiological consequence analysis. The following sections present safety analyses for migration of C-14 in the gas phase. As discussed in Nagra (2024k), the gas produced in the HLW

emplacement drifts (mainly H₂), carrying C-14 methane, will not undergo significant advective flow through the HLW-V1 seals towards the access tunnels, but rather is expected to migrate slowly by diffusion through the host rock and its confining geological units, where C-14 methane will decay to insignificant concentrations. Based on this system understanding, the transport of C-14 methane from an HLW repository is not considered further in the consequence analysis of the reference safety scenario for the safety-based site comparison. However, the transport of C-14 methane in the gas phase from an HLW repository is considered in the analysis of the alternative safety scenario involving an undetected fault, since this could lead to more rapid migration of C-14 to the biosphere. The transport of C-14 methane from an L/ILW repository, where it will undergo advective flow along the repository structures from the waste towards the access tunnels and shafts, is considered for all the safety scenarios.

6.3.1 Reference safety scenario analysis including barrier performance and dose rates

The consequence analyses for C-14 methane begin with the analysis of a deterministic reference case for each siting region, based on the reference safety scenario. The concepts and models for analysing radionuclide migration in the gas phase are described in App. B.2, with the parameters described in App. H. The main characteristics of the L/ILW models for the three siting regions are presented in the Tab. 6-9.

Tab. 6-9: Summary of the main characteristics of an L/ILW repository in the JO, NL and ZNO siting region

	JO	NL	ZNO
Depth of central area (m)	505	835	615
Pore volume (m ³)	229,873	211,312	239,303
Length of tunnels (m)	8,972	7,992	10,808
Thickness of the upper confining units (m)	38	150	96
Thickness of the Opalinus Clay (m)	125	107	114
Thickness of the lower confining units (m)	54	69	76
Number of shafts/ramps ¹⁷	1 / 1	3 / 0	3 / 0

According to the provisional repository design (Nagra 2023a), and as also shown in Tab. 6-9, an L/ILW repository in JO would have one shaft and an access ramp, while an L/ILW repository in either NL or ZNO would have access shafts.

¹⁷ In Nagra (2023a), two shafts are provisionally designed for an L/ILW repository in ZNO. There is no specific L/ILW repository design in NL. In the provisional combined repository design in NL, three shafts are planned. In modelling work in the present report, the number of shafts is conservatively assumed to be three for both NL and ZNO repositories, since shafts could provide the critical pathway for gas migration.

Fig. 6-103 shows the shaft macroelements (see App. B.2) for all three siting regions, indicating the depth of the repository level as well as the length of the shaft sections that pass through the Opalinus Clay and the upper confining units up to the Malm aquifer in the NL and ZNO siting regions, and up to the Calcareous Dogger in the JO siting region. The depth of the repository and the thickness of the upper confining units are greatest in NL, followed by ZNO and finally by JO.

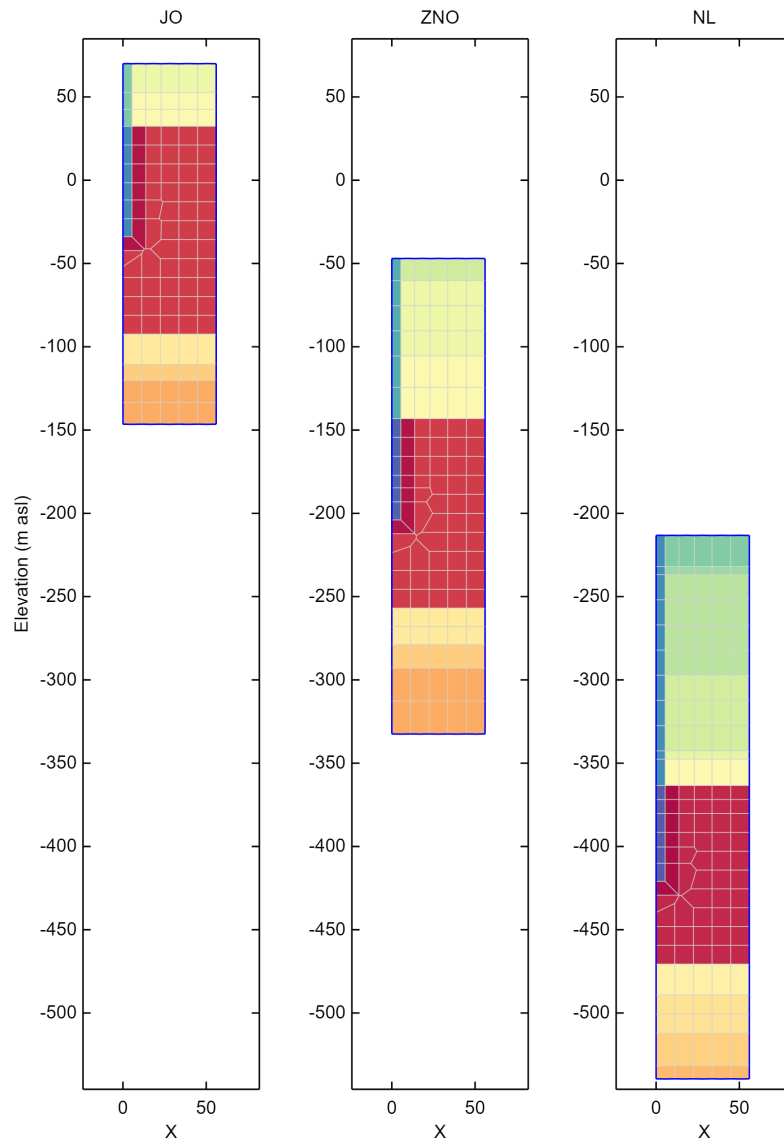


Fig. 6-103: Vertical section through the shaft macroelements of the three siting regions

The figure illustrates the increasing depth of the repository (difference between surface and repository elevation) as well as the increasing length of the shaft section in the upper confining units from JO via ZNO to NL.

Each section of the shaft that passes through the Opalinus Clay is plugged with a V3 seal, and the rest of each shaft passing through the upper confining units is backfilled with the same permeable material used for backfilling of the other tunnels of the closure system. Regarding the ramp, only the access tunnel up to the V4 seal within the ramp is included explicitly in the model. Beyond

the V4 seal, a hydrostatic pressure boundary condition is assumed, along with instantaneous transfer of gaseous C-14 to the biosphere. No gas generation is assumed to take place in the shaft after the closure of the repository, including the V3 seals, whereas the reinforcement materials within the ramp, including within the V4 seal section, are assumed to generate gas.

Gas-mediated transport of C-14 is controlled by the two-phase system behaviour (incl. gas entry pressure effect, see (Jung et al. 2018)). Fig. 6-104 illustrates the two-phase system behaviour of an L/ILW repository in the reference calculation case in the radiological consequence analysis in each of the three siting regions, using the indicators of gas pressure, gas saturation, overpressure (difference between the absolute gas pressures and hydrostatic pressure) and gas generation/flow rates in various repository components. More detailed cases concerning the fate of the repository-generated gas are performed and introduced in Nagra (2024k).

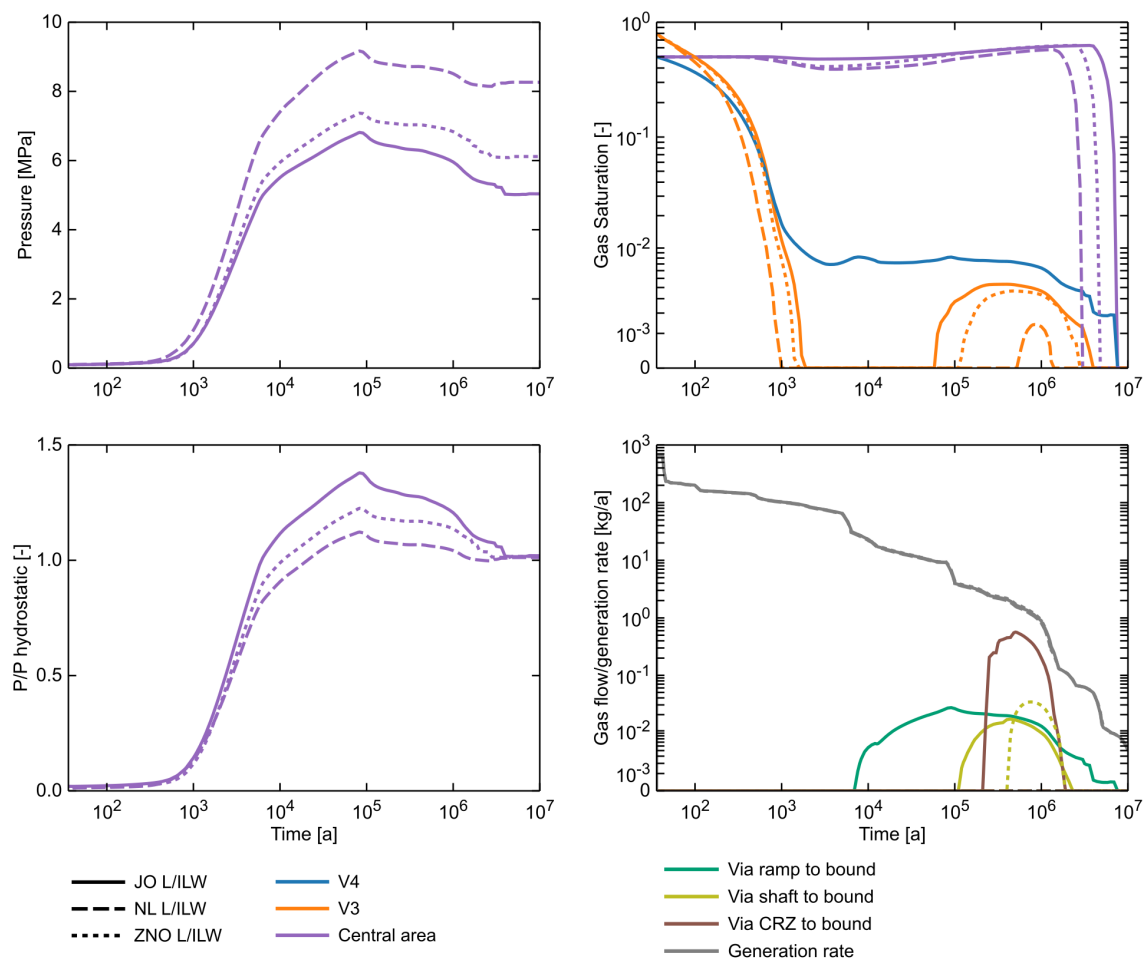


Fig. 6-104: Left: Evolution of absolute (top) and relative gas pressures (pressure against hydrostatical pressure) (bottom) in the L/ILW repository in each of the three siting regions in the central repository area. Right: Gas saturation in central area, V3 and V4 seals (top) and gas generation and advective flow rates through model boundaries (bottom). The different siting regions are indicated by the line style (solid: JO, dashed: NL, dotted: ZNO).

There are several fundamental points related to this behaviour as listed below:

- The gas generation rate is identical in the three site-specific models (grey curves at bottom right in Fig. 6-104)
- Overpressures within the repository, which is the difference between the absolute gas pressures and hydrostatic pressure, decrease with increasing repository depth and with increasing hydrostatic pressure. At greater depths, gas densities are higher, leading to a greater storage capacity. Hence, a lower driving force for gas to flow out of the repository is required, either into the CRZ or along the ramp or shafts.
- At lower depths, hydrostatic pressure can be exceeded more readily. Combined with higher overpressure (with respect to hydrostatic pressure), this leads to a higher tendency for advective gas flow away from the repository.
- When gas pressure falls below hydrostatic pressure, resaturation of the repository will start. The deeper the repository and the higher the hydrostatic pressure, the earlier resaturation starts and finishes.

Fig. 6-104 (top right) shows that liquid saturation of the shafts and of the V3 seals takes place relatively rapidly. As noted above, there is no gas generation within the shafts. The ramp and V4 seal do, however, generate gas and do not become fully liquid-saturated at any time within the calculated period. The fully saturated V3 seals provide a strong (low-permeability and high gas entry pressure) barrier against gas transport. However, gas transport can occur relatively easily through the V4 seal once hydrostatic pressure is exceeded, since the gas permeability of the partially saturated seal is much higher. By contrast, advective gas flow via the V3 seals and shafts sets in much later because of the resistance they provide to gas flow.

According to Fig. 6-104, a repository in ZNO experiences a small gas flow via shafts only at very late stages, because of its higher depth, lower overpressures and longer shaft compared with a repository in JO. In the case of an L/ILW repository in NL, no advective gas flow along the shafts is observed at all in the reference safety scenario because of its even greater depth, even lower overpressures and a longer shaft compared with the repository in the ZNO siting region.

6.3.1.1 Jura Ost (JO)

As noted above, the L/ILW repository in JO has an access ramp and a shaft, and thus differs from the repositories in the other two siting regions in this respect as they have only access shafts. The access ramp generates gas, whereas no gas generation is assumed in the shaft, since all metal reinforcements in the bottom part of the shaft are assumed to be removed during the closure of the repository (Nagra 2024k).

Fig. 6-105 shows the total dose rate evolution, and the dose rates due to releases of C-14 methane from the ramp, the shaft and the confining units, for an L/ILW repository in the reference case for the JO siting region. The total dose rate remains below the level of the significant dose rate (10^{-7} mSv/a) during the entire time period for assessment. The maximum dose rate is 1.8×10^{-9} mSv/a, which is more than 7 orders of magnitude lower than the protection criterion of 0.1 mSv/a.

The total dose rate is dominated by transport of gas via the ramp, which increases rapidly towards its maximum value after hydrostatic pressure is exceeded and advective transport of gas begins, at about 8,000 years (see Fig. 6-104). The dose contributions from the shaft and from the confining units of the CRZ are several orders of magnitude lower, with maxima of 1.5×10^{-15} mSv/a via the shaft and CRZ 4.0×10^{-17} mSv/a via the rock. Advective transport through the shaft starts at around 10^5 years, which is much later than via the ramp because of the very low gas permeability

of the saturated shaft seal (V3). As discussed above, along the ramp, and through the V4 seal, materials remain only partially liquid-saturated because of local tunnel gas production, and advective gas transport can start earlier.

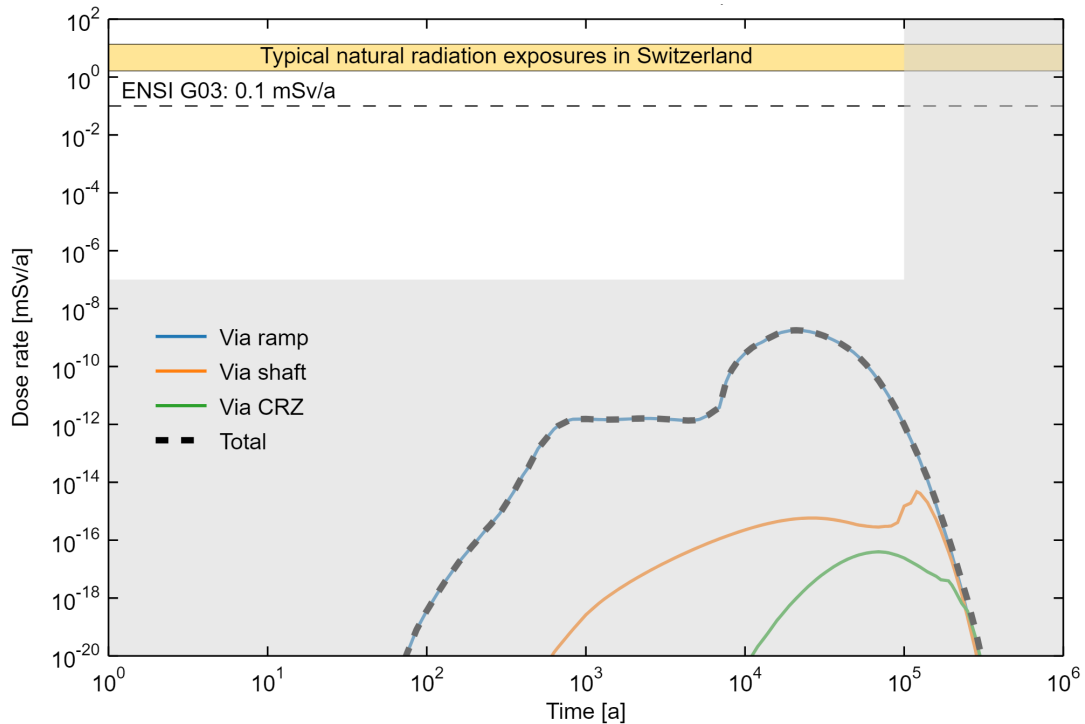


Fig. 6-105: Total dose rate of C-14 methane with contributions from the ramp, from the shaft and from the CRZ for an L/ILW repository in the reference case for JO. The graph extends down to extremely low dose rates in order to illustrate system behaviour

Fig. 6-106 shows C-14 methane fluxes at various locations within the repository and through the CRZ, converted to hypothetical dose rates as indicator using the C-14 BDCF. The red line labelled “From waste” represents the C-14 methane released from L/ILW, where an initial peak is caused by a fraction of about 16% of the total C-14 methane inventory that is assumed to be released rapidly: the “instant release fraction”, or IRF. The orange line labelled “From V1” represents the C-14 methane that migrates, along with other, repository-generated gas (H_2) from the corrosion of metals and degradation of organic materials, through the partially saturated V1 seals at the end of the emplacement caverns into the pore spaces of the backfilled access tunnels of the repository. The maximum C-14 methane release through the V1 seals is reached after 100 years. Gas can also readily pass through the partially saturated V2 seals, with the pink curve labelled “From V2” showing a maximum C-14 release rate through these seals at about 1,000 years.

Some of the C-14 methane within the L/ILW emplacement caverns and closure system can migrate into the EDZ and undisturbed host rock, where it dissolves in porewater. The maximum activity flux due to this release pathway, is shown by the dashed grey curve labelled “To OPA”. Most of this flux decays during transport through the host rock, resulting in the very low release rate to the confining geological units, shown by the dashed blue curve labelled “To CU”.

The activity release rate to the model boundaries (into the biosphere), i.e., the thick dashed black curve labelled “To biosphere”, is dominated by the outflow through the V4 seal of the ramp.

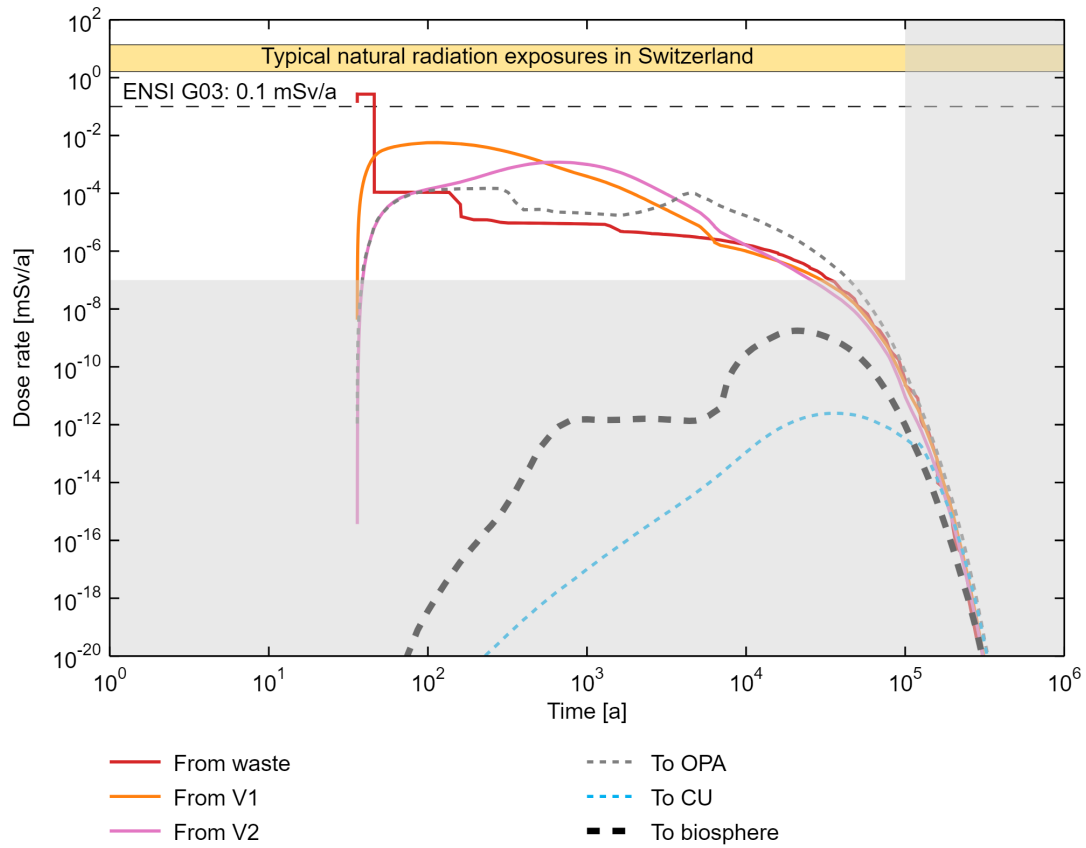


Fig. 6-106: Activity fluxes of C-14 methane within an L/ILW repository and through the CRZ in the JO siting region, converted to dose rates using the BDCF for C-14. The graph extends down to extremely low dose rates in order to illustrate system behaviour

Fig. 6-107 illustrates the distribution of C-14 methane, expressed as radiotoxicity, within the repository, within the CRZ and outside the CRZ (see Section 3.1 for the definition of radiotoxicity). The red curve labelled “Waste” shows the activity contained within the waste packages for L/ILW, where most of the total C-14 resides (the thick black dashed curve labelled “Total”) throughout the 10^5 -year time period for assessment. This is because most of the C-14 is contained within activated metals, and is released congruently with metal corrosion, which is a slow process in the high-pH near-field environment.

The activity in the emplacement caverns that is not contained (anymore) within the waste packages is shown by the dark blue curve. The early rapid increase in this activity is caused by the IRF, which is assumed to be released at the start of the post-closure phase. As discussed above, the C-14 from the IRF is distributed by advection throughout the backfill of the closure system, including the V2 seals and central area. Some C-14 also migrates into the EDZ and undisturbed host rock (the yellow curve labelled “EDZ and OPA”) and, from there, diffuses into the confining units (the grey curve). The activity that exists outside the CRZ (the green curve) is mostly the result dominated by the release via access ramp and its V4 seal.

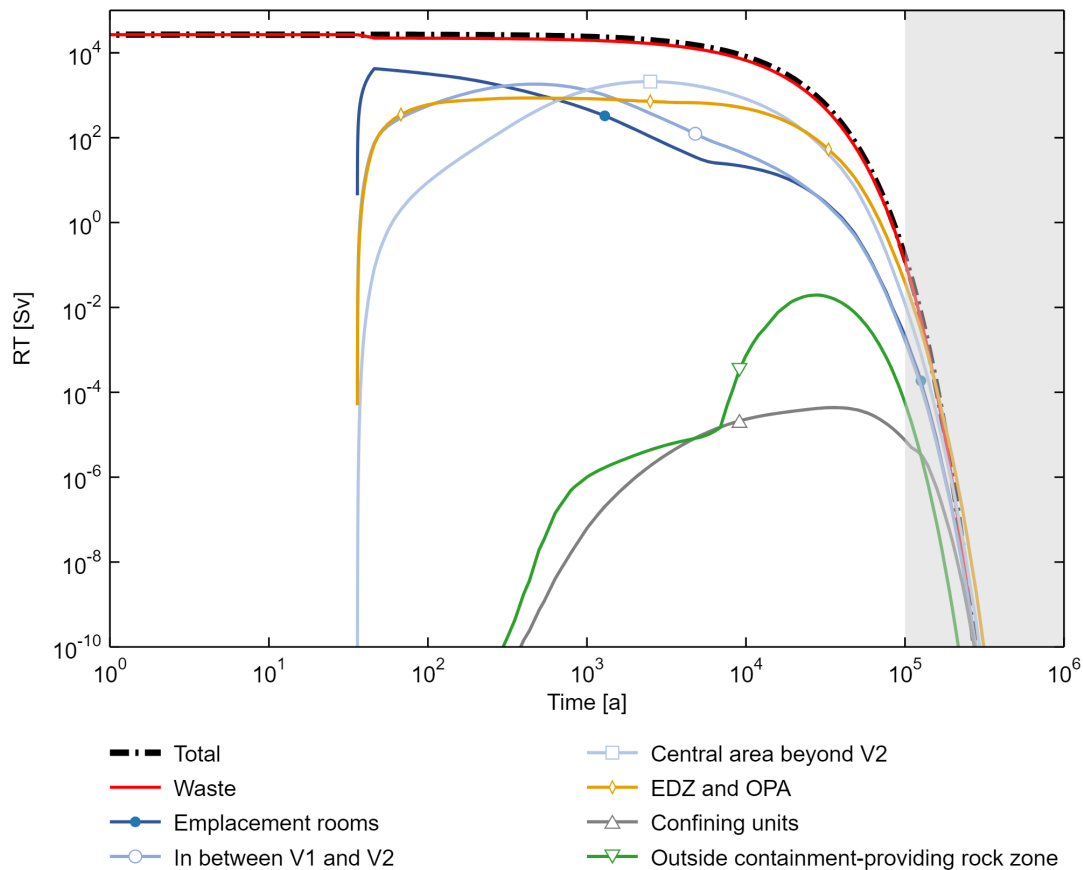


Fig. 6-107: Distribution of C-14 methane activity, expressed as radiotoxicity, within an L/ILW repository in the JO siting region, within the CRZ and outside the CRZ

6.3.1.2 Nördlich Lägern (NL)

Fig. 6-108 shows the total dose rate evolution, and the dose rates due to releases of C-14 methane from shafts and from the confining units, for an L/ILW repository in the reference case for the NL siting region. The total dose rate remains orders of magnitude below the level of the significant dose rate (10^{-7} mSv/a) during the entire time period for assessment, with a maximum that is more than 15 orders of magnitude lower than the protection criterion of 0.1 mSv/a (ENSI 2023).

The total dose rate is dominated by diffusive transport through the CRZ. Because of the great depth of the repository, gas pressure within the repository exceeds hydrostatic pressure only slightly, and there is no advective release via the shafts (see Fig. 6-104). What little release does occur is via the shafts (which are also longer than in the other siting regions) due to diffusion of dissolved C-14 methane through the V3 seals.

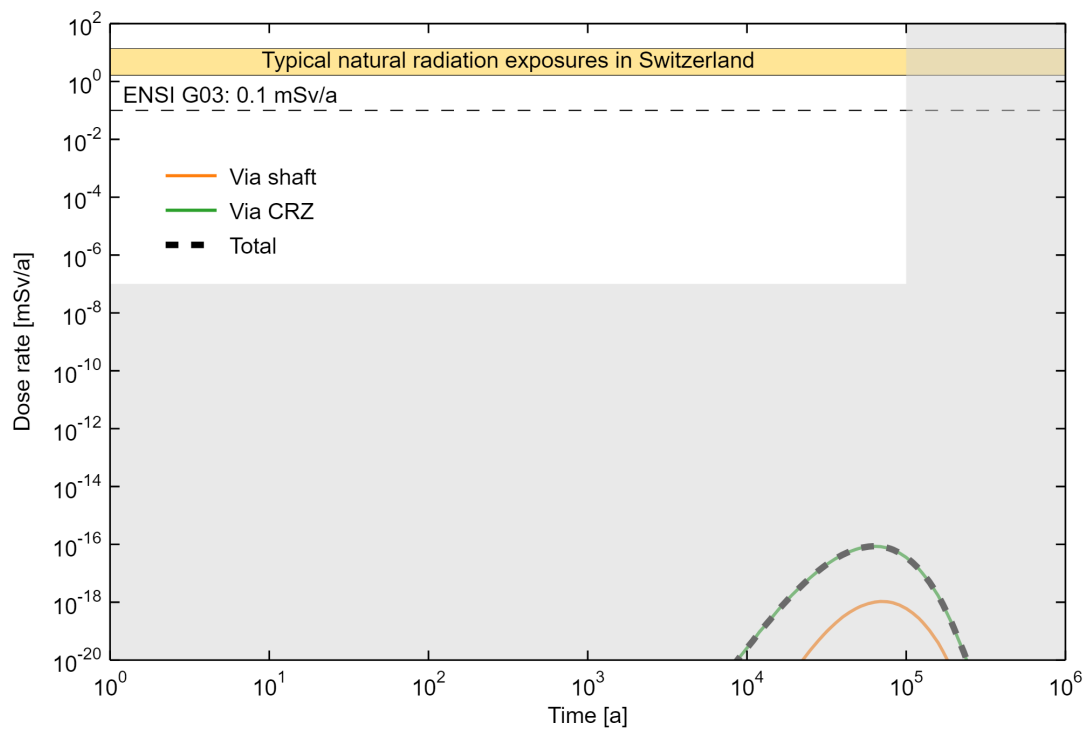


Fig. 6-108: Total dose rate of C-14 methane with contributions from the shaft and from the CRZ for a L/ILW repository in the reference case for NL. The graph extends down to extremely low dose rates in order to illustrate system behaviour

Fig. 6-109 shows activity fluxes at various locations within the repository and through the CRZ, converted to dose rates using the BDCF for C-14. The distribution of C-14 methane within the L/ILW emplacement caverns and closure system up to the V3 seals, as represented by the orange line labelled “From V1” and pink curve labelled “From V2”, are also almost identical to the corresponding curves for the repository in JO shown in Fig. 6-106, as the properties assigned to the seals and backfill are identical in both siting regions. The rate at which C-14 located within the L/ILW emplacement caverns and closure system migrates into the EDZ and the undisturbed host rock, is also similar and shown by the dashed grey curve labelled “To OPA”. The activity flux released to the confining units, though still much lower than the release to the host rock, is somewhat higher for NL compared with JO, because of the lower thickness of the Opalinus Clay in NL (see Tab. 6-9) and the higher diffusion coefficient associated with the higher ambient temperature at greater repository depth.

The main difference compared with the repository in JO is the much lower activity release rate to the model boundaries, shown by the thick dashed black curve labelled “To biosphere”. For a repository in JO, this is dominated by the outflow through the V4 seal of the ramp. The ramp is absent in the provisional repository design for NL, and the releases to the model boundaries occur only via the shafts, with their rapidly saturated and hence low-permeability V3 seals, and via the CRZ.

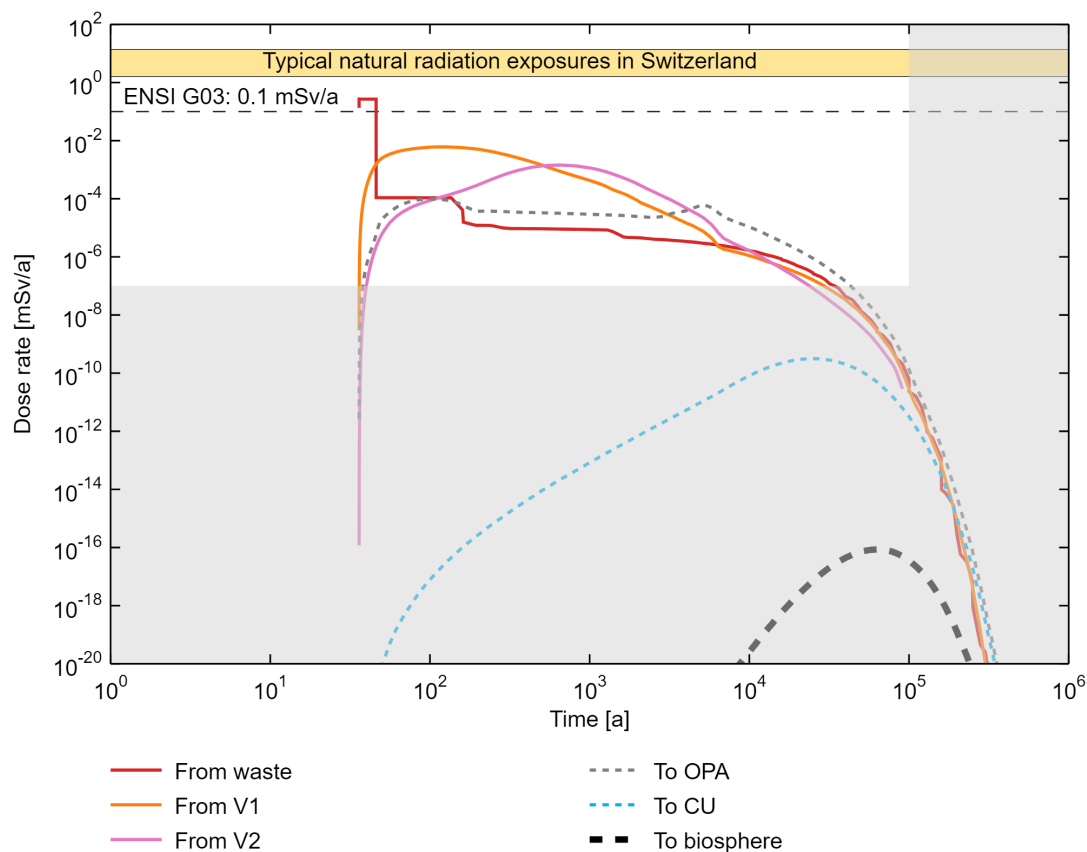


Fig. 6-109: Activity fluxes of C-14 methane within an L/ILW repository and through the CRZ in the NL siting region, converted to dose rates using the BDCF for C-14. The graph extends down to extremely low dose rates in order to illustrate system behaviour

Fig. 6-110 illustrates the distribution of C-14 methane over time, expressed as radiotoxicity, within the repository, and within and outside the CRZ. The main differences with the corresponding results for an L/ILW repository in the JO siting region are the amount of activity that reaches the confining units (the grey curve), which is somewhat higher in NL compared with JO, and the amount of C-14 methane that exists at any time outside the CRZ (the green curve), which is much lower in NL compared with JO, since most of the C-14 methane either remains within the repository, or diffuses into the rock, where it decays to insignificant levels.

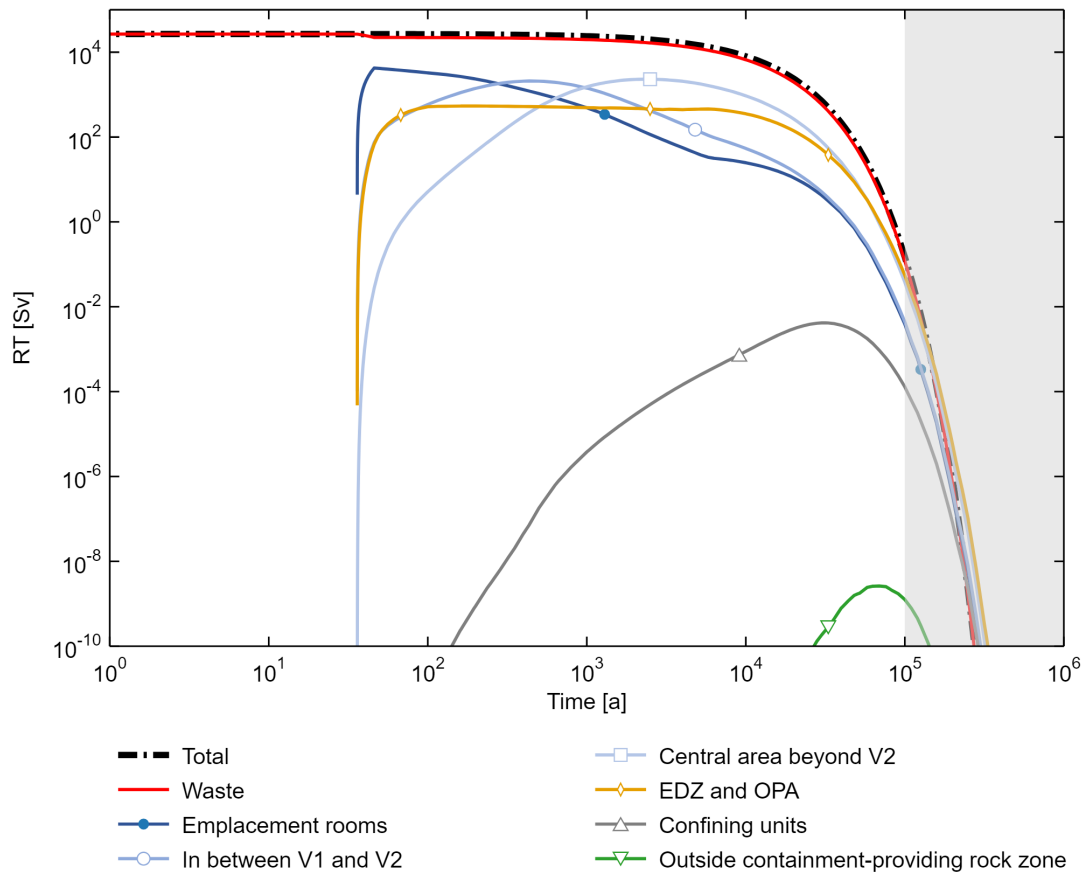


Fig. 6-110: Distribution of C-14 methane activity, expressed as radiotoxicity, within an L/ILW repository in the NL siting region, within the CRZ and outside the CRZ

6.3.1.3 Zürich Nordost (ZNO)

The behaviour of the L/ILW repository in the ZNO siting region is similar to that in the NL repository in that the access structures are shafts only. In both NL and ZNO, most of the C-14 methane that escapes from the repository diffuses in the CRZ towards the lower confining units. What little C-14 does not decay during transport then diffuses into the aquifers. The transport length through the rock in ZNO is greater than in the NL siting region, which leads to slightly lower dose rates, as can be seen by comparing Fig. 6-111 for ZNO with Fig. 6-108 for NL. This behaviour is consistent with the radionuclide transport in the liquid phase discussed in Section 6.2. In both cases, the total dose rate remains orders of magnitude below the level of significant dose rate (10^{-7} mSv/a) during the entire time period for assessment, with a maximum that is more than 15 orders of magnitude lower than the protection criterion of 0.1 mSv/a. Because the L/ILW repository in ZNO is less deep than the repository in NL, there is some advective gas flow along the shafts, starting at 500,000 years (see Fig. 6-104). However, virtually all C-14 has decayed by this time, which is equivalent to around 100 times the half-life of C-14.

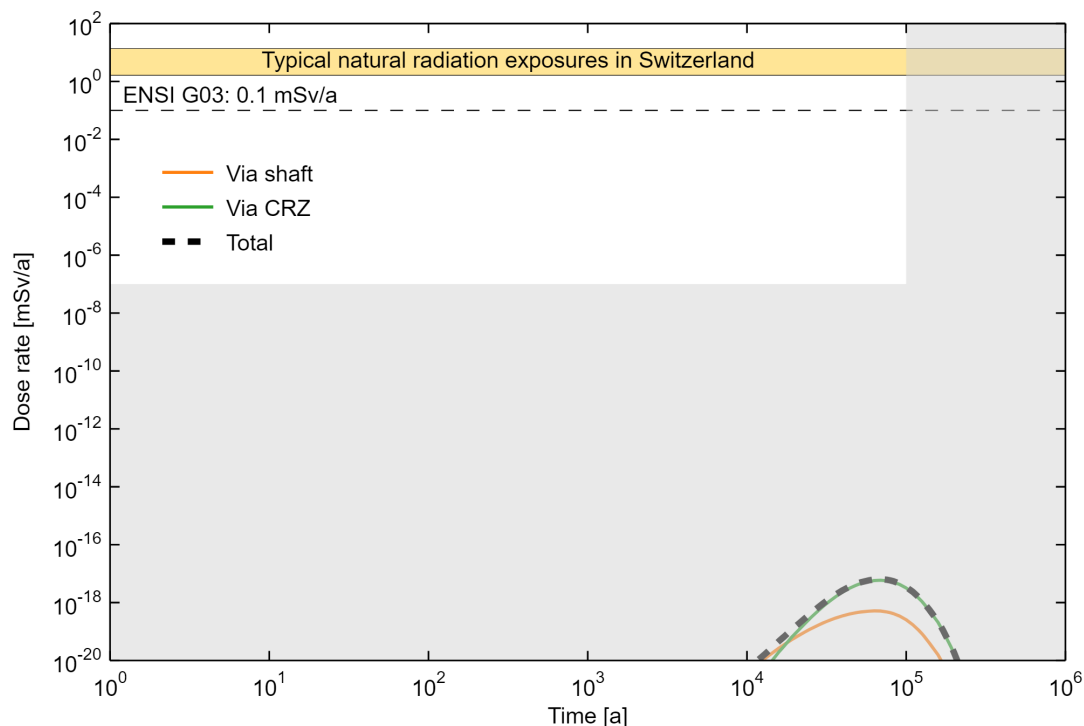


Fig. 6-111: Total dose rate of C-14 methane with contributions from the shaft and from the CRZ for an L/ILW repository in the reference case for ZNO. The graph extends down to extremely low dose rates in order to illustrate system behaviour

Fig. 6-112 shows C-14 methane fluxes at various locations within the repository and through the CRZ, converted to dose rates using the BDCF for C-14. The activity fluxes are very similar to those calculated for the repository in the NL siting region, as shown in Fig. 6-109.

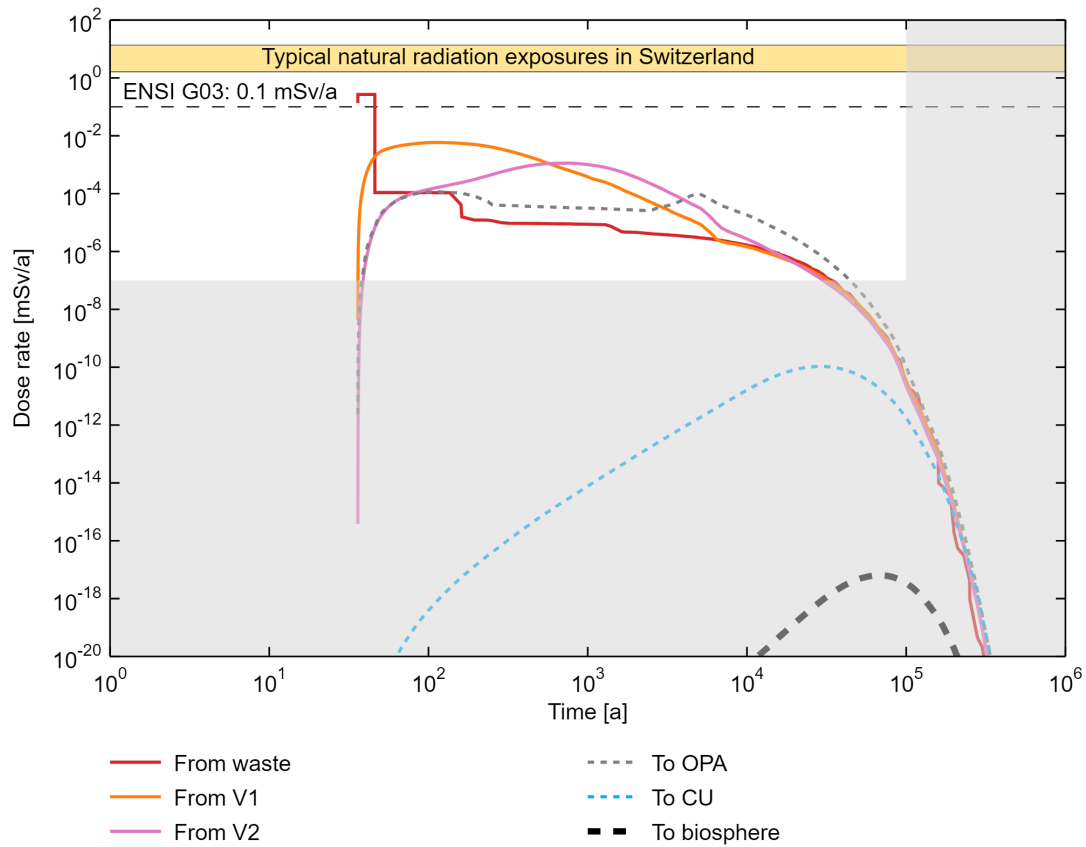


Fig. 6-112: Activity fluxes of C-14 methane within an L/ILW repository and through the CRZ in the ZNO siting region, converted to dose rates using the BDCF for C-14. The graph extends down to extremely low dose rates in order to illustrate system behaviour

Fig. 6-113 illustrates the distribution of activity of C-14 methane, expressed as radiotoxicity, within the repository, within and outside the CRZ. The activity distribution is very similar to that calculated for the repository in the NL siting region, as shown in Fig. 6-110. Most of the C-14 methane either remains within the repository, or diffuses in the CRZ, where it decays to insignificant levels. The amount of C-14 methane that exists at any time outside the CRZ is smaller than in the case of NL, because of the longer dominant transport pathway in ZNO.

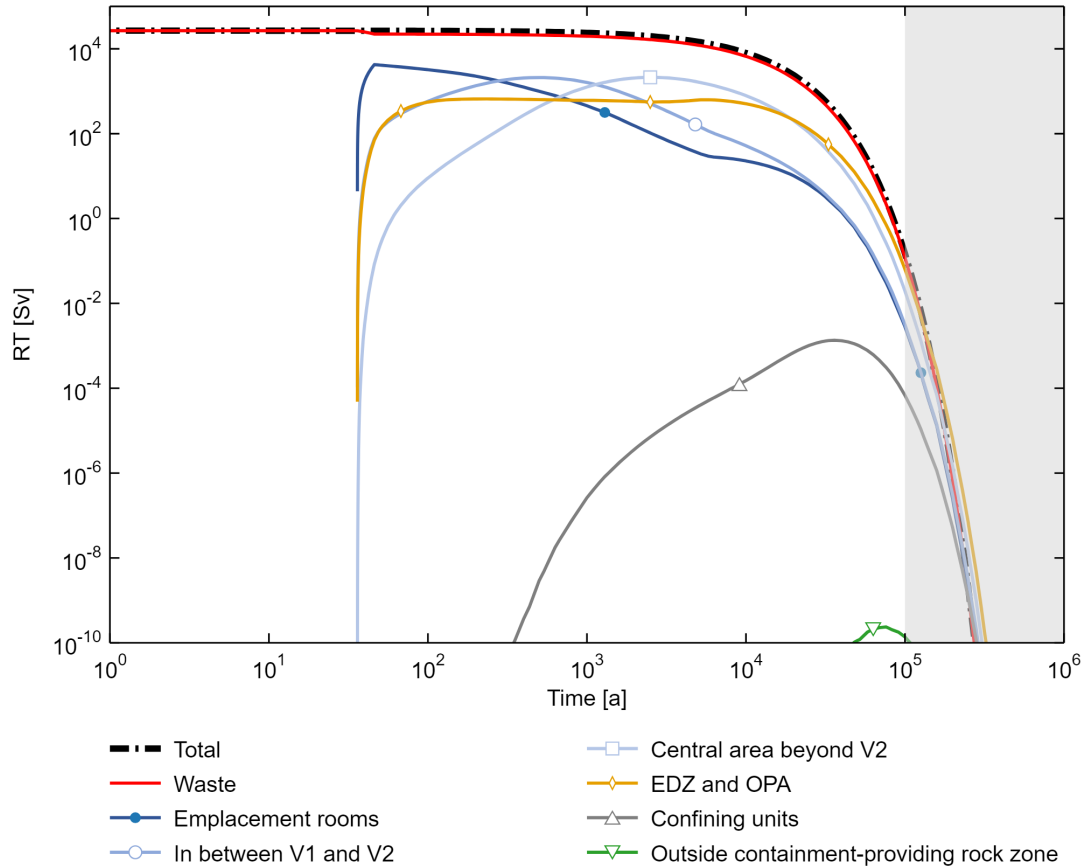


Fig. 6-113: Distribution of C-14 methane activity, expressed as radiotoxicity, within an L/ILW repository in the ZNO siting region, within the CRZ and outside the CRZ

6.3.2 Probabilistic and deterministic analysis covering parameter uncertainty

In accordance with the workflow presented at the start of this chapter, probabilistic analyses of the reference safety scenario are performed for each site-specific model, along with deterministic analyses of pessimistic cases, in which those parameters identified as the most sensitive in the probabilistic analyses are set to pessimistic, bounding values. This includes a deterministic case that combines the pessimistic bounding values of all the most sensitive parameters. The results of these probabilistic and deterministic analyses are presented for each siting region in the following sections. Details of the Monte-Carlo simulation approach and of the sensitivity analysis methods used in the probabilistic analyses are given in App. G.

6.3.2.1 Jura Ost (JO)

Fig. 6-114 shows statistical percentiles calculated from 4,000 Monte-Carlo simulations of the dose rate evolution due to C-14 methane from an L/ILW repository in the JO siting region, with each simulation carried out by sampling input parameters from probability distribution functions representing parameter uncertainty. Only a few of the realisations provide dose rates above the level of the significant dose rate, taken to be 10^{-7} mSv/a, showing a robust safety margin between the calculated dose rates and the protection criterion of 0.1 mSv/a. In all the simulation realisations, the maximum dose rates are reached in the time period for assessment, which means that after 100,000 years, the dose rate is far below the lower bound value of the typical natural radiological exposures in Switzerland (BAG 2021).

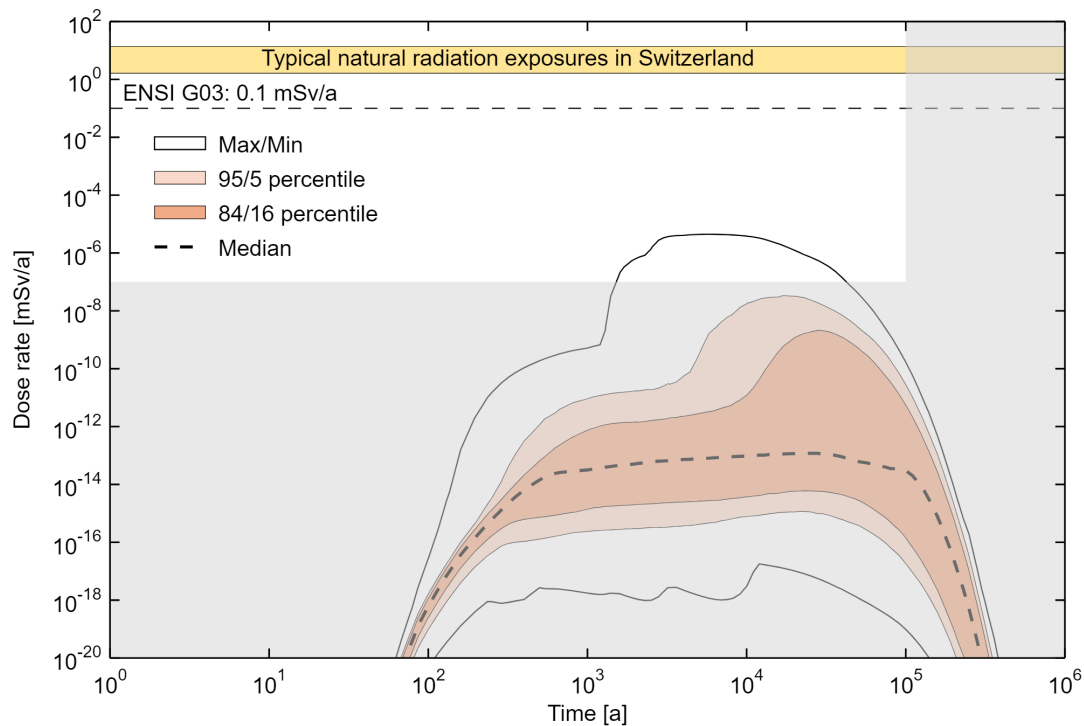


Fig. 6-114: Statistical percentiles of the dose rate evolution of C-14 methane for an L/ILW repository in the JO siting region calculated from 4,000 Monte-Carlo simulations

Sensitivity analyses have been performed based on the results from the Monte-Carlo simulations. The first step is a graphical analysis using scatter plots showing the maximum dose within the 10^5 -year period for assessment against individual input parameter values sampled in the Monte-Carlo simulations for selected parameters. Some examples of such scatter plots are shown in Fig. 6-115 to Fig. 6-118.

Fig. 6-115 shows a clear monotonic relationship between the maximum dose rate and the normalised corrosion/degradation rates, and hence the rate of gas generation. A higher corrosion/degradation rate leads to higher gas pressures, higher advective gas flow and higher C-14 methane transport via the ramp through the V4 seal. Higher gas pressures also lead to earlier gas and C-14 methane releases through the V3 seal, leading to higher dose rates, as evidenced by the increased occurrence of the shaft as the dominant release pathway (the red points in Fig. 6-115).

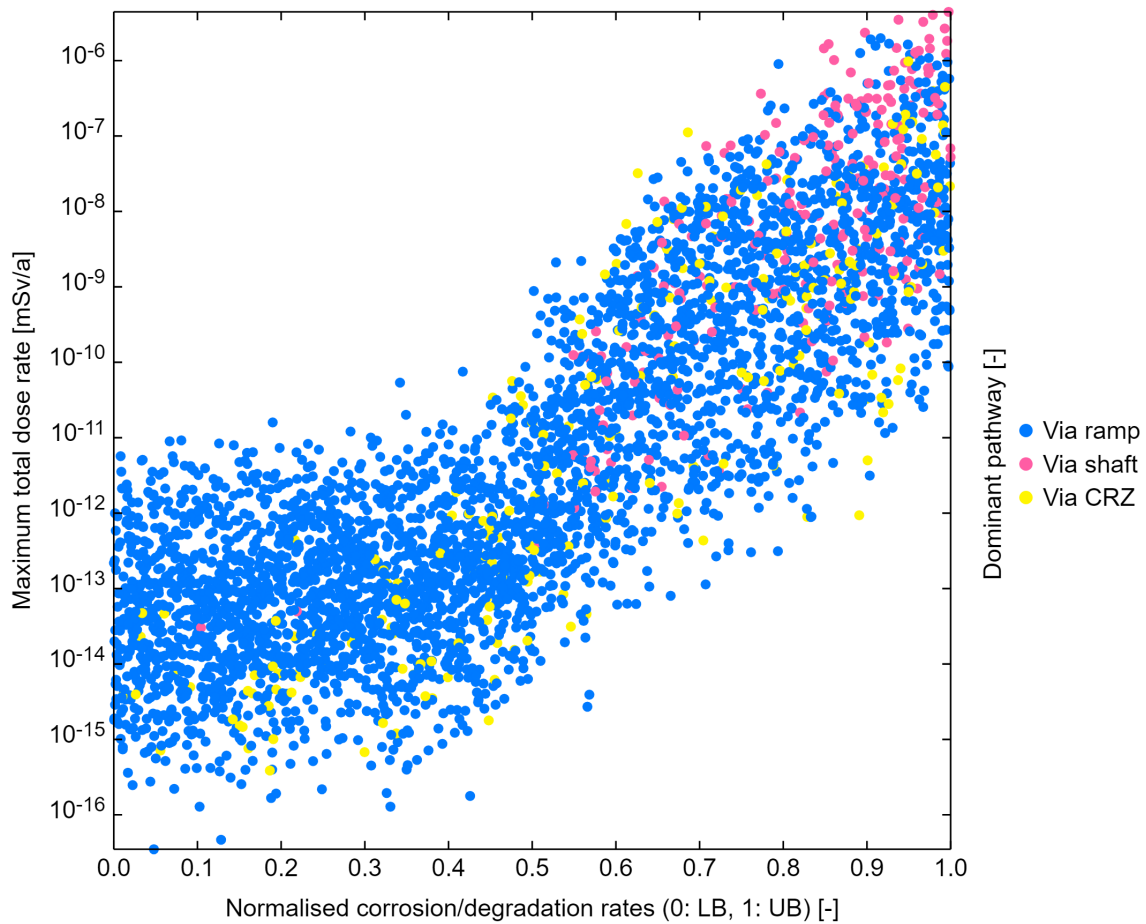


Fig. 6-115: Scatter plot showing the maximum total dose rate of C-14 methane from an L/ILW repository in the JO siting region against normalised corrosion and degradation rates, sampled in Monte-Carlo simulations. The different colours show the dominant pathway for each realisation, i.e., blue: via ramp, red: via shaft, yellow: via CRZ

Fig. 6-116 shows a complicated non-monotonic relationship between the maximum dose rate and the permeability of the V4 seal. The key parameter explaining this behaviour is the corrosion/degradation rate, which determines the gas generation rate. At high gas generation rates (orange/yellow points in the right-most scatter plot), the gas pressure will be at a higher level. Under these conditions, the permeability of the V4 seal shows a positive correlation to the maximum dose rate, which is dominated by advective release via the seal. Increased V4 permeability allows more advective gas flow through the V4 seal, which leads to a higher dose rate. At low gas generation rates (blue/red points in the right-most scatter plot), on the other hand, since the gas pressure in the near-field will stay at a relatively low level, a higher V4 permeability leads to faster saturation of the V4 seal, which then provides more resistance against the gas release along the ramp.

The left-most scatter plot in Fig. 6-116 shows that, at low V4 permeabilities, high dose rates still occur at high gas generation rates, tend to be dominated by releases via either the shafts (red points) or the CRZ (yellow points), rather than by the ramp.

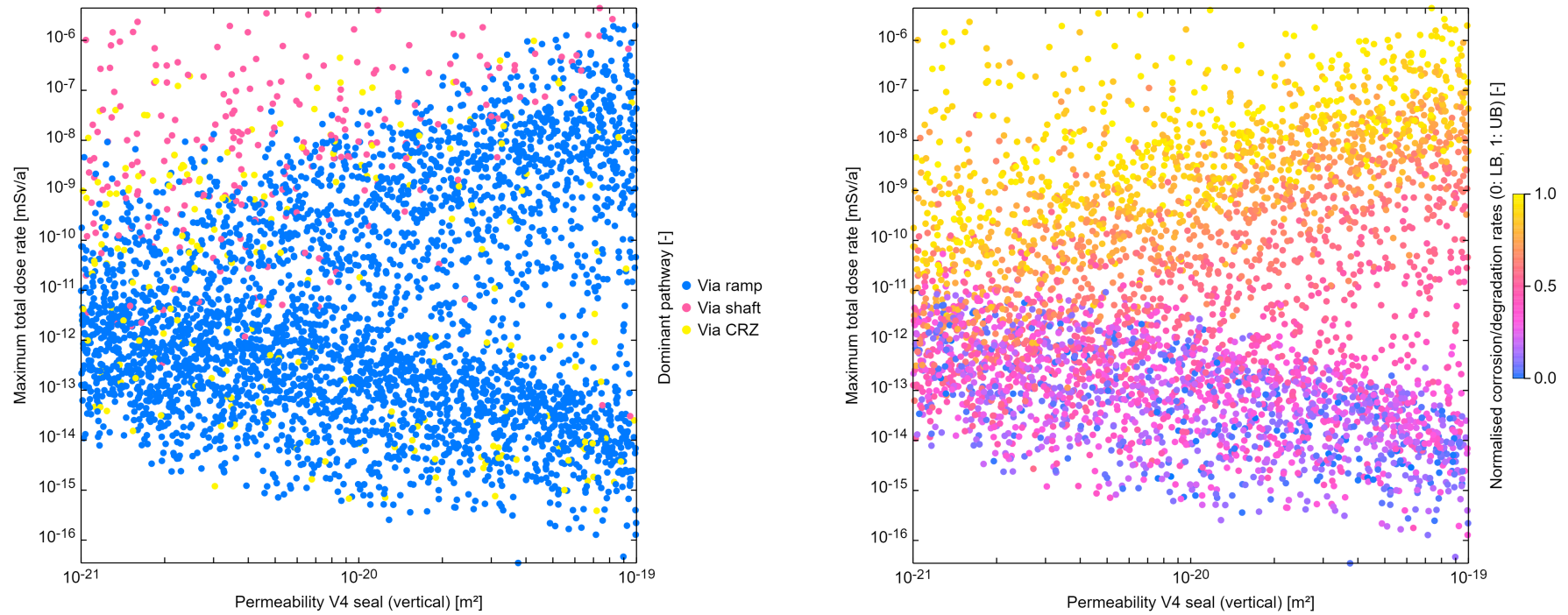


Fig. 6-116: Scatter plots showing the maximum total dose rate of C-14 methane from an L/ILW repository in the JO siting region against the permeability of the V4 ramp seal, sampled in Monte-Carlo simulations. The left plot shows the dominant pathway for each realisation, i.e., blue: via ramp, red: via shaft, yellow: via CRZ. The right shows the corresponding normalised corrosion and degradation rates leading to gas generation (see scale to the right of the plot)

Fig. 6-117 shows the relationship between the maximum dose rate and the permeability of the V3 seals in shafts. In most of the Monte-Carlo realisations, C-14 methane release is dominated by the path via the ramp through the V4 seal (blue points), where transport is dominated either by advection, which is responsible for the comparatively higher dose rates, or by diffusion, which results in comparatively lower dose rates. Since the path via the shaft is less important, there is generally little sensitivity to the permeability of the V3 seal. However, in cases where a more permeable V3 seal occurs in combination with a less permeable V4 seal or Opalinus Clay, C-14 methane released can be dominated by the pathway along the shafts through the V3 seals, as seen by the red points that occur in the upper-right corner of Fig. 6-117.

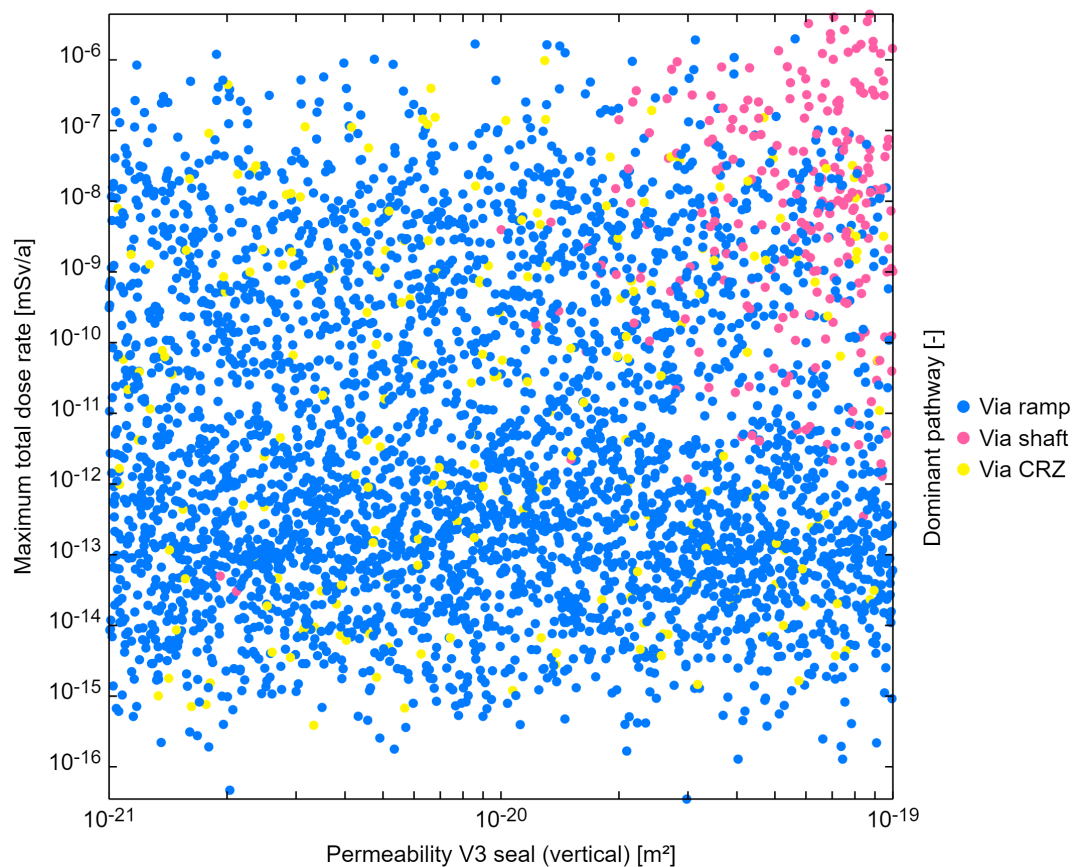


Fig. 6-117: Scatter plot showing the maximum total dose rate of C-14 methane from an L/ILW repository in the JO siting region against permeability of the V3 shaft seals, sampled in Monte-Carlo simulations. The different colours show the dominant pathway for each realisation, i.e., blue: via ramp, red: via shaft, yellow: via CRZ

Fig. 6-118 shows a negative correlation between the maximum dose rate and the vertical permeability of the Opalinus Clay (k_{OPA}). Decreasing the permeability of the Opalinus Clay leads to higher gas pressures within the repository, which forces more C-14 methane along the ramp or up the shafts. This causes the comparatively higher dose rate. However, higher permeability of the Opalinus Clay allows more flow of C-14 methane into the host rock and then diffuses in the CRZ. Thus, there are some simulation realisations with the CRZ as the dominating pathway (yellow points in Fig. 6-118) in the high CRZ permeability area.

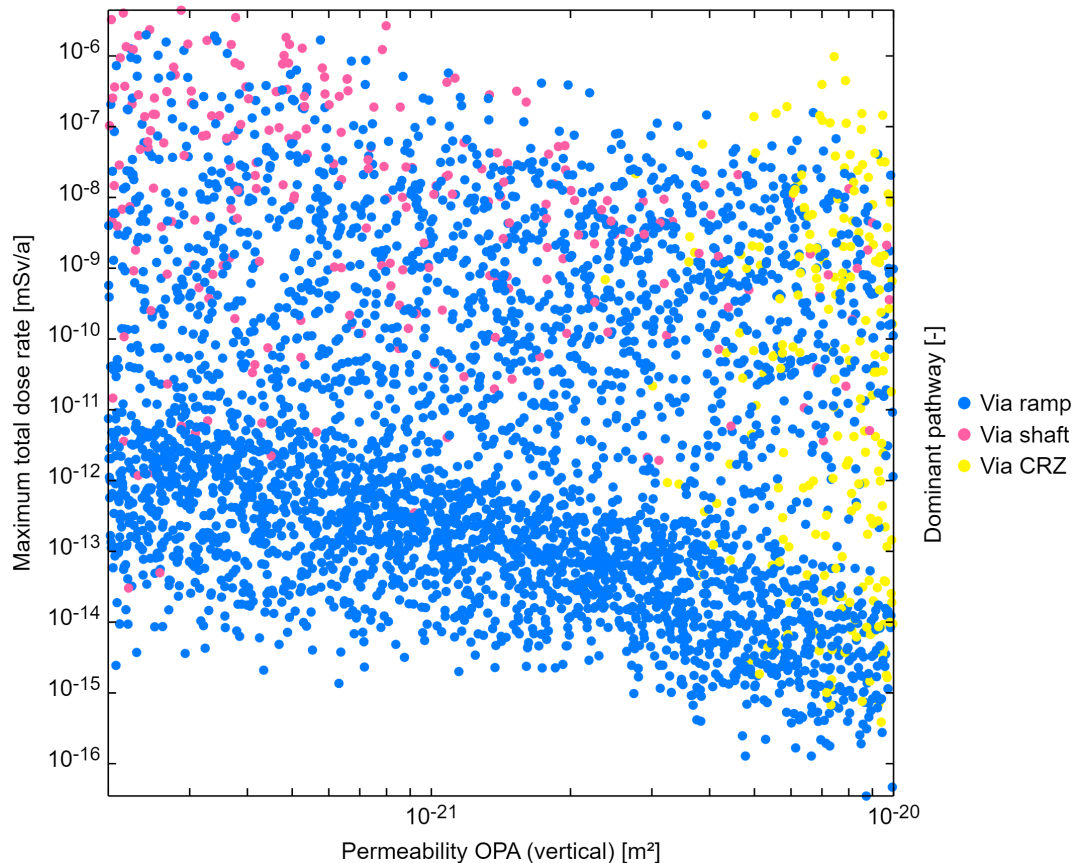


Fig. 6-118: Scatter plot showing the maximum total dose rate of C-14 methane from an L/ILW repository in the JO siting region against permeability of OPA, sampled in Monte-Carlo simulations. The different colours show the dominant pathway for each realisation, i.e., blue: via ramp, red: via shaft, yellow: via CRZ

The sensitivity of the maximum dose rate to the variance in the input parameters is evaluated in terms of sensitivity measures using non-graphical statistical methods. The sensitivity measures are the Pearson correlation coefficient, the Spearman correlation coefficient and the modified EASI first-order sensitivity index (for non-monotonic relationships). Tab. 6-10 shows these sensitivity measures calculated for the sensitive parameters considered in the probabilistic analyses.

Consistent with the scatter plots above, the performance measures indicate a high positive correlation with the corrosion and degradation rates, and hence the gas generation rate, and a negative correlation with the hydraulic conductivity of the Opalinus Clay. There are less pronounced correlations and less consistency between sensitivity measures for other parameters, including, for example, the hydraulic conductivities of the V2 seals and the backfill materials in the tunnel system.

Tab. 6-10: Sensitivity measures for the parameters showing at least one significant correlation with total dose rate of C-14 methane released from an L/ILW repository in the JO siting region

Values above the calculated “threshold of significance” are marked in blue. (+) or (-) indicates the selected bounding value for the individual and combined pessimistic calculations

Parameter	Description	Pearson correlation coefficient	Spearman correlation coefficient	Modified EASI sensitivity index
	<i>Significance threshold</i>	0.053	0.040	0.0044
KorrDegRate_Szenario(+) 0 - 1	Normalised corrosion/degradation rates	0.20	0.84	0.10
k_V3(+) 1×10^{-21} - $1 \times 10^{-19} \text{ m}^2$	Permeability of V3 seal	0.13	0.038	0.021
k_V4(+) 1×10^{-21} - $1 \times 10^{-19} \text{ m}^2$	Permeability of V4 seal	0.10	0.031	0.013
k_OPA(-) 2×10^{-22} - $1 \times 10^{-20} \text{ m}^2$	Permeability of OPA (vertical)	-0.088	-0.20	0.024
por_Rest(-) 0.3 - 0.5	Porosity of the backfill material in the tunnels	-0.070	-0.033	0.010
k_Rest(+) 1×10^{-16} - $1 \times 10^{-14} \text{ m}^2$	Permeability of the backfill material in the tunnels	0.011	0.049	0.0012
De_C14_1_25(-) 8.7×10^{-13} - $3.2 \times 10^{-12} \text{ m}^2/\text{s}$	Eff. diffusion coefficient for C-14 in liquid phase at 25 °C	-0.013	0.044	0.0025
k_V2SMA(+) 5×10^{-19} - $5 \times 10^{-17} \text{ m}^2$	Permeability of V2 seals in the L/ILW section	0.033	0.044	0.0037

In order to provide a better understanding of the impact of various parameters, additional deterministic cases have been analysed, switching each of the individual sensitive parameters to their most pessimistic, bounding values, and, in addition, a “combined pessimistic case” in which all parameters are set to their most pessimistic, bounding values.

The results shown in Fig. 6-119 are in line with expectations from the scatter plots and sensitivity measures, with parameters with higher sensitivity measures, causing a relatively greater increase in the maximum dose rate (e.g., corrosion/degradation rate or permeability of V4 seal) than those with lower sensitivity measures (such as the permeability of the V2 seal). The case in which the pessimistic bounding values of the sensitive parameters are combined results in a far higher dose maximum than any of the individual parameter variations, showing the importance of including combinations of parameters in the analysis. The likelihood of pessimistic bounding values occurring together in this way is low, nonetheless, even in this case, the maximum dose rate ($2.1 \times 10^{-5} \text{ mSv/a}$) remains more than three orders of magnitude below the protection criterion of 0.1 mSv/a.

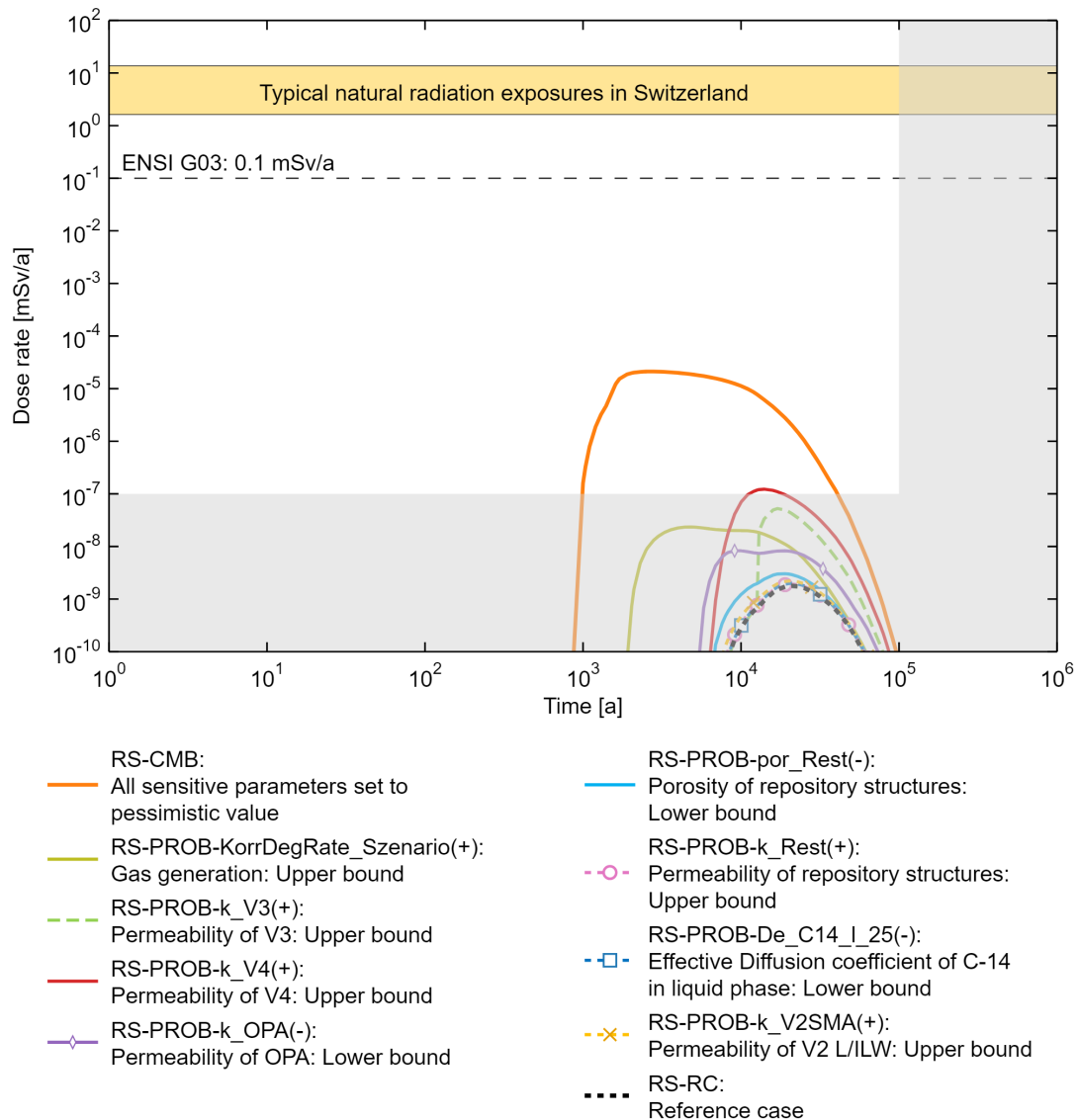


Fig. 6-119: Total dose rates of C-14 methane in the reference case for an L/ILW repository in the JO siting region, and in cases where sensitive parameters are set to their most pessimistic, bounding values, both individually and in combination. (+) indicates the most pessimistic upper bound values and (-) indicates the most pessimistic lower bound values, according to Tab. 6-10

The reference case uses the C-14 BDCF for a reference biosphere based on present-day climatic conditions to convert release rates into dose rates. Fig. 6-120 shows the results of three deterministic calculation cases defined to assume different, though still steady-state, climatic and surface conditions:

- RS-BIOS/WARM_DRY, based on a warmer and drier climate,
- RS-BIOS/COLD, based on a colder climate, and
- RS-BIOS/DRAINED_FARMLAND, which assumes a drained farmland.

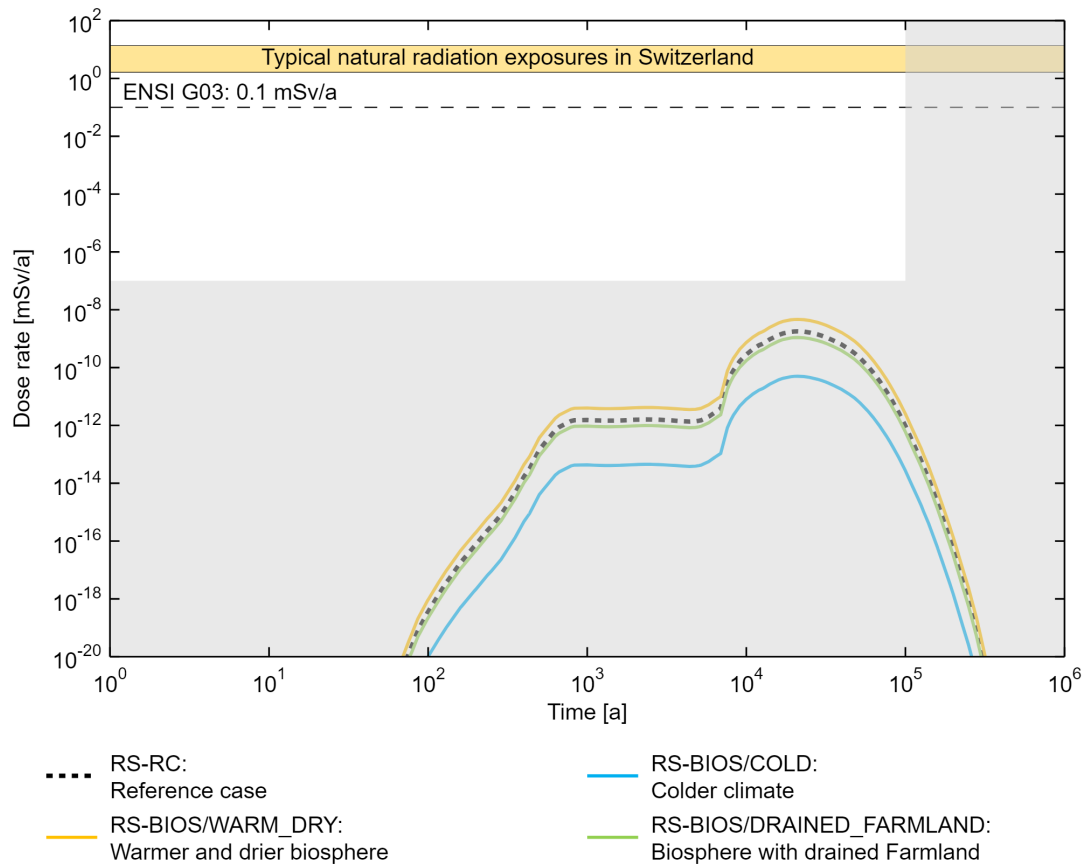


Fig. 6-120: Total dose rates of C-14 methane for an L/ILW repository in the JO siting region in the reference case and in cases assuming different climatic and surface conditions

The maximum dose rates in all cases are well below the level of the significant dose rate of 10^{-7} mSv/a, which shows a high level of robustness of the L/ILW repository in JO regarding the transport of C-14 methane to the biosphere.

6.3.2.2 Nördlich Lägern (NL)

Fig. 6-121 shows statistical percentiles calculated from 4,000 Monte-Carlo simulations of the dose rate evolution due to C-14 methane from an L/ILW repository in the NL siting region, with each simulation carried out by sampling input parameters from probability distribution functions representing parameter uncertainty. Only the most pessimistic realisations give dose rates above the level of the significant dose rate, taken to be 10^{-7} mSv/a, and show a robust safety margin between the calculated dose rates (about 10^{-6} mSv/a) and the protection criterion of 0.1 mSv/a (ENSI 2023). In all the simulation realisations, the maximum dose rates are reached in the time period for assessment, which means the dose rate after 100,000 years is far below the lower bound value of the typical natural radiological exposures in Switzerland (BAG 2021).

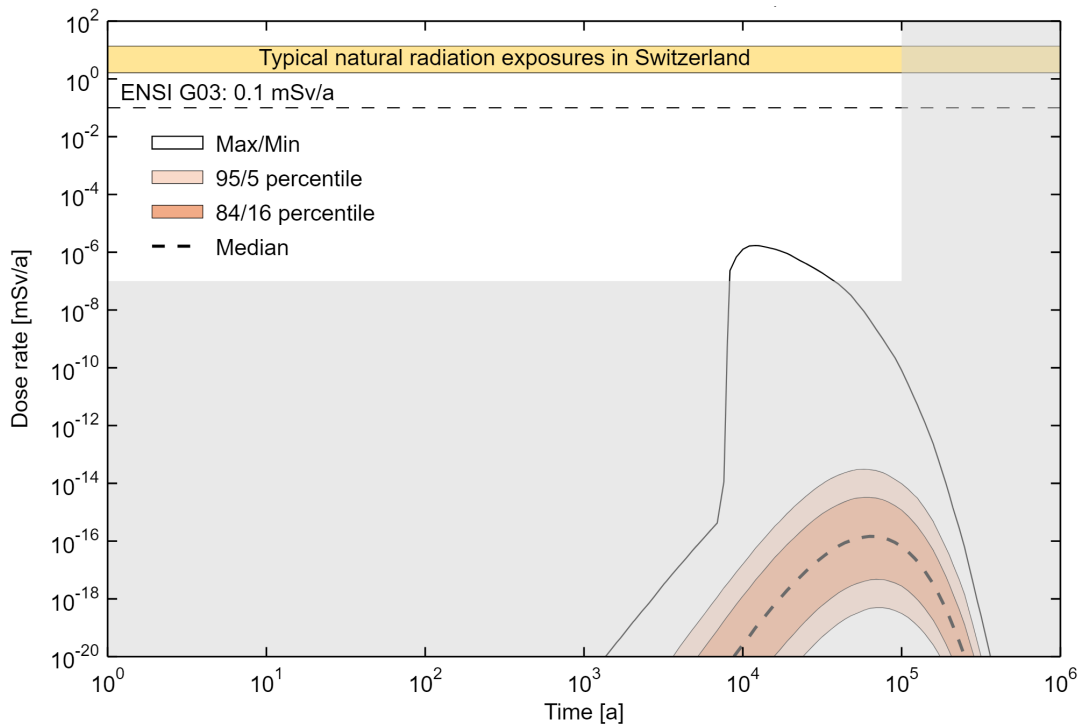


Fig. 6-121: Statistical percentiles of the dose rate evolution of C-14 methane for an L/ILW repository in the NL siting region calculated from 4,000 Monte-Carlo simulations

Sensitivity analyses have been performed based on the results from the Monte-Carlo simulations, with the first step being a graphical analysis using scatter plots. Some examples of such scatter plots are shown in Fig. 6-122 to Fig. 6-125.

The repository in NL is accessed by shaft only, with three shafts instead of the single shaft and single ramp in the provisional design for JO. As discussed in the context of Fig. 6-104, the V3 seal saturates relatively early, and provides a low-permeability barrier against the release of repository-generated gas, including C-14 methane, which is transported to the biosphere from the repository mainly by advection and, once dissolved, by diffusion through the CRZ.

Fig. 6-122 shows that there is no discernible correlation between the maximum dose rate and the corrosion/degradation rates in the simulation realisations when the CRZ behaves as the dominating pathway (yellow points in Fig. 6-122). However, at higher corrosion/degradation rates, when higher gas pressures can result in advection through the shafts (see blue points in Fig. 6-122), some correlation can be detected.

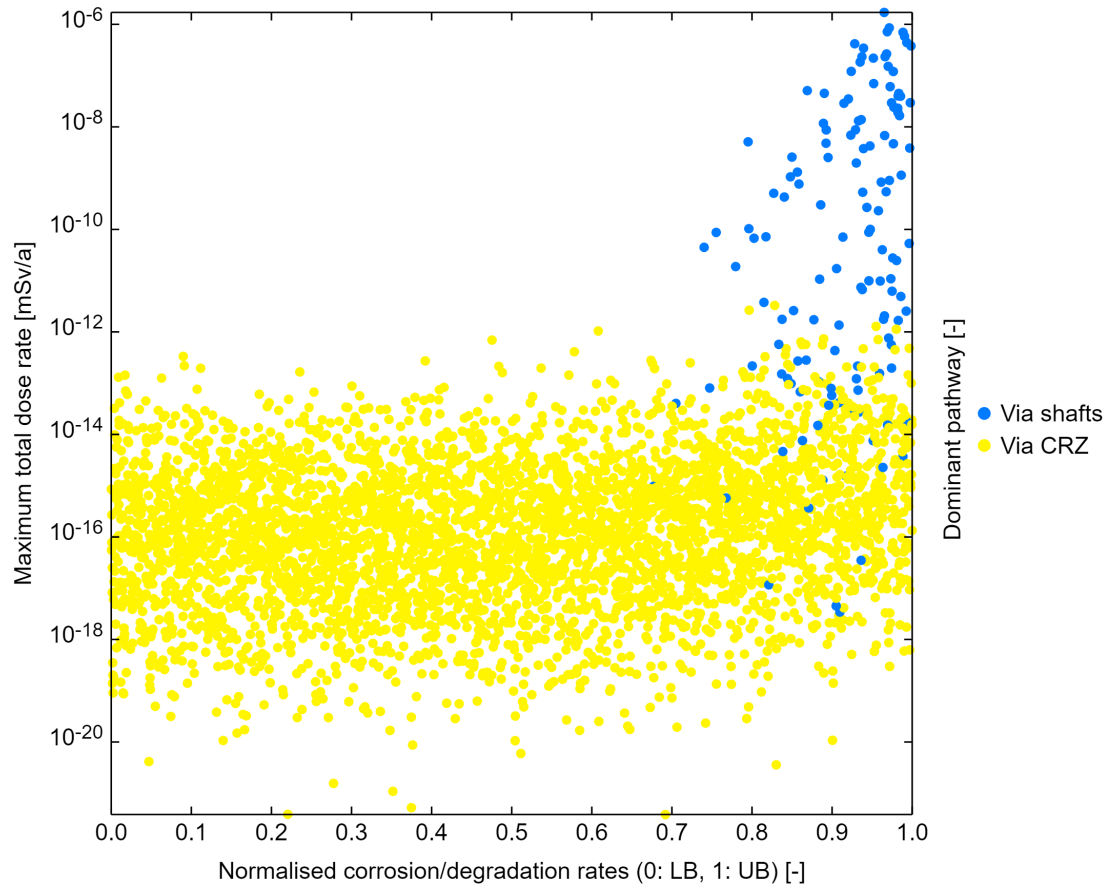


Fig. 6-122: Scatter plot showing the maximum total dose rate of C-14 methane from an L/ILW repository in the NL siting region against normalised corrosion and degradation rates sampled in Monte-Carlo simulations. The different colours show the dominant pathway for each realisation, i.e., blue: via shafts, yellow: via CRZ

The scatter plots in Fig. 6-123 and Fig. 6-124 show that the highest dose rates occur in simulation realisations with more permeable V3 seals (blue points in Fig. 6-123) and with less permeable Opalinus Clay (blue points in Fig. 6-124), meaning that gas containing C-14 methane can more easily pass through the shafts and through their V3 seals.

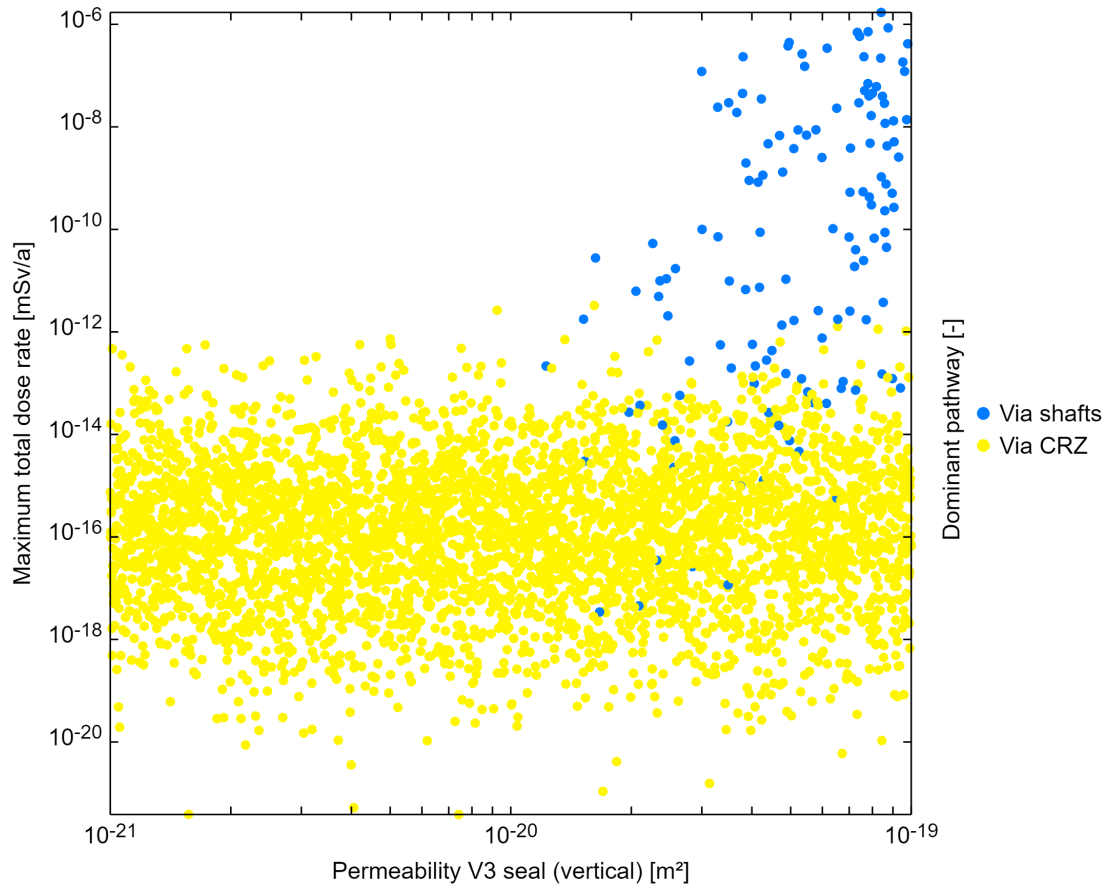


Fig. 6-123: Scatter plot showing the maximum total dose rate of C-14 methane from an L/ILW repository in the NL siting region against the permeability of the V3 seals, sampled in Monte-Carlo simulations. The different colours show the dominant pathway for each realisation, i.e., blue: via shafts, yellow: via CRZ

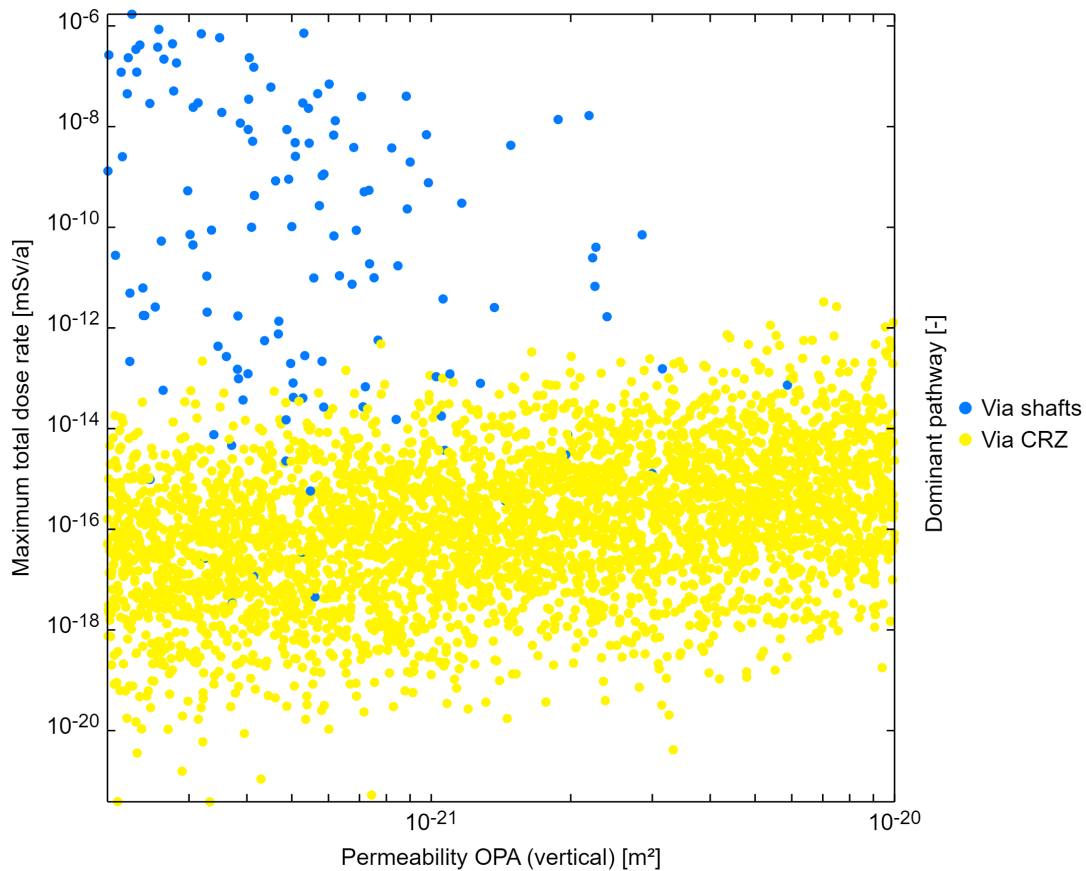


Fig. 6-124: Scatter plot showing the maximum total dose rate of C-14 methane from an L/ILW repository in the NL siting region against the permeability of the Opalinus Clay, sampled in Monte-Carlo simulations. The different colours show the dominant pathway for each realisation, i.e., blue: via shafts, yellow: via CRZ

The scatter plot in Fig. 6-125 shows a clear correlation between the maximum dose rate and the effective diffusion coefficient for C-14 in the Opalinus Clay, in cases where transport through the CRZ dominates (see yellow points in Fig. 6-125), showing that, in the bulk of the host rock, C-14 methane has dissolved in the porewater and diffusion in the CRZ is the dominant transport process.

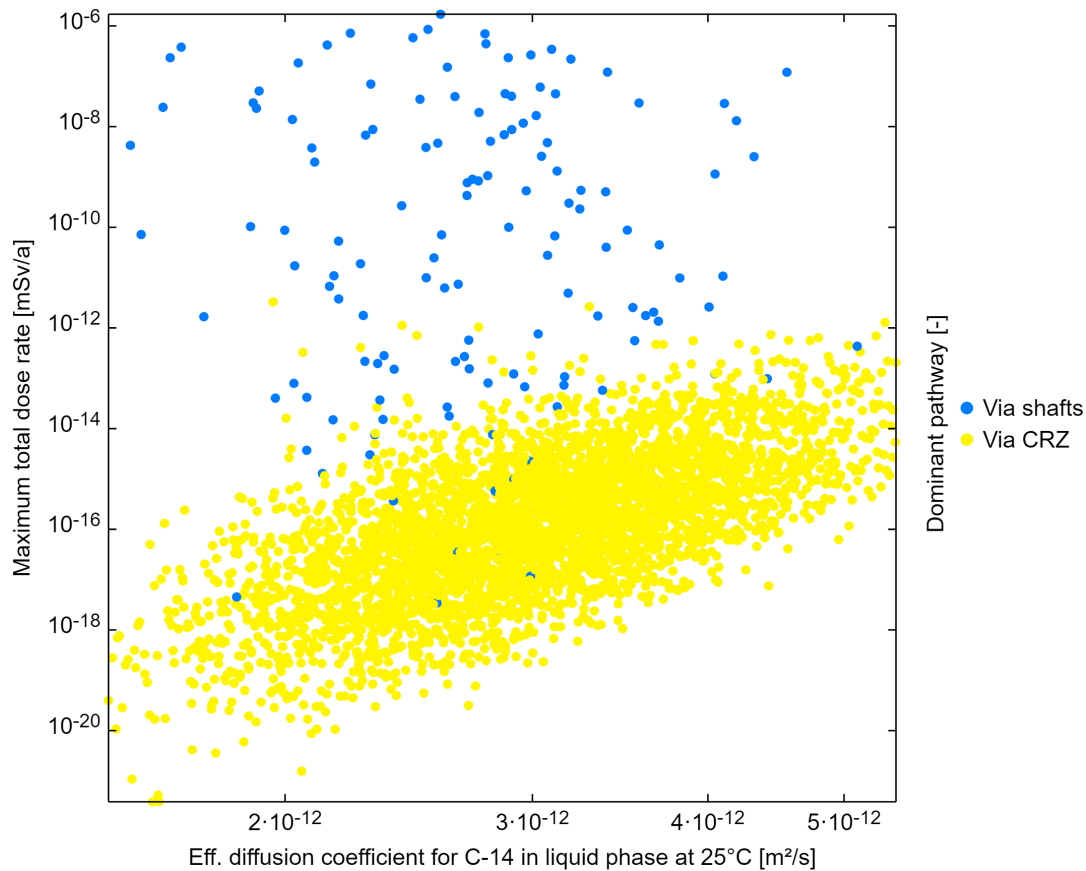


Fig. 6-125: Scatter plot showing the maximum total dose rate of C-14 methane from an L/ILW repository in the NL siting region against the effective diffusion coefficient for C-14 in the Opalinus Clay, sampled in Monte-Carlo simulations. The different colours show the dominant pathway for each realisation, i.e., blue: via shafts, yellow: via CRZ

Just as in the case for JO, the sensitivity of the maximum dose rate to the input parameters is evaluated in terms of the Pearson correlation coefficient, the Spearman correlation coefficient and the modified EASI first-order sensitivity index. Tab. 6-11 shows these sensitivity measures calculated for the parameters considered in the probabilistic analyses.

Similar to JO, the sensitivity measures indicate a high positive correlation with the corrosion/degradation rate, and hence the gas generation rate, and with the permeability of the V3 seals since these can lead to advective C-14 flow through the tunnel system along the shafts, which leads to a comparatively higher dose rate.

Moreover, because the diffusive migration in the CRZ dominates C-14 transport in most of the simulation realisations, the diffusion-relevant parameters such as the effective diffusion coefficient of C-14 in the Opalinus Clay and activation energy (E_a) covering the temperature impact on the diffusion can show sensitivity. Interestingly, both parameters, together with the permeability of the Opalinus Clay, show opposing Pearson and Spearman correlations. This is because increases in the diffusion coefficient, activation energy and the permeability of the Opalinus Clay cause more diffusive gas migration in the CRZ. However, at the same time, increased values of these parameters will reduce the likelihood of advective gas flow along the shafts. The first effect is better captured by the Spearman correlation coefficient, and the latter by the Pearson correlation coefficient. This is because realisations with lower maximum dose can be better captured by the Spearman coefficient thanks to its mathematical transformation (see description in App. G.2.2).

Tab. 6-11: Sensitivity measures for the parameters showing at least one significant correlation with total dose rate of C-14 methane released from an L/ILW repository in the NL siting region

Values above the calculated “threshold of significance” are marked in blue. (+) or (-) indicates the selected bounding value for the individual and combined pessimistic calculations.

Parameter	Description	Pearson correlation coefficient	Spearman correlation coefficient	Modified EASI sensitivity index
	<i>Significance threshold</i>	<i>0.039</i>	<i>0.033</i>	<i>0.0041</i>
k_V3(+) $1 \times 10^{-21} - 1 \times 10^{-19} \text{ m}^2$	Permeability of V3 seals	0.11	0.075	0.016
KorrDegRate_Szenario(+) 0 - 1	Normalised corrosion/degradation rates	0.087	0.21	0.031
k_OPA(-) $2 \times 10^{-22} - 1 \times 10^{-20} \text{ m}^2$	Permeability of OPA (vertical)	-0.046	0.27	0.011
por_Rest(-) 0.3 - 0.5	Porosity of the backfill material in the tunnels	-0.047	-0.077	0.0052
De_C14_1_25(-) $1.5 \times 10^{-12} - 5.5 \times 10^{-12} \text{ m}^2/\text{s}$	Eff. diffusion coefficient for C-14 in liquid phase at 25 °C	-0.036	0.57	0.0026
Ea(-) $1.5 \times 10^4 - 2.5 \times 10^4 \text{ J/mol}$	Activation energy (for temperature correction of eff. diffusion coefficient)	-0.019	0.20	0.0013
k_Rest(+) $1 \times 10^{-16} - 1 \times 10^{-14} \text{ m}^2$	Permeability of the backfill material in the tunnels	-0.014	-0.042	0.0019

In order to provide a better understanding of the impact of various parameters, additional deterministic cases were analysed, switching each of the individual sensitive parameters to their most pessimistic, bounding values. In addition, a “combined pessimistic case” was analysed in which all the sensitive parameters in the table above were set to their most pessimistic, bounding values.

The results shown in Fig. 6-126 are in line with expectations from the scatter plots and sensitivity measures, with parameters for higher sensitivity measures, such as the corrosion/degradation rates and the permeability of the V3 seal, causing a greater increase in the maximum dose rate than parameters for lower sensitivity measures. However, as discussed above, some parameters show an opposing correlation depending on whether the dominant release path is via the CRZ or the shaft. One example is Opalinus Clay permeability: in the combined pessimistic case, in order to capture the most pessimistic bounding combination, the dominant path is via the shafts and the lower bound of Opalinus Clay permeability is selected as the most pessimistic parameter. To remain consistent, it was decided to set up the individual deterministic cases covering the sensitive parameters accordingly, even though these cases show lower dose rate compared to the reference case, because the diffusive migration pathway along the CRZ is still the dominating pathway.

The combined pessimistic case results in a far higher dose maximum than any of the individual parameter variations, showing the importance of including combinations of parameters in the analysis. The likelihood of pessimistic bounding values occurring together in this way is low, nonetheless, even in this case, the maximum dose rate (9.4×10^{-6} mSv/a) remains more than 4 orders of magnitude below the protection criterion of 0.1 mSv/a (ENSI 2023).

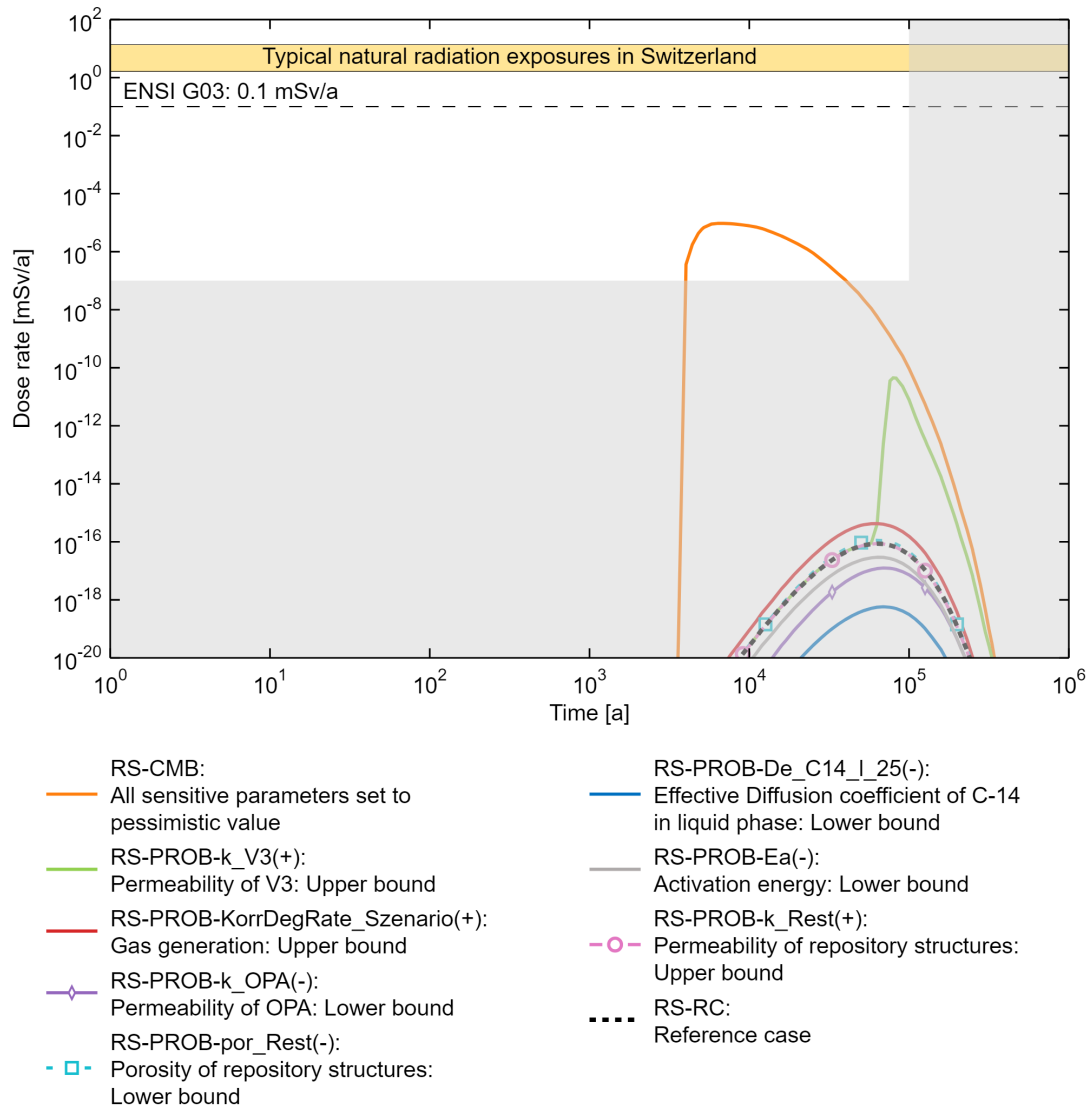


Fig. 6-126: Total dose rates of C-14 methane in the reference case for an L/ILW repository in the NL siting region, and in cases where sensitive parameters are set to their most pessimistic, bounding values, both individually and in combination. (+) indicates the most pessimistic upper bound values and (-) indicates the most pessimistic lower bound values, according to Tab. 6-11

As in the case for JO, Fig. 6-127 shows the results of three additional deterministic calculation cases using BDCFs calculated for different, though still steady-state, climatic and surface conditions.

The maximum dose rates in all cases are well below the threshold of the significant dose rate of 10^{-7} mSv/a, which shows a high level of robustness of the L/ILW repository in NL regarding the transport of the C-14 methane towards the biosphere.

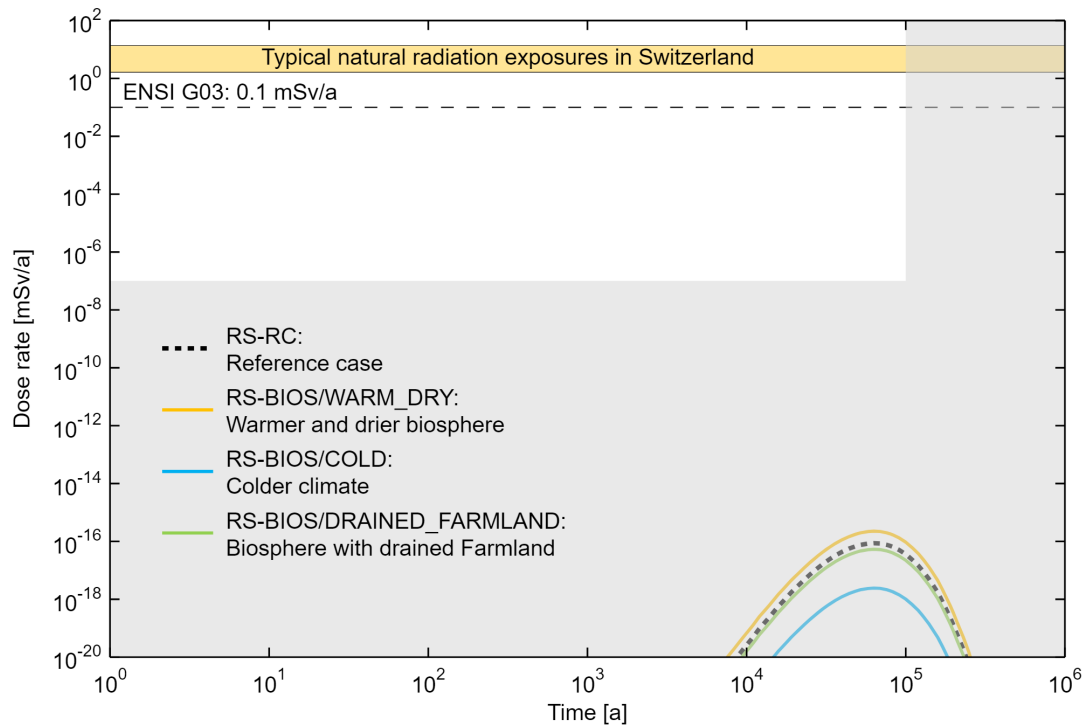


Fig. 6-127: Total dose rates of C-14 methane for an L/ILW repository in the NL siting region in the reference case and in cases assuming different climatic and surface conditions

6.3.2.3 Zürich Nordost (ZNO)

Fig. 6-128 shows statistical percentiles calculated from 4,000 Monte-Carlo simulations of the dose rate evolution resulting from the release of C-14 methane from an L/ILW repository in the ZNO siting region, with each simulation carried out by sampling input parameters from probability distribution functions representing parameter uncertainty. As observed for the other siting regions, only the most pessimistic realisations can give dose rates above the significant dose rate level of 10^{-7} mSv/a, showing a robust safety margin between the calculated maximum dose rates (about 5.3×10^{-6} mSv/a) and the protection criterion of 0.1 mSv/a (ENSI 2023). The 95 percentile dose rates are notably higher than those calculated for the NL siting region, because the repository in ZNO is less deep, leading to higher gas overpressure, which in turn leads to higher release rates of repository-generated gas, including C-14 methane, along the shafts.

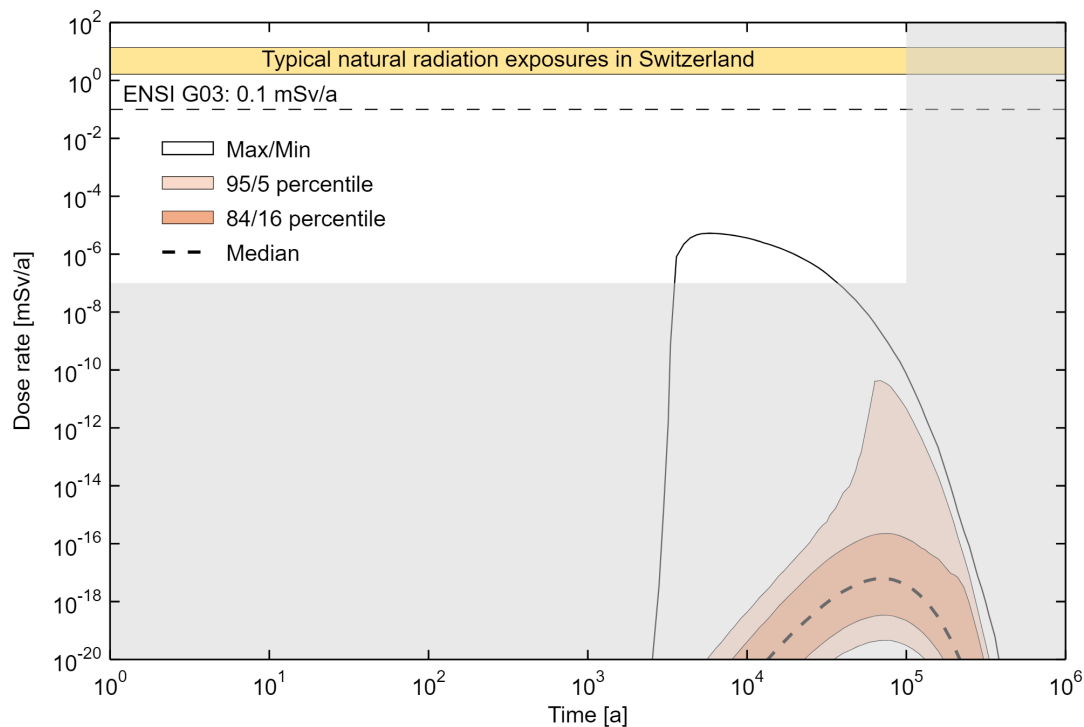


Fig. 6-128: Statistical percentiles of the dose rate evolution of C-14 methane for an L/ILW repository in the ZNO siting region calculated from 4,000 Monte-Carlo simulations

Sensitivity analyses were performed based on the results from the Monte-Carlo simulations, with the first step being a graphical analysis using scatter plots. Some examples of such scatter plots are shown in Fig. 6-129 to Fig. 6-131.

As in the case of NL, the repository in ZNO is accessed by shafts only, with three shafts instead of the single shaft and single ramp in the provisional design for JO. Fig. 6-129 shows that there is a visible correlation between the maximum dose rate and the corrosion/degradation rate, and hence the gas generation rate, especially at high corrosion rates, when the higher gas pressures can result in advection through the shafts becoming the dominant pathway.

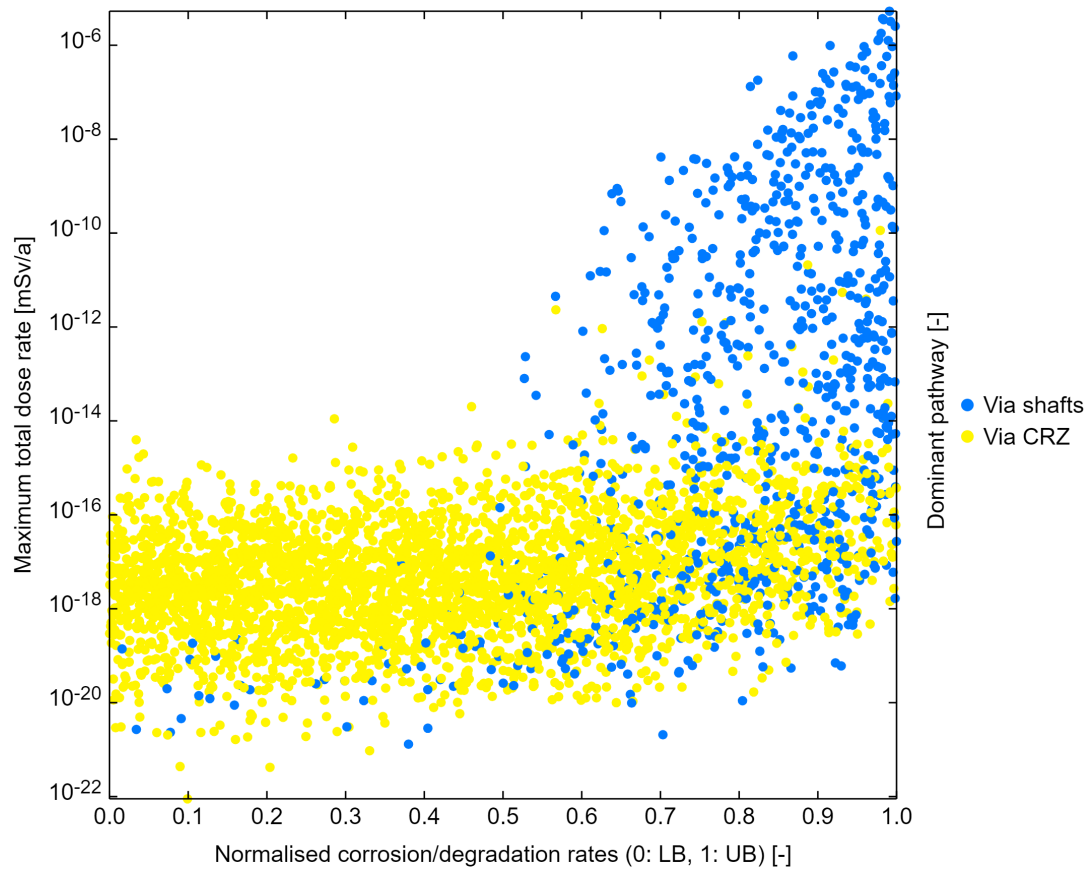


Fig. 6-129: Scatter plot showing the maximum total dose rate of C-14 methane from an L/ILW repository in the ZNO siting region against the normalised corrosion and degradation rates, sampled in Monte-Carlo simulations. The different colours show the dominant pathway for each realisation, i.e., blue: via shafts, yellow: via CRZ

As in the case of the NL siting region, the scatter plots in Fig. 6-130 and Fig. 6-131 show that the highest dose rates occur in cases with more permeable V3 seals and a less permeable Opalinus Clay, meaning that more gas is forced through the shafts and through their V3 seals.

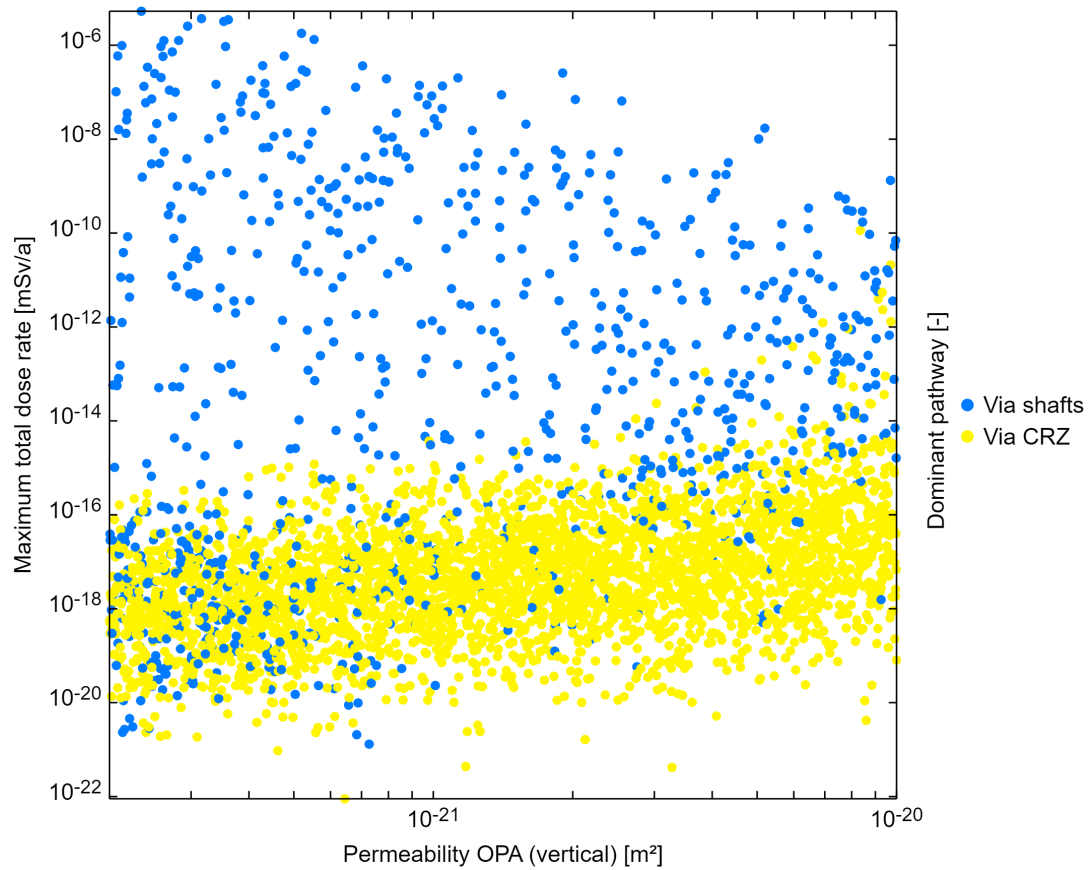


Fig. 6-130: Scatter plot showing the maximum total dose rate of C-14 methane from an L/ILW repository in the ZNO siting region against the permeability of the Opalinus Clay, sampled in Monte-Carlo simulations. The different colours show the dominant pathway for each realisation, i.e., blue: via shafts, yellow: via CRZ

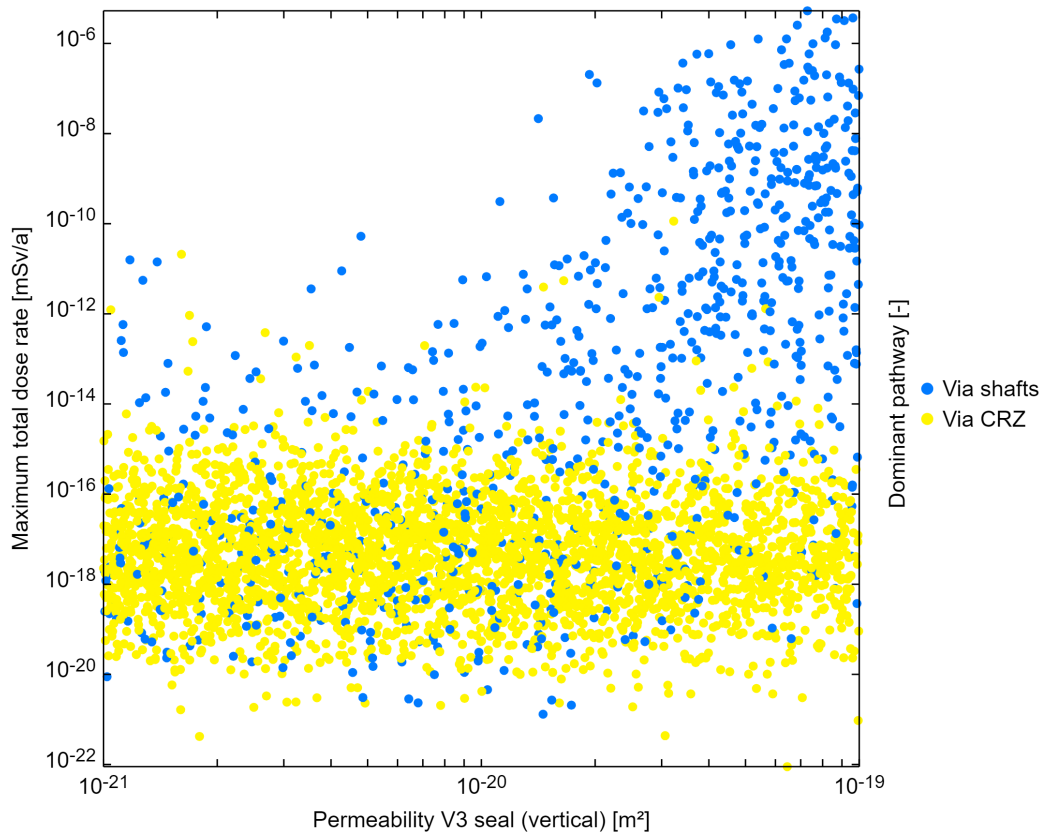


Fig. 6-131: Scatter plot showing the maximum total dose rate of C-14 methane from an L/ILW repository in the ZNO siting region against the permeability of the V3 seals, sampled in Monte-Carlo simulations. The different colours show the dominant pathway for each realisation, i.e., blue: via shafts, yellow: via CRZ

Again, the sensitivity of the variance in the maximum dose rate to the variance in the input parameters is evaluated in terms of the Pearson correlation coefficient, the Spearman correlation coefficient and the modified EASI first-order sensitivity index. Tab. 6-12 shows these sensitivity measures calculated for the parameters considered in the probabilistic analyses.

Consistent with the scatter plots above, and similar to the case of NL, the performance measures indicate a high positive correlation with the corrosion/degradation rate, and hence the gas generation rate, and with the permeability of the V3 seals. As in NL, the permeability of the Opalinus Clay shows opposing correlations in the Pearson and Spearman coefficients, (explained in Section 6.3.2.2).

Tab. 6-12: Sensitivity measures for the parameters showing at least one significant correlation with total dose rate of C-14 methane released from an L/ILW repository in the ZNO siting region

Values above the calculated “threshold of significance” are marked in blue. (+) or (-) indicates the selected bounding value for the individual and combined pessimistic calculations.

Parameter	Description	Pearson correlation coefficient	Spearman correlation coefficient	Modified EASI sensitivity index
<i>Significance threshold</i>		0.038	0.029	0.0033
k_V3(+) $1 \times 10^{-21} - 1 \times 10^{-19} \text{ m}^2$	Permeability of V3 seals	0.13	0.19	0.020
KorrDegRate_Szenario(+) 0 - 1	Normalised corrosion/degradation rates	0.10	0.46	0.040
k_OPA(-) $2 \times 10^{-22} - 1 \times 10^{-20} \text{ m}^2$	Permeability of OPA (vertical)	-0.051	0.29	0.0093
por_Rest(-) 0.3 - 0.5	Porosity of the backfill material in the tunnels	-0.040	-0.027	0.0023
De_C14_1_25(-) $1.7 \times 10^{-12} - 6.6 \times 10^{-12} \text{ m}^2/\text{s}$	Eff. diffusion coefficient for C-14 in liquid phase at 25 °C	0.033	0.40	0.0029
Ea(-) $1.5 \times 10^4 - 2.5 \times 10^4 \text{ J/mol}$	Activation energy (for temperature correction of eff. diffusion coefficient)	0.025	0.087	0.0020

As for the other siting regions, in order to provide a better understanding of the impact of various parameters, additional deterministic cases were analysed, switching each of the individual sensitive parameters to their most pessimistic, bounding values. In addition, a “combined pessimistic case” was analysed in which all parameters are set to their most pessimistic, bounding values.

The results shown in Fig. 6-132 are in line with expectations from the scatter plots and sensitivity measures, with parameters with higher sensitivity measures, such as the corrosion/degradation rate and the permeability of the V3 seal, causing a greater increase in the maximum dose rate than those with lower sensitivity measures. These sensitivities are similar to those observed for a repository in NL, which is to be expected given the similar provisional repository design. The combined pessimistic case gives a far higher dose maximum than any of the individual parameter variations, showing the importance of including combinations of parameters in the analysis. The likelihood of pessimistic bounding values occurring together in this way is low, nonetheless, even in this case, the maximum dose of $1.4 \times 10^{-5} \text{ mSv/a}$ rate remains almost 4 orders of magnitude below the protection criterion of 0.1 mSv/a (ENSI 2023).

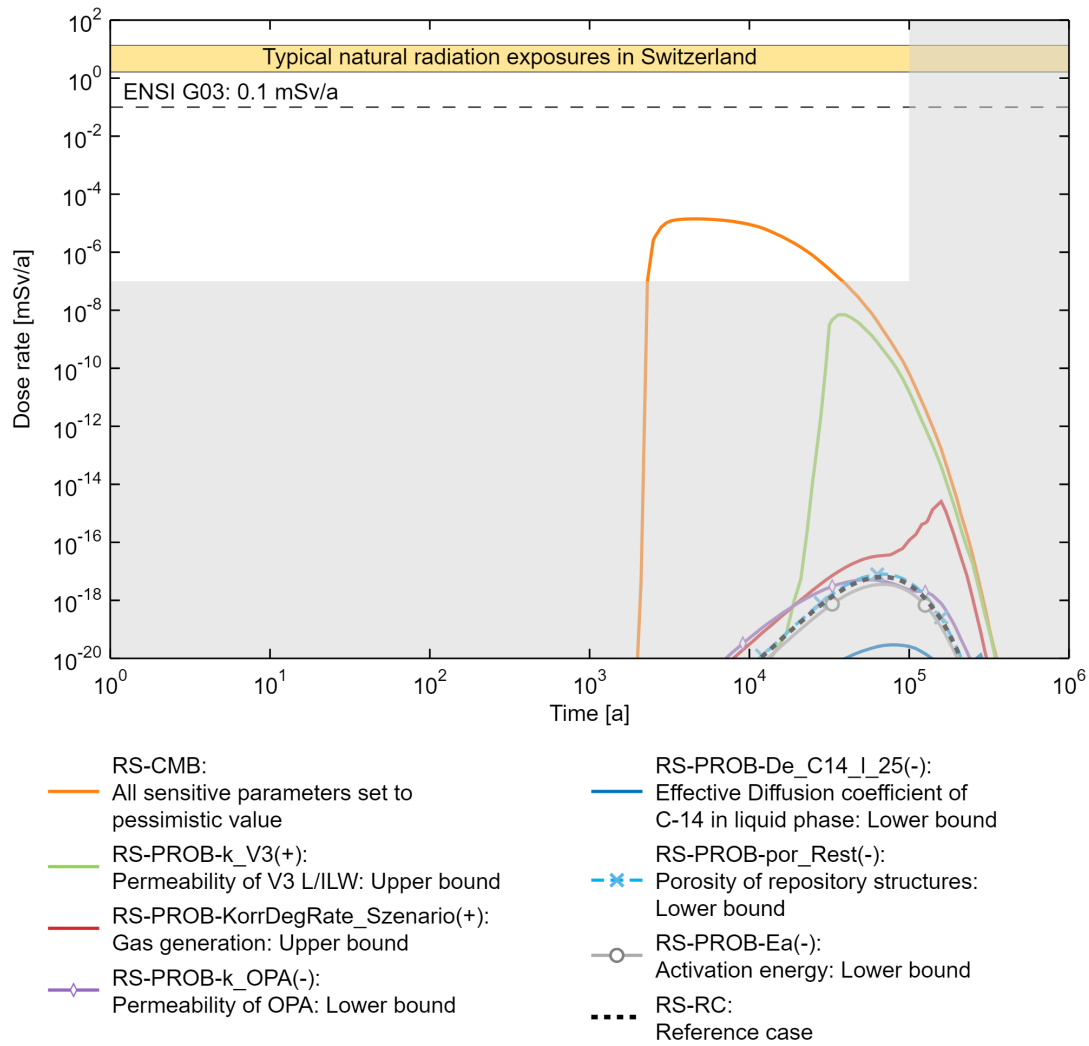


Fig. 6-132: Total dose rates of C-14 methane in the reference case for an L/ILW repository in the ZNO siting region, and in cases where sensitive parameters are set to their most pessimistic, bounding values, both individually and in combination. (+) indicates the most pessimistic upper bound values and (-) indicates the most pessimistic lower bound values, according to Tab. 6-12

Finally, Fig. 6-133 shows the results of three additional deterministic calculation cases using BDCFs calculated for different, though still steady-state, climatic and surface conditions. The maximum dose rates in all cases are well below the threshold of the significant dose rate of 10^{-7} mSv/a, which shows a high level of robustness of the L/ILW repository in ZNO concerning the transport of the C-14 methane towards the biosphere.

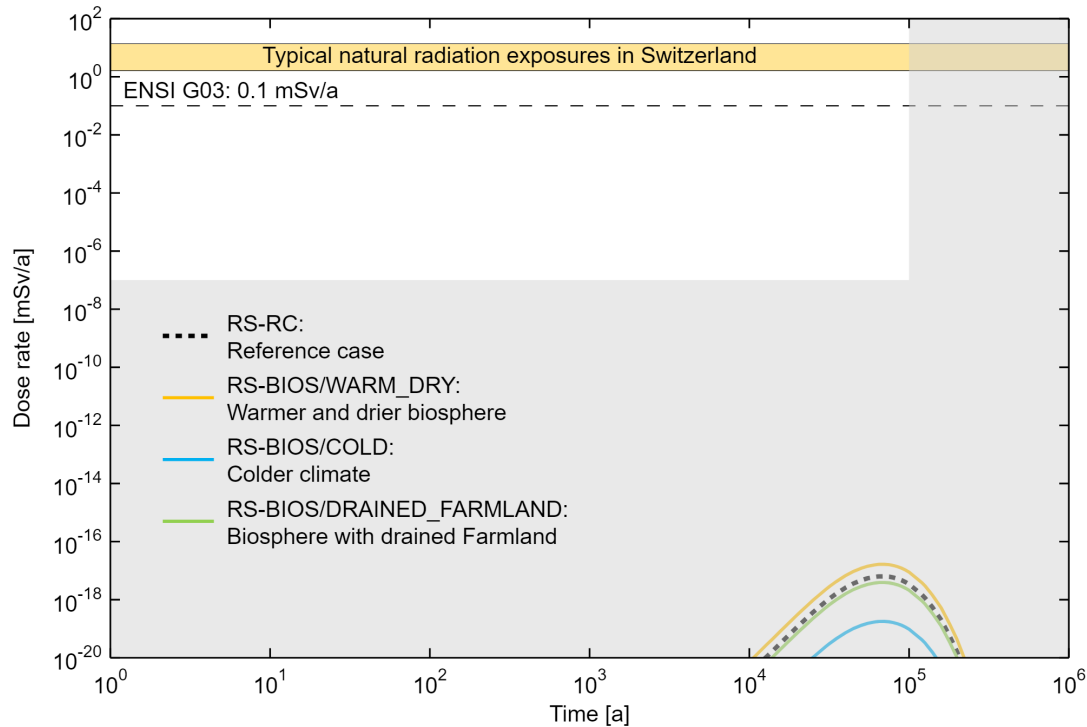


Fig. 6-133: Total dose rates of C-14 methane for an L/ILW repository in the ZNO siting region in the reference case and in cases assuming different climatic and surface conditions

6.3.3 Radiological consequence analysis for the alternative safety scenarios

In addition to the reference safety scenario, alternative safety scenarios are also considered in the site comparison, and are evaluated deterministically, with the results for each siting region presented in the following sections. Sections 6.3.3.1 to 6.3.3.3 focus on an L/ILW repository in each of the three siting regions. Section 6.3.3.4 considers an HLW repository in the three siting regions.

As described in Nagra (2024b) and summarised in Section 4.2, specific uncertainties flagged for further consideration as alternative safety scenarios concern uncertainties in geological characterisation, and, specifically, the possibility that there could be:

- a hydraulically active confining unit above or below the Opalinus Clay; or
- an undetected fault in the vicinity of the repository emplacement rooms.

The variants and calculation cases for these two safety scenarios are summarised in Tab. 4-2 and Tab. 4-3, respectively.

The concepts and models for analysing radionuclide migration in the gas phase in these alternative safety scenarios are described in App. B.2.

6.3.3.1 Jura Ost (JO)

A similar set of calculation cases is analysed as in the case of porewater-mediated transport for an L/ILW repository in JO (Section 6.2.3.1), with the exception that the only hydraulically active confining unit that is considered for gas-mediated transport of C-14 methane is the SCD unit (Sandy-Calcareous Dogger) within the upper confining units, since this is the more unfavourable for gas transport of the two potentially conductive units (SCD and KEU).

Fig. 6-134 shows that assuming that the SCD unit is hydraulically active has no significant impact on dose rate evolution. This is to be expected, since analyses of the reference safety scenario have shown that the ramp is the dominant pathway for the release of repository-generated gas, including C-14 methane, in the case of JO. A hydraulically active SCD unit does not reduce the transport length of gaseous C-14 out of the ramp compared to the reference case.

Two calculation cases are defined for the safety scenario with an undetected fault (see Tab. 4-3):

- AS-FLT-L/ILW-Along, where the fault passes along one of the L/ILW emplacement caverns; and
- AS-FLT-L/ILW-Across, where the fault passes through all the L/ILW emplacement caverns, perpendicularly to their axes.

As in the modelling for the radionuclide transport in the liquid phase, these cases are modelled with extremely conservative assumptions:

- The fault is assumed to exist and connects the two deep aquifers (Keuper and Calcareous Dogger).
- The fault will either partly affect all the L/ILW emplacement caverns (AS-FLT-L/ILW-Across) or one entire emplacement cavern (AS-FLT-L/ILW-Along); it has to be noted that such a fault can be easily detected and avoided.
- Transmissivity of the fault is set to be $10^{-10} \text{ m}^2/\text{s}$ which is not obtained in the investigation of the potential siting region (Nagra 2024e).

There is a clear effect on the dose rate evolution in these cases, because they involve a new pathway that is shorter and more conductive for the gas than the pathways in the reference safety scenario. The case with a fault passing along the emplacement cavern shows an earlier breakthrough than the fault running perpendicularly to the caverns, because the former has a larger interface surface with the affected cavern. This leads to a higher water ingress with a faster liquid saturation and gas pressure increase, and therefore to a more rapid release to the biosphere of the C-14 methane. However, a fault crossing the emplacement caverns has a slightly higher maximum dose rate, because all seven cavern are affected and contribute to the C-14 methane release through the fault.

Even with the increase in the significant dose rate caused by the presence of a fault, a robust safety margin is maintained, with the maximum dose rate more than four orders of magnitude below the protection criterion.

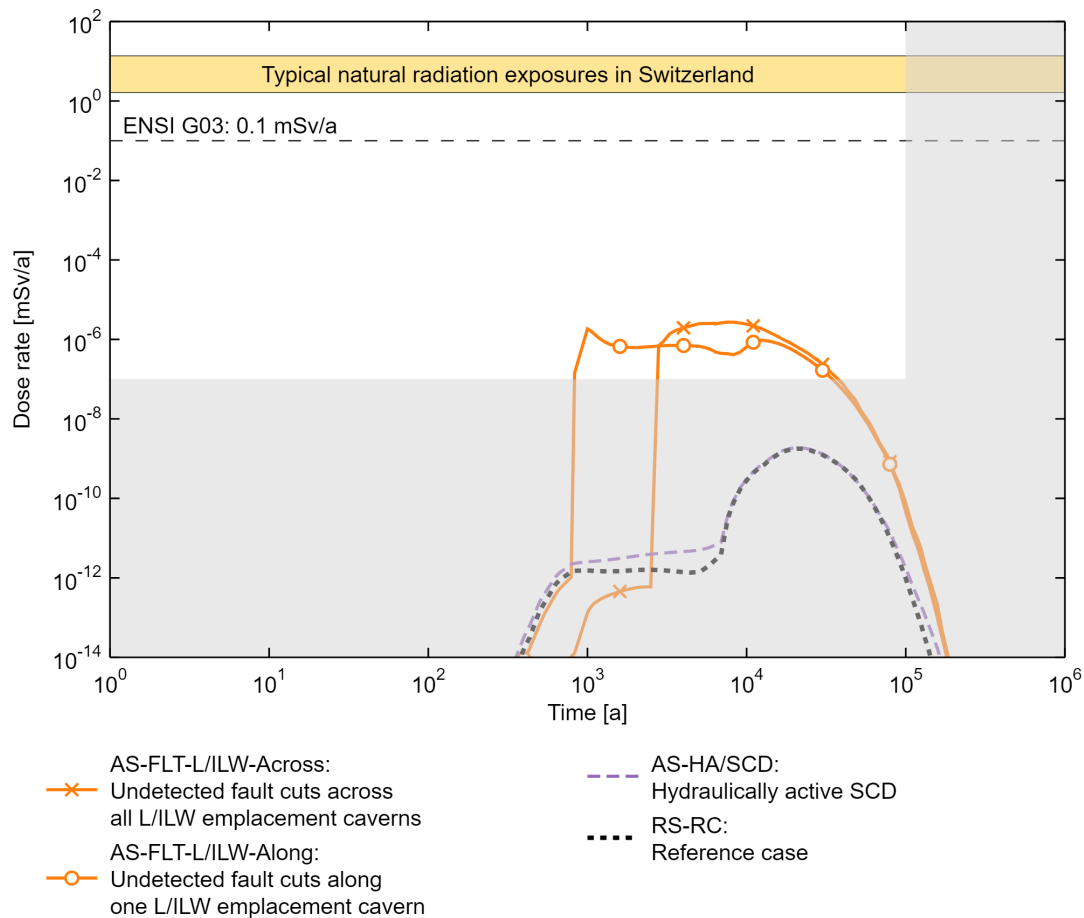


Fig. 6-134: Total dose rates of C-14 methane for an L/ILW repository in the JO siting region in the reference case, for one case where the SCD unit is hydraulically active and for two cases where an undetected fault intersects the emplacement caverns

6.3.3.2 Nördlich Lägern (NL)

The same calculation cases as considered above for an L/ILW repository in the JO siting region have been analysed for NL. The only hydraulically active confining unit that is considered is the SCD unit (Sandy-Calcareous Dogger) in the upper confining units, since this is the most unfavourable one of the various potentially conductive units for gas migration. Fig. 6-135 shows that, unlike in the case of JO, assuming that this unit is hydraulically active has a marked impact on dose rate evolution. This can be understood by noting, as illustrated in Fig. 6-108, that the total dose rate in the reference case is dominated by diffusive transport through the CRZ and confining units. Because the half-life time of C-14 is only about 5,700 years, which is much shorter than the dominating radionuclides I-129 (about 1.6×10^7 years) and Cl-36 (about 3.0×10^5 years) in the liquid phase, the transport time (transport length) is an important factor for the dose rate due to the C-14 release. The assumption of a hydraulically active SCD unit results in a significant shortening of the diffusive transport pathway within the CRZ, leading to an increase in the dose rate compared to the reference case.

The same conservatism as for an L/ILW repository in JO is considered for the cases concerning an undetected fault. The effect is similar to that of a repository in the JO siting region (Fig. 6-134), because it leads to a new pathway from the repository, which is shorter and more conductive for the gas than the pathways of the reference safety scenario, resulting in higher dose rates. As in the case of JO, resulting peak dose rates are higher for the fault running across all the emplacement caverns compared to the fault running along one emplacement cavern.

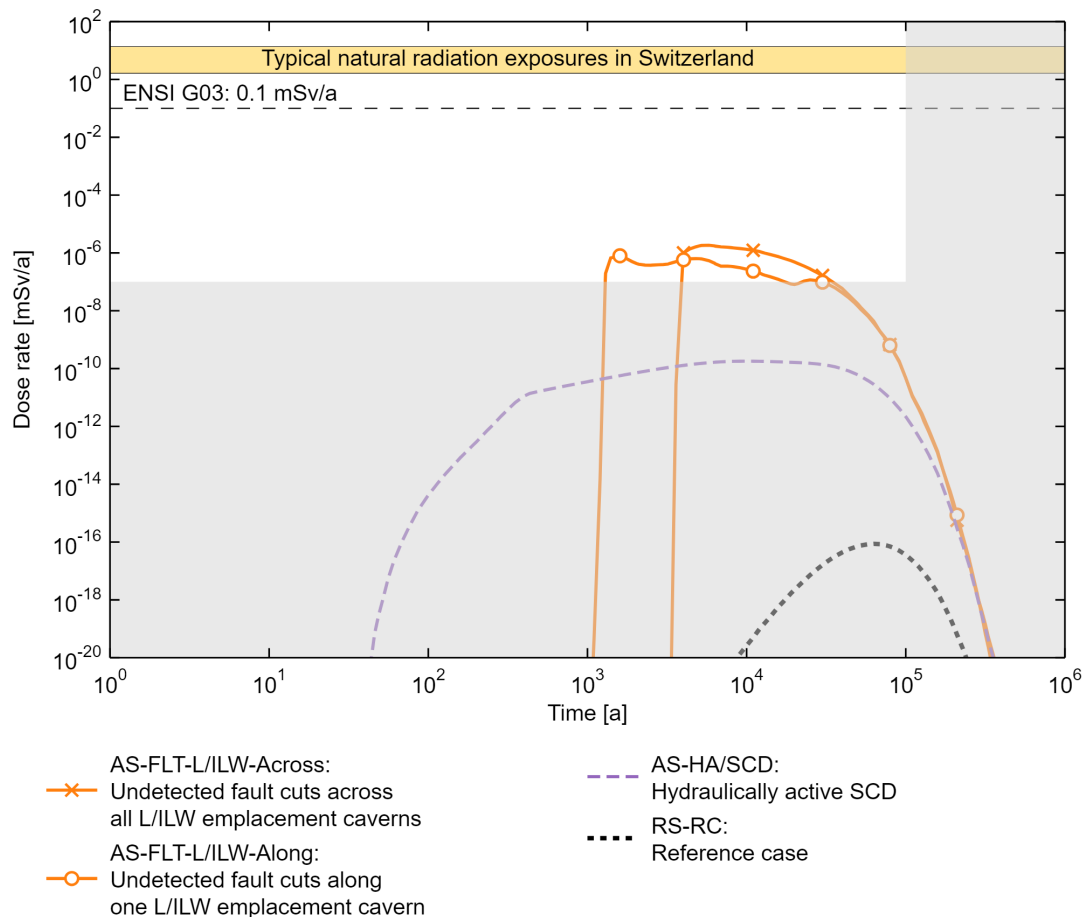


Fig. 6-135: Total dose rates of C-14 methane for an L/ILW repository in the NL siting region in the reference case, for one case where the SCD unit is hydraulically active and for two cases where an undetected fault intersects the emplacement caverns

6.3.3.3 Zürich Nordost (ZNO)

The results for an L/ILW repository in ZNO (Fig. 6-136) are very similar for those of NL, due to the similarity in the provisional repository design. As in all the cases for the alternative safety scenarios, a robust safety margin is maintained.

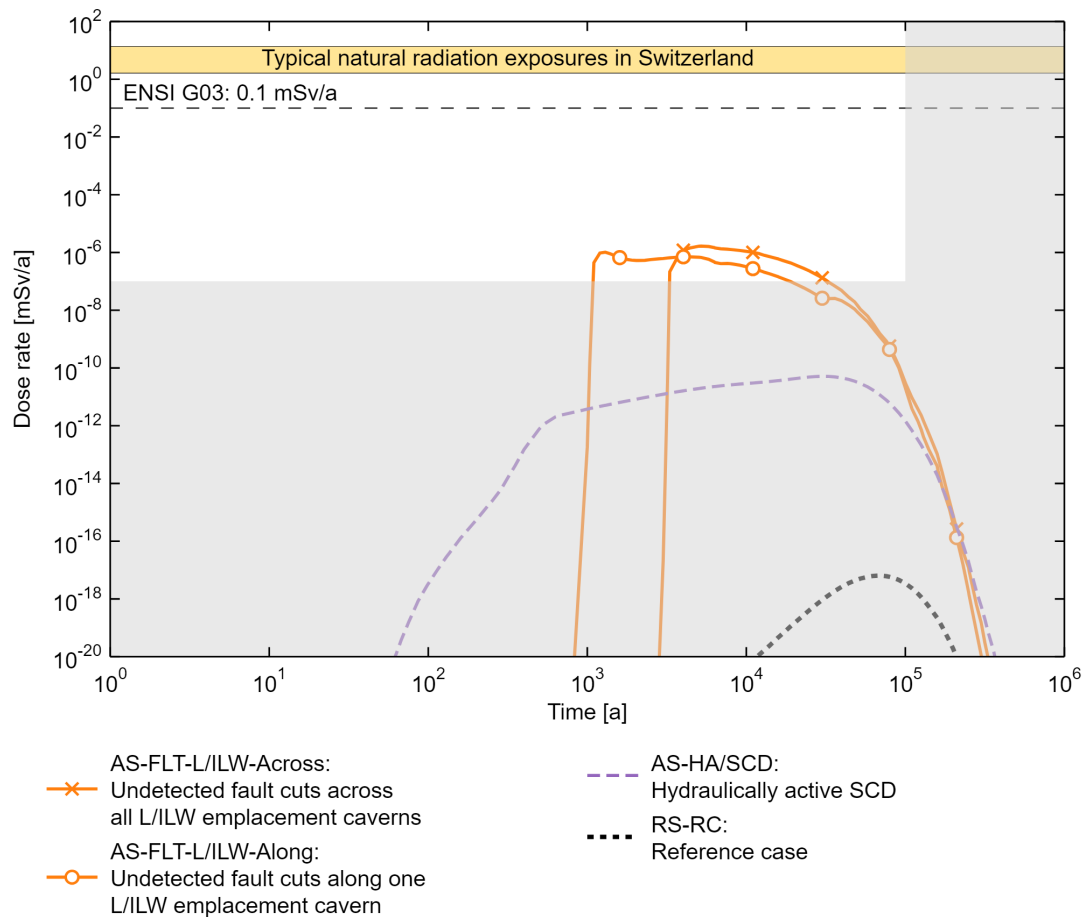


Fig. 6-136: Total dose rates of C-14 methane for an L/ILW repository in the ZNO siting region in the reference case, for one case where the SCD unit is hydraulically active and for two cases where an undetected fault intersects the emplacement caverns

6.3.3.4 Calculation cases concerning an undetected fault in an individual HLW repository

As mentioned at the beginning of Chapter 6.3, the transport of C-14 methane in the gas phase from an HLW repository is considered in the analysis of the alternative safety scenario involving an undetected fault, since this could lead to more rapid migration of C-14 to the biosphere.

Fig. 6-137 shows the total dose rates in the reference case for C-14 containing methane release for an HLW repository in all three siting regions, and for six cases (two for each siting region) of an undetected fault intersecting the emplacement drifts:

- AS-FLT-HLW-Along, where the fault passes along one of the HLW emplacement drifts; and
- AS-FLT-HLW-Across, where the fault passes through all the HLW emplacement drifts, perpendicularly to their axes.

Because just a part of the HLW emplacement drift(s) are affected by the fault, a small part of the total C-14 methane inventory can be released more quickly into the biosphere, therefore, for all the cases for the alternative safety scenarios concerning an undetected fault, a robust safety margin is still maintained. JO is the only siting region, where undetected fault leads to significant dose rate ($>1\text{e-}7$ mSv/a). Still, a robust safety margin of 5 orders of magnitude exists.

To understand the results for the cases with an undetected fault intersecting the HLW emplacement drift(s), the following system behaviour must be considered:

- For the fault along an emplacement drift, C-14 methane release is driven by gas generation from all canisters in this single emplacement drift (about 100 canisters). Most of the generated gas flows into the fault. Only a minor part can migrate into EDZ and Opalinus Clay.
- For the fault across all emplacement drifts, C-14 methane release has two drivers:
 - i) gas generated from the canisters in the fault plane (one per tunnel, total of 20) that feeds directly into the fault.
 - ii) gas generated from canisters outside the fault plane that feeds via EDZ/OPA into the fault. Lateral gas migration along the drifts towards the fault is prevented by the tight bentonite backfill and small drift cross section.

The HLW repository at NL has the deepest location with the lowest overpressures and the longest transport distance from the repository through the fault to the upper aquifer. In this case, driver ii) dominates the C-14 methane release through a fault running perpendicularly through all of the HLW emplacement drifts, i.e. gas generated by the high number of canisters outside the fault plane. Therefore, C-14 methane release starts earlier and has a higher peak for the fault running perpendicularly through all of the HLW emplacement drifts compared to the fault running along just one drift.

ZNO shows a similar behaviour; driver ii) still dominates the C-14 methane release, but driver i) becomes more important due to the lower depth and higher overpressures combined with the lower transport distance through the fault. These factors reduce the difference between the two cases concerning the orientation of the fault terms of initiation time and peak rates of the C-14 release.

In JO, which is located at even lower depths with higher overpressures and lower transport distances, driver i), i.e. gas generation from a small number of canisters in the fault plane, dominates gas and C-14 methane release through the crossing fault. In this case, the fault along a drift shows an earlier and higher C-14 methane release compared to the crossing fault.

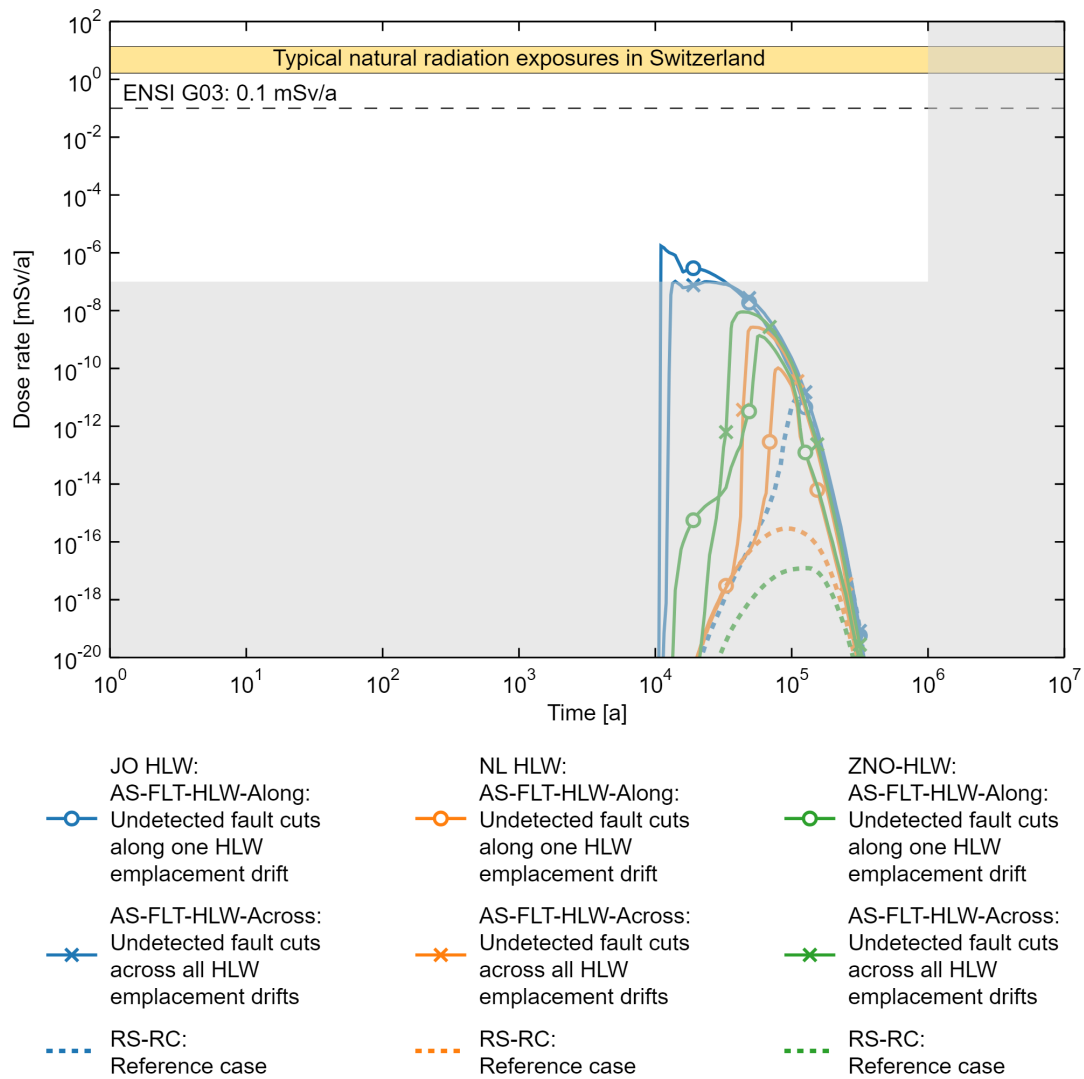


Fig. 6-137: Total dose rates of C-14 methane in the reference case for an HLW repository in all three siting regions, and for six cases (two for each siting region) with an undetected fault intersecting the emplacement drifts

6.3.4 Comparison between the siting regions

Consistent with the radiological consequence analysis in Stage 2 of the SGT process (Nagra 2014b), 0.01 mSv/a can be considered as a threshold dose rate below which the siting regions under consideration should be considered equivalent from a post-closure safety perspective (see Fig. 2.1-3 in Nagra (2014c)).

The dose rate evolution in the reference case for C-14 methane from an L/ILW repository in all three siting regions is illustrated in Fig. 6-138. For all siting regions, the L/ILW repository shows a robust safety margin, with dose rates remaining well below the level of significant dose rate of 10^{-7} mSv/a. The radiological consequences of C-14 methane from the L/ILW repository in the reference case can thus be considered equivalent, and negligible, in all three siting regions. Nevertheless, the highest dose rates are for a repository in the JO siting region, where the dominant release pathway is advection along the ramp and through the V4 seal. For the other siting regions, diffusive transport through the CRZ is the dominant pathway in the reference case.

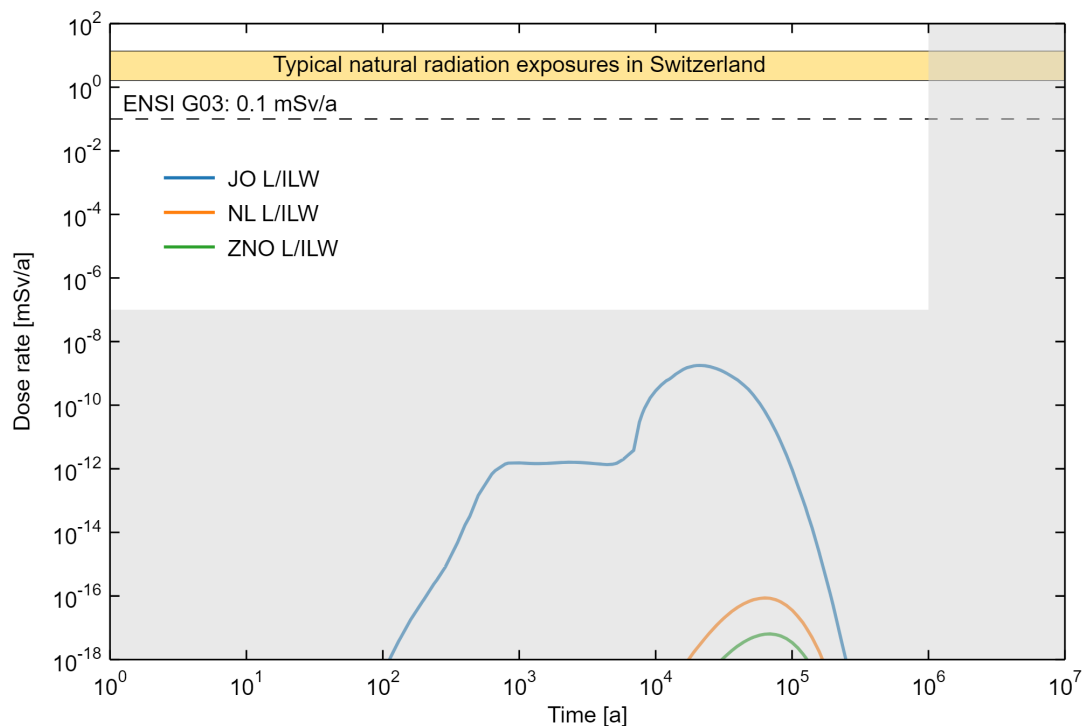


Fig. 6-138: Total dose rates of C-14 methane in the reference case from an L/ILW repository in all three siting regions

The characteristic dose intervals in Fig. 6-139 are based on the maximum dose rates in the probabilistic simulations. For each set of simulations, the dose rate intervals for all three siting regions are far below the protection criterion of 0.1 mSv/a, which shows the robustness of the safety margin.

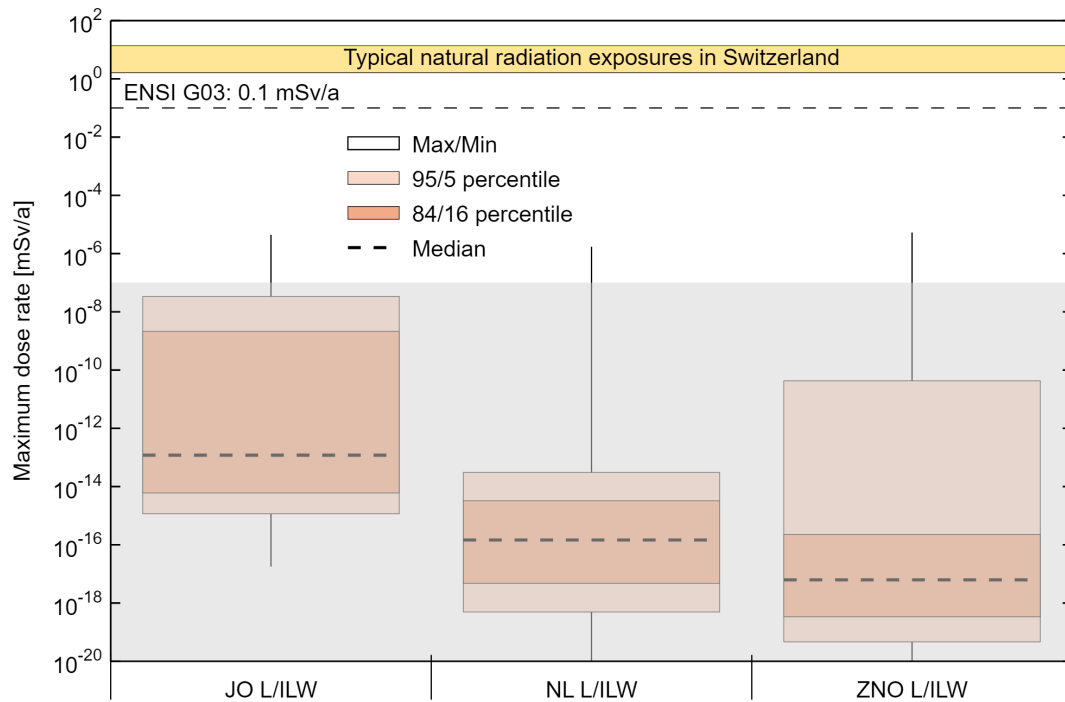


Fig. 6-139: Characteristic dose intervals of C-14 methane based on the results of the probabilistic dose calculations carried out for an L/ILW repository in the three siting regions. The box plots show the maxima of the 0%, 5%, 16%, 50%, 84%, 95% and 100% percentiles.

The characteristic dose intervals in Fig. 6-140 are based on the maximum dose rates in the “combined pessimistic cases” (RS-CMB) and different assumptions for the climate and surface conditions. Consistently with probabilistic simulations, the repository in the JO siting region produces the highest dose rates. However, the RS-CMB cases combining pessimistic values of sensitive parameters give rise to comparable maximum dose rates.

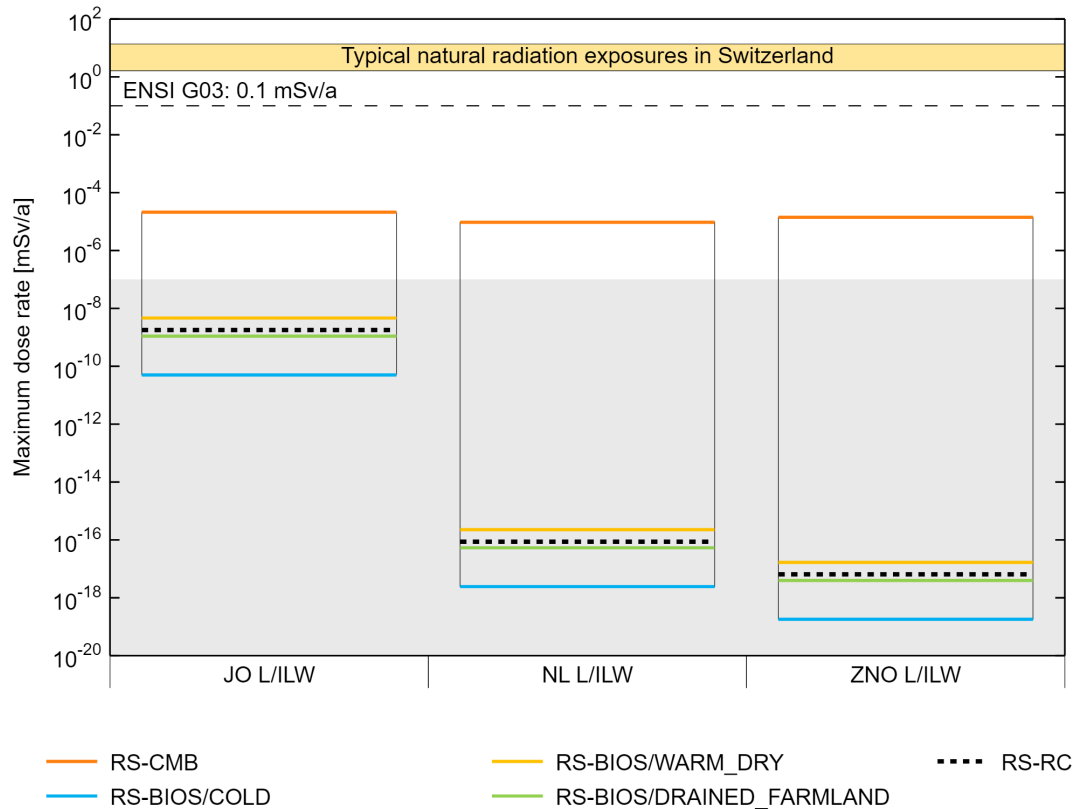


Fig. 6-140: Characteristic dose intervals of C-14 methane based on deterministic calculations carried out for combined pessimistic cases, as well as different assumptions for the climate and surface conditions, for an L/ILW repository in the three siting regions

Finally, the dose intervals shown in Fig. 6-141 are based on deterministic calculations carried out for the reference case and for the alternative safety scenarios. The results of the cases considering an undetected fault passing through the L/ILW emplacement caverns are comparable in the three siting regions. On the other hand, in the cases considering an undetected fault passing through the HLW emplacement drifts, the maximum dose rates for the NL and ZNO siting regions are, as in the reference case, lower than those for JO. All the cases, however, have large safety margins compared with the protection criterion of 0.1 mSv/a.

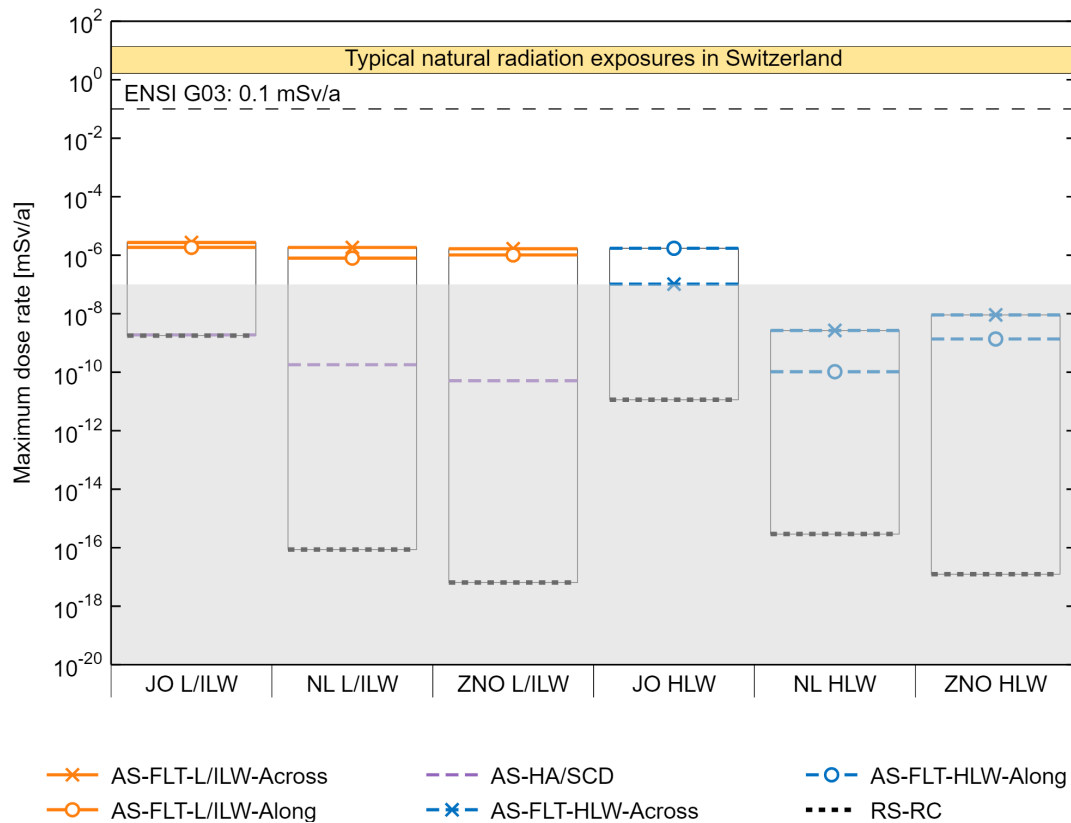


Fig. 6-141: Characteristic dose intervals of C-14 methane based on deterministic calculations carried out for the reference safety scenario and for the alternative safety scenarios for the L/ILW and HLW repositories in the three siting regions

Since the characteristic dose intervals in the current section are all far lower than 0.01 mSv/a, the siting regions can be considered equivalent concerning C-14 methane from a post-closure safety perspective.

6.4 Discussion on two repository options: combined repository vs. two separate repositories for HLW and for L/ILW

According to the description of the reference safety scenario in Section 4.1, diffusion is the primary transport mechanism for radionuclides dissolved in the liquid phase within the repository's near-field. This is mainly due to the low hydraulic conductivity of the sealing system, the bentonite buffer, and the surrounding CRZ, as well as the dead-end design of the emplacement drifts and caverns. The EDZ around the HLW emplacement drifts does not represent a significant lateral transport pathway for dissolved radionuclides (Nagra 2024p). Advection of dissolved radionuclides due to the displacement of near-field porewater by gas can be considered negligible (Nagra 2024p).

Therefore, when considering radionuclide transport in the liquid phase, radionuclides are assumed to be released directly from the L/ILW emplacement caverns and HLW emplacement drifts into the host rock; the other underground openings and access structures are assumed not to provide a significant release pathway. Thus, for a combined repository, the radionuclide transport in the liquid phase can be considered separately for the HLW and L/ILW repository sections, meaning that the radiological consequences of radionuclide transport in the liquid phase are the same for the individual repository sections as they are for separate HLW and L/ILW repositories considered in Sections 6.1 and 6.2. This is not, however, the case for radionuclide transport in the gas phase, where the differences in layout, and hence differences in the gas storage volume, between a combined repository and two separate repositories affects the fate of repository-generated gas, and hence of the release rates of C-14 methane to the biosphere. The impact of these differences is explored further in this section.

As discussed in Section 6.3, the main source of gas and C-14 methane that is transported towards the access tunnels and shafts is the L/ILW, and so the following comparison focuses on the L/ILW section of a combined repository in the NL siting region and on a separate repository for L/ILW in NL. The following cases are considered:

- The reference case for a separate L/ILW repository in the NL siting region, as described in Section 6.3.1.2 and the reference case for a combined repository, which will be shown in Section 7.2.1.1.

In both cases, the dose rate is dominated by migration through the CRZ.

- The case combining pessimistic bounding values for all sensitive parameters for a separate L/ILW repository in the NL siting region, as described in Section 6.3.2.2, and the corresponding case for a combined repository, which will be shown in Section 7.2.1.2.

In both cases, the dose rate is dominated by advective release via the repository shafts.

The most important characteristics of the combined and single L/ILW repository are summarised in Tab. 6-13. The two main differences are the accessible pore volume of the backfill materials, which is 30% higher in the combined repository, and the total tunnel length (which is also proportional to the gas storage volume in EDZ), which is 40% higher.

Tab. 6-13: Summary of the main characteristics relevant to C-14 methane transport for a separate L/ILW repository and for a combined repository

	Separate L/ILW	Combined
Depth of central area (m)	835	835
Pore volume (m ³)	211,312	281,103
Length of tunnels (m)	7,992	10,978
Thickness of upper confining units (m)	150	150
Thickness of the Opalinus Clay (m)	107	107
Thickness of lower confining units (m)	69	69

Fig. 6-142 shows the dose rate due to C-14 methane in all four cases.

In the reference cases, there is no advective gas and C-14 release via the shafts (see Sections 6.3.1.2 and 7.2.1.1). Transport of C-14 methane is dominated by diffusive transport through the CRZ, the parameters for which are identical in both reference cases. Therefore, no difference in the dose rate can be observed between a combined repository and a separate L/ILW repository.

In the cases combining pessimistic bounding values, the combined repository shows lower C-14 dose rates than the separate L/ILW repository. This is attributable to the higher pore volume, and hence gas storage volume in the tunnels and EDZ (proportional to tunnel length) in the combined repository, which leads to lower gas pressures and flow rates of gas, including C-14 methane, through the V3 seals to the biosphere. Note, however, that in all cases, the dose rates are still well below the protection criterion of 0.1 mSv/a (ENSI 2023).

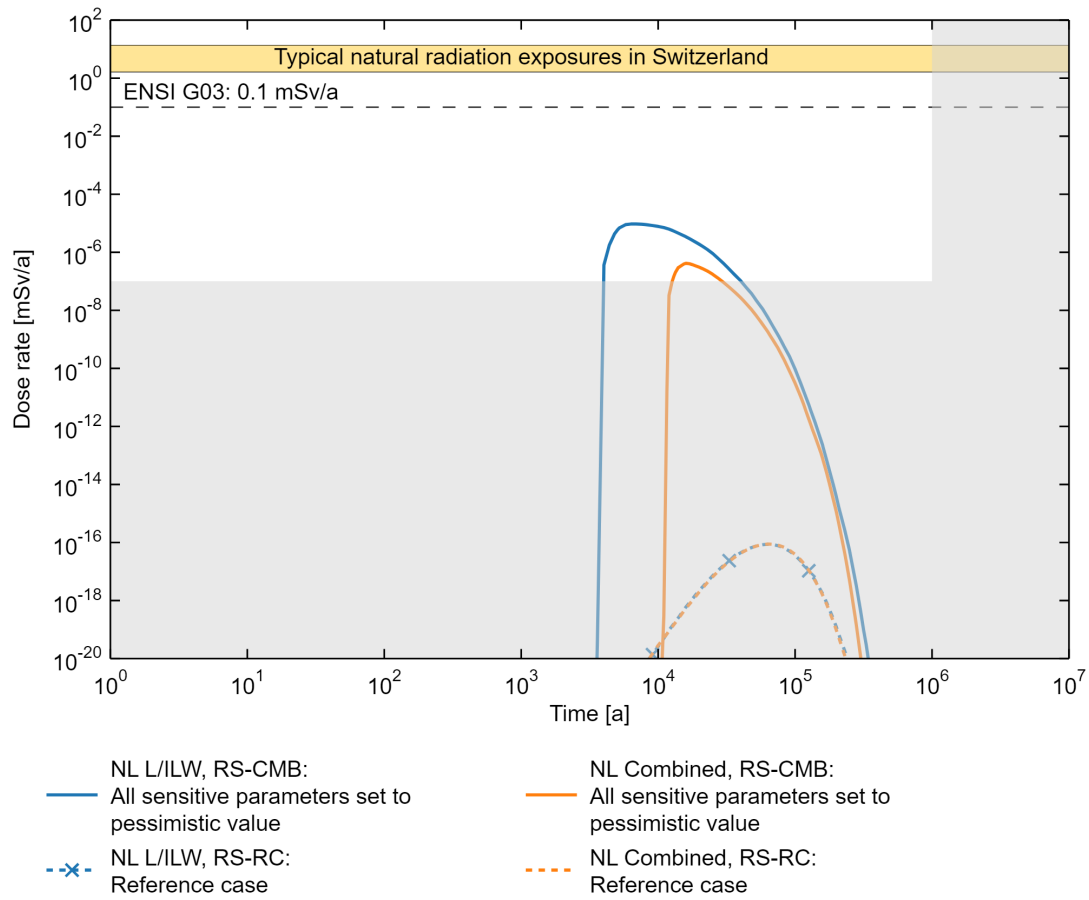


Fig. 6-142: Comparison between the dose rate evolution of C-14 methane from the L/ILW section of a combined repository and a separate L/ILW repository

7 Radiological consequence analysis for the safety case for a combined repository for the RBG

As noted in the introduction to this report, Nagra has concluded that NL is the safest siting region and offers the greatest flexibility with regard to layout of the three siting regions considered in Stage 3 of the SGT. Fig. 7-1 gives an overview of the workflow for the development of the post-closure safety case for a repository for both HLW and L/ILW (terms combined repository in this report) in the NL siting region, including the analysis of the radiological consequences of such a repository.

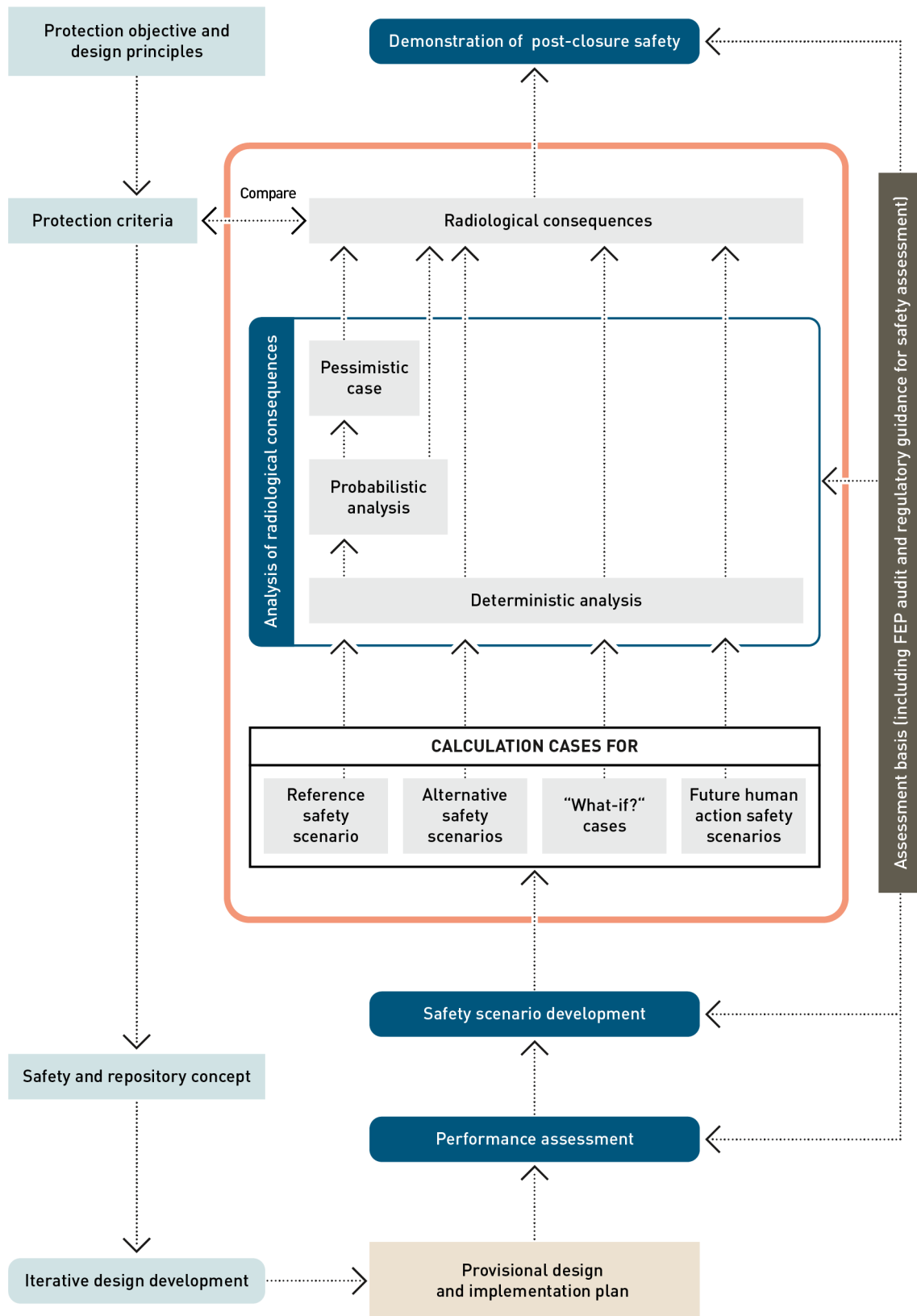


Fig. 7-1: Workflow to develop the post-closure safety case for a combined repository for the RBG, showing, in the orange box, the workflow of the analysis of radiological consequences. The overall workflow is described in Nagra (2024o)

The analysis of radiological consequences includes:

- the reference case, and probabilistic and deterministic analyses of the reference safety scenario covering the relevant uncertainty (see cases listed in Tab. 4-1);
- cases for the alternative safety scenarios considering hydraulically active confining units (cases in Tab. 4-2) and an undetected fault (cases in Tab. 4-3);
- “what-if?” cases concerning a fault with elevated transmissivity (cases in Tab. 4-4);
- “what-if?” cases about a fault reactivated by geological processes or repository-induced effects (cases in Tab. 4-5); and
- “what-if?” cases covering extreme, hypothetical assumptions and parameter variations (cases listed in Tab. 4-6)

The above-mentioned cases are respectively performed for radionuclide transport in the liquid phase and transport under two-phase flow conditions. Organic C-14 is considered in both the liquid phase calculations and the two-phase flow calculations. As the entire organic C-14 inventory is considered separately in both calculations, the results are also presented separately in this chapter, i.e., one in which all methane is assumed to be fully dissolved despite its volatility and the low solubility of methane gas, and one in which methane is partitioned between the liquid and gas phases. In fact, summing both results would correspond to counting the organic C-14 inventory twice. A further reason for presenting the results separately is because otherwise, the distinct characteristics of the two-phase flow results would be barely visible since the absolute values of dose rate contributions in most of these cases are small when compared with the liquid phase contributions. Therefore, results considering radionuclide migration in the liquid phase are presented in Section 7.1, and results considering the migration of organic C-14 in the gas phase under two-phase flow conditions are presented in Section 7.2.

7.1 Radiological consequence analysis considering radionuclide migration in the liquid phase

The total dose rate from a combined repository is obtained by summing calculated dose rates due to releases from the HLW and L/ILW repository sections. The concepts and models for analysing radionuclide migration in the liquid phase in the reference safety scenario, in the alternative safety scenarios and in the “what-if?” cases are described in App. B.1.

7.1.1 Reference safety scenario

7.1.1.1 Reference case analysis including barrier performance and dose rates

Fig. 7-2 shows the total dose rates for a combined repository, the dose rates from the respective HLW and L/ILW repository sections, and the dominant radionuclide in each case. The total dose rate reaches 1.5×10^{-4} mSv/a at 1 million years, which is about three orders of magnitude lower than the protection criterion of 0.1 mSv/a given by (ENSI 2023), thus indicating a large safety margin. Furthermore, the total dose rate continues to increase slightly thereafter, reaching a maximum of 2.0×10^{-4} mSv/a at about 4.5 million years, but remains about four orders of magnitude lower than the lower bound value of the typical natural radiological exposures in Switzerland (BAG 2021). The dominant radionuclide for releases from the HLW repository section and from the repository as a whole is I-129. Cl-36 is the dominant radionuclide for releases from the L/ILW repository section in the period up to about one million years. Thereafter, the long-lived I-129 also dominates the releases from L/ILW.

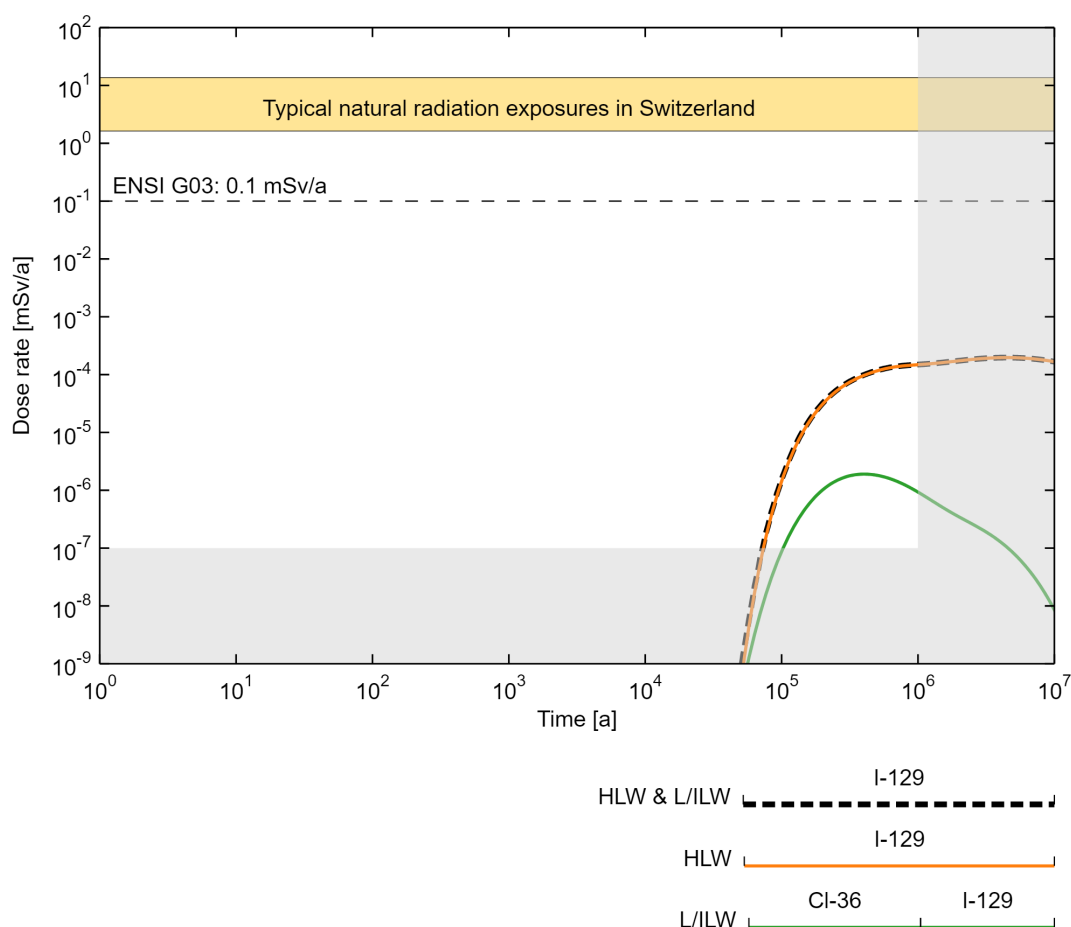


Fig. 7-2: Total dose rates for a combined repository, the dose rates from the respective HLW and L/ILW repository sections, and the dominant radionuclide in each case

Fig. 7-3 shows the radionuclide-specific and total activity release rates from the near-field, from the Opalinus Clay and from the confining geological units, i.e., from the geosphere model, for the HLW repository section, converted to dose rates using the reference BDCFs. Fig. 7-4 shows the corresponding results for the L/ILW repository section.

Considering the activity flow from the HLW bentonite buffer, the first peak after canister breaching at 10,000 years is due to the instant release fraction (IRF) of the HLW inventory; other radionuclides are released far more slowly, congruently with the corrosion/degradation rate and the gradual dissolution of the RP-HLW and SF. The initial peak slightly below the 0.1 mSv/a protection criterion (for releases to the biosphere), but rapidly falls below it once the IRF has passed. Most radionuclides, if released from the waste packages, are sorbed in the bentonite buffer, although some, such as U-233 and Ra-226, are slowly released to the host rock.

Considering next the activity flow from the Opalinus Clay and from the confining units due to HLW, these are dominated by just a few non-sorbing radionuclides: I-129, Cl-36 and Se-79. Retention by the confining geological units leads to some delay and reduction to the release rates from the Opalinus Clay. However, due to the long half-life and prolonged release of I-129 (1.57×10^7 years), the dominant radionuclide, the reduction of the maximum release rate is small in the reference case.

In fact, an equilibrium state is reached where the steady release rate of I-129 due to SF degradation (which continues up to 10^7 years) is essentially equal to the I-129 release rates across each of the model interfaces.

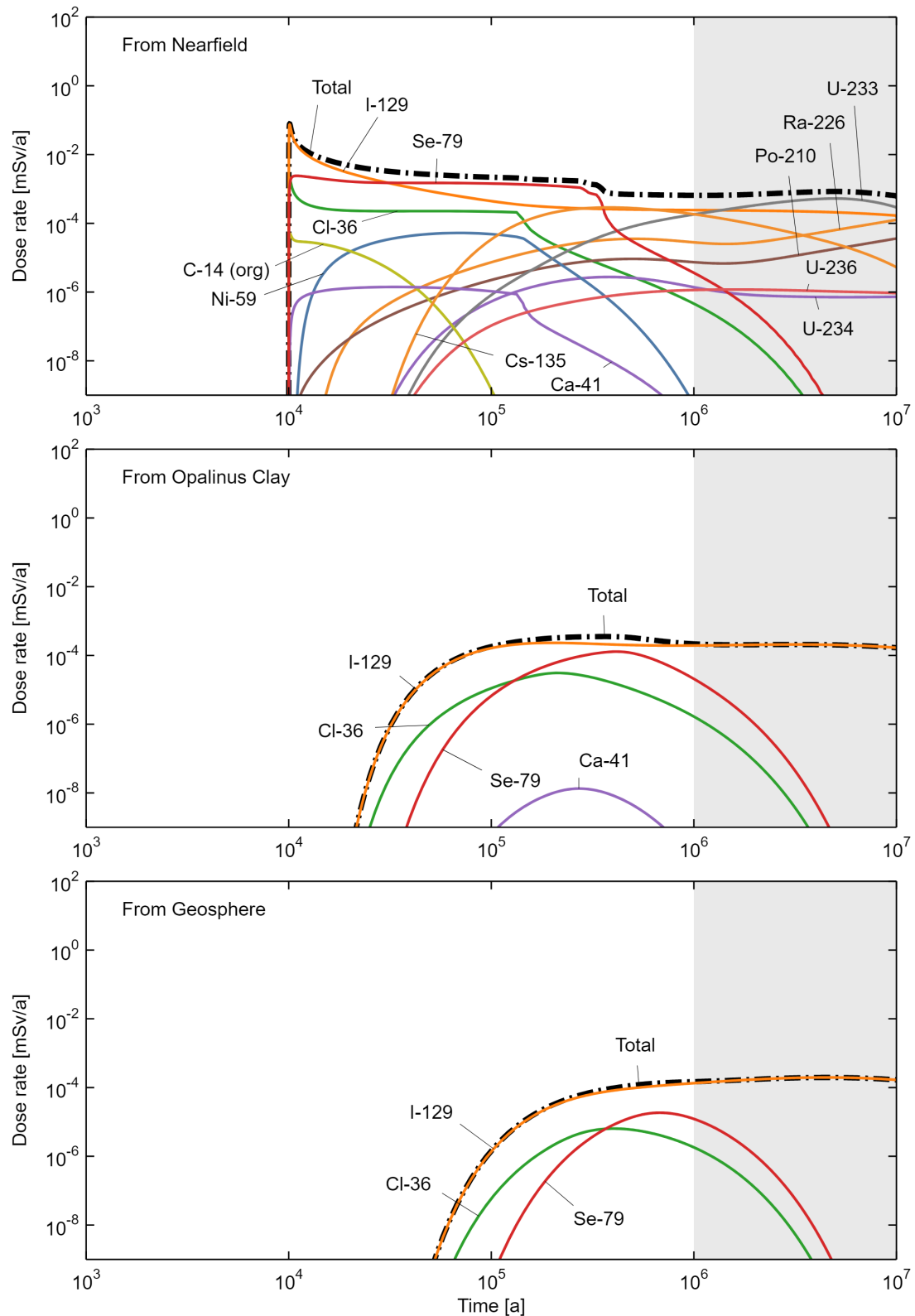


Fig. 7-3: Radionuclide-specific and total activity release rates from the near-field (above), from the Opalinus Clay (centre) and from the confining geological units, i.e., from the geosphere model (below), for the HLW repository section of a combined repository, converted to dose rates using the reference BDCFs

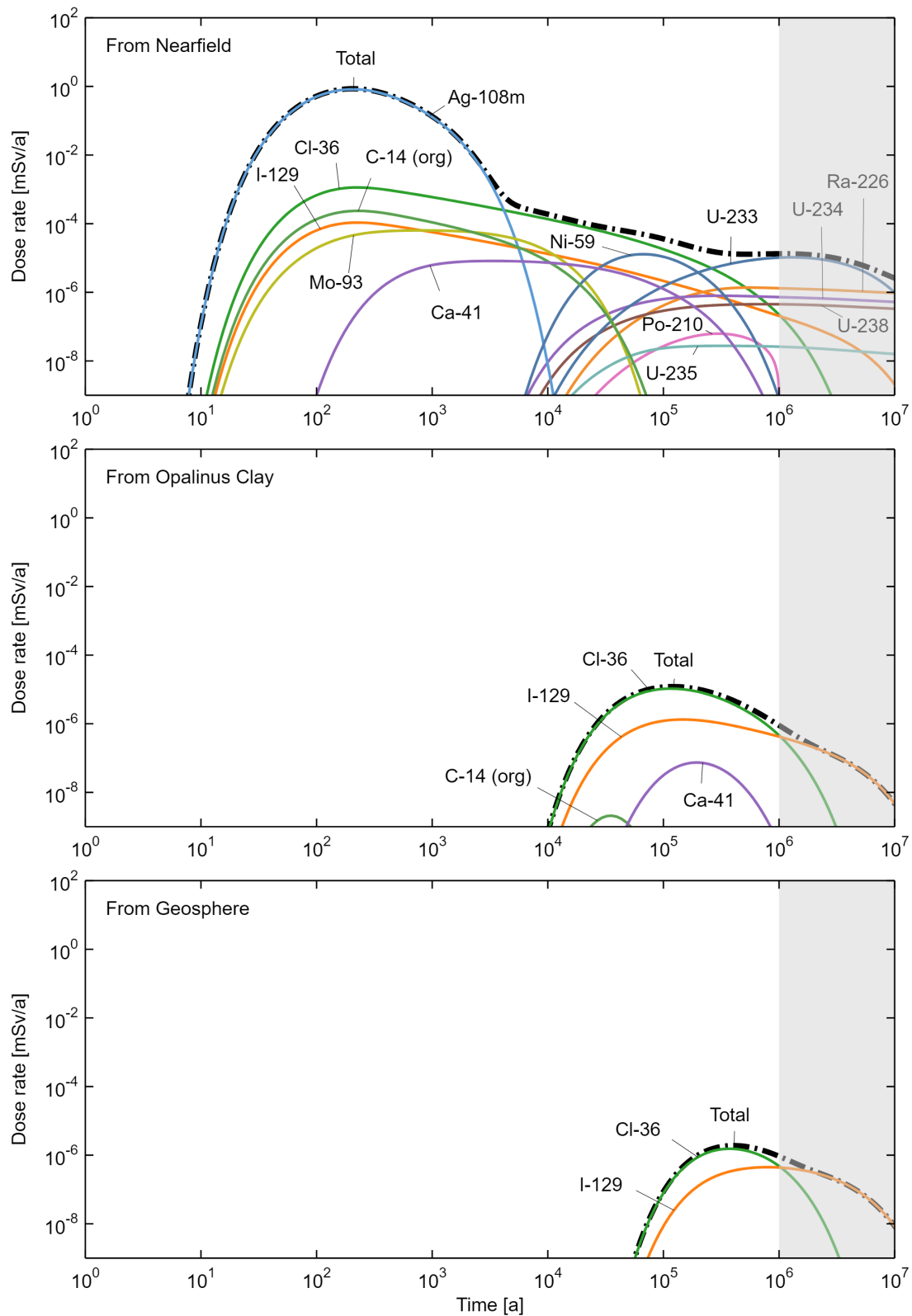


Fig. 7-4: Radionuclide-specific and total activity release rates from the near-field (above), from the Opalinus Clay (centre) and from the confining geological units, i.e., from the geosphere model (below), for the L/ILW repository section of a combined repository, converted to dose rates using the reference BDCFs

The release from the L/ILW near-field occurs much earlier than in the case of HLW because no period of complete containment is assumed for the L/ILW disposal containers and the most radionuclides (with the exception of organic C-14) are conservatively assumed to be instantaneously released. Most radionuclides are, however, retained, and decay within the Opalinus Clay. Only a few non-sorbing radionuclides reach the confining units at very low rates. The confining geological units provide additional retention capacity, further delaying and attenuating releases to the biosphere. The dominant radionuclide for L/ILW is Cl-36, which, though long-lived, has a much shorter half-life (about 3×10^5 years) than I-129. This allows for more attenuation of releases by radioactive decay during transport through the barriers in the case of the L/ILW releases compared with those for HLW.

In Fig. 7-5, maximum dose rates over 1 million years are shown at different vertical distances from the repository¹⁸. The figure illustrates how the maxima are attenuated as the radionuclides migrate through the barrier system. Only I-129, Cl-36 and Se-79 show dose rates higher than 10^{-7} mSv/a outside the Opalinus Clay, which is consistent with system understanding based on the previous figures. The dose rates close to the near-field are dominated by L/ILW releases because of the lower retention capacity of the cementitious near-field and the earlier release of radionuclides from these wastes. Conversely, the dose rates further away from the repository are dominated by radionuclides from HLW.

It should be noted that the above discussion concerns only the performance of the barriers in the reference case, which should not be taken to imply that any of the barriers, including the confining units, are unimportant. At a minimum, they provide robustness in the case of a degraded performance of other barriers, as discussed in the context of the “what-if?” cases in Section 7.1.4.

¹⁸ Because of the differences in the dimensions of the emplacement drifts and caverns, the EDZ starts at a vertical distance of 7 m from the mid-plane of the repository in the case of L/ILW, and 1.45 m in the case of HLW.

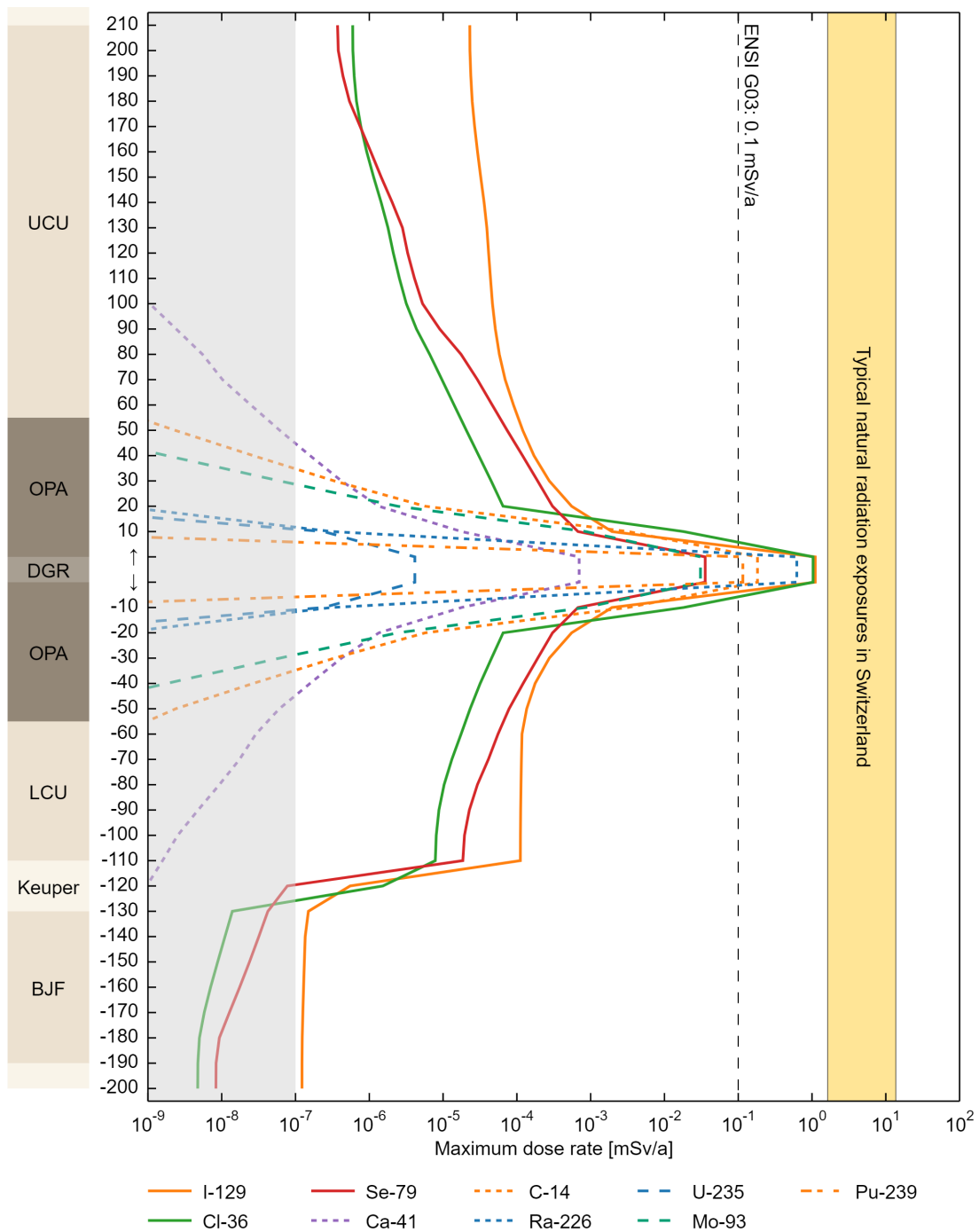


Fig. 7-5: Maximum dose rates obtained by applying BDCFs to selected radionuclide transport rates calculated for a combined repository as a function of distance from the repository centre point

UCU = upper confining unit, OPA = Opalinus Clay, LCU = lower confining unit, BJJ = Bänkerjoch Formation, groundwater markers indicate the deep groundwater aquifers: Malm (at the top of the UCU), Keuper (in-between the LCU and BJJ) and Muschelkalk (below the BJJ). Radionuclides with dashed lines would contribute less than 10^{-7} mSv/a to the hypothetical dose rate if their flux were captured at the boundary of the Opalinus Clay ca. 50 m away from the middle of the repository into the geosphere.

The reference case uses BDCFs for a reference biosphere based on present-day climatic conditions. Three additional deterministic calculation cases are defined that assume different, though still steady-state, climatic and surface conditions:

- RS-BIOS/WARM_DRY, based on a warmer and drier climate,
- RS-BIOS/COLD, based on a colder climate, and
- RS-BIOS/DRAINED_FARMLAND, which assumes a drained farmland.

The evolution of the dose rate in each of these cases is shown in Fig. 7-6. A warmer and drier climate is found to result in a maximum dose rate of 1.33×10^{-3} mSv/a at 10^6 years, which is about a factor of ten higher than that of the reference case. Other climatic and surface conditions result in lower dose rates.

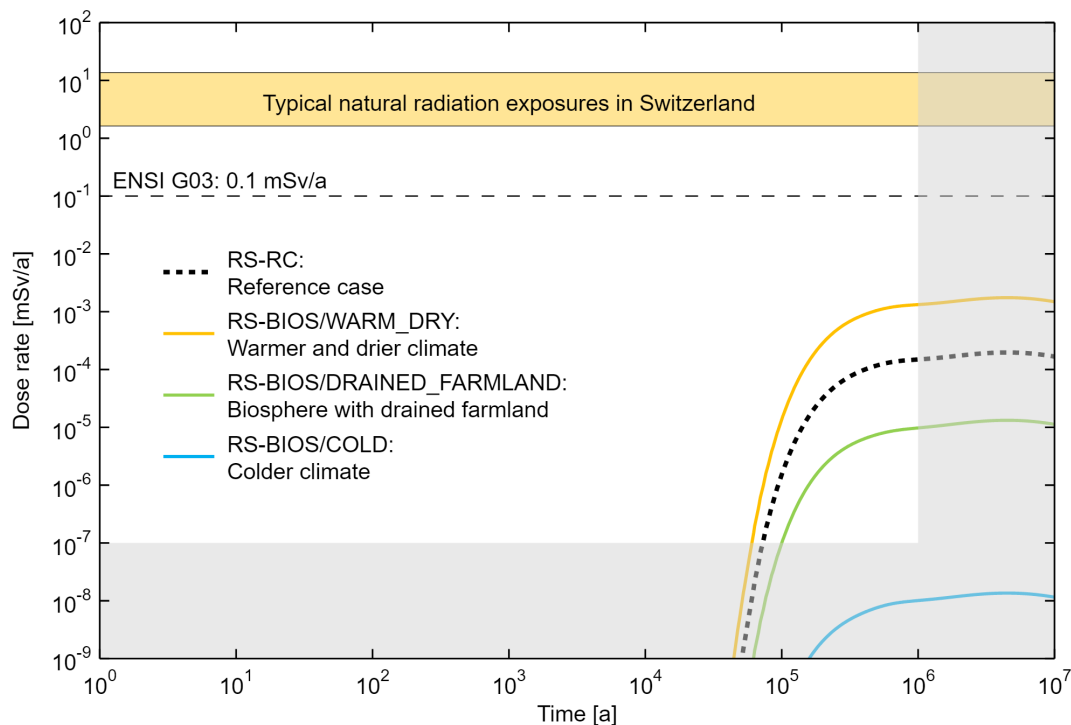


Fig. 7-6: Total dose rates due to the combined repository in the reference case and in cases assuming different climatic and surface conditions

7.1.1.2 Probabilistic and deterministic analyses covering parameter uncertainty

In accordance with the workflow described at the start of this chapter, probabilistic analyses of the reference safety scenario are performed, along with deterministic analyses of pessimistic cases, in which those parameters identified as the most sensitive in the probabilistic analyses are set to pessimistic, bounding values. This includes a deterministic case that combines the pessimistic bounding values of all the most sensitive parameters. The results of these probabilistic and deterministic analyses are presented in the following paragraphs. Details of the Monte-Carlo simulation approach and of the sensitivity analysis methods used in the probabilistic analyses are given in App. G.

Fig. 7-7 shows statistical percentiles calculated from 4,000 Monte-Carlo simulations of the dose rate evolution of a combined repository. The bandwidth of the maximum dose rate due to uncertainty in the input parameter values spans about an order of magnitude. The highest calculated dose rate in the period up to one million years is 1.1×10^{-3} mSv/a and reaches the maximum of 1.2×10^{-3} mSv/a shortly thereafter.

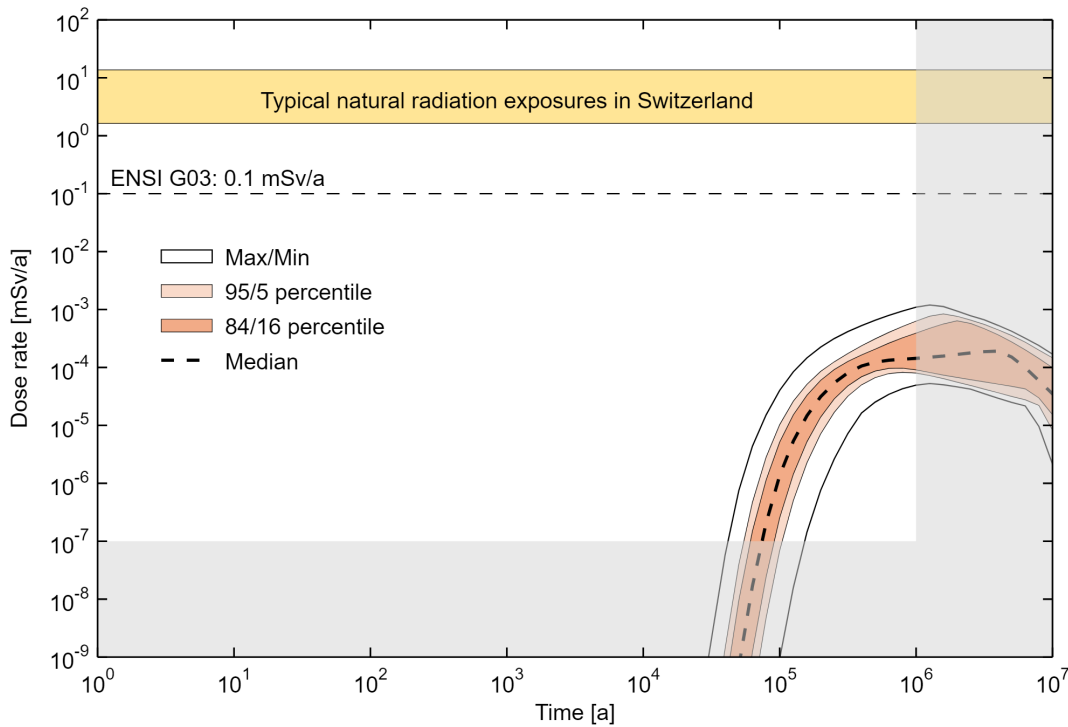


Fig. 7-7: Statistical percentiles calculated from 4,000 Monte-Carlo simulations of the dose rate evolution of a combined repository

Because the dose rate is strongly dominated by the radionuclides from the HLW repository section of the combined repository, the curves are visually almost identical to those of a single HLW repository shown in Fig. 6-25. Furthermore, sensitivity analyses show that for both the HLW and the combined repository the same parameters are the most sensitive in terms of the variance in the maximum dose rate to the variance in the input parameters. The only difference in the set of sensitive parameters between the HLW and the combined repository is the radionuclide-accessible porosity of halogens of the Opalinus Clay, which is slightly above the threshold of significance for the combined repository and slightly below for the HLW repository. As the results of the sensitivity analyses presented in Section 6.1.2.2 for an HLW repository also apply to the combined repository, the analyses and results of the “RS-PROB-Param” cases (see Tab. 4-1) are not repeated here. Rather, it is sufficient to present a single case for the combined repository in which pessimistic bounding values are set for all the sensitive parameters, i.e., the parameters listed in Tab. 7-1.

Dose rates for this “combined pessimistic case” are compared with those of the reference case in Fig. 7-8. The maximum dose rate is higher in the combined pessimistic case by ca. an order of magnitude compared with the reference case. It remains, however, almost two orders of magnitude below the protection criterion of 0.1 mSv/a stipulated in ENSI Guideline G03 (ENSI 2023) and more than two orders of magnitude below the lower bound values of the typical natural

radiological exposures in Switzerland (BAG 2021). Although the likelihood of pessimistic bounding parameter values occurring together in this way is low, the combined pessimistic case further demonstrates the robustness of the repository from a post-closure safety perspective.

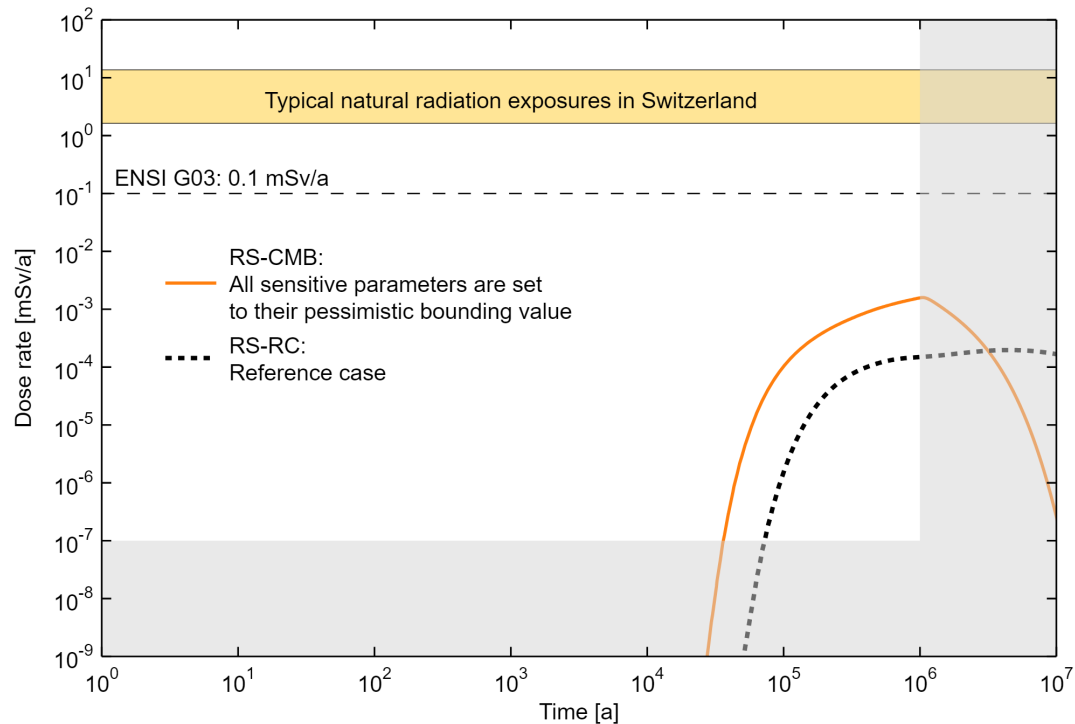


Fig. 7-8: Total dose rates for a combined repository in the reference case and in a case in which pessimistic bounding values are set for all sensitive parameters

Tab. 7-1: Sensitivity measures for the parameters of the probabilistic analyses with at least one significant correlation for a combined repository

Values above the calculated “threshold of significance” are marked in blue. Signs of the Pearson and Spearman correlation coefficients indicate positive or negative correlation between the input and output parameters. (+) or (-) indicates the selected bounding value for the individual and combined pessimistic calculations.

Parameter	Description	Pearson correlation coefficient	Spearman correlation coefficient	Modified EASI sensitivity index
	<i>Significance threshold</i>	<i>0.036</i>	<i>0.041</i>	<i>0.0045</i>
k_M (+) $1 \times 10^{-8} - 1 \times 10^{-6} \text{ a}^{-1}$	Fractional dissolution rate of the SF matrix	0.95	0.91	0.90
$E_{a,wc}$ (+) $1.5 \times 10^4 - 2.5 \times 10^4 \text{ J/mol}$	Activation energy for diffusion in the porewater	0.12	0.17	0.014

Tab. 7-1: continued

Parameter	Description	Pearson correlation coefficient	Spearman correlation coefficient	Modified EASI sensitivity index
	<i>Significance threshold</i>	<i>0.036</i>	<i>0.041</i>	<i>0.0045</i>
Deff_OPA(Cl,I) (+) 1.2×10^{-12} - 5.6×10^{-12} m ² /s (Cl) 1.2×10^{-12} - 5.5×10^{-12} m ² /s (I)	Effective diffusion coefficient of halogens in the Opalinus Clay	0.12	0.15	0.015
Deff_KEU(Cl,I) (+) 1.6×10^{-12} - 8.7×10^{-12} m ² /s (Cl) 1.5×10^{-12} - 8.6×10^{-12} m ² /s (I)	Effective diffusion coefficient of halogens in the KEU	0.12	0.14	0.014
h_OPA (-) 100 - 115 m	Thickness of the Opalinus Clay	-0.039	-0.075	0.0025
i_v (-) ¹⁹ -0.5 - 0.5 m/m	Hydraulic gradient along the geological formations	-0.029	-0.06	0.0031
K_KAL (+) 1.0×10^{-9} - 1.0×10^{-5} m/s	Hydraulic conductivity of the KAL (Keuper aquifer)	0.025	0.060	0.0046
Deff_CD(Cl,I) (+) 9.1×10^{-13} - 9.9×10^{-12} m ² /s (Cl) 9.0×10^{-13} - 9.8×10^{-12} m ² /s (I)	Effective diffusion coefficient of halogens in the CD («Herrenwis Unit»)	0.045	0.051	0.0027
Phi_KAU(Ag,C,Ca,Hg,Se,C _{org}) (-) 0.03 - 0.11 (Ag,Ca,Hg,Se) 0.02 - 0.07 (C, C _{org})	Radionuclide-accessible porosity (except halogens) of the KAU	-0.044	-0.049	0.0033
DissRate_HLW_1 (+) 2.0×10^{-5} - 9.0×10^{-2} g/m ² /d	Fractional dissolution rate of RP-HLW Type 1 ²⁰	0.0046	0.048	0.0015
K_d_OPA(C) (-) 3.0×10^{-4} - 3.0×10^{-3} m ³ /kg	Sorption coefficient of inorganic C-14 in the Opalinus Clay	-0.041	-0.031	0.0029
Deff_ML(C _{org}) (+) 2.2×10^{-12} - 1.2×10^{-11} m ² /s	Effective diffusion coefficient of organic C-14 in the ML	0.036	0.021	0.0029
K_d_AAK(C) (-) 1.3×10^{-4} - 2.2×10^{-3} m ³ /kg	Sorption coefficient of inorganic C-14 in the AAK	-0.0076	-0.01	0.0057
Phi_OPA(Cl,I) (-) 0.03 - 0.06 (Cl,I)	Radionuclide-accessible porosity of halogens of the Opalinus Clay	-0.031	-0.041	0.0022

¹⁹ The hydraulic conductivity (K_{v,OPA}) is not detected as a sensitive parameter in the analysis, nevertheless, in order to have a higher vertical Darcy flow to bound the dose rate, the upper boundary of K_{v,OPA}(+) is considered in the combined pessimistic case

²⁰ There are two types of RP-HLW. Type 1 is the vitrified RP-HLW from Areva named "J-Z-005000" in MIRAM

7.1.1.3 Variant conceptualisation assuming an inactive Keuper aquifer

In the reference conceptualisation of the reference safety scenario, which provides the basis for the reference case, it is conservatively assumed that the Keuper aquifer below the HLW repository is hydraulically active and forms a significant advective transport pathway for radionuclides migrating downwards from the repository. As noted in Section 4.1.2, a variant conceptualisation is also defined in which the Keuper aquifer below the HLW repository section is hydrologically inactive and radionuclides are transported vertically across it by diffusion. The results of the calculation case (RS-KEUPER_INACTIVE) illustrating this variant are shown in Fig. 7-9.

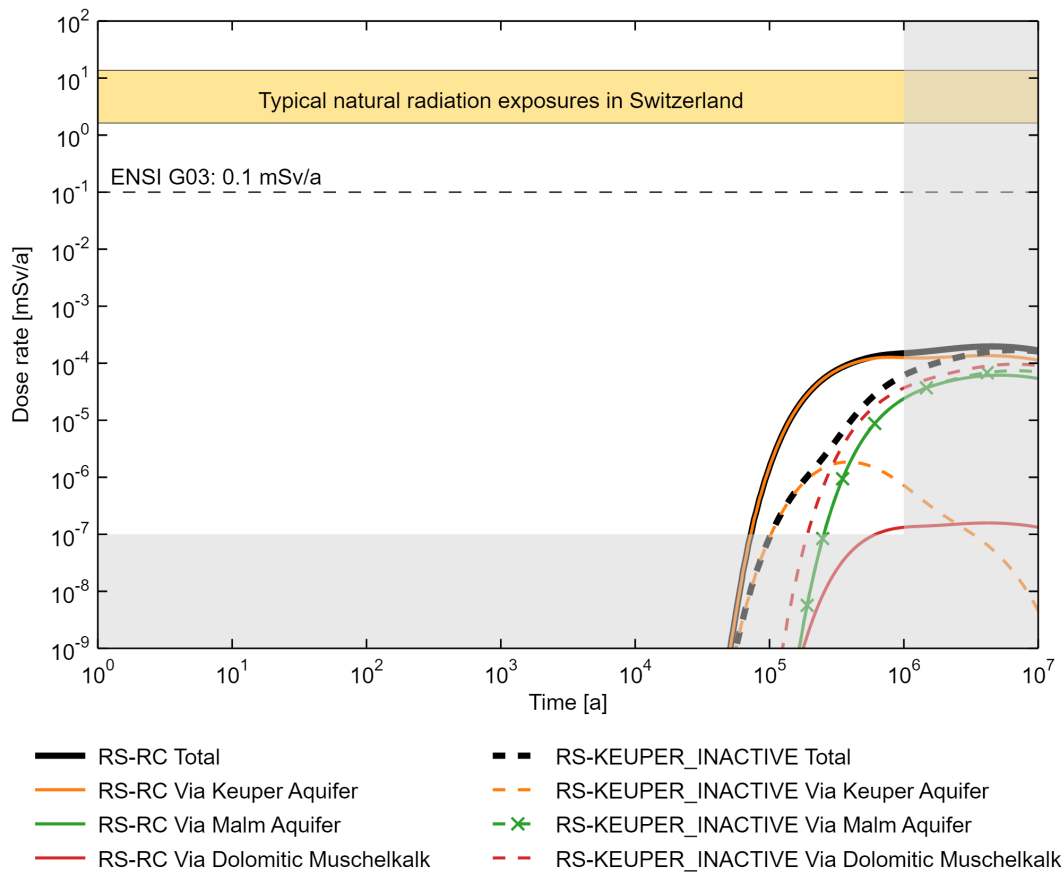


Fig. 7-9: Total and nuclide-specific dose rates for a combined repository in the reference case, and in a variant of the reference safety scenario in which the Keuper aquifer below the repository is hydraulically inactive

In the reference case, the Keuper aquifer under the repository is the dominant release pathway, contributing more to the total dose rate than releases via the Malm aquifer above the repository or via the Muschelkalk, which is below the Keuper aquifer. However, the alternative conceptual case with an inactive Keuper aquifer can reduce the total dose rate by almost a factor of 2.5. The release via the Keuper aquifer originates from the L/ILW side only, where the Keuper aquifer is still set to be active.

7.1.2 Alternative safety scenarios

As in the comparison of the siting regions, in addition to the reference safety scenario, alternative safety scenarios are analysed deterministically for the combined repository. Specific uncertainties flagged for consideration as alternative safety scenarios concern uncertainties in geological characterisation, and, specifically, the possibility that there could be:

- a hydraulically active confining unit above or below the repository; or
- an undetected fault in the vicinity of the repository emplacement rooms.

The variants and calculation cases for these two safety scenarios are summarised in Tab. 4-2 and Tab. 4-3, respectively.

7.1.2.1 Hydraulically active confining unit

As illustrated in Fig. 2-5, there are five potentially hydrogeologically active confining units considered in the NL siting region: SCD (Sandy-Calcareous Dogger), CD («Herrenwis Unit»), and CM (Calcareous Malm) in the upper confining geological units, and KEU (Calcareous Lias) and KAU (Dolomitic Keuper) in the lower confining geological units. The impact of these is analysed in five deterministic calculation cases (see also Tab. 4-2):

- AS-HB/SCD, where the SCD is assumed to be hydraulically active;
- AS-HB/CD, where the CD is assumed to be hydraulically active;
- AS-HB/CM, where the CM is assumed to be hydraulically active;
- AS-HB/KEU, where the KEU is assumed to be hydraulically active; and
- AS-HB/KAU, where the KAU is assumed to be hydraulically active.

The evolution of the dose rate in these five cases is compared with the reference case in Fig. 7-10, which shows only a slight increase in the dose rate caused by any of these units being hydraulically active. This is because the hydraulically active units can shorten the transport pathway in the upper or lower confining units leading to an earlier breakthrough of radionuclides into the biosphere. However, according to the system understanding discussed in Fig. 7-5, thanks to the excellent retention capacity of the Opalinus Clay, the confining units can only contribute a limited reduction of the maximum dose rate. Therefore, shortening the transport length in the confining unit due to the “hydraulically active confining units” will not cause a significant increase in the maximum dose rate.

The closer the unit is located to the Opalinus Clay and the larger the water flow in it, the higher the impact should be. Following this system understanding, the potential hydraulically active units relatively close to the Opalinus Clay (SCD, CD in the upper confining geological units and KEU in the lower confining geological units) can increase the dose rate slightly. In contrast, the units KAU and CM cannot raise the dose rate significantly.

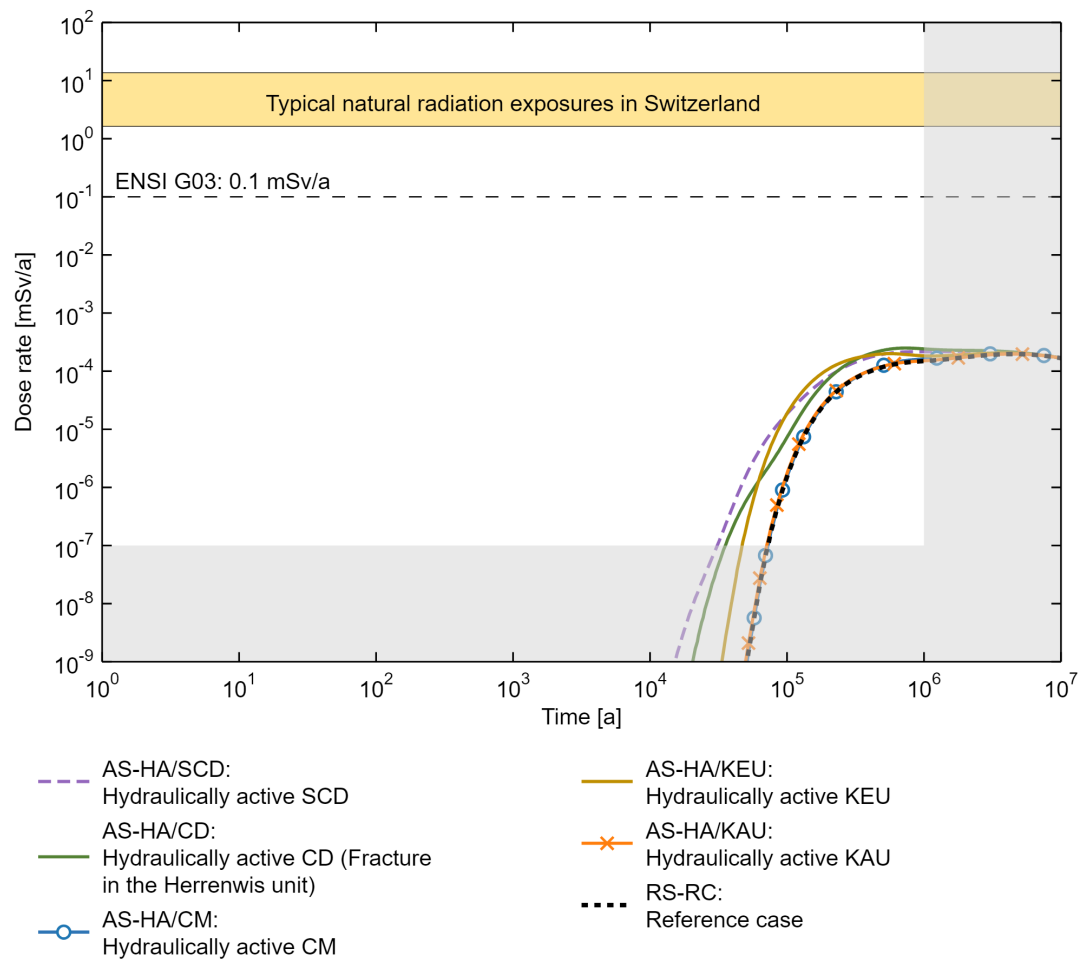


Fig. 7-10: Total dose rates in the reference case for a combined repository, and in five cases of hydraulically active units within the confining units above and below the Opalinus Clay

7.1.2.2 Undetected fault

The evolution of dose rates in the reference case and in the four cases defined for the safety scenario with an undetected fault is shown in Fig. 7-11. There are two cases in which the fault intersects the HLW repository section, one in which it runs along one of the HLW emplacement drifts and one in which it cuts perpendicularly across all the drifts. Similarly, there are two cases in which the fault intersects the L/ILW repository section, one in which it runs along one of the L/ILW emplacement caverns and one in which it cuts perpendicularly across all the caverns. The vertical hydraulic gradients in the fault and in the rock matrix are taken to be upwardly directed. Tab. 4-3 provides summary definitions of these cases. In this safety scenario, the assumption is made that the HLW canister lifetime is unaffected, and hence the canisters remain intact for 10,000 years, as in the reference case. Furthermore, the expected release behaviour of the SF, including the IRF and CRF and the sorption capacity of the CRZ, will not be impacted by the fault.

These cases concerning undetected faults are modelled with extremely conservative assumptions:

- The fault is assumed to exist since the start of construction work through the whole CRZ connecting the two deep aquifers (Keuper and Malm aquifers).
- The fault will either partly affect all the HLW or L/ILW emplacement rooms (AS-FLT-HLW-Across, AS-FLT-L/ILW-Across) or an entire emplacement room (AS-FLT-HLW-Along, AS-FLT-L/ILW-Along); the fault can be easily detected and avoided.
- Transmissivity of the fault is set to 10^{-10} m²/s, which has not been observed in the geological investigations of the potential repository fields (Nagra 2024e).

In each case, the undetected fault provides an additional transport pathway from the repository to the overlying Malm aquifer. In the cases concerning HLW emplacement drift(s) with an undetected fault, release of radionuclides out of the CRZ due to advective transport of the IRF (instantaneous release fraction) radionuclides along the fault begins almost immediately following canister breaching, which leads to a breakthrough at about 10,000 years. Since the radionuclides in L/ILW are assumed to be instantaneously released (with the exception of organic C-14) from the containers after repository closure, an earlier breakthrough can be observed in the cases concerning L/ILW emplacement cavern(s) with a fault. In all the cases shown in Fig. 7-11, however, transport along the fault does not greatly increase the maximum dose rate. There are basically two reasons why the system behaves like this:

- In the cases concerning a fault affecting the HLW emplacement drifts, just a limited number of HLW disposal canisters are affected by the fault ($20 \times 3 = 60$ canisters in the case of AS-FLT-HLW-Across and 97 canisters in the case of AS-FLT-HLW-Along); therefore, a small part of the total IRF inventory can be released more quickly into the biosphere.
- The Darcy velocity in the fault (transmissivity = 10^{-10} m²/s) is set to about 7×10^{-12} m/s by considering the water availability in the Keuper aquifer, which can limit the speed of the advective transport in the fault.

As observed for separate HLW and L/ILW repositories, a fault passing along one of the HLW drifts or L/ILW caverns gives rise to slightly lower dose rates than the case of a fault passing perpendicularly through all the drifts. This is connected to differences of interface areas between the drifts, the fault and the rock matrix in the two calculation cases.

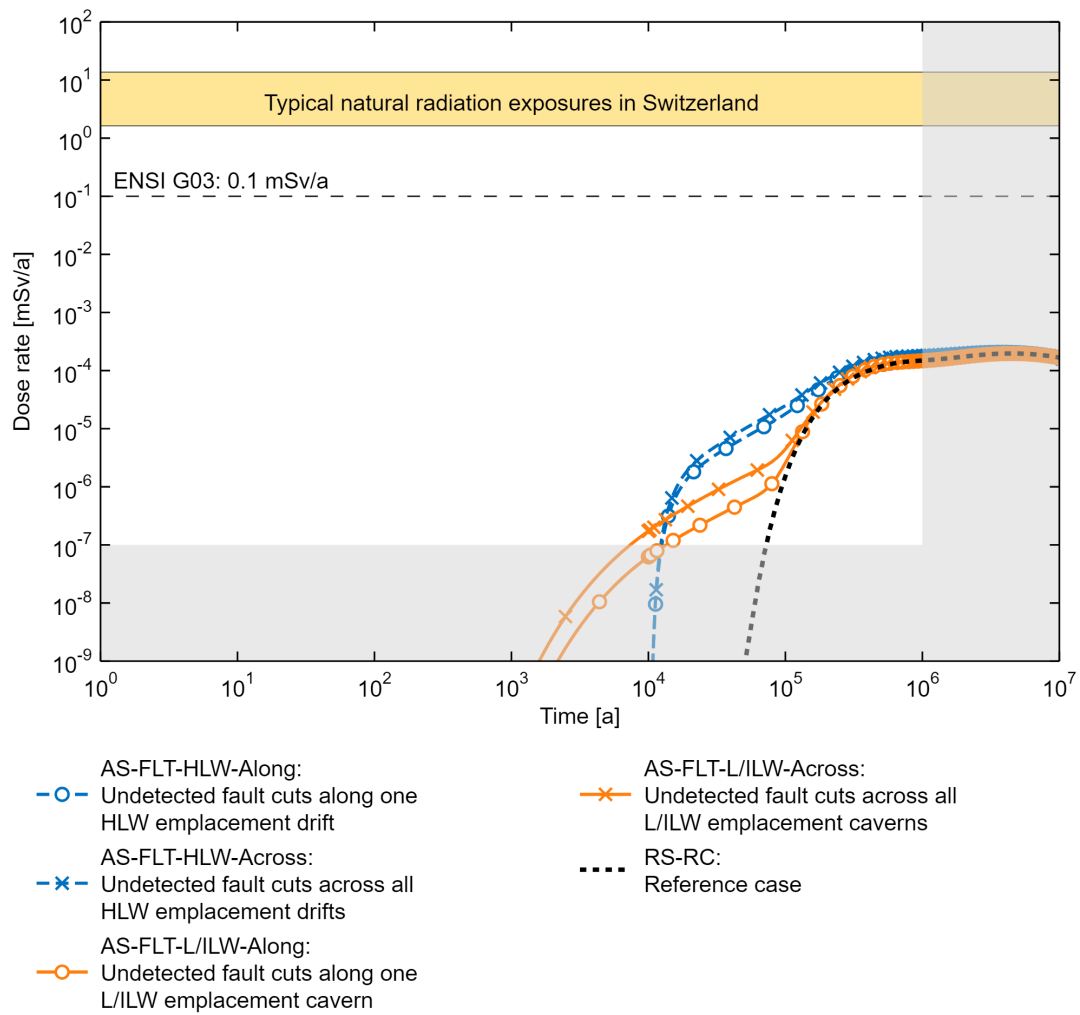


Fig. 7-11: Total dose rates in the reference case for a combined repository, and in four cases of an undetected fault intersecting the HLW emplacement drifts and L/ILW emplacement caverns

7.1.3 “What-if?” cases related to physical phenomena

As described in Section 4.3.1, a number of “what-if?” cases have been defined that concern the occurrence of features and processes either with characteristics that lie outside the range of possibilities supported by currently available evidence and knowledge, or whose occurrence during the one-million-year time period for assessment is judged to be exceedingly unlikely. Their purpose is to demonstrate the robustness of the repository system. Two such groups of “what-if?” cases, defined in Nagra (2024b), are analysed in the following paragraphs:

- the occurrence, in the vicinity of the repository, of an undetected transmissive fault with elevated transmissivity; and
- the future creation or reactivation of a fault either by geological processes or as a repository-induced effect.

7.1.3.1 Undetected fault with elevated transmissivity

Four “what-if?” cases are defined that assume the presence of an undetected fault. As in the alternative safety scenario of an undetected fault analysed in Section 7.1.2.2, there are two cases in which the fault intersects the HLW repository section, one in which it runs along one of the HLW emplacement drifts and one in which it cuts perpendicularly across all the drifts. Similarly, there are two cases in which the fault intersects the L/ILW repository section, one in which it runs along one of the L/ILW emplacement caverns and one in which it cuts perpendicularly across all the caverns. However, after taking over the whole conservatism for the cases in Section 7.1.2.2, the transmissivity of the fault in the “what-if?” cases is set much higher than could reasonably be expected: 10^{-7} m²/s, compared with 10^{-10} m²/s in the alternative safety scenario of an undetected fault. Tab. 4-4 provides summary definitions of the “what-if?” cases.

Dose rates in these cases are compared with those in the reference case in Fig. 7-12. As expected, the impact of the fault is significantly greater than in the alternative safety scenario of an undetected fault shown in Fig. 7-11 due to the hypothetically increased transmissivity of the fault.

Because the radionuclides in the L/ILW are assumed to be released instantaneously (with exception of organic C-14), the fault along the L/ILW emplacement cavern leads to an earlier release to the biosphere and a higher dose rate. However, the maximum dose rate of 7.9×10^{-3} mSv/a is still more than one order of magnitude lower than the protection criterion of 0.1 mSv/a.

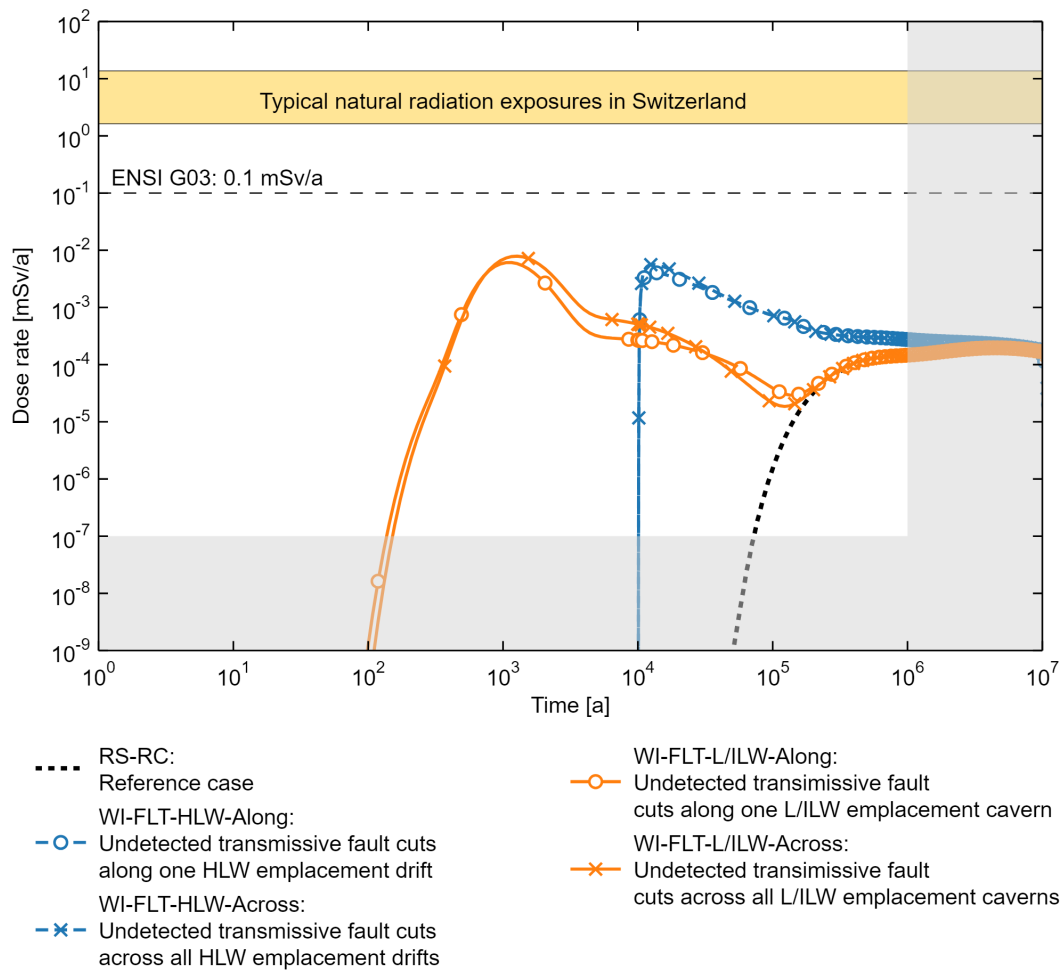


Fig. 7-12: Total dose rates in the reference case for a combined repository, and in four “what-if?” cases of an undetected fault with elevated transmissivity ($10^{-7} \text{ m}^2/\text{s}$) intersecting the emplacement drifts and caverns

7.1.3.2 Fault creation or reactivation by geological processes or repository-induced effects

A further four “what-if?” cases are defined that assume the generation of a new fault or the reactivation of an existing, non-transmissive fault, during the post-closure period. Tab. 4-5 provides summary definitions of these “what-if?” cases. There are two cases in which the fault intersects the HLW repository section, one in which it runs along one of the HLW emplacement drifts and one in which it cuts perpendicularly across all the drifts. In these cases, the fault is assumed to be created or reactivated at 10,000 years post closure, which coincides with the assumed canister failure time and the development of overpressure in the HLW near-field (see Nagra 2024k). There are another two cases in which the fault intersects the L/ILW repository section, one in which it runs along one of the L/ILW emplacement caverns and one in which it cuts perpendicularly across all the caverns. For these cases, the fault is assumed to be created or reactivated at 20,000 years post closure. In those case, 20,000 years is pessimistic, since it

corresponds to the time when there is a risk of overpressure in the L/ILW near-field (Nagra 2024k). As in the previous “what-if?” cases, the fault transmissivity (once created or reactivated) is set to $10^{-7} \text{ m}^2/\text{s}$. All the conservative assumptions made for cases concerning undetected fault are considered here as well.

Dose rates in these cases are compared with those in the reference case in Fig. 7-13. Unlike the undetected fault with elevated transmissivity (Fig. 7-12), the highest dose rates, this time up to $5.6 \times 10^{-3} \text{ mSv/a}$, occur in cases where the fault intersects the HLW emplacement drifts. This is because, in the cases shown in Fig. 7-13, there is no transmissive fault impacting the L/ILW emplacement caverns when the activity of the radionuclides in these caverns is highest. The calculated maximum dose rates remain more than one order of magnitude below the protection criterion of 0.1 mSv/a .

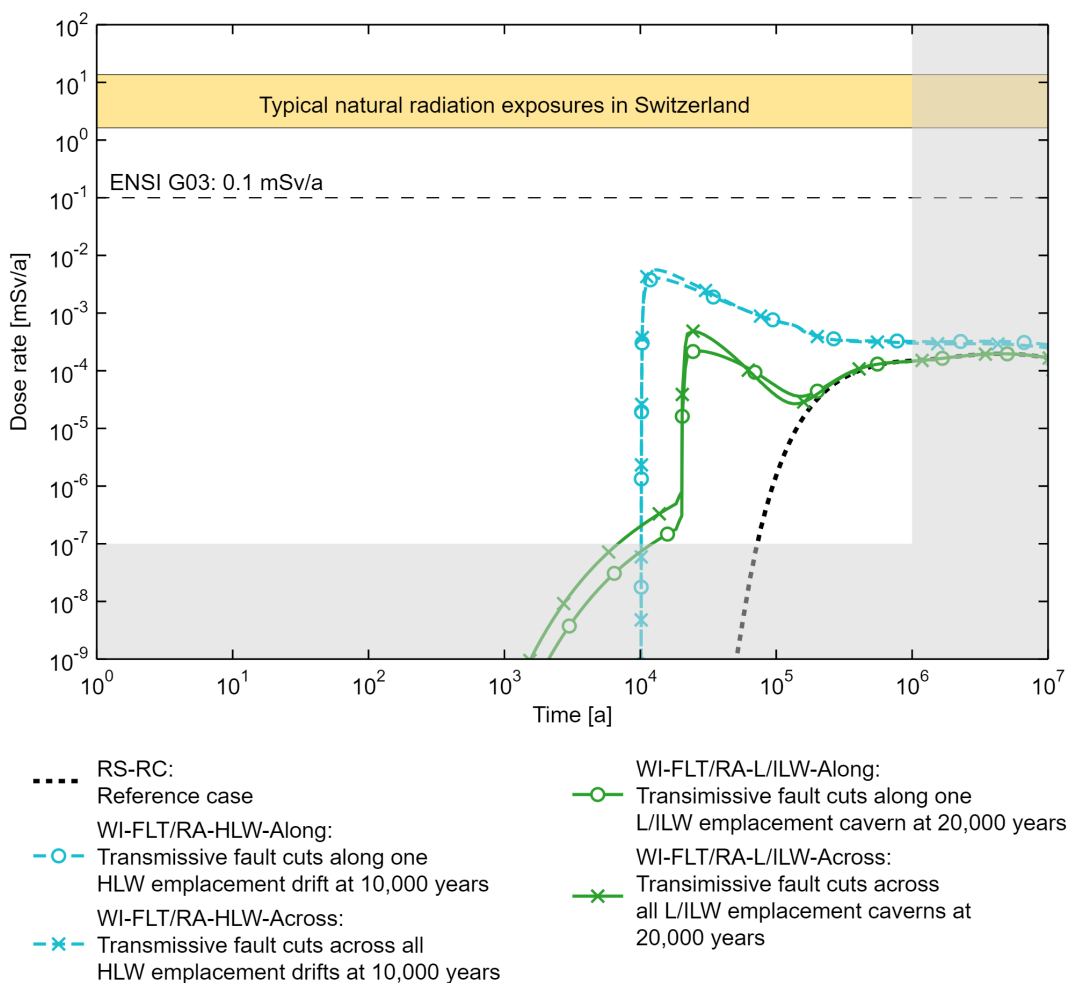


Fig. 7-13: Total dose rates in the reference case for a combined repository, and in four “what-if?” cases of a fault with a transmissivity of $10^{-7} \text{ m}^2/\text{s}$ created or reactivated by geological processes or repository-induced effects intersecting the emplacement drifts and caverns

7.1.4 “What-if?” cases postulating a hypothetically degraded performance of the pillars of safety

Further “what-if?” cases are defined in Tab. 4-6 to test the robustness of the repository system by illustrating the effects of a hypothetically degraded performance of the system components that are the main contributors to the pillars of safety.

Fig. 7-14 shows the evolution of the dose rates in the “what-if?” cases that postulate a degraded performance of the CRZ. Fig. 7-15 shows the evolution of the dose rates in the “what-if?” cases that postulate a degraded performance of the engineered barriers (with the exception of the sealing system, which is most relevant to gas-mediated transport of C-14, as discussed in Section 7.2.4).

For the CRZ, the WI-CRZ-DIFF case, which assumes a 10 times higher diffusion coefficient than the upper bound value used in the sensitivity analyses, shows the largest increase in the dose rate, which highlights the importance of diffusion as the dominant transport mechanism. The inflections in the dose-rate curve are caused by the changes in the dominant radionuclide. When sorption is omitted, as in the WI-CRZ-NOSORB case, the dose rate increases because some sorbing radionuclides, such as Cs-135, are then released into the geosphere. In this case, the dominant radionuclide is Cs-135 rather than I-129. The assumption of a high hydraulic gradient in the WI-CRZ-GRADdown case causes an increase in the maximum dose rate by one order of magnitude. When the presence of the upper and lower confining units is disregarded, as in the WI-CRZ-NOCONFINING case, the maximum dose rate is increased by about a factor of 4, highlighting the strength of the Opalinus Clay for radionuclide retention. An increase in the assumed radial extent of the EDZ does not significantly increase the dose rate.

Considering Fig. 7-15, an increase in the SF dissolution rate, as assumed in the WI-SF/HLW-DISS case, causes a significant increase in the maximum dose rate by almost one order of magnitude, because a higher dissolution rate of the SF causes a faster release of the dominant radionuclide I-129. Assuming a hypothetically high (100%) IRF of all radionuclides (including I-129) in the WI-SF-IRF case also causes a significant increase in the maximum dose rate, as well as earlier releases to the biosphere. In general, however, because of the strength of the CRZ, degradation of most engineered barriers does not generally have significant impact on the dose rate evolution. For example, the assumption of an earlier breaching of the HLW canister at 1,000 years post closure in the WI-SF/HLW-CAN case (compared with 10,000 years assumed in the reference case), although it results in slightly earlier releases to the biosphere, does not significantly increase the maximum dose rate.

In all of these hypothetical “what-if?” cases, the maximum dose rate remains at least one order of magnitude below the protection criterion of 0.1 mSv/a (ENSI 2023), demonstrating the robustness of the multi-barrier system.

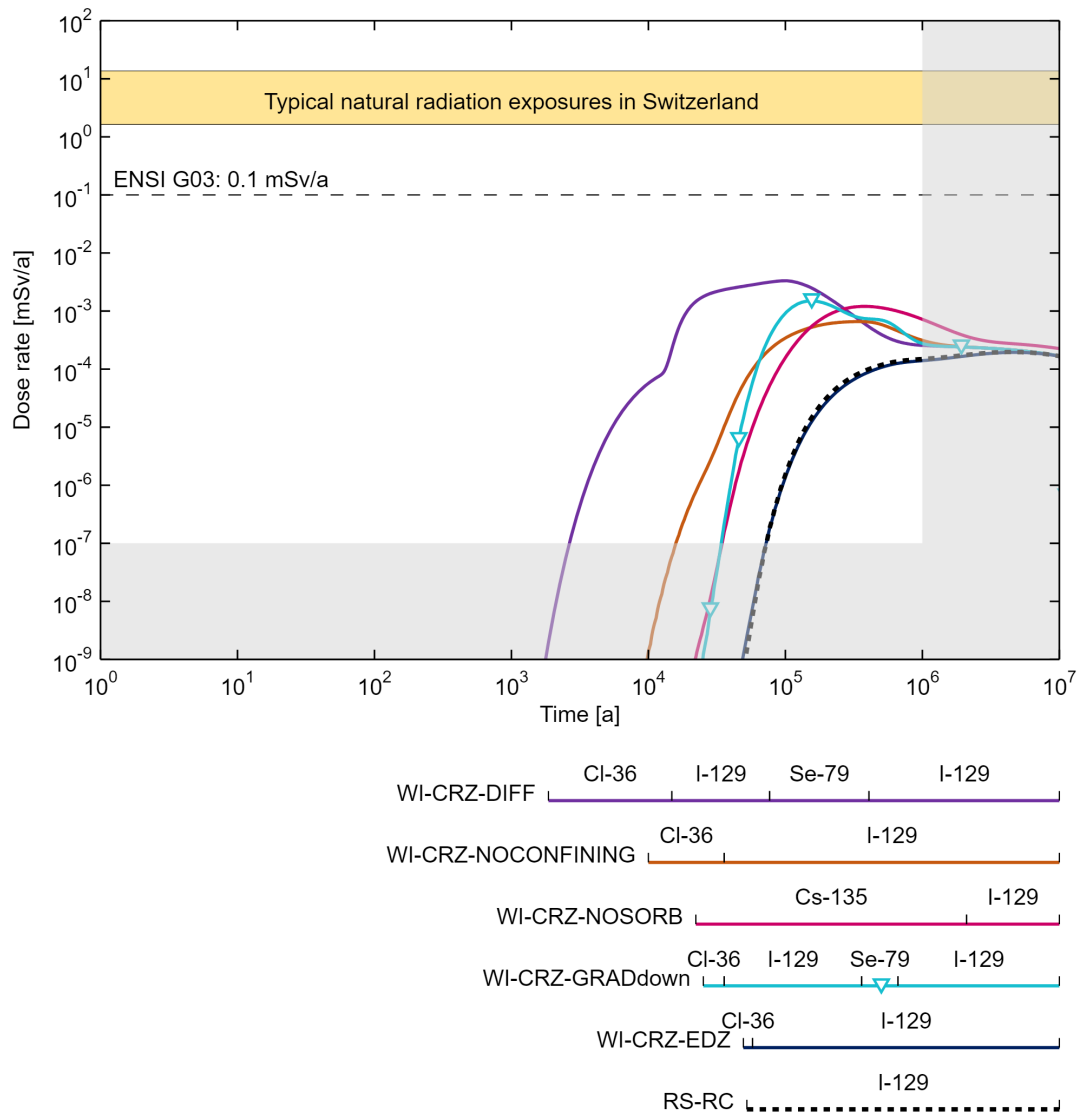


Fig. 7-14: Total dose rates in the reference case for a combined repository, and in five “what-if?” cases that postulate a degraded performance of the CRZ, including the depiction of the dominating radionuclides over the different time phases

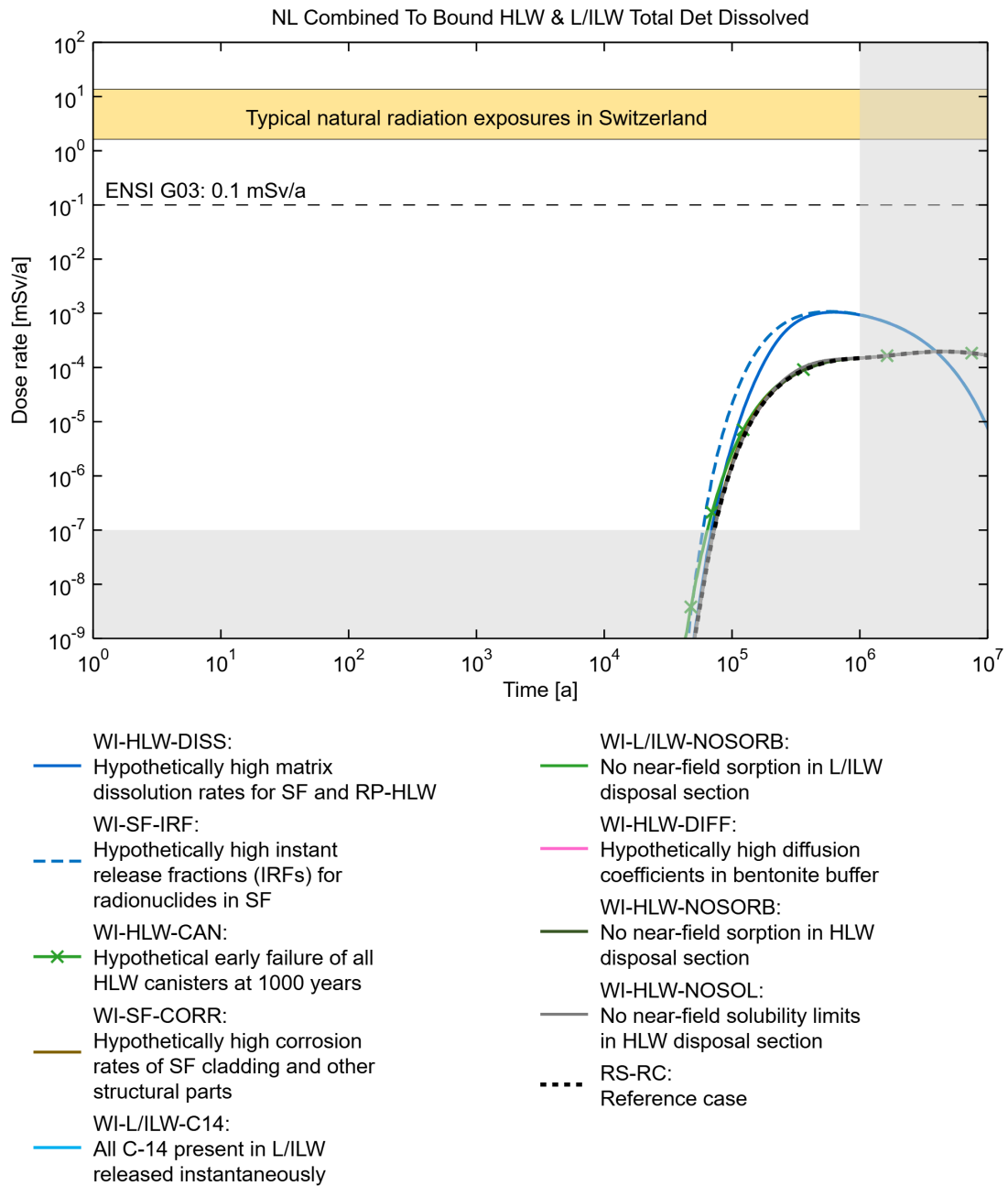


Fig. 7-15: Total dose rates in the reference case for a combined repository, and in nine “what-if?” cases that postulate a degraded performance of the engineered barriers

7.1.5 Summary of maximum dose rates due to radionuclide migration in the liquid phase

Fig. 7-16 gives an overview of the maximum dose rates from a combined repository in all cases examining radionuclide transport in the liquid phase. The dose interval labelled “Probabilistic” gives the statistical percentages of the calculated dose rates in the probabilistic simulations. The dose intervals labelled “Deterministic”, “Alternative” and “What-if” show the maximum dose rates in all deterministic analyses for the reference safety scenario, including alternative biospheres, alternative safety scenarios and “what-if?” cases, respectively. All four intervals, including the interval representing extreme, hypothetical “what-if?” cases, are at least one order of magnitude below the protection criterion of 0.1 mSv/a (ENSI 2023), which shows the robustness of the repository system from a post-closure safety perspective. In some cases analysed in Section 7.1, the maximum dose rates are reached after the time period for assessment. They are, however, far below the lower bound value of the typical natural radiological exposures in Switzerland (BAG 2021).

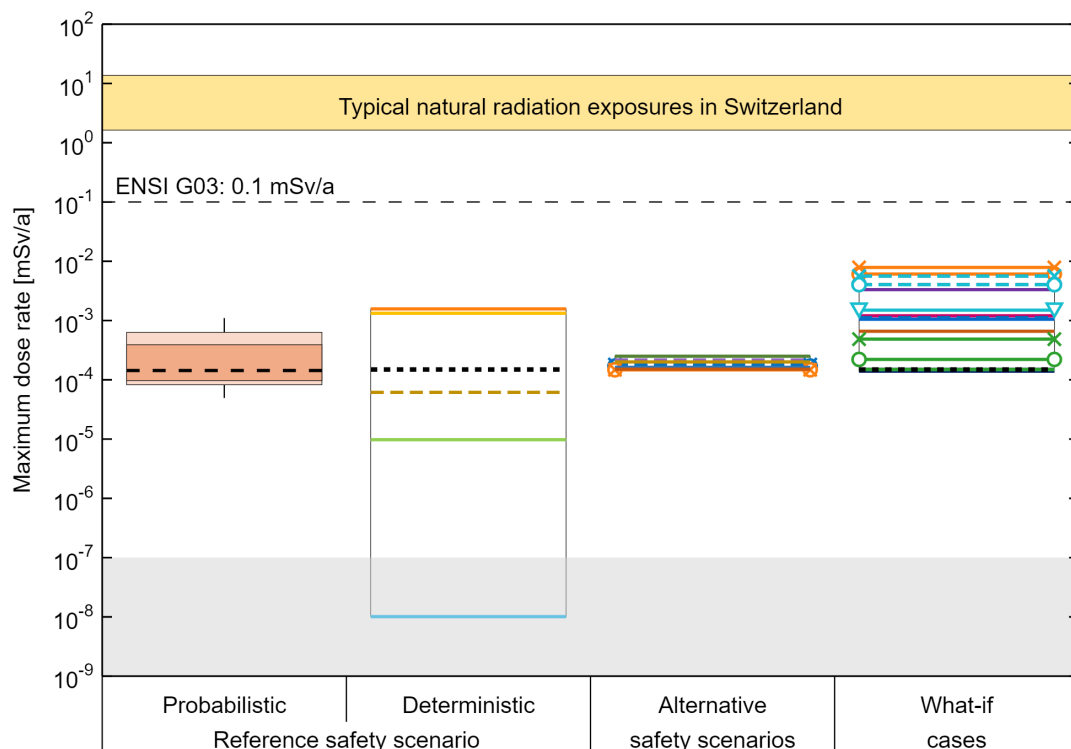


Fig. 7-16: Summary of maximum dose rates from a combined repository in all cases examining radionuclide transport in the liquid phase. The box plots show the maxima of the 0%, 5%, 16%, 50%, 84%, 95% and 100% percentiles

7.2 Radiological consequence analysis considering the two-phase migration of C-14 methane

The concepts and models for analysing radionuclide migration of C-14 in the gas phase in the reference safety scenario, in the alternative safety scenarios and in the “what-if?” cases are described in App. B.2. As there is some potential for limited interaction between the HLW repository section and the L/ILW repository section, which can influence gas pressures and the transport of C-14 methane, the two repository sections are not modelled separately, but together in a single, integrated model.

7.2.1 Reference safety scenario

Gas-mediated transport of C-14 is driven by two-phase system behaviour. Since the system behaves differently in a combined repository compared with a single repository for either HLW or L/ILW, two-phase system behaviour is investigated and summarised in Fig. 7-17, in order to provide a background for understanding the results of the radiological consequence analyses presented in this and the following sections.

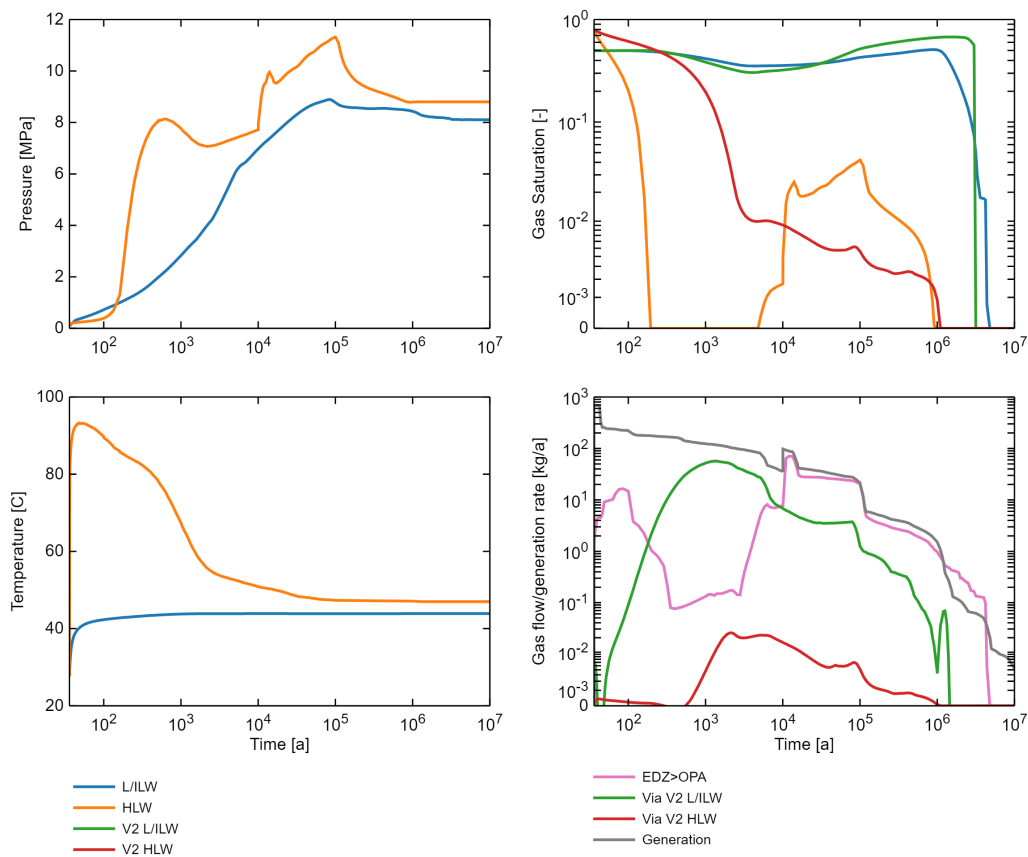


Fig. 7-17: Evolution of pressure (top left), temperature (bottom left), gas saturation in the emplacement rooms and in the V2 seals (top right) and gas generation and gas flows through the V2 seals and into the host rock (bottom right)

In the L/ILW repository section, gas generation in the L/ILW emplacement caverns after backfilling leads to pressure buildup, as is illustrated by the blue curve in the top-left graph in Fig. 7-17. Advective gas flow takes place towards the central area through the V1 seals and the V2 seals separating the L/ILW repository section from the central area (green curve in the bottom-right graph), which are relatively permeable and remain partially saturated (see App. H.4). However, gas flow from the central area through the V2 seals that separate the HLW repository section from the central area is strongly limited by the low permeability of these seals, which become almost fully liquid saturated after 1,000 years (red line in the figure top right). Due to tight V3 seals, no gas flow can occur up the shafts. Rather, gas is forced to flow into the EDZs and undisturbed host rock around the underground structures, where it dissolves and migrates, predominantly by diffusion, further through the CRZ.

In the HLW repository section, pressure in the emplacement drifts (orange curve in the top-left graph in Fig. 7-17) shows two major peaks. The first is a thermo-hydraulic peak at 500 years caused by thermal expansion of porewater in the host rock. The second peak is caused by increased gas generation upon canister breaching at 10,000 years. More gas is generated in the HLW emplacement drifts when the canisters breach and water (in either liquid or vapour form) comes in contact with the inner canister surfaces. The tight HLW bentonite buffer leads to higher overpressures in the HLW emplacement drifts than in the L/ILW emplacement caverns, and also forces gas to flow almost entirely into the EDZs and undisturbed host rock, where, as in the case of gas from the L/ILW emplacement caverns, it dissolves and migrates, predominantly by diffusion, further in the CRZ.

7.2.1.1 Reference case analysis including barrier performance and dose rates

Fig. 7-18 shows the total dose rate of C-14 methane from the combined repository as well as the contribution from the HLW and L/ILW sections.

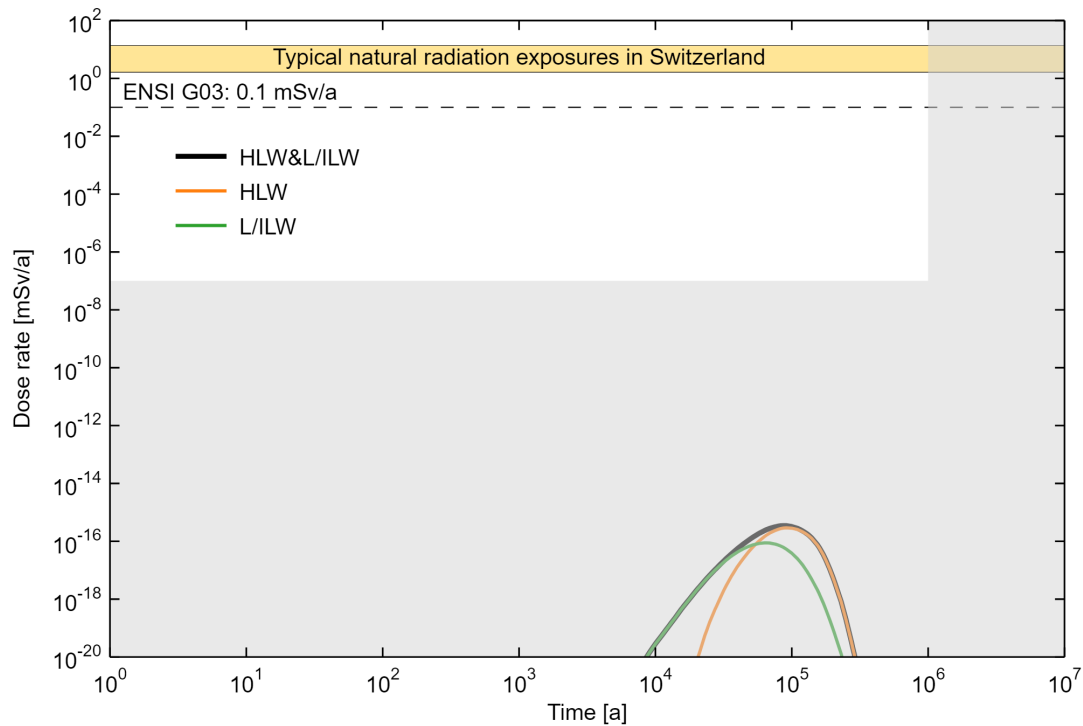


Fig. 7-18: Total dose rates of C-14 methane from the HLW and L/ILW sections of a combined repository

The total dose rate remains far below the level of the significant dose rate (10^{-7} mSv/a) during the whole time period for assessment. Prior to 70,000 years, the total dose rate is dominated by C-14 from L/ILW, which is not assumed to have any containment time within the L/ILW containers, and so release starts directly upon emplacement. At later times, releases from the HLW repository section dominate the total dose rate due to its higher C-14 inventory. As noted above, because of the low permeability of the bentonite buffer, overpressure develops, which forces gas to flow into the EDZ and host rock, carrying C-14 methane.

Fig. 7-19 shows activity fluxes at various locations within the repository and through the CRZ, converted to dose rates using the BDCF for C-14.

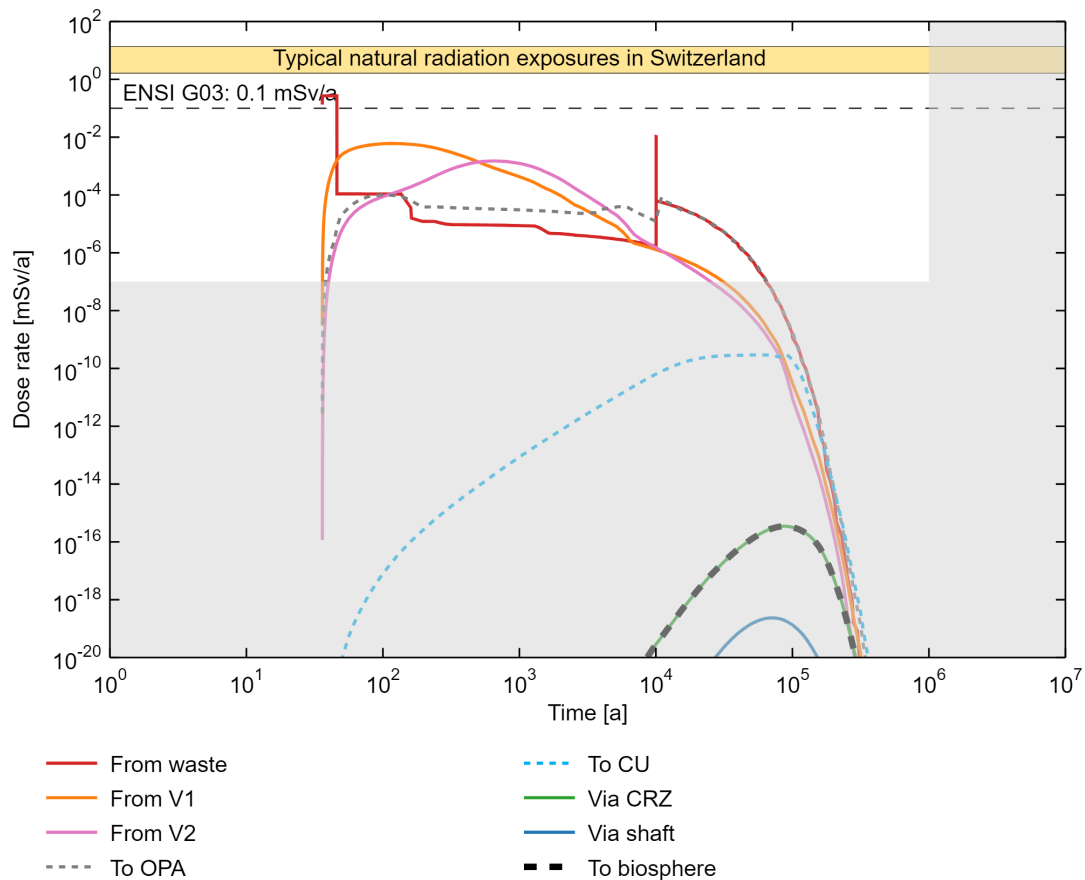


Fig. 7-19: Activity fluxes of C-14 methane within a combined repository and through the CRZ, converted to dose rates using the BDCF for C-14. The graph extends down to extremely low dose rates in order to illustrate system behaviour

From V1/V2 shows the sum of flows of C-14 released from the HLW through the V1/V2-HLW seals, and C-14 released from L/ILW through the V1/V2-L/ILW seals.

The red line labelled “from waste” represents the C-14 source term for both L/ILW and HLW. The L/ILW IRF is released upon emplacement, whereas the HLW IRF is released upon canister breaching after 10,000 years, leading to two visible peaks. The total release of C-14 from L/ILW is dominated by the IRF (16% of total inventory), as congruent release is very slow in the reference case (due to the slow corrosion of stainless steel in the high-pH conditions of the cementitious L/ILW near-field).

Because of the high permeability of the cementitious near-field of the L/ILW emplacement caverns and the backfill of the access tunnels, as well as the high gas permeability of the V1-L/ILW seals and the V2 seals that separate the L/ILW repository section from the central area (see App. H.4), C-14 is transported advectively along the L/ILW repository section. The release of C-14 methane from HLW starts at 10,000 years and, as noted above, directly migrates into the host rock because of the overpressure in the HLW near-field, where it dissolves and diffuses towards the model boundaries. The long transport times due to slow advection and diffusion through the Opalinus Clay and confining geological units lead to substantial decay of C-14 during transport; note the difference in the orders of magnitude between the source term and the release rates across the model boundaries to the biosphere.

The dose rate is dominated by diffusive transport through the CRZ (the curve labelled “via CRZ” in Fig. 7-19). The repository is located at great depth (the central area is 835 m b.g.l.), with the resultant high hydrostatic pressure allowing for high gas storage capacity in the pore space of the repository and of the adjacent host rock. The overpressure, combined with the tight V3 shaft seals, is not sufficient to cause advective release via the shaft in the reference case. Release via the shaft is therefore also dominated by diffusion, but at a much lower rate (see the curve “via shaft” in Fig. 7-19) than the release via the CRZ.

Fig. 7-20 illustrates the distribution of C-14 methane, expressed as radiotoxicity, within the repository, within the CRZ and outside the CRZ (see Section 3.1 for the definition of radiotoxicity). The red curve labelled “From waste” shows the activity contained within the waste packages, where most of the total C-14 methane resides (the thick black, dashed curve labelled “Total”) and decays throughout the 10^6 -year time period for assessment. This is because of the low corrosion rate of the activated metals that contain most of the C-14 methane in L/ILW (i.e., low corrosion of metals in high-pH condition in the cementitious L/ILW near-field). The figure also shows how the remaining activity, initially dominated by the IRF from L/ILW, is initially contained mainly in the emplacement rooms (the dark blue curve), before being distributed throughout the repository system, and, at the same time, entering the EDZ and undisturbed Opalinus Clay. The small peak in the dark blue curve at 10,000 years corresponds to the release of the C-14 as IRF from HLW upon canister breaching. Only a small fraction of the total amount of C-14 methane is present in the confining units (grey curve), and far less still always present outside the CRZ (green curve).

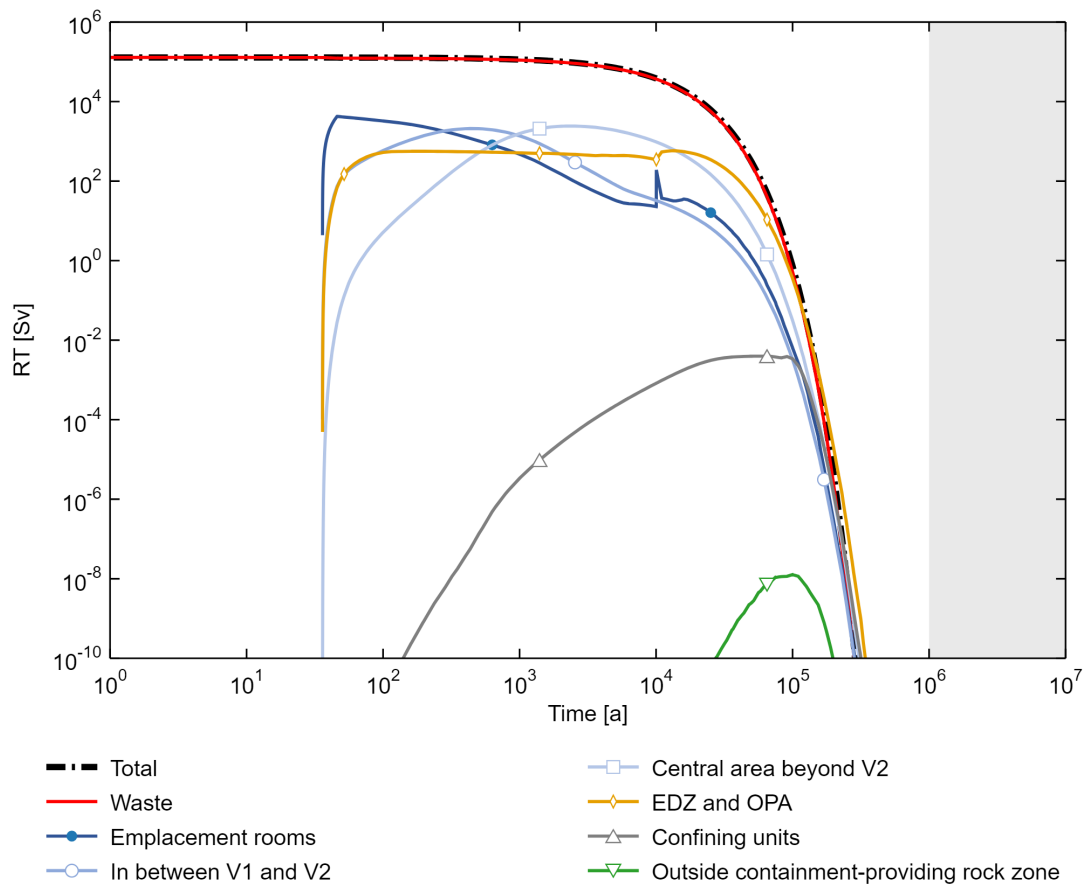


Fig. 7-20: Distribution of C-14 methane activity, expressed as radiotoxicity, within a combined repository, within the CRZ and outside the CRZ

Three additional deterministic calculation cases are defined that assume different, though still steady-state, climatic and surface conditions:

- RS-BIOS/WARM_DRY, based on a warmer and drier climate;
- RS-BIOS/COLD, based on a colder climate; and
- RS-BIOS/DRAINED_FARMLAND, which assumes a drained farmland.

The evolution of the dose rate in each of these cases is shown in Fig. 7-21. A warmer and drier climate results in the highest maximum dose rate, but all calculated dose rates are far below the level of the significant dose rate of 10^{-7} mSv/a.

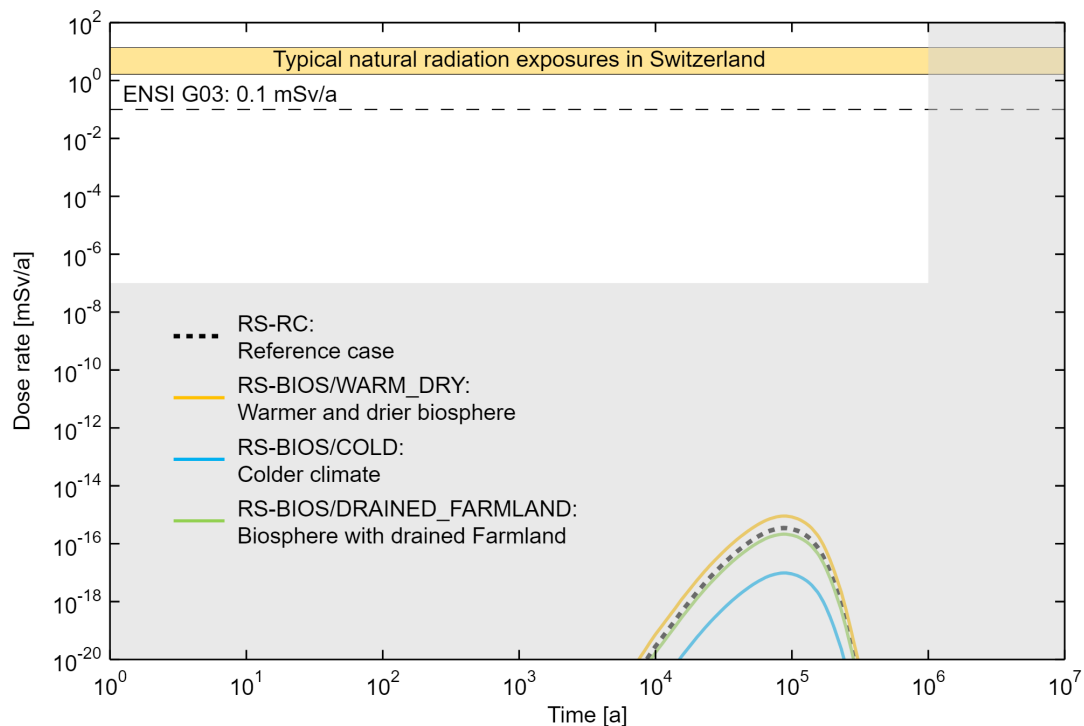


Fig. 7-21: Total dose rates of C-14 methane for a combined repository in the reference case and in cases assuming different climatic and surface conditions

7.2.1.2 Probabilistic and deterministic analyses covering the parameter uncertainty

In accordance with the workflow described at the start of this chapter, probabilistic analyses of the reference safety scenario are performed for C-14 methane from the combined repository, along with deterministic analyses of pessimistic cases, in which those parameters identified as the most sensitive in the probabilistic analyses are set to pessimistic, bounding values. This includes a deterministic case that combines the pessimistic bounding values of all most sensitive parameters. Details of the Monte-Carlo simulation approach and of the sensitivity analysis methods used in the probabilistic analyses are given in App. G.

Fig. 7-22 shows statistical percentiles calculated from 4,000 Monte-Carlo simulations of the dose rate evolution of a combined repository. The bandwidth of the maximum dose rate due to uncertainty in the input parameter values spans ten orders of magnitude. The highest calculated dose rate in the time period for assessment of up to one million years is 2.8×10^{-7} mSv/a, just above the level of significant dose rate of 10^{-7} mSv/a.

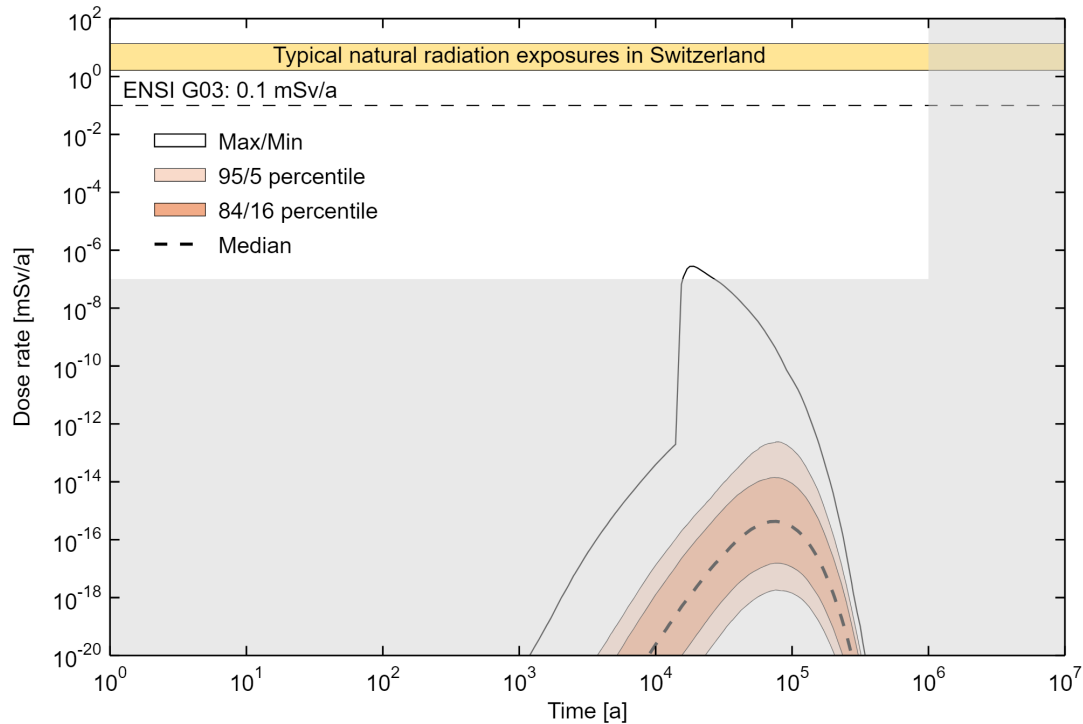


Fig. 7-22: Statistical percentiles of the dose rate evolution of C-14 methane for a combined repository calculated from 4,000 Monte-Carlo simulations

Sensitivity analyses have been performed based on the results from the Monte-Carlo simulations. The first step is a graphical analysis using scatter plots showing the maximum dose within the one-million-year time period for assessment against individual input parameter values sampled in the Monte-Carlo simulations. Some examples of such scatter plots are shown in Fig. 7-23.

The yellow points in Fig. 7-23 mean that, in most realisations (around 99%), diffusion through the CRZ is the dominant transport mechanism for C-14 methane migration. The highest dose rates occur in cases combining a higher corrosion/degradation rate with more permeable V3 seals and a less permeable Opalinus Clay, meaning that more gas is forced through the shafts and through their V3 seals.

Higher corrosion/degradation rate (scatter plot top right in Fig. 7-23), and hence the rate of gas generation, leads to the highest dose rates caused by transport via shafts (blue points in Fig. 7-23), because the higher gas pressure can result in advection through the shafts becoming the dominant pathway. Moreover, among the simulation realisations with the CRZ as the dominating pathway (yellow points in Fig. 7-23), a slight correlation is visible as well at the higher corrosion/degradation rate area. This is because the higher pressure caused by the high corrosion/degradation rate will also force more C-14 methane to flow into the EDZ and host rock, where it diffuses further through the CRZ.

The bottom right scatter plot in Fig. 7-23 shows a clear correlation between the maximum dose rate in cases where transport through the CRZ (see yellow points) dominates and the effective diffusion coefficient for C-14 in the Opalinus Clay, showing that, in the bulk of the host rock, C-14 has dissolved in the porewater, and diffusion in the CRZ is the dominant transport process.

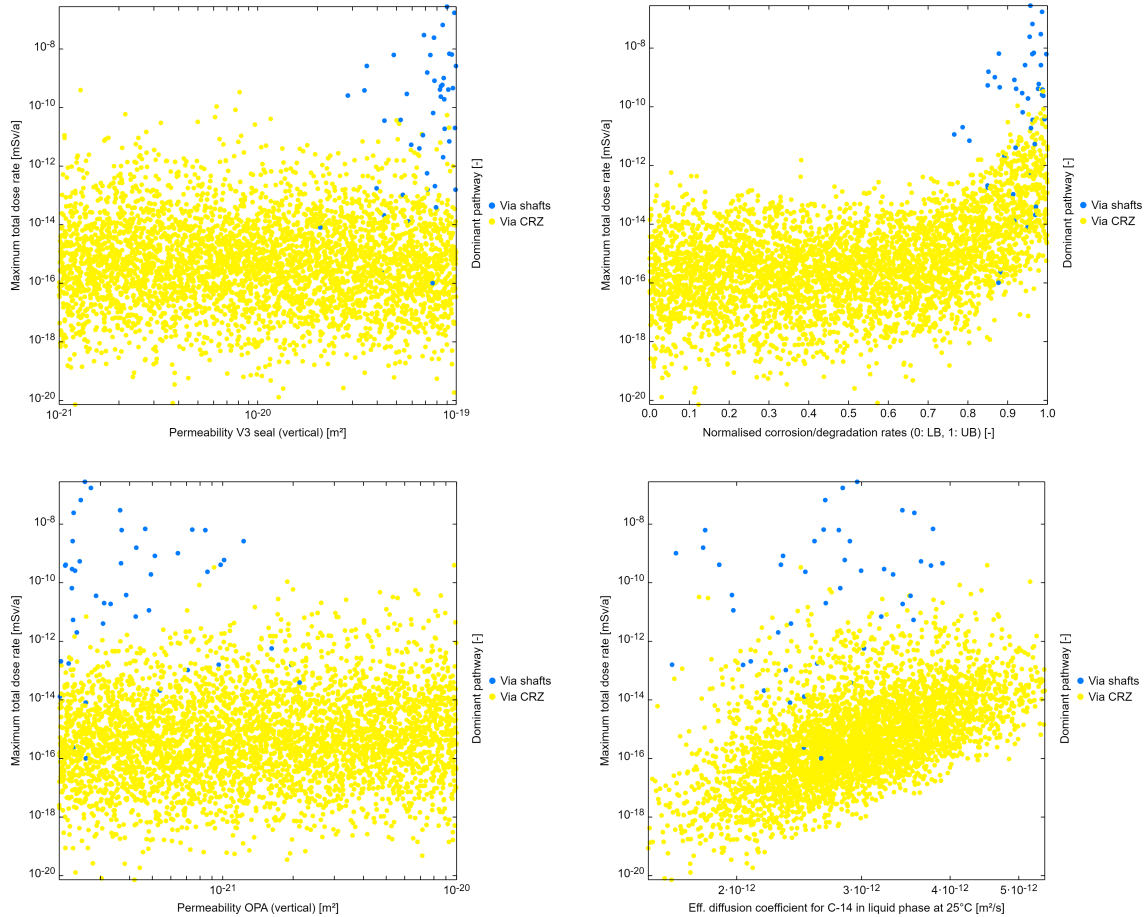


Fig. 7-23: Scatter plots showing the maximum total dose rate of C-14 methane from a combined repository against the permeability of the V3 seals (top left), the permeability of the Opalinus Clay (bottom left), the normalised corrosion and degradation rates (top right) and the effective diffusion coefficient of C-14 in the Opalinus Clay (bottom right), sampled in Monte-Carlo simulations. The different colours show the dominant pathway for each realisation, i.e., blue: via shafts, yellow: via CRZ

The sensitivity of the variance in the maximum dose rate to the variance in the input parameters is evaluated in terms of the Pearson correlation coefficient, the Spearman correlation coefficient and the modified EASI first-order sensitivity index. Tab. 7-2 shows these sensitivity measures calculated for the parameters considered in the probabilistic analyses.

Consistent with the scatter plots above, the sensitivity measures indicate a high positive correlation with the corrosion/degradation rate, and hence the gas generation rate, and with the permeability of the V3 seals.

Moreover, because the diffusive migration in the CRZ dominates the C-14 transport in most of the simulation realisations, the diffusion-relevant parameters such as the effective diffusion coefficient of C-14 in the Opalinus Clay ($De_{C14_1_25}$) and the activation energy (Ea) covering the temperature impact on the diffusion can show sensitivity as well. These parameters, together with the hydraulic permeability of the Opalinus Clay (k_{OPA}), show opposing Pearson and Spearman correlations. This is because the increased diffusion coefficient, activation energy and the permeability of the Opalinus Clay will cause more diffusive gas migration in the CRZ. However, at the same time, it will reduce the likelihood of advective gas along the shafts. This correlation is well detected by the Pearson correlation coefficient because the higher dose rate will have more weight in calculating the Pearson correlation coefficient (see description in App. G.2.1). On the other hand, the sensitivity shown in the simulation realisations with lower dose rates (such as the cases marked in yellow in the scatter plots above) can be better captured by the Spearman coefficient thanks to its mathematical transformation (see description in App. G.2.2). Thus, the opposing Spearman and Pearson correlation coefficients of the diffusion-relevant parameters are well understandable.

Tab. 7-2: Sensitivity measures for the parameters showing at least one significant correlation with total dose rate of C-14 methane released from a combined repository in the NL siting region

Values above the calculated “threshold of significance” are marked in blue. (+) or (-) indicates the selected bounding value for the individual and combined pessimistic calculations.

Parameter	Description	Pearson correlation coefficient	Spearman correlation coefficient	Modified EASI sensitivity index
	<i>Significance threshold</i>	<i>0.038</i>	<i>0.042</i>	<i>0.0041</i>
$k_{V3(+)}$ $1 \times 10^{-21} - 1 \times 10^{-19} \text{ m}^2$	Permeability of V3 seals	0.078	0.0039	0.0095
KorrDegRate_Szenario(+) 0 – 1	Normalised corrosion/degradation rates	0.047	0.40	0.0090
$De_{C14_1_25(-)}$ $1.5 \times 10^{-12} - 5.5 \times 10^{-12} \text{ m}^2/\text{s}$	Eff. diffusion coefficient for C-14 in liquid phase at 25 °C	-0.0055	0.55	0.0023
$Ea(-)$ $1.5 \times 10^4 - 2.5 \times 10^4 \text{ J/mol}$	Activation energy (for temperature correction of eff. diffusion coefficient)	-0.0082	0.16	0.00095
$k_{OPA(-)}$ $2 \times 10^{-22} - 1 \times 10^{-20} \text{ m}^2$	Permeability of OPA (vertical)	-0.025	0.093	0.0043

To provide a better understanding of the impact of the various parameters, additional deterministic cases have been analysed, switching each of the individual sensitive parameters to their most pessimistic, bounding values, and, in addition, a “combined pessimistic case” in which all parameters are set to their most pessimistic, bounding values. The results are shown in Fig. 7-24.

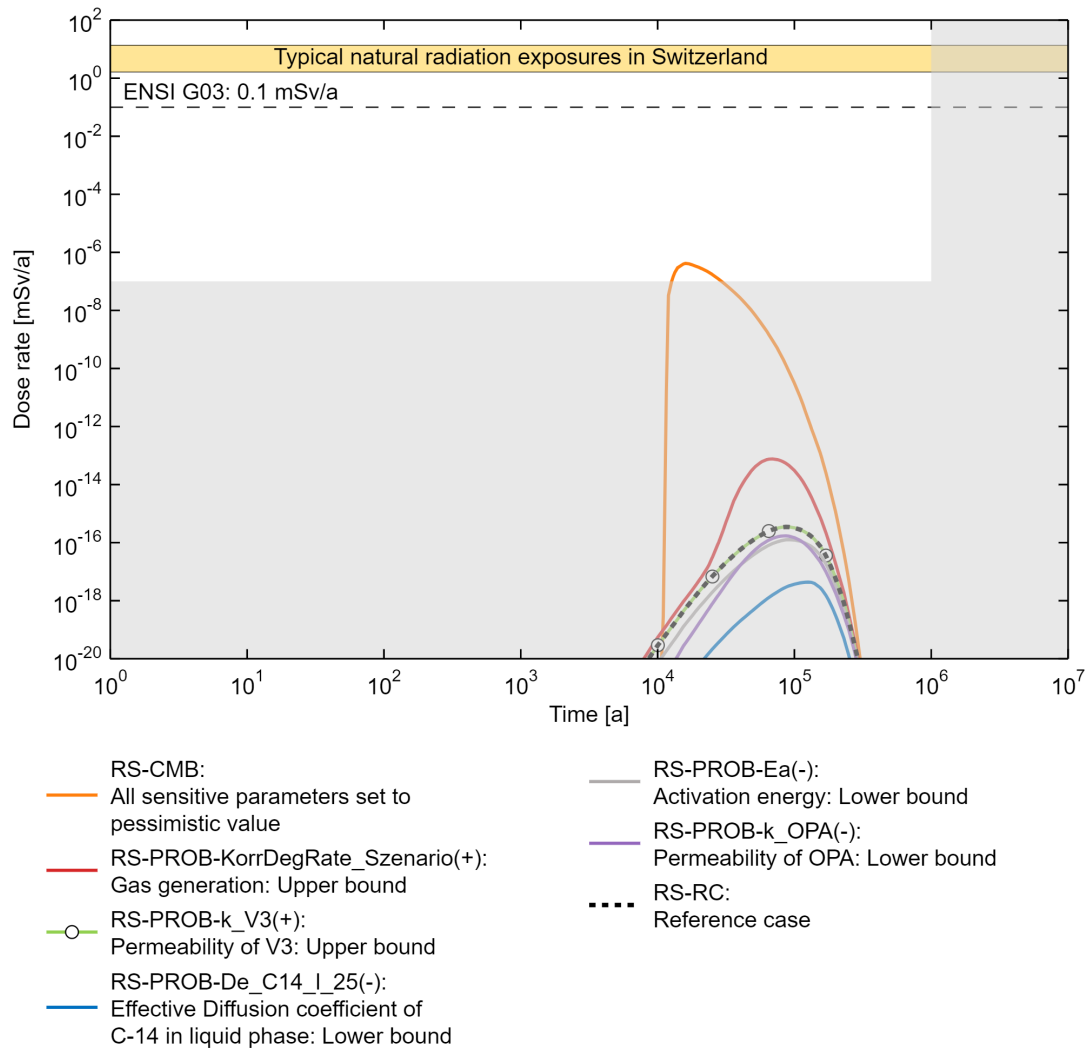


Fig. 7-24: Total dose rates of C-14 methane in the reference case for a combined repository, and in cases where sensitive parameters are set to their most pessimistic, bounding values, both individually and in combination. (+) indicates the most pessimistic upper bound values and (-) indicates the most pessimistic lower bound values, according to Tab. 7-2

In line with the corresponding scatter plot and sensitivity measures, an increase in the maximum dose rate is observed in the case where a high value is assigned to the corrosion/degradation rate. The permeability of the V3 seal, however, does not show a visible effect on the dose rate, in spite of the correlations indicated by the scatter plots and sensitivity measures. This is because the permeability of the V3 seal can only show its significance when it is combined with the pessimistic corrosion/degradation rate and permeability of the Opalinus Clay, activating the pathway via shafts (Fig. 7-23). In addition, as discussed above, some parameters show an opposing correlation depending on whether the dominant release pathway is via the CRZ or the shaft. One example is Opalinus Clay permeability: in the combined pessimistic case (RS-CMB), in order to capture the most pessimistic bounding combination, the dominant pathway is via the shafts and the lower bound of Opalinus Clay permeability is selected as the most pessimistic parameter. For the sake of consistency, the individual deterministic cases were set to cover the sensitive parameters in the same manner, even though these cases show lower dose rates compared to the reference case, because the diffusive migration pathway along the CRZ is still the dominating pathway.

The “combined pessimistic case” (RS-CMB) shows the power of combining the pessimistic bounding values of the sensitive parameters. It is the only case in which the maximum dose rate, at 4.2×10^{-7} mSv/a, slightly exceeds the level of significant dose rate of 10^{-7} mSv/a.

7.2.1.3 Variant conceptualisation assuming an inactive Keuper aquifer

In the reference conceptualisation of the reference safety scenario, which provides the basis for the reference case, it is conservatively assumed that the Keuper aquifer below the repository is hydraulically active and forms a significant advective transport pathway for radionuclides migrating downwards from the repository. As noted in Section 4.1.2, a variant conceptualisation is also defined in which the Keuper aquifer below the HLW repository at the selected site, or below the HLW repository section of a combined repository, is inactive and radionuclides are transported vertically across it by diffusion.

The total dose rate and dose rate contribution from the HLW and L/ILW repository sections are illustrated separately in Fig. 7-25. Since the absence of the Keuper aquifer is only possible below the HLW repository section, one can see that the contribution from L/ILW in the “RS-KEUPER-INACTIVE” case (dashed green line) remains almost identical to that in the reference case. However, the contribution from HLW (dashed orange line) decreases by several orders of magnitude and is not visible. The maximum total dose rate of “RS-KEUPER-INACTIVE” decreases by about a factor of 5 compared to the reference case.

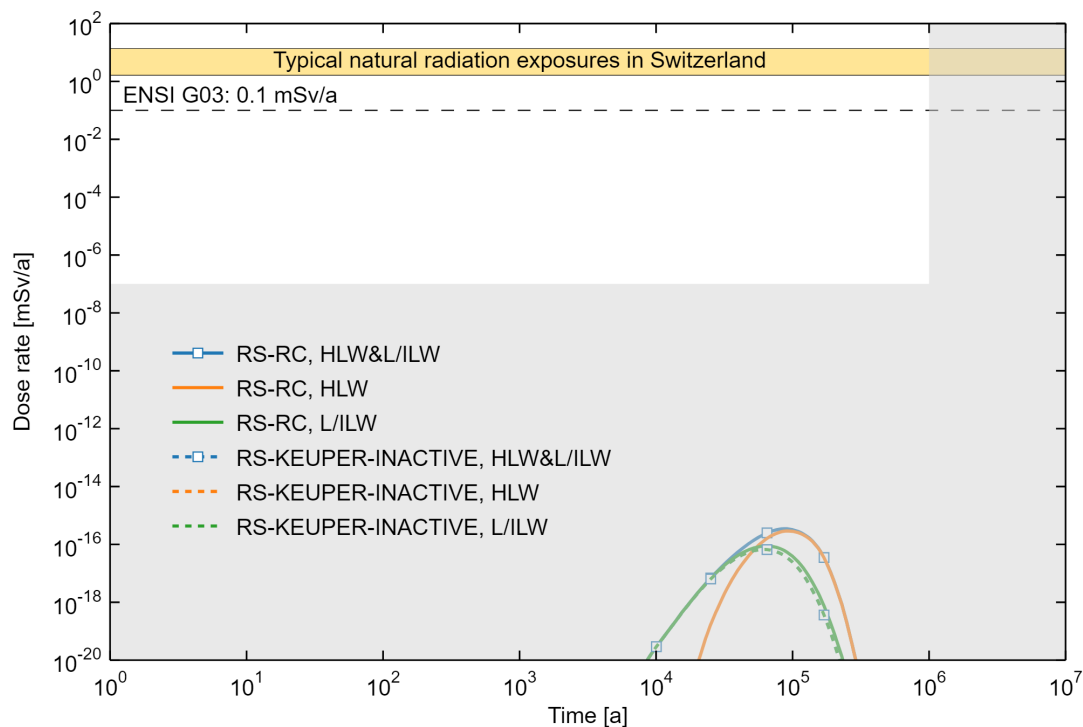


Fig. 7-25: Total dose rates of C-14 methane for a combined repository in the reference case and in a variant of the reference safety scenario in which the Keuper aquifer below the repository is hydraulically inactive

7.2.2 Alternative safety scenarios

The same alternative safety scenarios that were analysed when considering radionuclide migration in the liquid phase are analysed when considering the migration of C-14 in the gas phase. Specific uncertainties flagged for consideration as alternative safety scenarios concern uncertainties in geological characterisation, and, specifically, the possibility that there could be:

- a hydraulically active confining unit above or below the Opalinus Clay; or
- an undetected fault in the vicinity of the repository emplacement rooms.

For the scenario with a hydraulically active confining unit, the unit that is considered for transport of C-14 methane is the SCD (Sandy-Calcareous Dogger) unit in the upper confining units, since this could be the most pessimistic of the various potentially conductive units concerning C-14 methane. The activation of the SCD unit will shorten the transport length in the upper confining units and in the shaft above the Opalinus Clay.

For the undetected fault, as in the analysis of radionuclide migration in the liquid phase, there are two cases in which the fault intersects the HLW repository section, one in which it runs along one of the HLW emplacement drifts and one in which it cuts perpendicularly across all the drifts. Similarly, there are two cases in which the fault intersects the L/ILW repository section, one in which it runs along one of the L/ILW emplacement caverns and one in which it cuts perpendicularly across all the caverns. Tab. 4-3 provides summary definitions of these cases.

As in the modelling for the radionuclide transport in the liquid phase, these cases are modelled with extremely conservative assumptions:

- The fault is assumed to exist since the start of construction work through the whole CRZ connecting the two deep aquifers (Keuper and Malm aquifers).
- The fault will either partly affect all the HLW or L/ILW emplacement rooms (AS-FLT-HLW-Across, AS-FLT-L/ILW-Across) or an entire emplacement room (AS-FLT-HLW-Along, AS-FLT-L/ILW-Along); the fault can be easily detected and avoided.
- Transmissivity of the fault is set to $10^{-10} \text{ m}^2/\text{s}$, which has not been observed in the geological investigations of the potential repository fields (Nagra 2024e).

Fig. 7-26 summarises the dose rates calculated for the alternative safety scenarios. Assuming that this SCD unit is hydraulically active has a marked impact on dose rate evolution. As noted above, the total dose rate in the reference case is dominated by diffusive transport through the CRZ and confining units. The assumption of a hydraulically active SCD unit cannot change the properties of the sealing system and the dominance of the diffusive transport. However, it leads to a significant shortening of the diffusive transport pathway within the CRZ, resulting in an increase in the dose rate compared to the reference case. The maximum dose rate is still, however, well below the level of significant dose rate of 10^{-7} mSv/a .

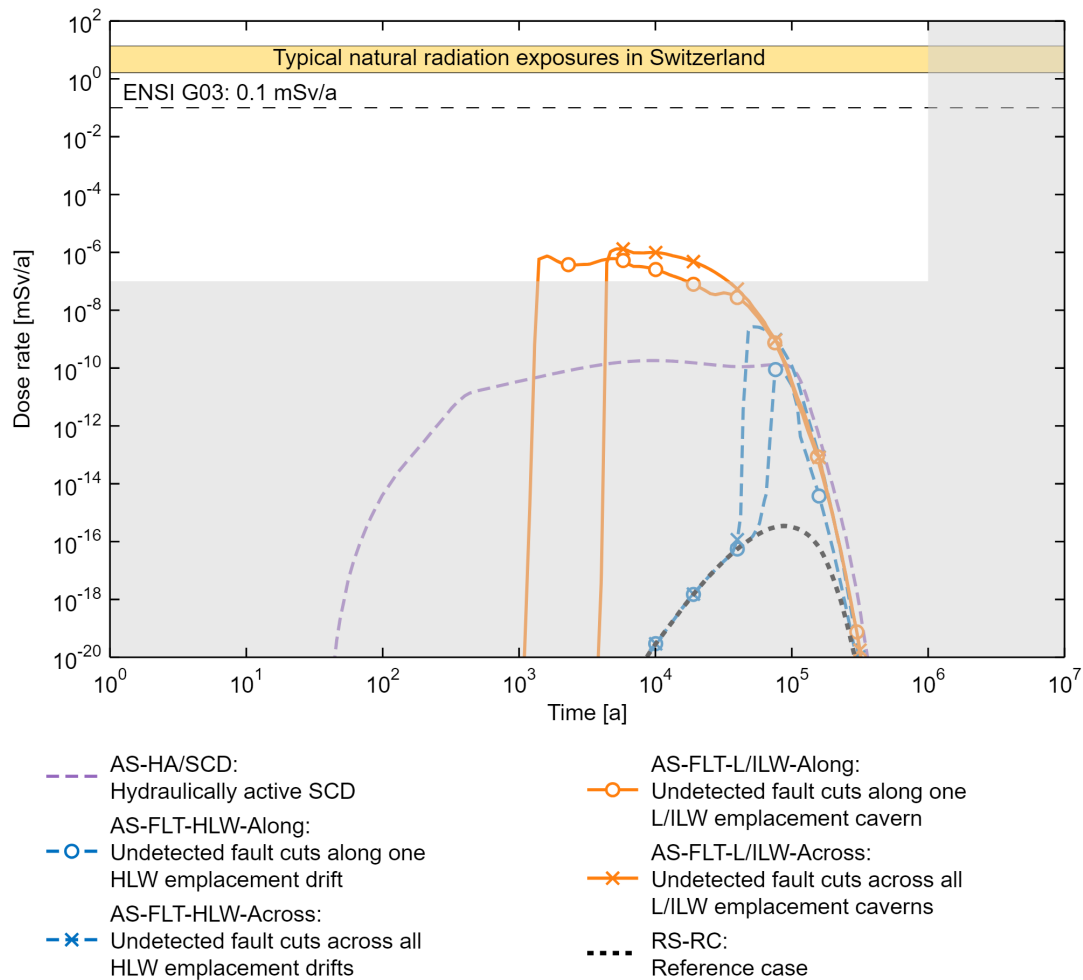


Fig. 7-26: Total dose rates of C-14 methane for a combined repository in the reference case, for one case where the SCD unit is hydraulically active and for four cases of an undetected fault intersecting the emplacement caverns and drifts

As in the cases for the porewater-mediated radionuclide transport, the presence of an undetected fault through the whole CRZ provides an additional advective pathway from the emplacement rooms to the deep aquifers and biosphere. A fault affecting the L/ILW emplacement caverns is especially consequential, because of the earlier release from L/ILW compared with HLW. The two cases of a fault affecting the L/ILW emplacement caverns result in maximum dose rates just above the level of the significant dose rate of 10^{-7} mSv/a. By contrast, a fault affecting the HLW emplacement drifts has a lower impact because of the assumed 10,000-year containment time of canisters.

The peaks in the dose rates associated with transport of C-14 methane through the faults in the two cases of a fault affecting the HLW emplacement drifts are below the level of the significant dose rate of 10^{-7} mSv/a.

7.2.3 “What-if?” cases related to physical phenomena

The same “what-if?” cases related to physical phenomena that are analysed when considering radionuclide migration in the liquid phase are analysed when considering the migration of C-14 methane.

These “what-if?” cases consider:

- the occurrence, in the vicinity of the repository, of an undetected transmissive fault (cases in Tab. 4-4), and
- the future creation or re-activation of a fault either by geological processes or as a repository-induced effect (cases in Tab. 4-5).

The same conservative assumptions used for the alternative safety scenarios concerning undetected fault are taken over here in the “what-if?” cases, however, with a more hypothetical fault transmissivity ($10^{-7} \text{ m}^2/\text{s}$):

- two cases in which the fault intersects the HLW repository section, one in which it runs along one of the HLW emplacement drifts (WI-FLT-HLW-Along) and one in which it cuts perpendicularly across all the drifts (WI-FLT-HLW-Across); and
- two cases in which the fault intersects the L/ILW repository section, one in which it runs along one of the L/ILW emplacement caverns (WI-FLT-L/ILW-Along) and one in which it cuts perpendicularly across all the caverns (WI-FLT-L/ILW-Across).

Compared with the cases for an undetected fault with a more realistic ($10^{-10} \text{ m}^2/\text{s}$) transmissivity in Fig. 7-26, a significantly higher impact on the dose rate can be observed in the “what-if?” cases in Fig. 7-27 with three orders of magnitude higher transmissivity. The maximum dose rate is $9.0 \times 10^{-3} \text{ mSv/a}$ where the fault runs perpendicular to the emplacement caverns and $2.6 \times 10^{-3} \text{ mSv/a}$ where it runs along one of the caverns. These maximum dose rates are still more than one order of magnitude below the protection criterion (ENSI 2023) of 0.1 mSv/a . Because the fault will not affect the HLW canisters, the two cases in which the fault intersects the HLW repository section give rise to peaks in the dose rate, but these remain below the level of the significant dose rate of 10^{-7} mSv/a .

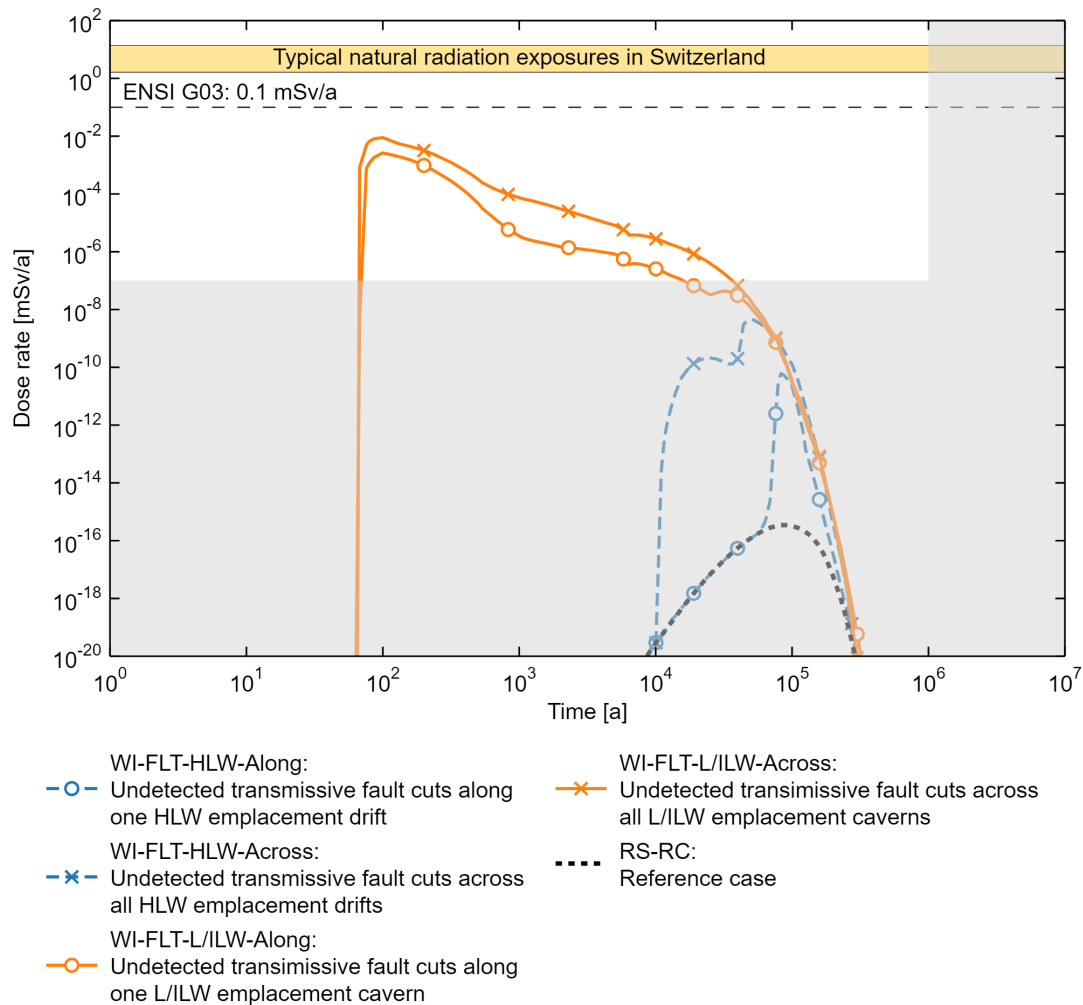


Fig. 7-27: Total dose rates of C-14 methane for a combined repository in the reference case and in four “what-if?” cases of an undetected fault with elevated transmissivity ($10^{-7} \text{ m}^2/\text{s}$) intersecting the emplacement drifts and caverns

Four further “what-if?” cases are also defined that consider future creation or reactivation of a fault either by geological processes or as a repository-induced effect (see Tab. 4-5). The fault geometry and assumptions are the same as in the cases considering an undetected fault with elevated transmissivity. However, in the cases involving a fault intersecting the HLW emplacement drifts (WI-FLT/RA-HLW-Along and WI-FLT/RA-HLW-Across), the fault is assumed to be created or reactivated at 10,000 years after repository closure, which coincides with the assumed canister failure time and the pressure evolution of the HLW near-field investigated in Nagra (2024k). In the cases involving a fault intersecting the L/ILW emplacement caverns (WI-FLT/RA-L/ILW-Along and WI-FLT/RA-L/ILW-Across), the fault is assumed to be created or reactivated at 20,000 years after repository closure, corresponding to the time when there is a risk of gas overpressure in the L/ILW near-field (see Nagra 2024k). As in the previous “what-if?” cases, the fault transmissivity (once created or reactivated) is hypothetically set to $10^{-7} \text{ m}^2/\text{s}$.

The presence of a transmissive fault across or along the L/ILW emplacement caverns, combined with a gas overpressure in the near-field, produces an almost instantaneous release of the C-14 methane from the near-field to the aquifer, leading to the spikes in the calculated dose rates shown

in Fig. 7-28. A fault running perpendicular to the L/ILW emplacement caverns causes the largest dose rate maximum, which, at 1.1×10^{-3} mSv/a, is still almost 2 orders of magnitude below the protection criterion. The cases of fault creation or reactivation in an HLW repository also increase the dose rate, but the maxima are all lower than the level of the significant dose rate of 10^{-7} mSv/a.

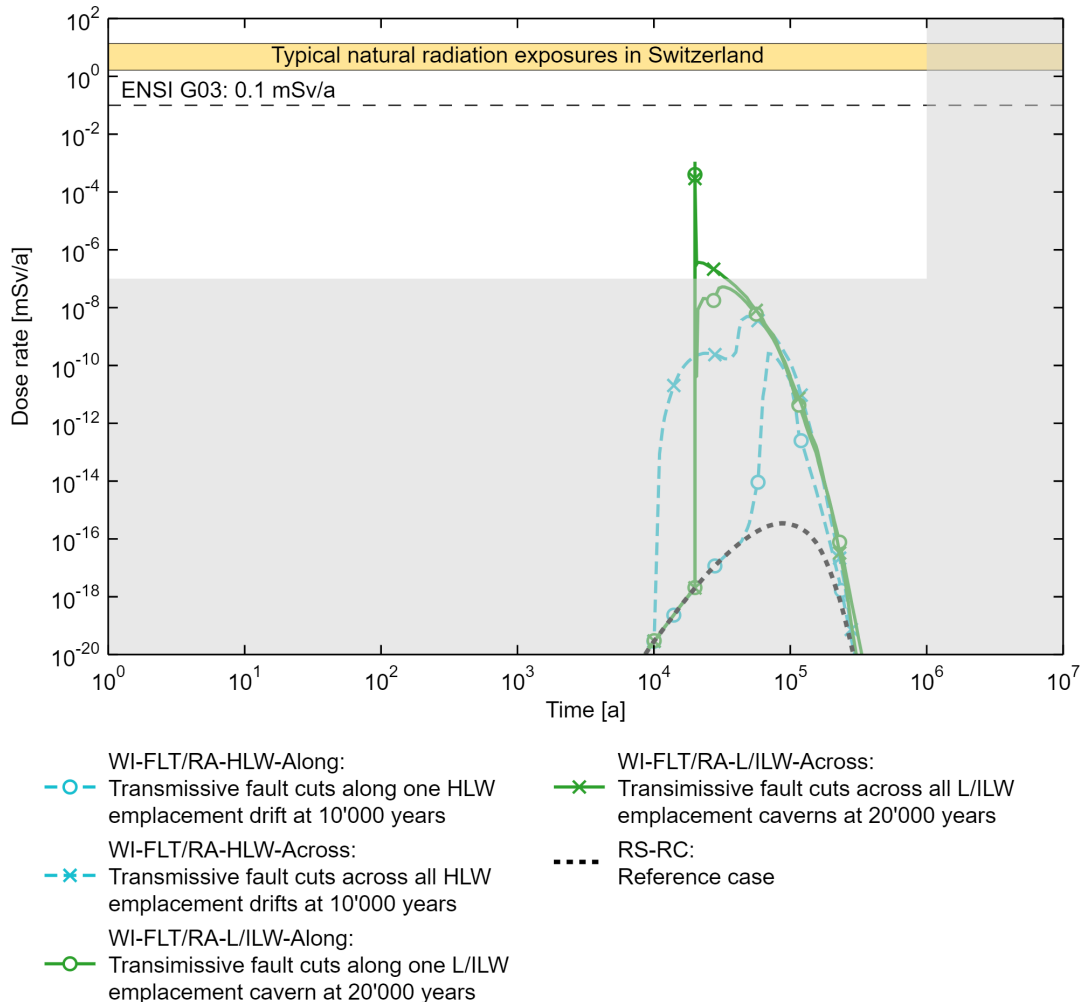


Fig. 7-28: Total dose rates of C-14 methane for a combined repository in the reference case and in four “what-if?” cases of a fault with a transmissivity of 10^{-7} m²/s created or reactivated by geological processes or repository-induced effects intersecting the emplacement drifts and caverns

7.2.4 “What-if?” cases postulating a hypothetically degraded performance of the pillars of safety

Additional “what-if?” cases (see Tab. 4-6) are analysed to test the robustness of the repository system by illustrating the effects of a hypothetically degraded performance of the system components that are the main contributors to the repository safety functions.

Fig. 7-29 shows the evolution of the dose rates in the “what-if?” cases that postulate a degraded performance of the CRZ, and Fig. 7-30 shows the evolution of the dose rates in the “what-if?” cases that postulate a degraded performance of the engineered barriers, excluding the sealing system and HLW bentonite buffer, which are covered in Fig. 7-31.

For the CRZ, the WI-CRZ-DIFF case, which assumes a 10 times higher diffusion coefficient of C-14 in the geosphere and near-field than the upper bound value used in the sensitivity analyses, shows the largest increase in the dose rate, which highlights the importance of diffusion as the dominant transport mechanism. Similarly, when the diffusive pathway is shortened by disregarding the presence of the upper and lower confining units (the WI-CRZ-NOCONFINING case), releases to the biosphere start earlier and the maximum dose rate is increased compared with the reference case. A downwardly directed hydraulic gradient (the WI-CRZ-GRADdown case) also leads to a marked increase in the maximum dose rate, since it reinforces the dominant transport pathway through the CRZ, which is downwards to the Keuper aquifer. By contrast, an upwardly directed hydraulic gradient (the WI-CRZ-GRADup case) even decreases the dose rate in comparison with the reference case. This is because the direction of the upwards flow goes against the shortest diffusive pathway from the repository to the Keuper aquifer. An increase in the assumed radial extent of the EDZ (the WI-CRZ-EDZ case) does not significantly increase the dose rate.

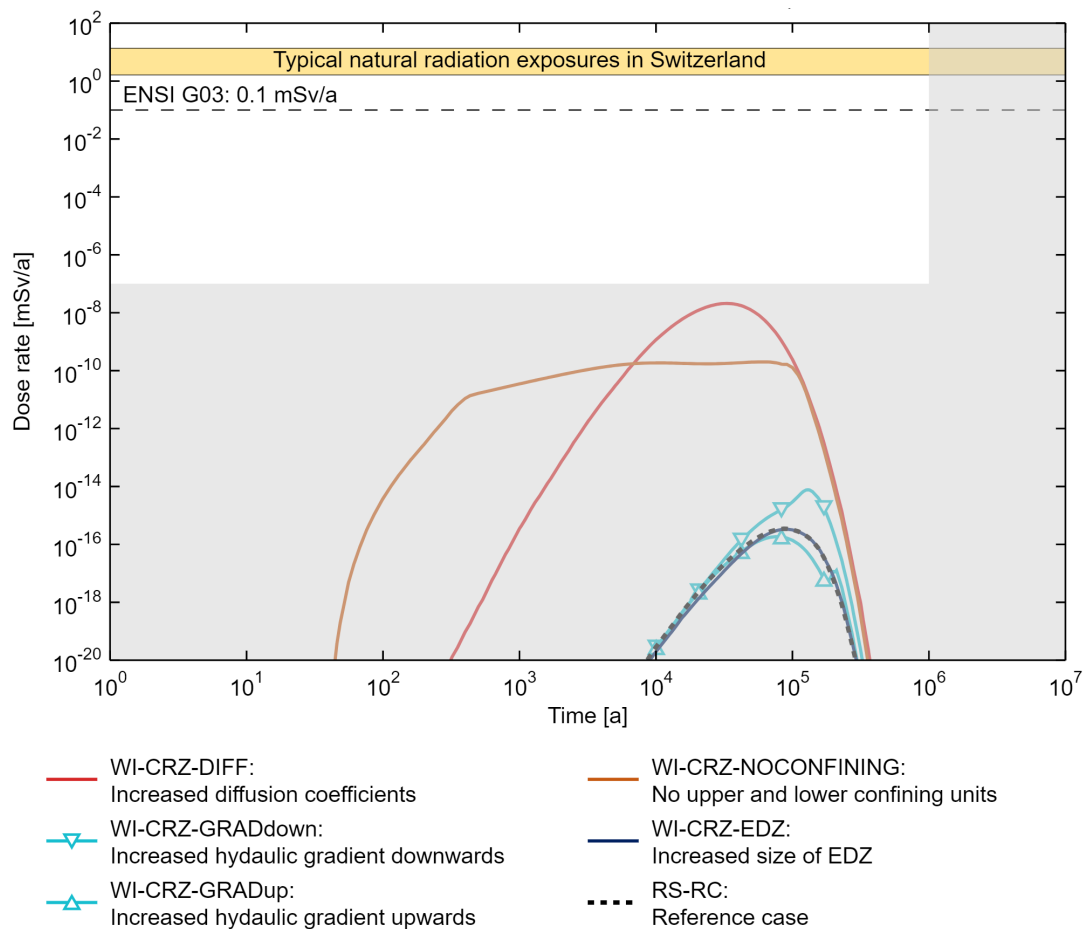


Fig. 7-29: Total dose rates of C-14 methane for a combined repository in the reference case and in five “what-if?” cases that postulate a degraded performance of the CRZ

Fig. 7-30 shows that a hypothetically unfavourable C-14 source term (WI-SF-IRF, WI-L/ILW-C14 and WI-SF-CORR, WI-HLW-CAN) has a minor impact on the maximum dose rate. None of these cases cause a maximum dose rate above the level of the significant dose rate of 10^{-7} mSv/a.

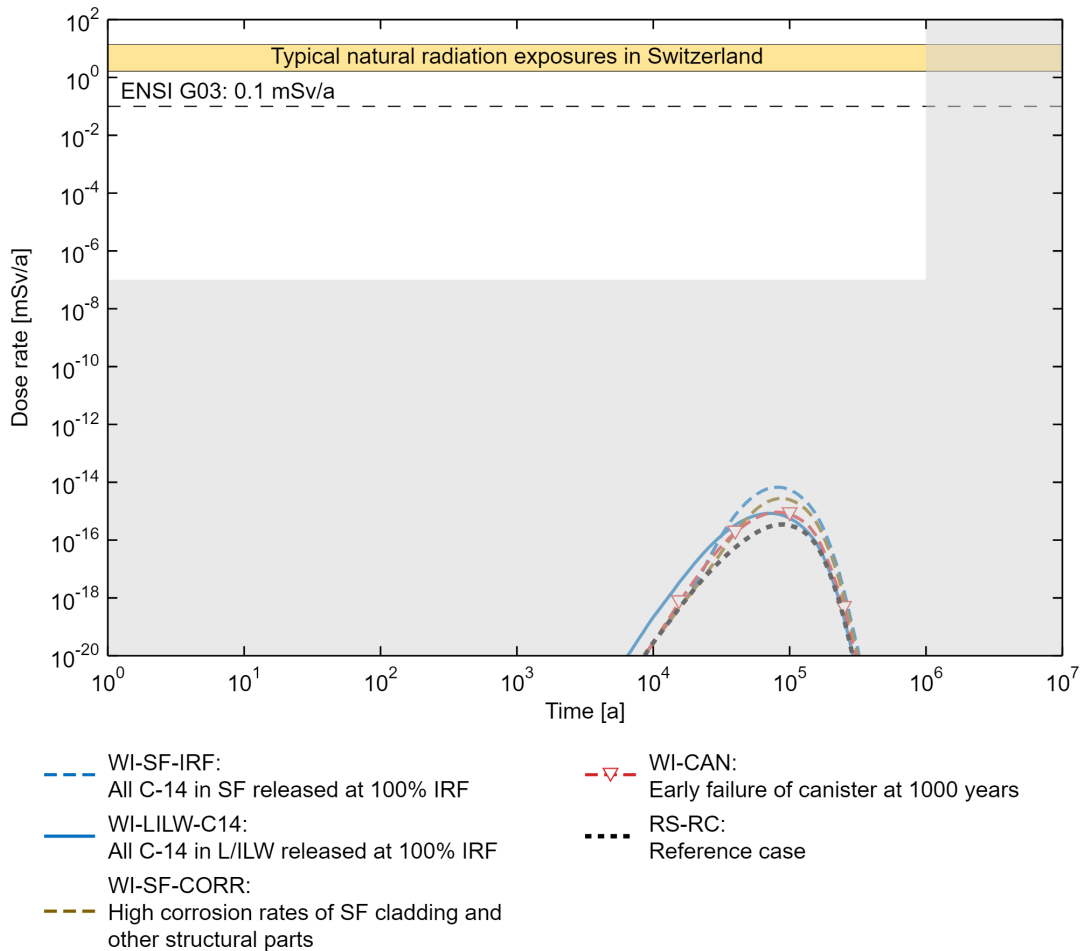


Fig. 7-30: Total dose rates of C-14 methane for a combined repository and in four “what-if?” cases that postulate a degraded performance of the engineered barriers concerning the C-14 source term

Fig. 7-31 shows the cases concerning the non-functioning V1 seals of HLW emplacement drifts (V1-HLW) and the V2 seals for the emplacement drifts in the HLW repository section (V2-HLW). These have little impact on the evolution of the dose rate, because axial flow of the repository-generated gas, including C-14 methane released from the HLW along the drifts is largely prevented by the bentonite buffer, causing most C-14 methane to enter the Opalinus Clay. If, on the other hand, the permeability of the buffer (WI-HLW-BUF) is increased, axial flow of C-14 methane is largely prevented by the V1-HLW seals, explaining why this also has little effect on the dose rate.

Non-functioning V1 seals of L/ILW emplacement caverns (V1-L/ILW) and V2 seals for the emplacement caverns in the L/ILW repository section (V2-L/ILW) also have little effect on the evolution of the dose rate since these seals are, in any case, provisionally designed to be gas-permeable. By contrast, increasing the permeability of the V3 seals increases the maximum dose

rate significantly, with a maximum of 2.5×10^{-5} mSv/a in the WI-V3 case. In the RS-PROB-k_V3 (+) case discussed in Section 7.2.1.2, setting the V3 seal permeability to its pessimistic upper bound value (1×10^{-19} m²) shows little impact on the dose rate evolution, although the probabilistic analysis shows some sensitivity when other parameters are also varied. In the “what-if?” case (WI-V3), the permeability is sufficiently high (1×10^{-15} m²)²¹, allowing more advective gas flow upwards along the shafts, even when other parameters are set to their reference values.

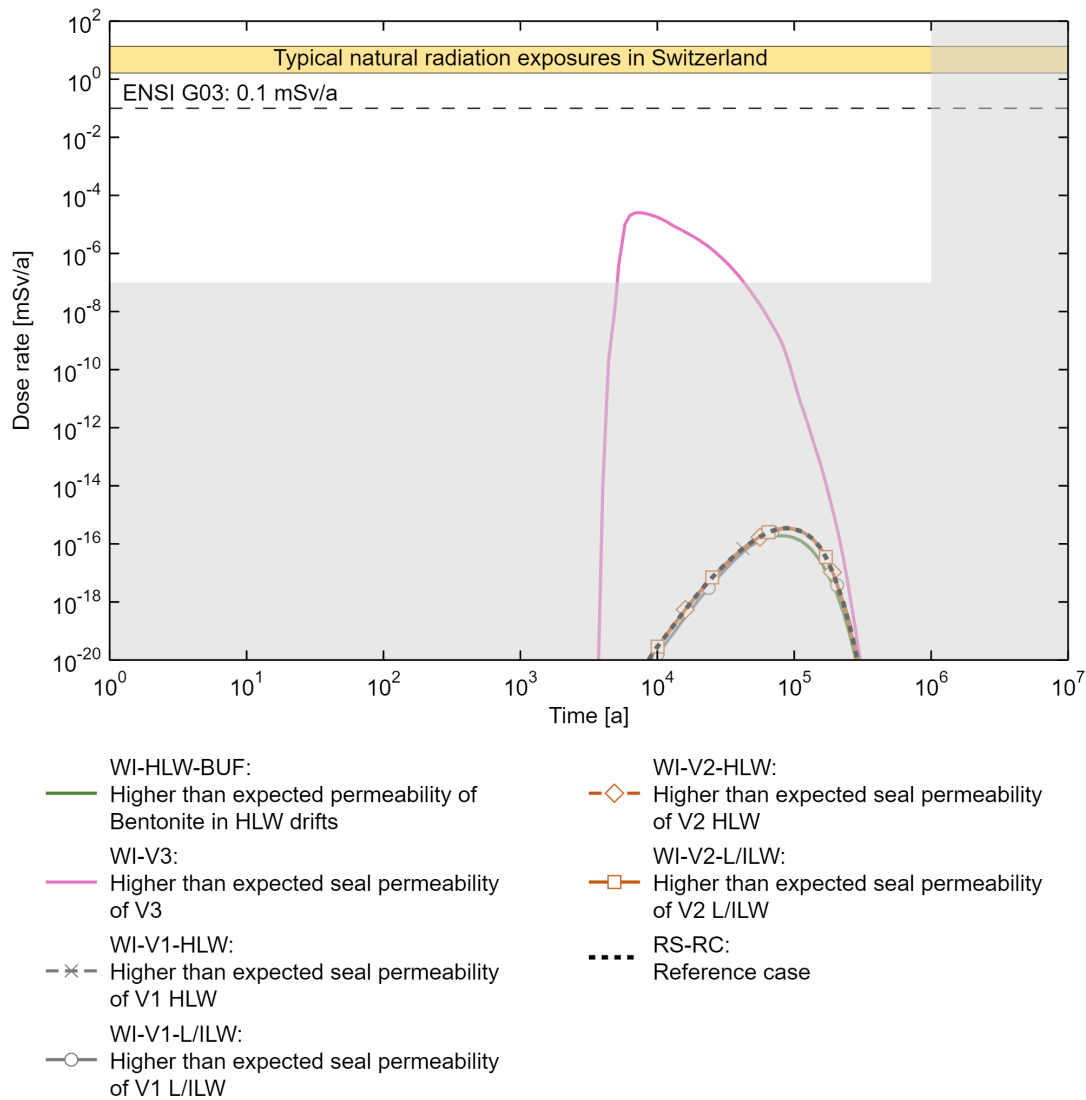


Fig. 7-31: Total dose rates of C-14 methane for a combined repository in the reference case and in six “what-if?” cases that postulate a degraded performance of the sealing system and HLW bentonite buffer

²¹ The Van Genuchten parameter P_0 is scaled according to changes in the permeability.

7.2.5 Summary of maximum dose rates of C-14 methane

Fig. 7-32 gives an overview of the maximum dose rates of C-14 methane from a combined repository. The dose interval labelled “probabilistic” are the percentiles of the calculated dose rate in the probabilistic simulations. The dose intervals labelled “deterministic”, “alternative safety scenarios” and “what-if?” cases” show the maximum dose rates in all deterministic analyses for the reference safety scenario, including alternative biospheres, alternative safety scenarios and “what-if?” cases, respectively. All four intervals, including the interval representing extreme, hypothetical “what-if?” cases, are at least one order of magnitude below the protection criterion of 0.1 mSv/a (ENSI 2023), which shows the robustness of the repository system from a post-closure safety perspective. In all the cases concerning C-14 methane described in Section 7.2, maximum dose rates are reached in the time period for assessment, which means that, after one million years, the dose rate is far below the lower bound value of the typical natural radiological exposures in Switzerland (BAG 2021).

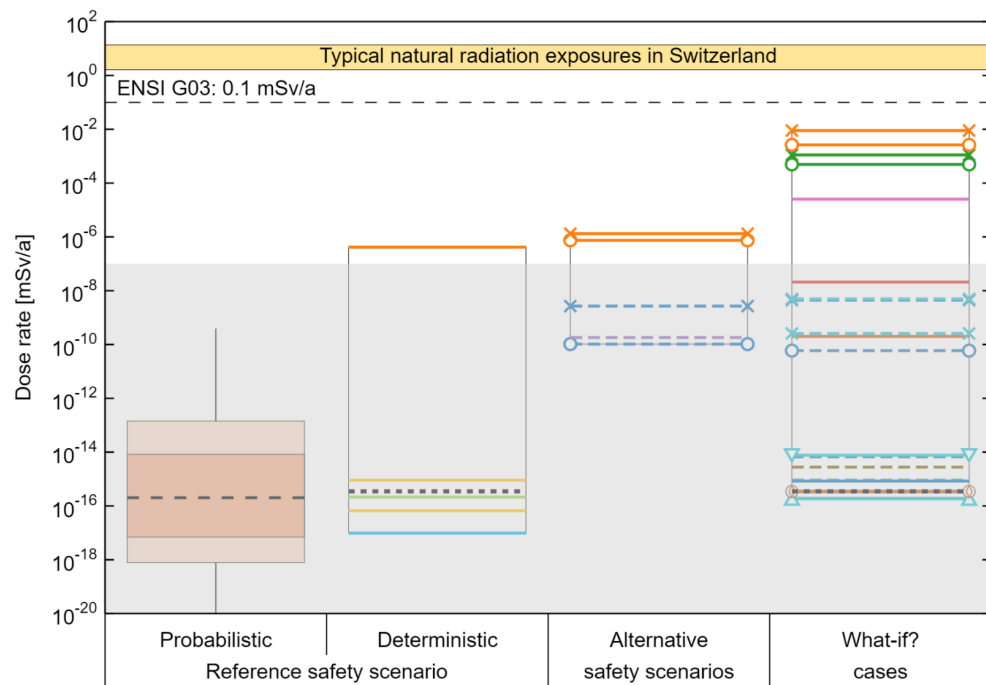


Fig. 7-32: Summary of maximum dose rates of C-14 methane for a combined repository. The box plots show the maxima of the 0%, 5%, 16%, 50%, 84%, 95% and 100% percentiles.

8 Main Conclusions

This report documents the radiological consequence analysis in support of the site comparison for Stage 3 of the Sectoral Plan (SGT-E3) and the safety case for the general licence application for a combined repository for both HLW and L/ILW. The calculation cases are defined based on the safety scenarios, consisting of a reference safety scenario, several alternative safety scenarios and a set of “what-if?” cases. The calculation cases derived for the reference and alternative safety scenarios are performed both for the site comparison and for the safety case for a combined repository. In addition, “what-if?” cases are analysed for the combined repository at the selected site, in line with regulatory requirements (ENSI 2018). Both the transport of aqueous radionuclides dissolved in porewater and the transport of C-14 methane by two-phase flow are addressed in the analysis.

Reference safety scenario

The reference safety scenario represents the expected initial state and evolution of a repository, including the corresponding conceptual and parameter uncertainties. Due to the high-level of system understanding provided by an extensive assessment basis, including the geological investigations, as well as the findings of the performance assessment, the modelling and computational strategies confidently represent the expected processes related to radionuclide transport, employing fully justified and conservative simplifications where appropriate. Probabilistic and deterministic approaches are implemented to cover the conceptual and parameter uncertainties.

The results of all analyses concerning dissolved radionuclides, including the consideration of uncertainties, demonstrate a large safety margin with respect to the regulatory protection criteria. Due to the excellent containment/retention capacity of the multi-barrier system, most of the radionuclides are retained in the engineered barriers or in the Opalinus Clay host rock surrounding the repository throughout the time period for assessment. While some non-sorbing and long-lived radionuclides, e.g., Cl-36 and I-129, can migrate further, the retention capacity of the confining geological units decrease and limit the transport of these radionuclides to the biosphere. Given the similarity in the properties of the CRZ (Nagra 2024j) and the provisional repository design (Nagra 2023a) across the three siting regions, the safety analyses in support of the site comparison confirm an equivalent level of safety for all three regions.

Most dose rates resulting from C-14 methane calculated within the context of the reference safety scenario are negligibly low, i.e., several orders of magnitude below the level of the significant dose rate (10^{-7} mSv/a). This level is only slightly exceeded when unlikely combinations of pessimistic bound values of several parameters are imposed (such as corrosion/degradation rate, properties of the V3 seal and of the Opalinus Clay). Some differences in C-14 release are observed between the siting regions, which arise from slight variations in the provisional repository designs (i.e., shaft versus ramp) and the different depths of the repositories.

In addition, the analyses of the barrier performance and the systematic sensitivity analyses have resulted in significantly improved system understanding, e.g.:

- Properties related to the radionuclide release such as the instantaneous release fraction and congruent release rate of radionuclides from spent fuel can significantly impact the calculated total dose rate;
- Diffusive transport properties in the CRZ are of significant importance to the total dose rate; and
- Two-phase flow properties of the shaft seals (V3 seal) are important for the migration of C-14 methane.

Collectively, all the siting regions show a robust safety margin in the radiological consequence analysis of the reference scenario for all repository types and can be considered equivalent in terms of the radiological consequences.

Alternative safety scenarios

Radiological consequence analyses have also been performed for the alternative safety scenarios, both for the site comparison as well as for the safety case for a combined repository. Alternative safety scenarios consider paths of evolution and performance of the repository system which are not to be expected but cannot be ruled out as impossible. These safety scenarios, and their calculation cases, concern:

- hydraulically active confining units; and
- undetected faults.

In the first safety scenario, the upper and lower confining units with lower clay content are assumed to be hydraulically connected to the regional aquifer; this has not been observed in any of the 12 boreholes but is conservatively assumed. This assumption leads to a significant shortening of the transport pathway length in the confining units. The analyses reveal that, as for the reference safety scenario, most of the radionuclides released from the engineered barriers are sorbed in the Opalinus Clay, though the shortening of the transport pathway length in the confining units does slightly weaken the retardation of the non-sorbing radionuclides (such as I-129, Cl-36 and C-14 methane). Thus, increases in the dose rates, compared to the reference case, are limited and the calculations still show a significant safety margin.

For the scenario concerning an undetected fault, the calculation cases are configured with the following extremely conservative assumptions:

- The fault extends across the entire CRZ, permanently connecting two aquifers, one above and one below the repository.
- The fault either partly impacts all the emplacement rooms or affects an entire emplacement room; in reality, it is likely the fault would be easily detected and avoided.
- The fault transmissivity is permanently set to 10^{-10} m²/s, even though no such fault has been observed in the Opalinus Clay during the geological investigations of the siting regions.

While the fault impacts the integrity of the CRZ and provides a new transport pathway for both aqueous radionuclides and C-14 methane, the analyses continue to show a large safety margin for the HLW and L/ILW repositories due to the stability of the near-field barriers and the limited water flow in the fault. Indeed, given the similar properties assumed for the fault in all cases, the three siting regions are found to be equivalent in terms of the radiological consequences.

“What-if?” cases

The “what-if?” cases concern the occurrence of features and processes either with characteristics that lie outside the range of possibilities supported by currently available evidence and knowledge, or whose occurrence during the one-million-year time period for assessment is judged to be exceedingly unlikely. They are nonetheless defined and analysed to demonstrate the robustness of the repository system. The “what-if?” cases are categorised in two classes:

- Cases concerning a fault with extremely elevated transmissivity, which is either undetected and thus active from the start of the post-closure phase, or is reactivated at a later point in time by geological processes or repository-induced effects; and
- Cases postulating a hypothetically degraded performance of the pillars of safety.

The cases concerning a fault with elevated transmissivity are defined using the same conservative assumptions as those for the alternative safety scenarios, with the additional extreme and hypothetical assumption of a transmissivity of $10^{-7} \text{ m}^2/\text{s}$.

All these “what-if?” cases show considerable safety margins, demonstrating a robust and safe repository.

“What-if?” cases postulating a hypothetically degraded performance of the pillars of safety demonstrate the robustness of the multi-barrier system. The response of the performance of the system to the hypothetical degradation of individual pillars of safety is consistent with the parameter sensitivity shown in the analyses for the reference safety scenario.

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App. A Classification of model assumptions and simplifications

A model is a simplification of a real-world system, achieved by eliminating unnecessary details, i.e., it is an abstraction. Model abstraction and the use of simplification and conservatism are discussed in general terms in Section 3.2.2 of Nagra (2024o), where the following types of abstraction are identified:

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

Abstractions and other modes of assumptions that are subject to uncertainty can be justified on the grounds that they either have a negligible impact on the calculation endpoints (e.g., performance and safety indicators), or that they are conservative²².

The following tables present the most important conceptual assumptions and simplifications made for modelling of the HLW near-field, the L/ILW near-field and the geosphere for radionuclide migration in the liquid phase and for modelling of C-14 migration considering two-phase flow.

Assumptions and simplifications are categorised as follows.

BE	Conceptual assumption corresponds to the likely/expected characteristics and evolution of the system
CA	Conservative assumption which will lead to an overestimation of the radiological consequence
CS	Conservative simplification which will lead to an overestimation of the radiological consequence
SN	Simplification with negligible impact on the radiological consequence

Tab. A-1 and Tab. A-2 present and classify the most important conceptual assumptions and simplifications for modelling the liquid-phase release and migration of radionuclides in the HLW near-field and in the L/ILW near-field, respectively. The assumptions and simplifications for modelling migration in the liquid phase in the geosphere are presented in Tab. A-3 and those for C-14 methane migration are given in Tab. A-4.

These conceptual assumptions and simplifications apply to the models used to analyse the radiological consequences of the reference safety scenario. However, most of these also apply to the models used for the analysis of the alternative safety scenarios and “what-if?” cases. Thus, in Table A-5, only those additional assumptions and simplifications that apply specifically to the alternative safety scenarios and “what-if?” cases are given. Specifically, additional assumptions and simplifications arise in scenarios and cases that consider:

- a transmissive fault intersecting the underground structures; and
- a potential hydraulically active unit within the topmost of the lower confining units.

²² The term “conservative” applies to simplifications, assumptions, parameter values, etc., that are confidently expected to lead to calculated consequences that are less favourable than would arise in reality, taking uncertainty into account.

Tab. A-1: Conceptual assumptions and simplifications for modelling release and migration in the liquid phase in the HLW near-field in the reference safety scenario

Main conceptual assumptions in the modelling	Category
Geometric abstraction	
The canisters are centrally located within the emplacement drifts; no significant canister displacement will take place. This radially symmetric geometry allows the 1D modelling for the HLW near-field transport (see App. B, Fig. B-1).	SN
Process abstraction	
Based on the canister design requirement, canister breaching is assumed to take place after the thermal phase in all safety scenarios and “what-if?” cases, such that the temperature gradients due to heat from the HLW do not significantly affect transport processes.	BE
All HLW disposal canisters are assumed to breach simultaneously ²³ at the same time (10,000 years), allowing water ingress and the release of radionuclides. This is conservative compared to the provisional system understanding in Nagra (2024a) that canisters will start to breach discontinuously after 10,000 years	CS
HLW canister breaching is assumed to be instant in the model and it is assumed that the breached canisters provide no physical barrier either to water ingress (instantaneous saturation of the void space in the canister interior is assumed) or to radionuclide release.	CS
Part of the radionuclide inventory is assumed to be released instantaneously as part of the instant release fraction (IRF). Other release rates of radionuclides are constrained by the congruent dissolution rates of the SF and RP-HLW matrices, and by the corrosion rates of the SF cladding/structural materials (Johnson et al. 2023).	BE
The bentonite is assumed to be saturated at the time of canister breaching and remains saturated thereafter (Nagra 2024h). Radionuclide transport is thus modelled under saturated conditions.	BE/CS
The concentrations of (stable) isotopes originating from sources other than the waste packages are conservatively neglected to calculate whether solubility limits have been reached.	CS
Sorption within the canister and on the canister outer surface, e.g., on corrosion products, is not considered.	CS
Element-specific solubility limits constrain concentrations of radionuclides in the liquid phase. Precipitation of a radionuclide will occur if the solubility limit of the corresponding element is reached, and redissolution will occur if the concentration falls below the solubility limit. Solubility limits are estimated based on the model-based assessments of the chemical conditions (Hummel et al. 2023).	BE
Radionuclide transport in the HLW bentonite buffer is assumed to take place by molecular diffusion, governed by Fick’s laws; the hydraulic properties of the bentonite buffer prevent any significant advective transport (Nagra 2024p). Lateral transport along the emplacement drifts and tunnel system plays a subordinate role compared with transport through the CRZ (Nagra 2024g, Poller et al. 2014) and is assumed to be negligible. The impact of local temperature on the effective diffusion coefficients is taken into account.	BE

²³ This is a conservative assumption. In reality, a distribution of breaching times is expected, leading to some spreading of releases, which has the most significant effect on radionuclides with an inventory component that is rapidly released upon canister breaching.

Tab. A-1: continued

Main conceptual assumptions in the modelling	Category
Process abstraction cont.	
Altered zones in the bentonite buffer around the HLW disposal canisters will be very limited (Nagra 2024q). They are taken into account by assigning them unfavourable retention and transport properties. This is a conservative approach given the evidence that any alteration at the canister-bentonite interface will have no significant impact on the retardation properties of bentonite.	CA
Radionuclides are retarded in the bentonite buffer by linear, equilibrium sorption. No account is taken for irreversible sorption or any other long-term immobilisation processes acting on radionuclides once released from the disposal canisters. Sorption coefficients are set based on expected chemical conditions.	CS
The retention capacity of the lining and the limited alteration extent of the buffer and OPA around the lining (Nagra 2024q) are neglected in the models.	CA
Any colloids potentially present in the bentonite buffer or in the canister interior are assumed to be immobile.	BE
The impact of temperature variations on the sorption and solubility limits in the bentonite buffer is not accounted for.	SN
Homogenisation	
For the modelling of radionuclide release from the cladding/structural materials (which consist of Zircaloy and stainless steel), stainless steel parts are assumed to corrode at the same rate as the Zircaloy cladding, which is conservative since the stainless steel has a lower estimated corrosion rate (Diomidis et al. 2023).	BE/CS
Radionuclide inventories are given as in the MIRAM-RBG database (Nagra 2023c). The average inventories for each of five different canister types are considered in the modelling (see App. H.2).	BE
Axial diffusion of radionuclides into the HLW bentonite buffer separating the disposal canisters is neglected.	CS
Boundary and initial conditions	
The boundary of the near-field model is placed 50 m inside the Opalinus Clay, where a zero-concentration boundary condition is applied. This is conservative as it overestimates the concentration gradient at the boundary between the bentonite buffer and the rock.	CS

Tab. A-2: Conceptual assumptions and simplifications for modelling release and migration in the liquid phase in the L/ILW near-field in the reference safety scenario.

Main conceptual assumptions in the modelling	Category
Geometric abstraction	
When considering a combined repository, since there will be no significant safety-relevant interaction between the HLW and L/ILW repository sections (Nagra 2021); transport of liquid radionuclide species in the L/ILW repository near-field is modelled independently of transport in the HLW repository near-field.	SN
All emplacement caverns have the same size and are provisionally designed with a bilaterally symmetrical shape (Nagra 2023a). As there is no specific requirement on the waste location in the L/ILW emplacement cavern at the current project stage, 7 caverns are modelled by scaling them to a 2D model with half a cavern (as shown in App. B.1, Fig. B-2).	SN
Process abstraction	
Even though the L/ILW emplacement caverns are expected to stay partially saturated for several tens of thousands of years in the reference safety scenario, which can reduce the amount of aqueous diffusion (Nagra 2024g), the emplacement caverns are modelled as being fully saturated at the time of backfilling and to remain fully saturated throughout the time period for assessment.	CS
No credit is taken for radionuclide containment by the L/ILW containers.	CA
Gas-induced porewater overpressure in the L/ILW repository near-field does not reach any significant degree; radionuclides dissolve in the liquid phase along the backfilled underground structures or into the host rock (Nagra 2024g). Transport of dissolved radionuclides along the emplacement caverns is disregarded, as it is assumed to be negligible compared with radial transport to the geosphere.	BE
The prevailing gas components do not significantly change the chemical environment (Nagra 2024p), which allows the use of the retention properties given in Tits & Wieland (2023).	BE
Any solubility limitation of radionuclide concentrations in the L/ILW cementitious near-field (Hummel et al. 2022) is neglected.	CS
Transport of radionuclide-bearing colloids in the cementitious near-field cannot be fully excluded and is considered in the derivation of the radionuclide-specific sorption coefficients (Tits & Wieland 2023).	BE
The L/ILW cementitious near-field is modelled as a homogeneous porous medium with a representative porosity (20 vol.-%). For the transport of radionuclides from the cement-based near-field into the Opalinus Clay, anion exclusion effects by the clay are neglected in the model.	BE
Homogenisation	
Radionuclide inventories are as given in the MIRAM-RBG database (Nagra 2023c). Linear, equilibrium sorption is assumed. Two types of L/ILW (Nagra 2023b) are defined based on their chemical inventory (Nagra 2023c), which is accounted for in the derivation of the sorption coefficients for the cementitious near-field (Tits & Wieland 2023). The inventory of the two waste types is considered in the modelling (see App. H).	BE
Radionuclides released from the waste packages are assumed to be homogeneously distributed within the pore space of the L/ILW emplacement caverns.	CS

Tab. A-2: continued

Main conceptual assumptions in the modelling	Category
Boundary and initial conditions	
C-14 from activated waste materials is assumed to be released congruently with corrosion/degradation, mainly as organic species. Due to the cementitious near-field, high-pH conditions will prevail for many waste types (see Nagra 2023b) and most metals present as waste or construction materials will corrode at a slower rate (Nagra 2024r, Diomidis et al. 2023).	BE
Except for organic C-14 species in activated waste materials, all radionuclides are assumed to be released instantaneously at the beginning of the post-closure phase (2075) in the safety analysis (Nagra 2024r).	CS
The impact of temperature on the effective diffusion coefficients is considered.	BE
The boundary of the near-field model is placed 50 m inside the Opalinus Clay, where a zero-concentration boundary condition is applied. This is conservative as it overestimates the concentration gradient at the boundary between the bentonite buffer and the rock.	CS

Tab. A-3: Conceptual assumptions and simplifications for modelling release and migration in the liquid phase in the geosphere in the reference safety scenario

Main conceptual assumptions in the modelling	Category
Geometric abstraction	
The repository is assumed to be excavated in the middle of the Opalinus Clay (Nagra 2023a), which is abstracted in the model configuration illustrated in Fig. B-3.	BE
Radionuclide transport in the geosphere occurs by advection and diffusion and is taken to be one-dimensional and predominantly vertical (see Fig. B-3.), although some discrete features with horizontal flow and transport are also modelled. Advective transport in the geosphere is described by Darcy's Law and diffusion by Fick's Laws.	BE
The spreading of radionuclide releases over space and time due to the lateral extent of the repository, transverse dispersion and the three-dimensional nature of diffusive transport are neglected.	CS
Process abstraction	
The EDZ in the host rock around the emplacement rooms is included in the geosphere model (see, e.g., Fig. B-4). The properties of the EDZ are constant over the entire time period for assessment, i.e., self-sealing of the EDZ is disregarded.	CS
Due to the low hydraulic conductivity of the rock units within the CRZ, in comparison with the hydraulic conductivity of the outer geological units, the ambient hydraulic gradient across the CRZ and the natural water flow through the CRZ are assumed to be orientated perpendicular to its layered structure.	CS
The transport-relevant properties (such as porosity and conductivity) of the geosphere are assumed to be constant over the entire time period for assessment; changes in transport-relevant properties caused by geological and climatic processes are covered by the selected parameter ranges (Nagra 2024e).	SN
The presence of hydraulic underpressures in the Opalinus Clay (Nagra 2024f) is not taken into account.	CA
In cases where there is a hydraulic gradient between the upper and lower deep aquifers, the gradient is assumed to be constant along the entire transport pathway.	CA
No gas-induced expulsion of radionuclides in the liquid phase from the near-field into the host rock is considered (Nagra 2024p). Only radionuclide transport caused by concentration gradients (diffusion) and by natural groundwater flow (advection) is considered.	BE
Diffusion coefficients are applied based on the expected geochemical conditions in the geosphere. Some radionuclides are subject to anion exclusion in the geosphere, affecting their diffusion coefficients and the effective porosity that is available to them. The impact of the local rock temperature on the effective diffusion coefficients is considered (Glaus et al. 2024).	BE
Repository-induced effects (THMC and gas production processes) do not reduce the radionuclide retention capacity of the host rock (Nagra 2024p). Transport in the geosphere is retarded by linear, equilibrium sorption (Marques Fernandes et al. 2024). No credit is taken for irreversible sorption or any other long-term immobilisation processes in the geosphere.	CA
Any possible solubility limitation of radionuclide concentration is neglected.	CS
Any colloids are assumed to be immobile in the geosphere.	BE

Tab. A-3: continued

Main conceptual assumptions in the modelling	Category
Process abstraction cont.	
When considering a combined repository, since there will not be any significant safety-relevant interactions between the HLW and L/ILW repository sections (Nagra 2021), overall radionuclide release rates to the biosphere are obtained by summing the release rates from the geosphere for radionuclides originating from the HLW emplacement drifts and those originating from the L/ILW emplacement caverns.	CS/SN
Biosphere dose conversion factors (BDCFs), which are constant in time, are used to convert the radionuclide activity release rates to dose rates (Nagra 2024i).	CS
Homogenisation	
Even though there is some heterogeneity in the transport properties, each individual rock unit is represented as a homogeneous transport medium. Harmonic mean parameter values are considered as representative values for the individual rock units (Nagra 2024p).	BE
Boundary and initial conditions	
Where discrete features (potentially hydraulically active confining units in the alternative safety scenarios and the Keuper aquifer in all the safety scenarios) with horizontal flow and transport are present, the transport time along them is conservatively neglected; radionuclides are assumed to be conveyed instantaneously to the biosphere along these features (see Fig. B-3.).	CS
Radionuclides released vertically from the top and bottom of the CRZ are also assumed to be conveyed instantaneously to the biosphere. The transport time within the aquifers that bound the CRZ is conservatively neglected. Zero radionuclide concentration is set as a boundary condition at each exfiltration point from the geosphere, which overestimates the concentration gradient at the model boundaries.	CS

Tab. A-4: Conceptual assumptions and simplifications in the modelling of C-14 released as methane and transport in the reference safety scenario

Main conceptual assumptions in the modelling	Category
Geometric abstraction	
There is no specific requirement on the waste location in the emplacement rooms at the current project stage. The waste inventory is equally distributed in the emplacement room element as source term.	SN
Because most of the repository components of a given type have the same or a similar size, with bilaterally symmetrical shapes (Nagra 2023a), symmetry can be used to abstract the HLW emplacement drifts, L/ILW emplacement caverns and access tunnels to a half of their provisionally designed shape. The shafts are abstracted as a radially symmetrical structure (as shown in App. B.2).	SN
Gas transport in the geosphere is predominantly in the vertical direction; large-scale horizontal gas migration in the geosphere is not taken into account (Nagra 2024r).	SN
Process abstraction	
HLW canister breaching is assumed to occur after the thermal phase. Upon canister breaching, gas production from the material inside the HLW disposal canisters (incl. waste and canister material) begins (Nagra 2024k).	BE
Organic C-14 species released from the SF matrix, activated metals and other waste packages for L/ILW are treated as C-14 labelled methane. Inorganic C-14 species, notably CO ₂ , are generally more soluble and are therefore neglected in the modelling of gas-mediated transport (Nagra 2024r).	BE
Thermo-hydro-mechanical processes are modelled in a coupled fashion. The impact of heat generated by the waste (Nagra 2023c) on pore pressures and saturation processes is accounted for in the modelling of the fate of gas.	BE
The relationships between capillary pressure/relative permeability and liquid/gas saturation are taken into account.	BE
No containment period is assumed for L/ILW.	CA
The main gases produced in the L/ILW emplacement caverns under the reducing conditions expected to be established shortly after cavern closure are hydrogen (H ₂), methane (CH ₄) and carbon dioxide (CO ₂). CO ₂ is, however, dissolved and consumed by carbonation of cementitious materials. H ₂ and CH ₄ remain in the gas phase due to their low solubilities in water (Nagra 2024k).	BE
The main gas produced in the HLW emplacement drifts under the reducing conditions expected to be established shortly after drift closure is hydrogen (H ₂). Hydrogen is also the main gas produced in the underground tunnel system and access structures. After canister breaching, the organic C-14 from the spent fuel and structural materials is assumed to be released as methane and distributed between the liquid (dissolved) and gas phases, according to Henry's law.	BE
Gas migration in the near-field and geosphere is assumed to occur by visco-capillary (two-phase) flow, controlled by the interaction between the visco-capillary forces, gravity/buoyancy, solubility and diffusion, and by the connectivity and spatial variability of the pore network.	BE
Excavation-damaged zones (EDZs) around underground structures are assumed to have a higher permeability and higher porosity than the undisturbed Opalinus Clay. The properties of the EDZs are assumed to be constant over time, disregarding self-sealing of the EDZ fractures.	CA

Tab. A-4: continued

Main conceptual assumptions in the modelling	Category
Process abstraction cont.	
Fick's laws describe diffusion of gas in both the liquid and gas phases. The diffusion coefficient of the dissolved CH ₄ is the same as that used for porewater-mediated transport modelling (Glaus et al. 2024).	BE
Effective diffusion coefficients in both the liquid and gas phases are calculated in TOUGH according to the Millington-Quirk model and are a function of the porewater diffusion coefficient, porosity and phase saturation. Since the porewater diffusion in the TOUGH model is a global parameter for all materials, it is scaled such that the resulting effective diffusion coefficient of organic C-14 in fully saturated Opalinus Clay corresponds to the value given in the diffusion database (Glaus et al. 2024). The effective diffusion coefficients of the upper and lower confining geological units are scaled according to their porosity.	SN
The boundary value of the vertical hydraulic gradient between the aquifers given in Nagra (2024f) is omitted since its impact on the gas migration compared with other model parameters is negligible.	SN
Sorption of dissolved CH ₄ on solid surfaces in the near-field and geosphere is expected to be low and is omitted in the modelling (Marques Fernandes et al. 2024).	CA
Anisotropy of the transport properties of each unit of the geosphere model is taken into account (Nagra 2024e).	BE
Porewater consumption due to gas-generating chemical reactions is not taken into account in evaluating the saturation evolution of the repository. Gas generation is assumed to begin immediately following backfilling, irrespective of the expected water availability in the near-field. This simplification leads to an overestimation of the gas pressure and gas migration (Nagra 2024k).	CS
Apart from the sealing elements themselves, other components of the repository seals, such as abutments and transition layers, are not taken into account in the modelling since they provide limited resistance to gas migration.	SN
Homogenisation	
Even though there is some heterogeneity in the transport properties, each individual component (including engineered and geological barriers) is abstracted as homogeneous transport media.	SN
Boundary and initial conditions	
Gas is produced by corrosion of the metals (waste materials, canisters, containers, construction materials, etc.) and by the degradation of the organic materials (Nagra 2024k).	BE
Radionuclide inventories are as given in the MIRAM-RBG database (Nagra 2023c). The average inventories of each of five HLW canister types is considered in the modelling (see App. H.2).	BE
Gas production occurs in the emplacement caverns and drifts and in the underground tunnel system and access structures, with the exception of the shafts, where tunnel reinforcement is assumed to be removed before construction of the V3 seals (Nagra 2024k).	BE
An instant release fraction of the C-14 inventory is assumed from the SF matrix, activated metals and other waste packages for L/ILW in different proportions (Nagra 2024r).	CA

Tab. A-4: continued

Main conceptual assumptions in the modelling	Category
Boundary and initial conditions cont.	
The release of the remaining C-14 in HLW is constrained by the dissolution rate of SF and the corrosion rates of the cladding and structural materials (Nagra 2024r).	BE
The release of the remaining C-14 in L/ILW activated metals is constrained by their corrosion rates (Nagra 2024r).	BE
Deep aquifers represent the upper and lower boundaries of the model, where a constant temperature, zero H ₂ /C-14 concentrations and hydrostatic pressure conditions are assumed to be maintained.	CS
Since the critical advective pathway for gas flow is to the upper boundary of the model, the geological units below the Keuper aquifer are not taken into account in the modelling.	CS/SN
Radionuclides released to the deep aquifers are assumed to be conveyed instantaneously to the biosphere. The transport time within the aquifers is conservatively neglected.	CS
When considering a combined repository, overall radionuclide release rates to the biosphere are obtained by summing the release rates from the geosphere for radionuclides originating from the HLW repository section and for those originating from the L/ILW repository section.	SN

Tab. A-5: Additional or different conceptual assumptions and simplifications for calculation cases considered in the modelling of alternative safety scenarios and “what-if?” cases²⁴

Main conceptual assumptions in the modelling	Category
Calculation cases that consider a transmissive fault intersecting the underground structures	
The fault does not cause any safety-relevant interaction between the L/ILW and HLW repository sections.	BE
The fault is conservatively assumed to provide a continuous vertical pathway across the entire thickness of the CRZ. The orientation of fault is either across or along the longitudinal direction of the emplacement rooms. For cases considering a fault across the longitudinal direction of the emplacement room, depending on the case specifications, either all the HLW emplacement drifts or all the L/ILW emplacement caverns are assumed to be intersected. For cases considering a fault along the longitudinal direction of the emplacement rooms, the fault is assumed to affect either all the disposal canisters inside one HLW emplacement drift or all the disposal containers inside one L/ILW emplacement cavern.	CA
The fault is assumed to pass along or through the middle of the emplacement drifts or caverns, which allows making a symmetrical abstraction (shown in App. B1.3 and B2.3).	SN

²⁴ Since most of the assumptions in these cases are identical to those of the reference safety scenario, this table focuses on the assumptions about the faults and hydraulically active confining units that deviate from the model assumption for the reference safety scenario.

Tab. A-5: continued

Main conceptual assumptions in the modelling	Category
Calculation cases that consider a transmissive fault intersecting the underground structures cont.	
Where the fault affects one or more HLW emplacement drifts, it is assumed in porewater-mediated transport calculations that the affected drifts contain only canisters of the PWR-UO ₂ -ELB SF type (the fuel type with the highest instantaneous release fraction among the three types of SF considered in the safety assessment).	CA
For gas-mediated transport, the drift(s) affected by a fault contain canisters with an averaged inventory.	SN
Diffusive exchange of radionuclides between the fault and the surrounding CRZ is modelled.	BE
A conservative hydraulic conductivity is assumed for the fault (10^{-10} m ² /s in the alternative safety scenario with an undetected fault; 10^{-7} m ² /s in the “what-if?” cases) based on the geological findings (Nagra 2024f).	CA
In the case of a reactivated fault, the timing of the reactivation is set to be 10,000 years for a fault in the HLW repository section and 20,000 years for a fault in the L/ILW repository section. The latter represents the point in time when a gas overpressure ²⁵ can appear in the L/ILW repository near-field (Nagra 2024k).	CA
The Darcy flow in the fault is taken from more detailed 2D model calculations (Nagra 2024g).	BE
The sorption and diffusion properties of a fault are assumed to be the same as those of the EDZs, as presented in Poller et al. (2014).	BE
Calculation cases that consider individual confining units as conductive features	
Radionuclides that are released into a potential hydraulically active unit are assumed to be conveyed instantaneously to the biosphere. The transport time within such units and between these units and the biosphere is conservatively neglected. The same horizontal gradient as assumed for the Malm aquifer in NL and ZNO (Nagra 2024e) and for the Calcareous Dogger in JO is assumed for any conductive features within the upper confining units. Similarly, the same horizontal gradient as assumed for the Keuper aquifer is assumed for any conductive features in the lower confining units.	CA
In gas-mediated transport modelling, only conductive features in the upper confining units are considered. The upper model boundary is set to the location of the first such feature above the repository, where a zero-concentration boundary condition for C-14 is applied.	CA

²⁵ In the HLW repository or repository section, the overpressure induced by thermal effects is not considered because it occurs while the canisters are still intact and it is therefore irrelevant for radionuclide transport.

App. B Model setup for the radiological consequence analysis

Models and codes for radionuclide migration in the liquid phase and for the migration of C-14 methane are outlined in Chapter 5. This appendix provides further details, especially outlining how these models are configured for specific safety scenarios and calculation cases and for the different siting regions.

B.1 Conceptual model setup for radionuclide migration in the liquid phase

B.1.1 Safety scenarios without faults

Near-field model for an HLW repository or for the HLW section of a combined repository

As noted in Section 5.1, the near-field model for an HLW repository or for the HLW section of a combined repository includes either an individual SF or HLW disposal canister, together with its surrounding bentonite buffer, or an individual HLW emplacement drift. It also includes, in both cases, a limited region of the surrounding host rock, corresponding to the excavation-damaged zone (EDZ). These model elements are site-independent and are thus used for near-field modelling in all three siting regions.

The general conceptual model configuration for a section of an HLW emplacement drift containing a single HLW disposal canister is illustrated in Fig. B-1. Only the period after canister breaching is of concern. The model domain thus consists of:

- the radioactive waste (either SF or RP-HLW);
- a water-filled reservoir surrounding the waste, corresponding to the void space inside the canister;
- the surrounding bentonite buffer, consisting of two or more concentric units, which can be assigned different properties (see below); and
- a part of the surrounding host rock, corresponding to the EDZ.

As in the case of other waste types, the reason for including a part of the surrounding host rock in the near-field domain is to obtain satisfactory estimates of radionuclide releases across the interface between the engineered structures and the host rock.

The axial length of the model domain is set to the length of the canister (which varies between the different waste types), plus the assumed 3-metre canister spacing along the drifts.

The void space inside the disposal canister, i.e., the reservoir in the model, is assumed to become instantaneously saturated when the canister is breached. Nuclides (radionuclides plus stable isotopes of the same elements) are released from the waste packages to this reservoir, and are assumed to have a uniform concentration within.

Chemical interactions between the tunnel lining and the bentonite buffer, as well as between the (corroded) disposal canister and the bentonite buffer, can lead to mineral alteration of the bentonite in the vicinity of both contact surfaces. Mineral alteration can also occur due to thermal effects. Such alteration is handled by assigning different properties to the bentonite buffer as a unit called “degraded bentonite buffer” see Fig. B-1.

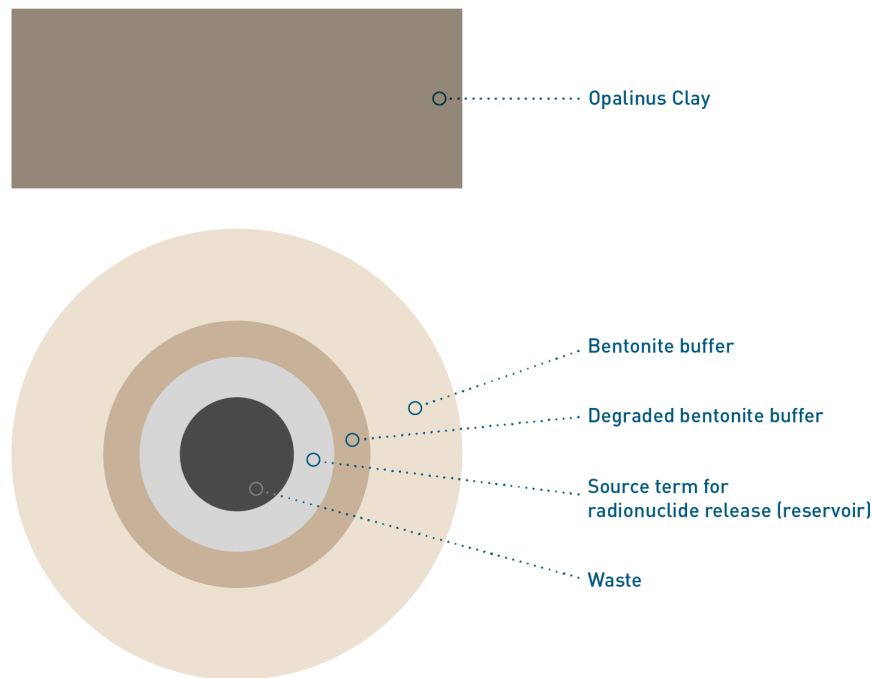


Fig. B-1: General conceptual model configuration for a section of an HLW emplacement drift containing a single HLW disposal canister, and the adjacent rock

Due to the very low hydraulic conductivity of the Opalinus Clay and the expected absence of discrete water-conducting features intersecting the emplacement drifts, nuclide transport within the drifts and their immediate surrounding is dominated by diffusion. Modelling the reservoir as an annular feature between the outer boundary of the disposal canister and the inner boundary of the bentonite buffer, disregarding any residual transport resistance from the breached canister and also disregarding axial diffusion in the space between the disposal canisters, the HLW near-field can be modelled with cylindrical geometry. Further away from the HLW emplacement drifts, nuclide transport is adequately described as a 1D vertical transport phenomenon. Thus, as shown in Fig. B-1, a hybrid approach is adopted in which the emplacement drift is modelled with a cylindrical geometry and the host rock is modelled using a linear geometry.

The host rock part of the model, using a linear geometry, is connected at its upstream end to the outer boundary of the cylindrical model of the emplacement drift. To correctly model the diffusive transport capacity of the host rock at the interface between the two parts of the model, the width of the host rock sub-model must be made equal to the circumference of the cylindrical emplacement room sub-model. The length of the host rock sub-model is conservatively set to 50 metres, which is less than the half the thickness of the host rock in the site-specific geosphere models for the three siting regions.

The release rate of the radionuclides from the bentonite buffer, multiplied by the number of disposal canisters for a given waste type, is taken as source term for the geosphere model to which the near-field model is connected.

Near-field model for an L/ILW repository or for an L/ILW section of a combined repository

The general conceptual model configuration for an L/ILW emplacement cavern is illustrated in Fig. B-2.

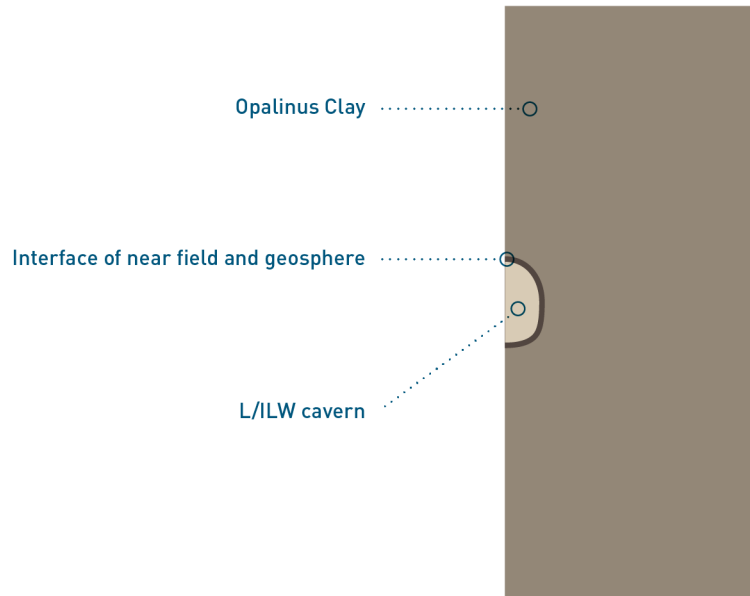


Fig. B-2: General conceptual model configuration for an L/ILW emplacement cavern and the adjacent rock

There are two groups of L/ILW, distinguished in terms of their chemical composition and its effects on the radionuclide retention capacity of the cementitious near-field (Tits & Wieland 2023). For modelling purposes, the entire radionuclide inventory for a given group is assigned to a single emplacement cavern. Thus, only two caverns, one for each group, are simulated using separate near-field model runs.

The L/ILW near-field model domain comprises:

- the concrete disposal containers filled with the radioactive waste;
- the cementitious backfill of the emplacement caverns;
- the construction concrete and the cavern lining; and
- a part of the surrounding host rock, corresponding to the EDZ.

For the purpose of radiological consequence analysis, it is assumed that the first three components form a single, cementitious, homogeneous porous medium. As in the case of the HLW near-field, the reason for including a part of the surrounding host rock in the L/ILW near-field is to obtain satisfactory estimates of radionuclide releases across the interface between the emplacement cavern and the host rock.

In calculation cases in which no water-conducting features intersect the caverns, 2D modelling of the L/ILW near-field is considered to be adequate. Making use of the inherent symmetries in the assumed layout, the L/ILW near-field model extends laterally from the vertical plane running along the axis in the middle of an emplacement cavern to the vertical plane at an intermediate

distance to the next, adjacent cavern. In the vertical direction, the L/ILW near-field model domain extends 50 m upwards and downwards from the centre of the emplacement cavern, similar to the configuration of the HLW near-field model.

The release rate of the radionuclides across the entire interface between the emplacement cavern and the host rock is taken as source term for the geosphere model to which the near-field model is connected.

Geosphere model (general)

The geosphere domain above and below the repository or repository section is modelled as two vertical stack of rock units, one stack above and the other below repository level. The stacks consist of the Opalinus Clay host rock and each of the rock layers forming the confining units. As described in Section 5.1.3, liquid phase radionuclide transport in the geosphere is modelled using the PICNIC-TD code. To implement the stack model in PICNIC-TD, each unit with the stacks is represented by a discrete vertical leg, which is connected in a series. Fig. B-3 illustrates a simplified, non-site-specific setup of the resulting chain of PICNIC-TD legs. The connections between the legs are configured as “junctions”, where the radionuclides released from one leg provide a source term for the connected leg(s).

Most rock units are conceptualised as homogeneous porous media, which means that all heterogeneity on a macroscopic scale is averaged over the entire unit thickness. For instance, the porosity and hydraulic conductivities of each unit, which are input parameters to the geosphere model, represent average values for the whole unit.

Where significant horizontal flow, and thus advective transport, is assumed within a unit, this is represented as a horizontal leg. These units are termed “potential hydraulically active units” (e.g., “hard beds”), or PHAUs. PHAUs include any deep aquifers above and below the repository that are inside the model domain (the Keuper aquifer, which is assumed to be hydraulically active in the reference safety scenario). The PHAUs are not, however, taken to include deep aquifers such as the Malm (Calcareous Dogger for the site-specific model for the JO siting region) and the Muschelkalk, which bound the geosphere model domain. These are handled via boundary conditions (see below).

The implementation of this conceptualisation of the geosphere in the case of two PHAUs is shown in Fig. B-3. Depending on the strength of the horizontal water flow, some part of the radionuclide flux from the repository will be diverted into the PHAUs and carried away by advection, and the rest of the radionuclide flux will be transported vertically across the PHAUs and into the next units of the model. Horizontal transport in the PHAUs is conservatively omitted; rather, radionuclides that enter the PHAUs are assumed to be transported instantaneously to the biosphere. The radionuclide release rates via the PHAUs are summed together with the radionuclide release rates from the upper and lower boundaries to obtain the total release rate from the geosphere, which is converted to a dose rate using the BDCFs.

Zero-radionuclide concentration boundary conditions are set at the upper and lower geosphere model boundaries, which is conservative for a diffusion-dominated pathway as it corresponds to an unlimited flow rate in the deep aquifers that form these boundaries. At the end of each PHAU, a “free release” (or zero-concentration-gradient) boundary condition is set, which is conservative for advection-dominated pathways. These boundary conditions are summarised in Tab. B-1.

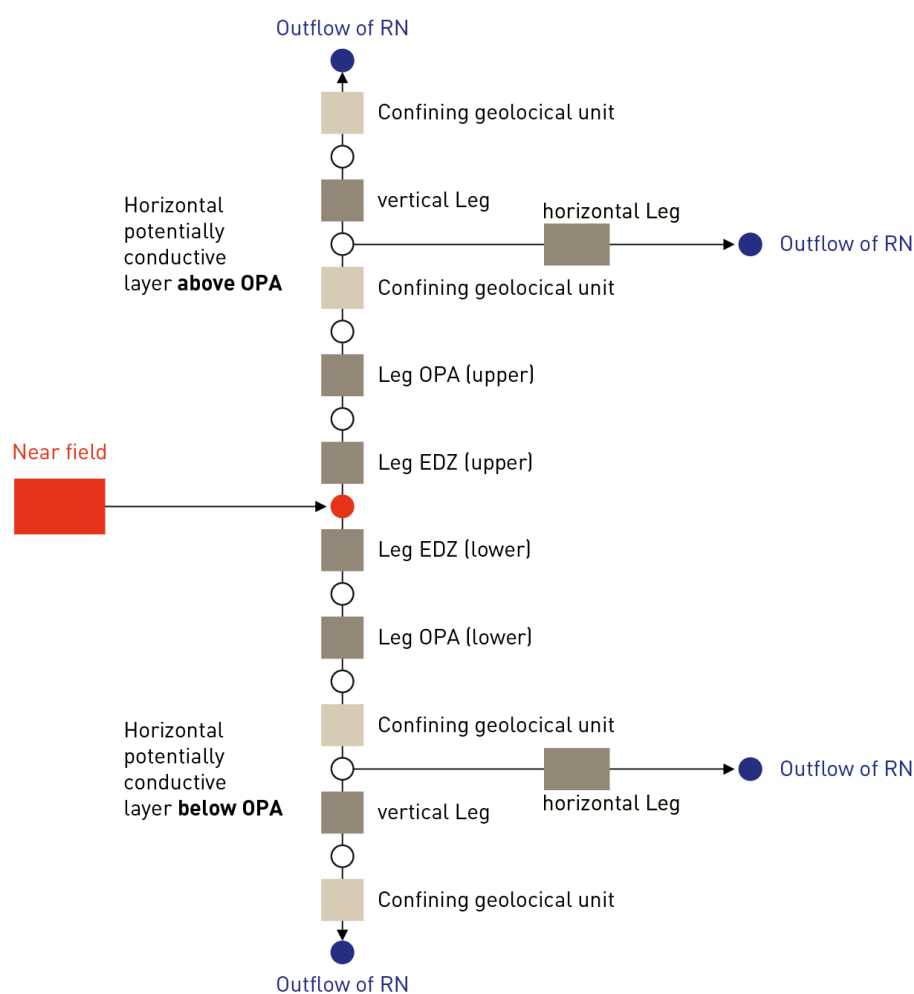


Fig. B-3: Generic representation of a leg network for modelling geosphere transport

Tab. B-1: Conditions set at the boundaries of the geosphere model

Model boundary	RN-transport
Interface with the near-field	Source terms corresponding to the near-field release rates for each waste type
Upper boundary	$C = 0$ (interface with aquifer)
Lower boundary	
Outflow in potential hydraulically active units	$\frac{\partial C}{\partial x} = 0$ (advective transport only, free radionuclide release boundary)

Unlike the approach adopted in Stage 2 of the SGT, where instantaneous transport across the EDZ was assumed, PICNIC-TD legs are used to represent the EDZ explicitly. The parametrisation of transport properties of the EDZ is documented in App. H.

Site-specific geosphere leg configurations

Site-specific geosphere leg networks models are shown in Figs. B-4 to B-6. The leg networks are configured according to the lithographical models the three siting regions presented in Chapter 2, Fig. 2-5, and also reproduced in Figs. B-4 to B-6. Each of the rock units in each siting region is abstracted as one model leg. The thicknesses of the rock units, and hence the length of each leg, are provided in the tables in App. H.3.

The figures correspond to the reference conceptualisation or the reference safety scenario, in which the Keuper aquifer, but none of the other confining units, is assumed to be hydraulically active. Thus, the Keuper aquifer, represented by the KAL leg (horizontal), is the only PHAU. However, for the alternative safety scenario that considers hydraulically active confining units, which is described in Section 4.2.1, all the units shown in Tab. B-2 are also included in the geosphere transport model as PHAUs.

Tab. B-2: PHAUs represented in the site-specific geosphere transport models of the three siting regions

JO	NL	ZNO
SCD	CM	SCD
	CD	
	SCD	
KEU	KEU	KEU
	KAU	
KAL	KAL	KAU

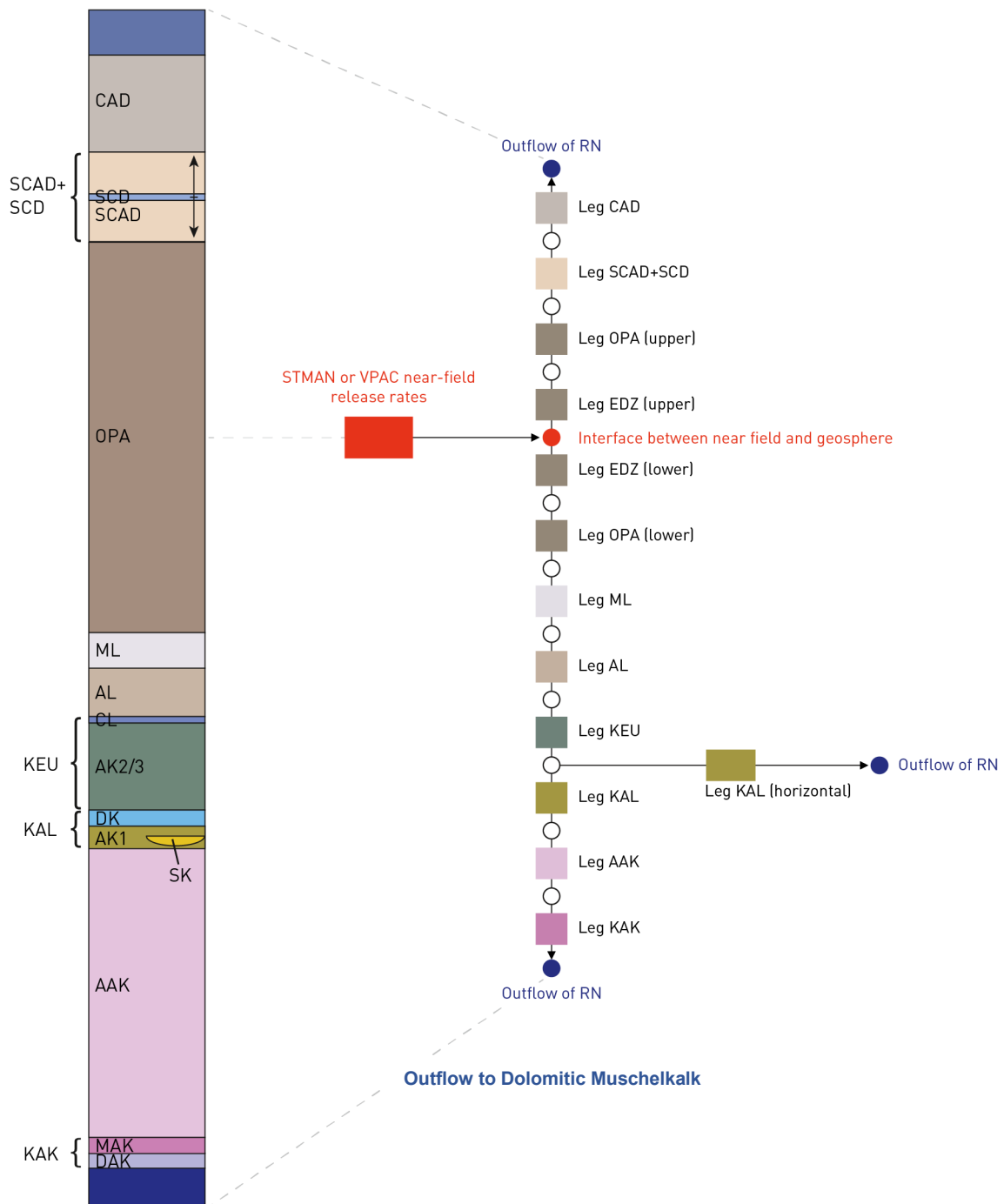


Fig. B-4: Conceptual geological model (left) and geosphere transport model (right) of the reference safety scenario for the Jura Ost (JO) siting. The horizontal leg KAL represents the Keuper aquifer

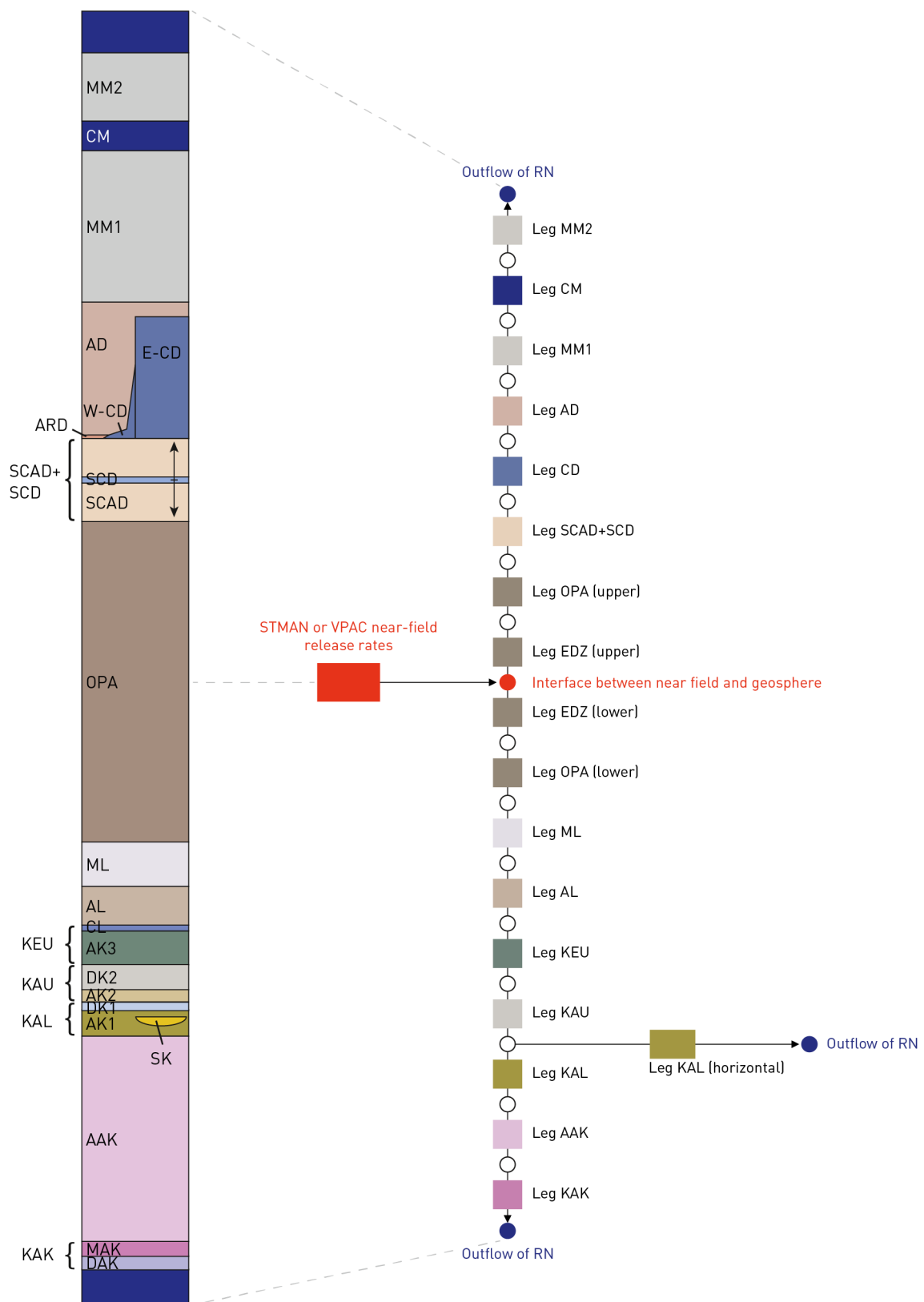


Fig. B-5: Conceptual geological model (left) and geosphere transport model (right) of the reference safety scenario for the Nördlich Läger (NL) siting region. The horizontal leg KAL represents the Keuper aquifer

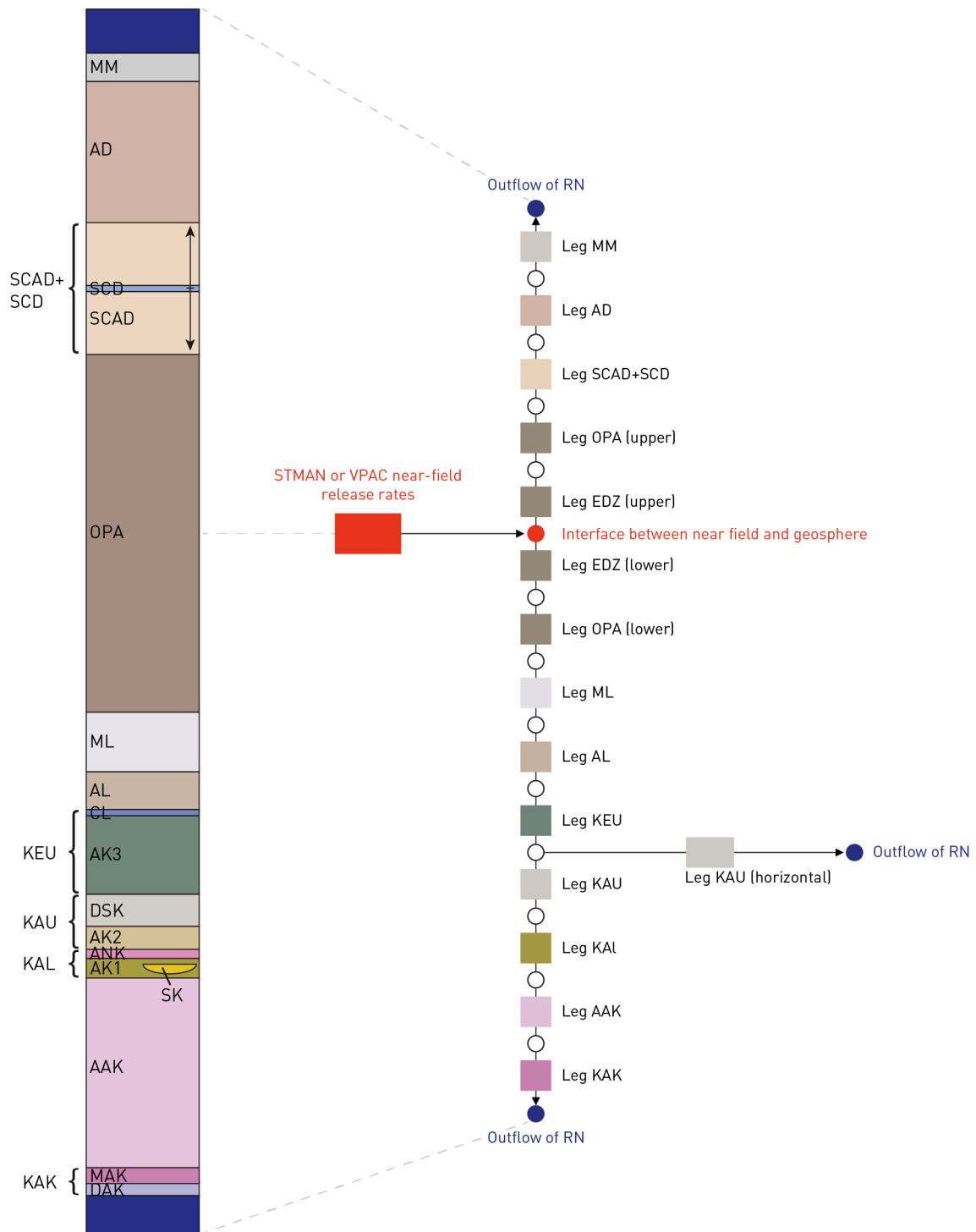


Fig. B-6: Conceptual geological model (left) and geosphere transport model (right) of the reference safety scenario for the Zürich Nordost (ZNO) siting region. The horizontal leg KAU represents the Keuper aquifer

B.1.2 Safety scenarios with faults

The alternative safety scenario “undetected fault” (Section 4.2.2) and the “what-if?” cases for “undetected fault with elevated transmissivity” (Section 4.3.1.1) and “fault reactivation by geological processes or repository-induced effects” (Section 4.3.1.2) all consider a vertical fault that intersects either the L/ILW emplacement caverns or the HLW emplacement drifts, and extends vertically across the entire thickness of the CRZ. This fault is assumed to be orientated either perpendicular or parallel to the emplacement cavern or drift axes. The different configurations of the fault with respect to the emplacement caverns and drifts are shown together in Fig. 4-4, and separately in Figs B-7 to B-10.

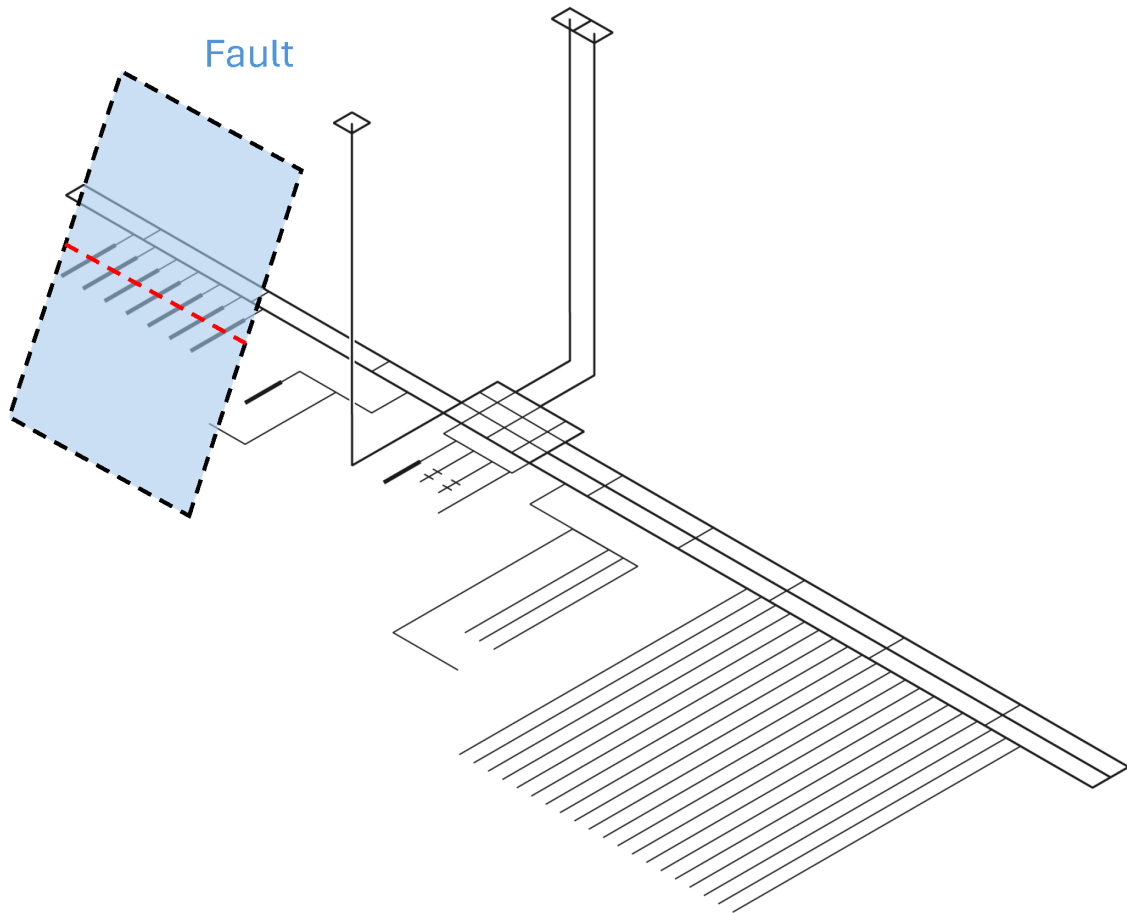


Fig. B-7: Conceptualisation of a fault affecting the L/ILW emplacement caverns perpendicular to the cavern axes

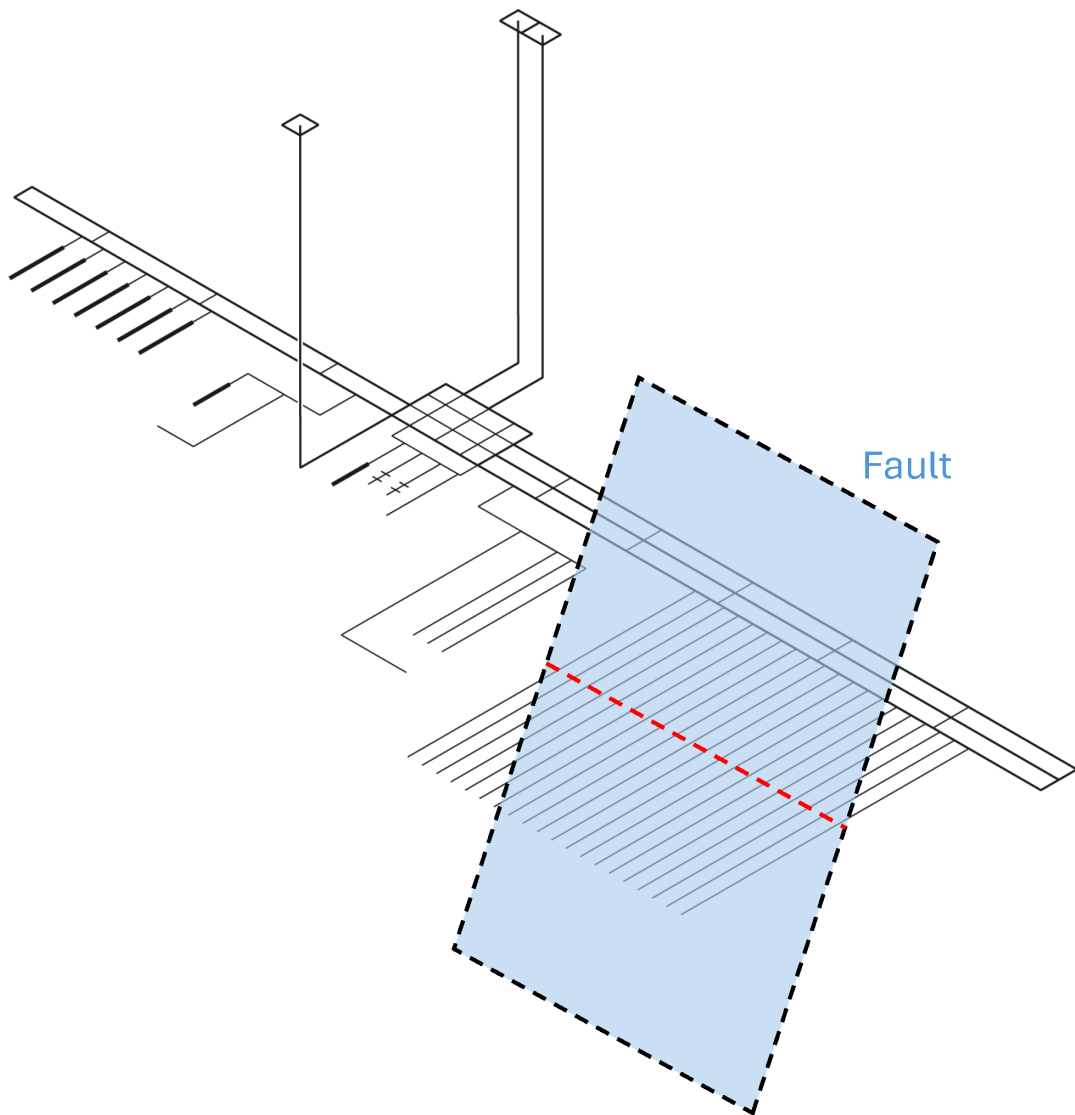


Fig. B-8: Conceptualisation of a fault affecting the HLW emplacement drifts perpendicular to the drift axes

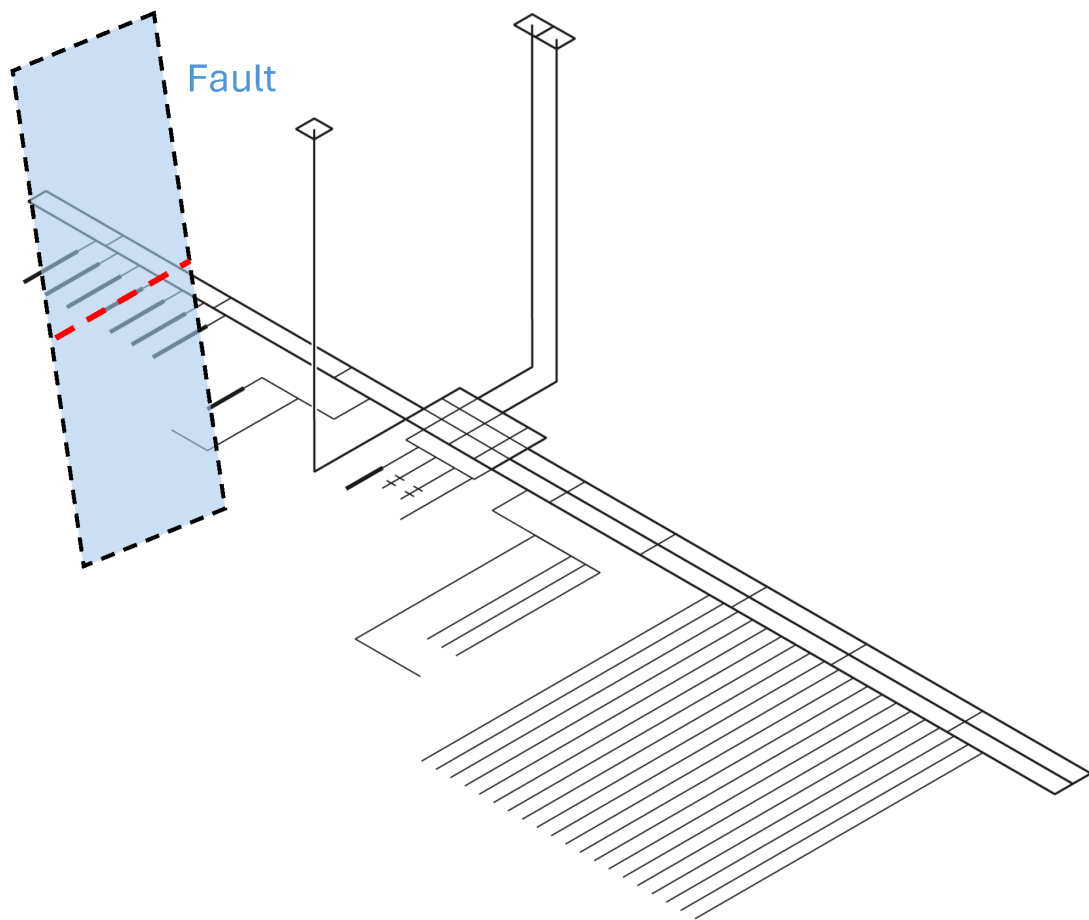


Fig. B-9: Conceptualisation of a fault affecting the L/ILW emplacement caverns parallel to the cavern axes

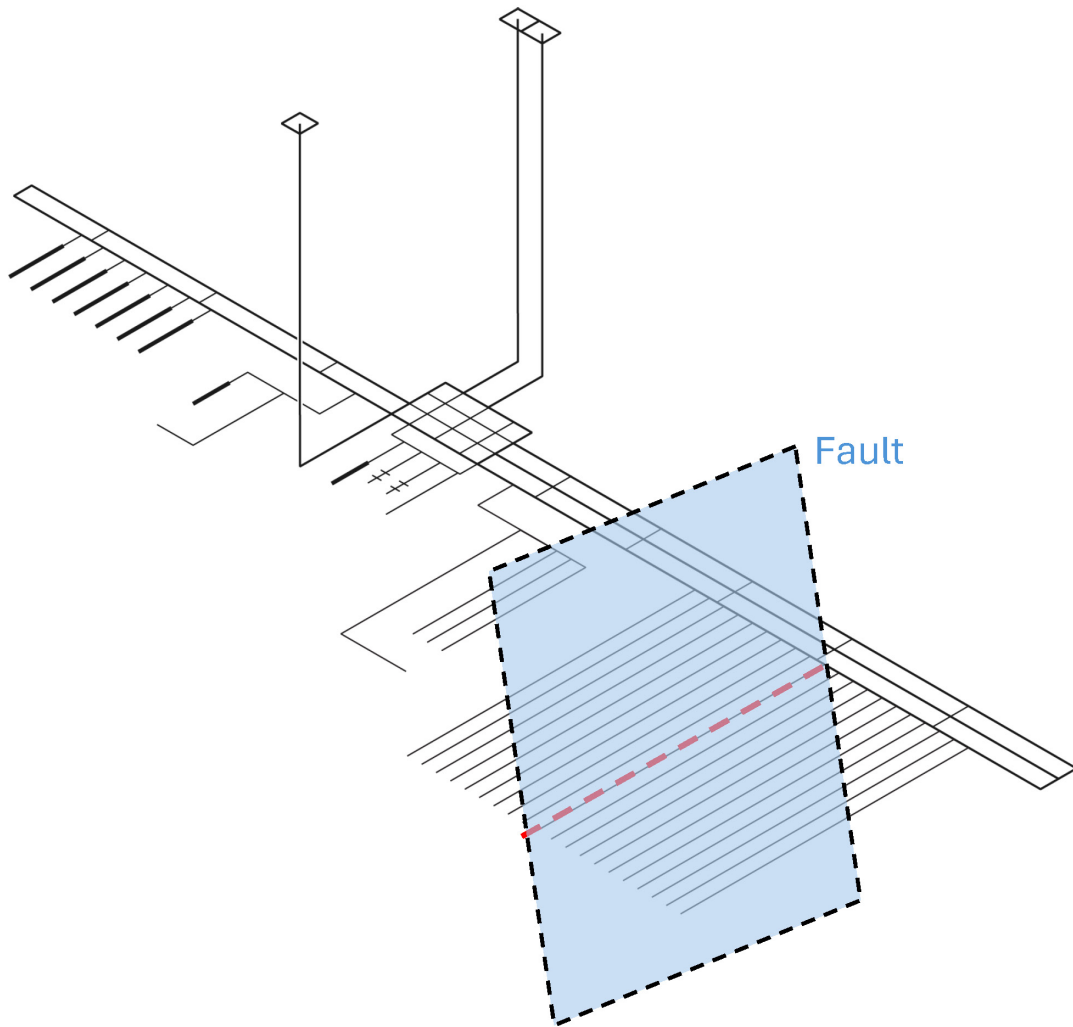


Fig. B-10: Conceptualisation of a fault affecting the HLW emplacement drifts parallel to the drift axes

The corresponding model domains defined for the L/ILW near-field are illustrated in Fig. B-11. For near-field modelling, in cases where the fault is parallel to the cavern axes, the fault is assumed to pass along the centre of one of the seven L/ILW emplacement caverns. The whole length of the cavern is then affected by the fault. Near-field radionuclide release to the geosphere is calculated using VPAC in 2 calculation steps:

- the release to the fault is calculated, with $1/7^{\text{th}}$ of the radionuclide inventory in the source term; and
- the release to the unaffected rock is calculated for the rest of the inventory.

2D VPAC simulations are used for both steps, exploiting the symmetries shown in the figure.

For cases where a fault is assumed to pass perpendicular to the cavern axes, all seven emplacement caverns are assumed to be affected by the fault. As in the reference safety scenario, for modelling purposes, the entire inventory is assumed to reside in a single cavern and only this cavern is modelled. A single 3D VPAC simulation is then used.

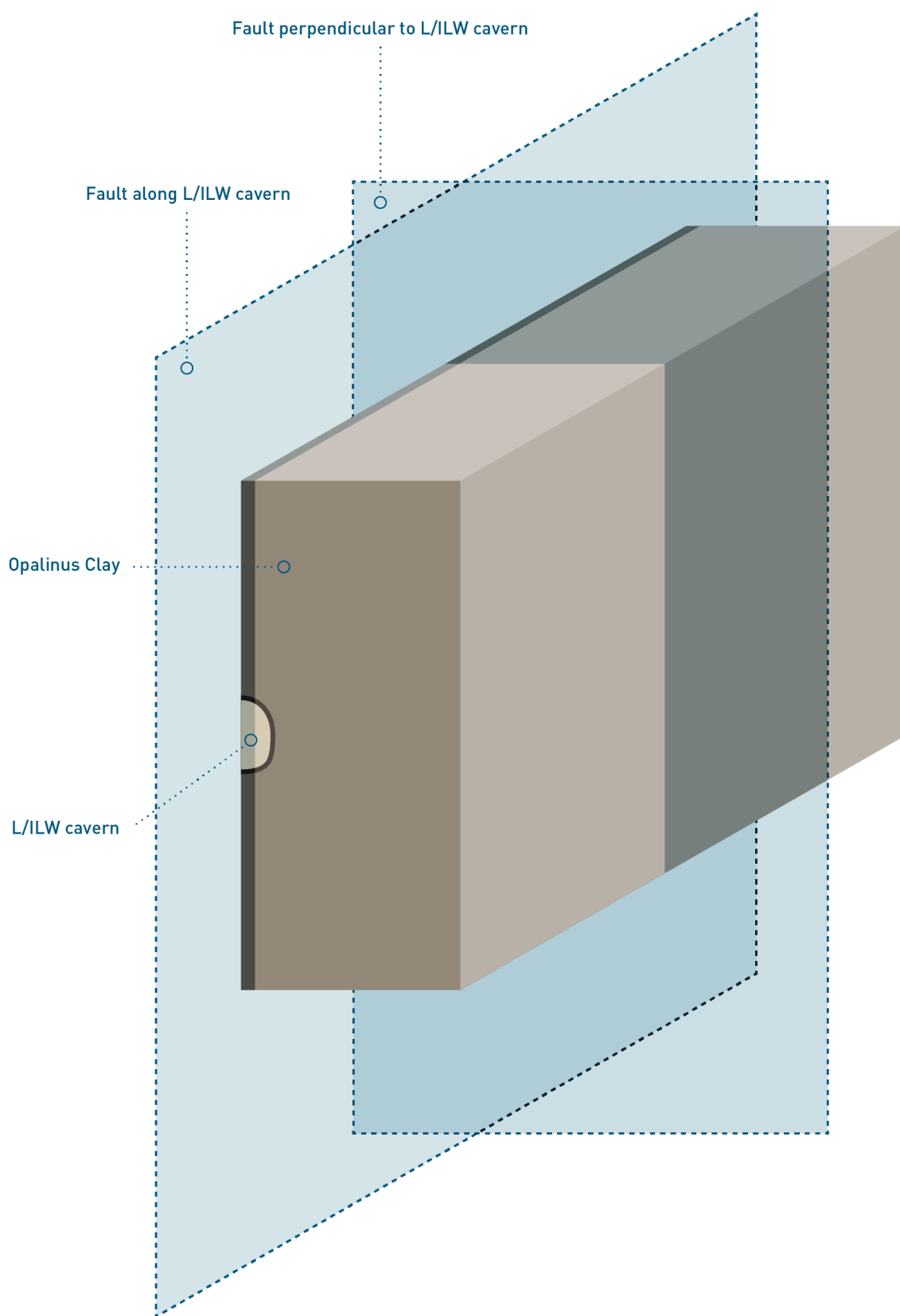


Fig. B-11: Model domain for analysing near-field release and transport in situations where a fault runs either parallel or perpendicular to the L/ILW cavern axis

For near-field modelling, in cases where the fault is parallel to the HLW drift axes, the fault is assumed to pass along the centre of one of the 20 HLW emplacement drifts, affecting releases from all 97 SF disposal canisters in that drift²⁶. Similarly to the case concerning the fault intersecting the drift, two STMAN models are configured in parallel, one with 97 SF canisters for the affected HLW near-field, another one for the remaining canisters for the intact near-field. Similarly to L/ILW, near-field radionuclide release to the geosphere is calculated using STMAN in two calculation steps:

- the release to the fault is calculated from the 97 SF canisters in the drift that is intersected by the fault; and
- the release to the unaffected rock is calculated for the remaining disposal canisters.

For cases where a fault is assumed to pass perpendicular to the drift axes, all 20 drifts are assumed to be affected by the fault, with three canisters affected per drift, meaning that the radionuclide releases from these 60 (i.e., 20×3) canisters can migrate through the buffer to the fault. Because of the low hydraulic conductivity of the bentonite buffer, the remainder of each drift is assumed to be unaffected, with releases from the disposal canisters diffusing into unaffected rock. Release to the geosphere is calculated using STMAN in two calculation steps:

- the release to the fault is calculated from the 60 SF canisters that are affected by the fault; and
- the release to the unaffected rock is calculated for the remaining disposal canisters.

For all configurations, for both L/ILW and HLW, there is a two-part source term for geosphere modelling consisting of radionuclide release to the fault and radionuclide release to the unaffected rock.

As in the case of the reference safety scenario, geosphere transport is modelled using a chain of PICNIC-TD legs, with one leg for each rock unit. However, for safety scenarios involving the presence of a fault, these legs account for the presence of the fault and for radionuclide transfer by diffusion between the fault of the adjacent rock matrix.

Fig. B-12 shows how the fault is conceptualised as a simple, narrow planar feature. It is assumed that both the fault and the rock matrix can conduct water in the vertical direction (although the flow of water in the rock matrix is small). A uniform radionuclide concentration is assumed in the fault follows the flow direction, and radionuclides are transferred between the fault and the rock matrix by diffusion. The releases from the near-field to the fault and to the rock matrix are provided by the two-part source term described above.

As illustrated in Fig. B-13, at the junctions between legs, the radionuclide flux leaving the fault in one leg in the flow direction is assumed to pass directly to the fault of the connected leg. Similarly, the radionuclide flux leaving the rock matrix in one leg is assumed to pass directly to the rock matrix of the connected leg.

²⁶ There is a total of 1,936 SF canisters in the HLW repository. By assuming an equal distribution of these throughout the 20 drifts, 97 canisters will be emplaced in one repository drift.

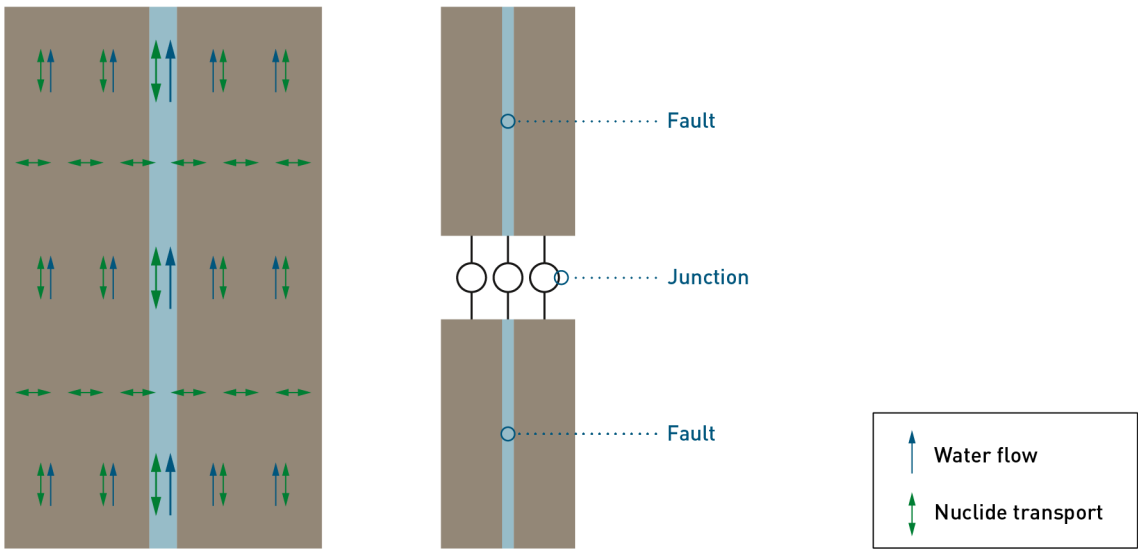


Fig. B-12: Conceptualisation of a fault and the adjacent rock matrix and its representation as a chain of connected PICNIC-TD legs

Junction between two fractured legs

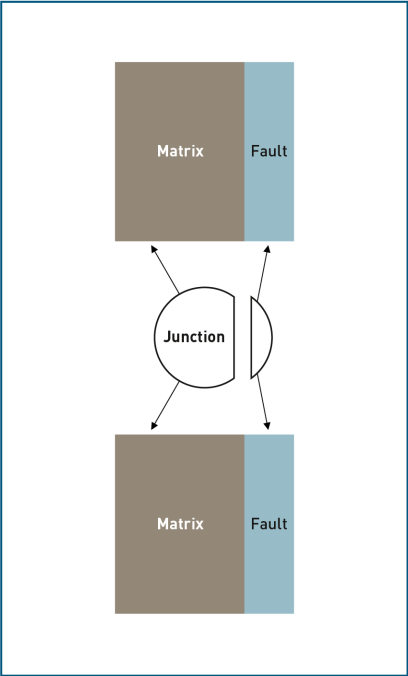


Fig. B-13: Connections between the faults and rock matrices at the junction between two PICNIC-TD legs

B.2 Conceptual model setup for gaseous radionuclide transport

The macroelement modelling approach for modelling the migration of C-14 released as methane under two-phase-flow conditions, using the TOUGH3-EOS75R computer codes, is outlined in Section 5.2. Further details are provided in the following paragraphs.

B.2.1 General conceptual model configuration

Macroelements provide a 3D modelling approach encompassing the entire repository system. Meshing of each macroelement is performed using an unstructured grid. The standard version of TOUGH3 was modified by introducing optional scaling factors for diffusive transport, advective transport and heat flow for each connection of the mesh. This was to account for process-specific factors that can vary according to the anisotropy of the material and the orientation of the connection.

The geometry of the repository is abstracted based on the description and the repository configuration in Nagra (2023a). However, in order to accelerate the simulation speed, the number of the numerical elements was significantly reduced by simplifying the similar and (quasi) symmetrically positioned repository structures along with the surrounding rock to representative 3D macroelements.

Two broad types of macroelements are implemented:

- tunnel elements; and
- shaft elements.

The macroelement representing the L/ILW emplacement caverns is illustrated in Fig. B-14 as an example of a tunnel element. Instead of explicitly meshing and modelling all seven caverns, each with its surrounding EDZ and geosphere, the mesh of the macroelement representing the caverns covers only a rectangular domain between a single cavern and a cavern adjacent to it, with vertical boundaries parallel to the caverns consisting of a symmetry plane passing through the cavern axis and a second symmetry plane parallel to this, at the half-axial distance between the caverns. Element volumes and cross-sectional areas between elements of the mesh are then scaled by a factor of 7 (the number of caverns) times 2 (to account for symmetry) in order to represent the entire set of L/ILW emplacement caverns. Macroelements (both tunnel and shaft) include the host rock (including the EDZs) and its confining units above and below the structures.

A further example of tunnel elements are the three co-axial operations, ventilation and construction tunnels of the HLW section of a combined repository. These are separated from the rest of the repository by V2 seals. Hence, the three co-axial tunnels are each split into two sections on either side of the V2 seals. The three tunnels of each section are combined into one structure and embedded into one macroelement. The combination is implemented in such a way that the total pore volume is conserved. The length of the combined structure is set equally to the axial length of the tunnels. Additional tunnels not running co-axially to the operations, ventilation and construction tunnels (e.g., cross-passages) do not lead to an increased length or scaling factor, but are accounted for by an increased porosity. It is assumed that the repository model structures represented by tunnel elements are at the centre of the host rock. Each tunnel element is discretised as a 2D vertical semi-axial-symmetric grid. Discretisation in the axial direction is also possible, but only implemented in practice for the V4 seal in the access ramp of the JO repository configuration. This is necessitated by the high-permeability contrasts between the V4 seal and the adjacent tunnels, leading to high pressure gradients.

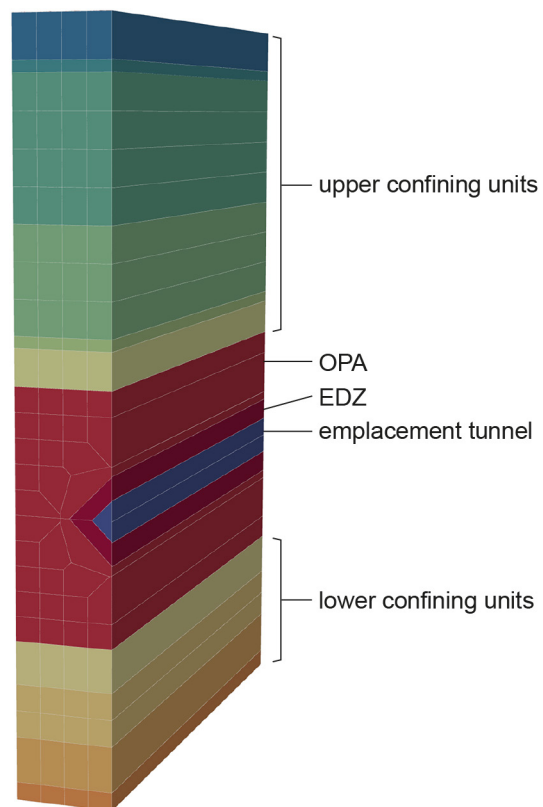


Fig. B-14: Example of a 3D macroelement for the L/ILW emplacement caverns

Each macroelement consists of the repository structure (e.g., emplacement cavern) and adjacent EDZ and CRZ (i.e., host rock and confining units). The macroelement only represents half of the repository structure to take advantage of the symmetry. To account for all 7 emplacement caverns, extensive properties (volumes, areas) are scaled by a factor of 7 (number of structures) times 2 (for the symmetry).

As illustrated in Fig. B-15, shaft elements are discretised as 2D radial-symmetric grids with vertical axes. The shafts themselves are laterally surrounded by the EDZ in the host rock. In the confining units, no EDZ is considered. Outside of the EDZ, the mesh size is identical to that of the tunnel elements.

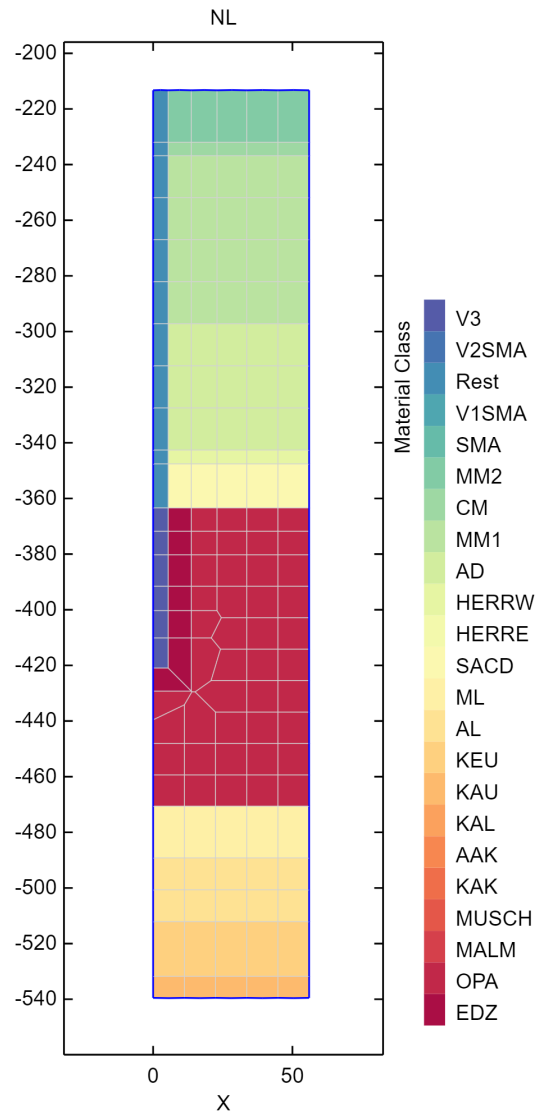


Fig. B-15: Structure of macroelement representing the shafts

The change of the elevation due to the inclination of the tunnel components is taken into account by fitting the elevation setting of the corresponding macroelement in the model according to the site-specific repository configuration (Nagra 2023a). Connections are established between the macroelements; these are generally inclined, allowing gravitational/buoyancy effects to be taken into account.

The extensive properties of the macroelements, such as volumes and source terms, are multiplied by the respective number of aggregated structures, whereas the intensive properties/states, such as temperature, material properties and pressure gradients, remain unscaled. The macroelements are linked together at the interface of the individual structures and the surrounding EDZ to allow

for two-phase flow between the macroelements and hence allow for C-14 methane release to transfer along repository structures. The rock parts of the adjoining macroelements are not connected, which reflects the expectation that the advective C-14 transport (as well as water and gas flows) mainly occurs in a plane perpendicular to the tunnel axis. A schematic view of a typical macroelement model layout for the combined repository is shown in Fig. B-16.

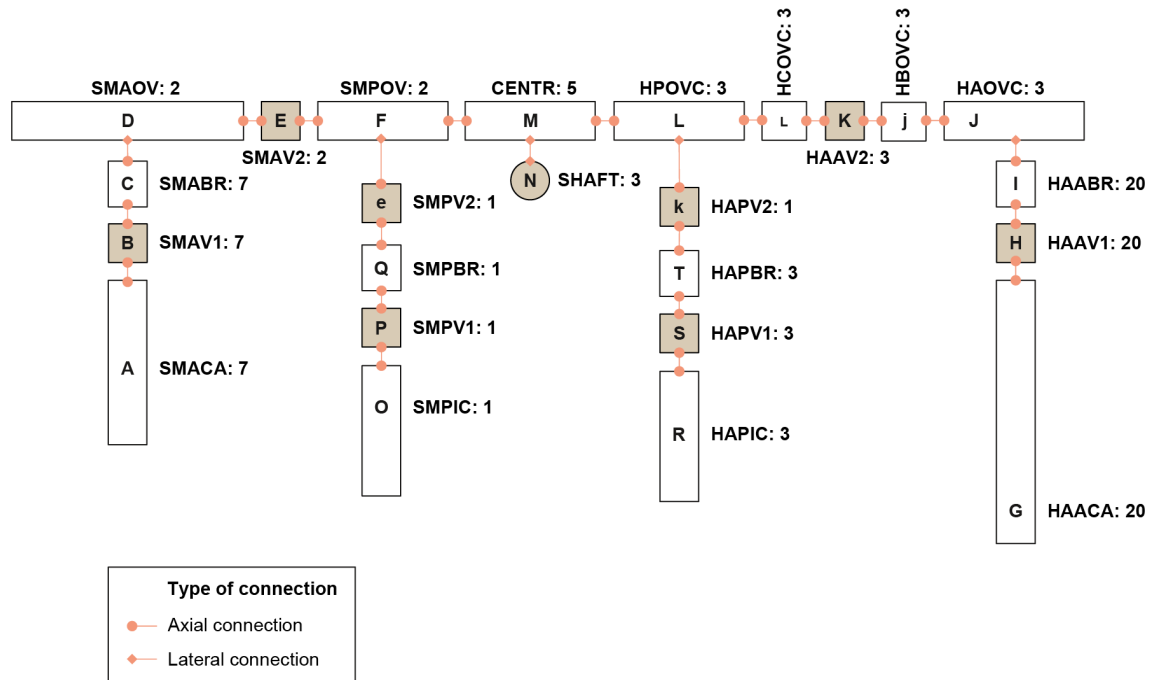


Fig. B-16: Schematic view of a typical macroelement model layout for a combined repository to simulate the gas-mediated migration of C-14

Fixed pressure/temperature and zero radionuclide concentration boundary conditions are assigned at the top and bottom of each macroelement, as well as in the ramp in the case of a repository in JO (beyond the V4 seal). All macroelements are initialised with a hydrostatic pressure distribution. Site-specific temperature distributions for each individual geological unit are taken into account when setting the initial temperature conditions and scaling the effective diffusion coefficient.

The impact of repository-generated heat and gas is simulated from the time of backfilling of the emplacement drifts and caverns in the year 2075. Heat generation takes place within the emplacement drifts and caverns and is computed by summing the production rates of heat from all waste packages, which are given in MIRAM-RBG (Nagra 2023c). Two sources of gas generation are taken into account:

- Gas generation from the corrosion of construction materials, which is computed using the gas generation tool described in Nagra (2024k), and which is assumed to occur within all repository structures, with the exception of the V3 shaft seals, where reinforcement installations are assumed to be removed prior to seal construction.
- Gas generation due to the corrosion/degradation of waste and waste packages, which is also computed with the gas-generation model described in Nagra (2024k).

The total gas generation from L/ILW is distributed among all emplacement caverns and the total gas generation from HLW is distributed among all emplacement drifts.

B.2.2 Macroelement models for scenarios without faults

In the following sections, site-specific macroelement models are presented, based on the site-specific repository configurations (Nagra 2023a) and geological layering. As explained in Section 5.2.1, the migration of C-14 as methane generally focuses on L/ILW, and is modelled for individual L/ILW repositories in all three siting regions in support of the site comparison. The migration of C-14 methane in individual HLW repositories is not modelled explicitly for the calculation cases without faults, since aqueous diffusion of C-14 modelled using the approach described in Section 5.1 is more conservative. The C-14 methane from individual HLW repositories is considered only in alternative safety scenarios involving the presence of a fault. Additionally, in support of the safety case, the combined repository in the NL siting region is modelled taking into account both the L/ILW and HLW repository sections. The cross-sections of the various underground structures are the same in each siting region. However, there are also some differences, mainly in the lengths of the access tunnels due to the different placements of the repository sections.

Below, macroelement models are presented for an L/ILW repository in each of the siting regions and for a combined repository at the selected site.

L/ILW repository in JO

The macroelement model for an L/ILW repository in JO is shown in Figs. B-18 and B-19, based on the site-specific repository configurations shown in Fig. B-17. Fig. B-18 illustrates the connections between macroelements, whereas Fig. B-19 shows the 3D geometry of the model. The macroelements representing the L/ILW emplacement caverns (including those of the pilot repository) are connected to V1 seal macroelements, which are in turn connected to branch tunnel macroelements. These are connected, via a series of macroelements, to macroelements representing the ventilation shaft and access ramp, with their V3 and V4 seals. The access ramp is only modelled up to the V4 seal. Beyond the V4 seal, hydrostatic pressure is assumed.

Several simplifications are applied in this model. For example, the cross-sectional areas of the different tunnels are averaged to provide an equivalent cross-section for the corresponding macroelement.

The detailed geometrical parameters for each of the macroelements are listed in Tab. B-3.

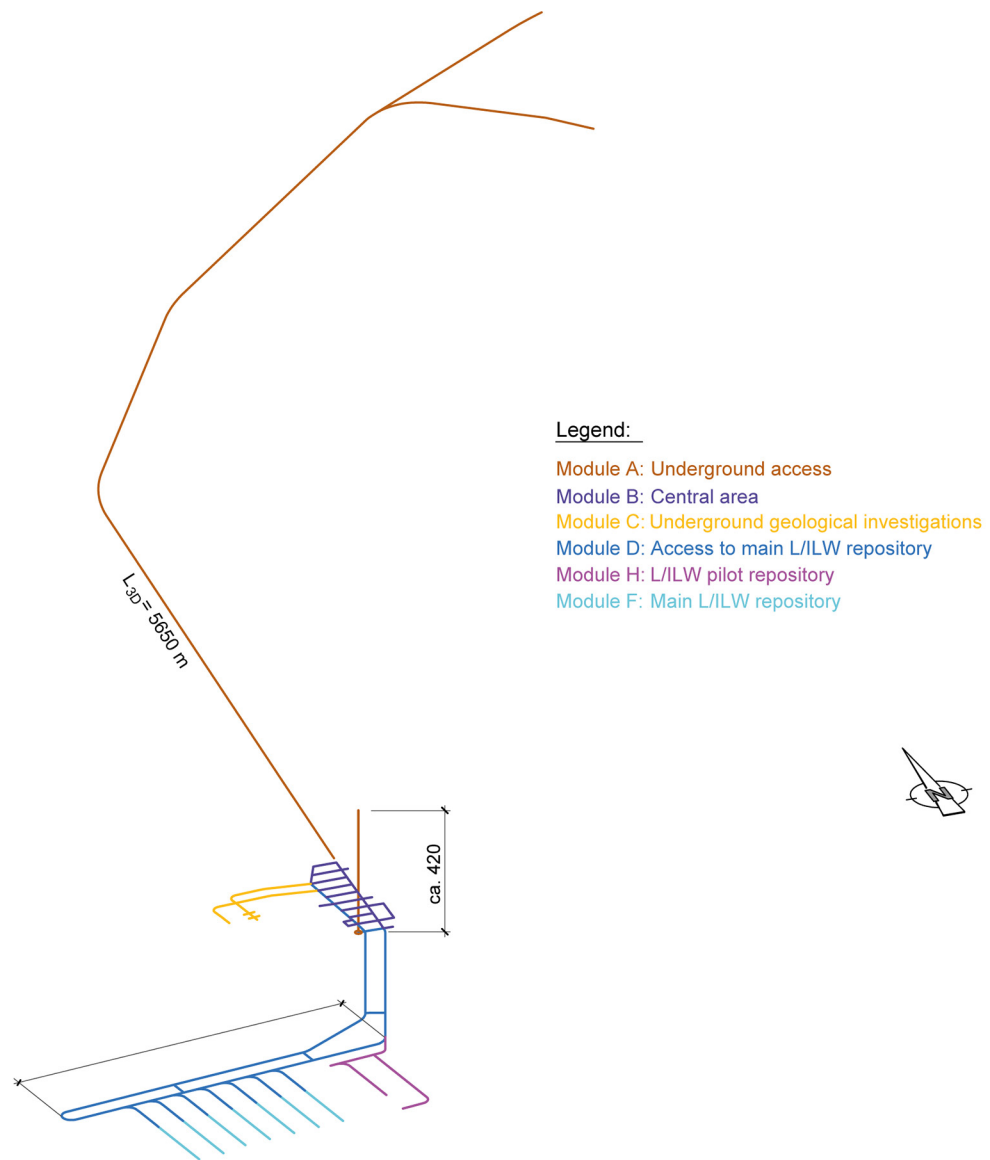


Fig. B-17: Configuration of an L/ILW repository in the JO siting region
(source: Fig. 8-1 in Nagra (2023a))

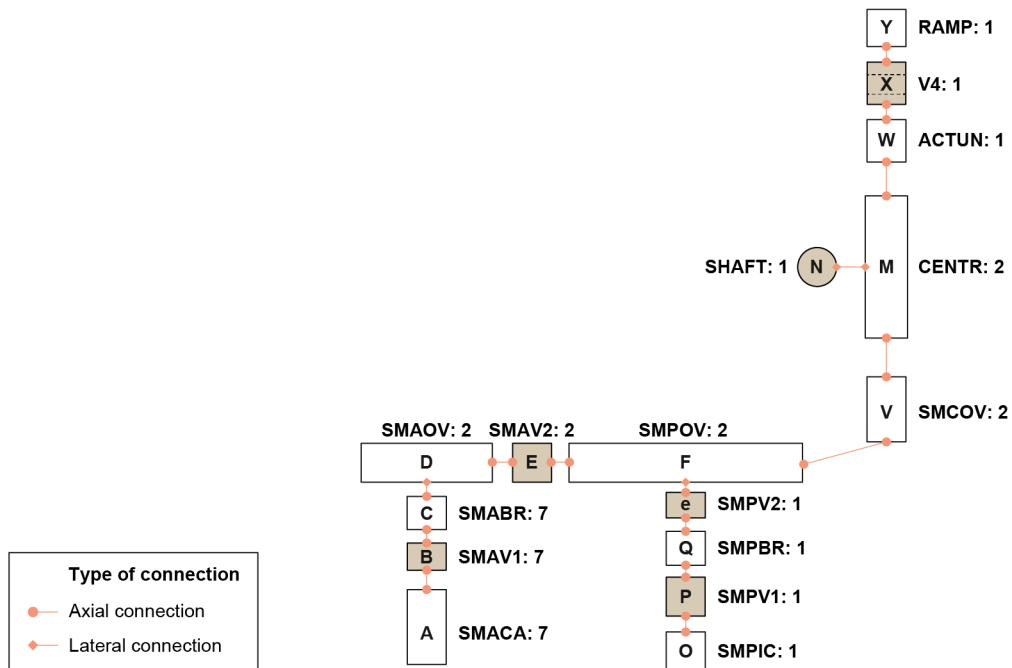


Fig. B-18: Schematic illustration of the macroelement model layout of an L/ILW repository in the JO siting region

The letters marking the macroelements are for modelling purposes that are not consistent with the module letters in Fig. B-17

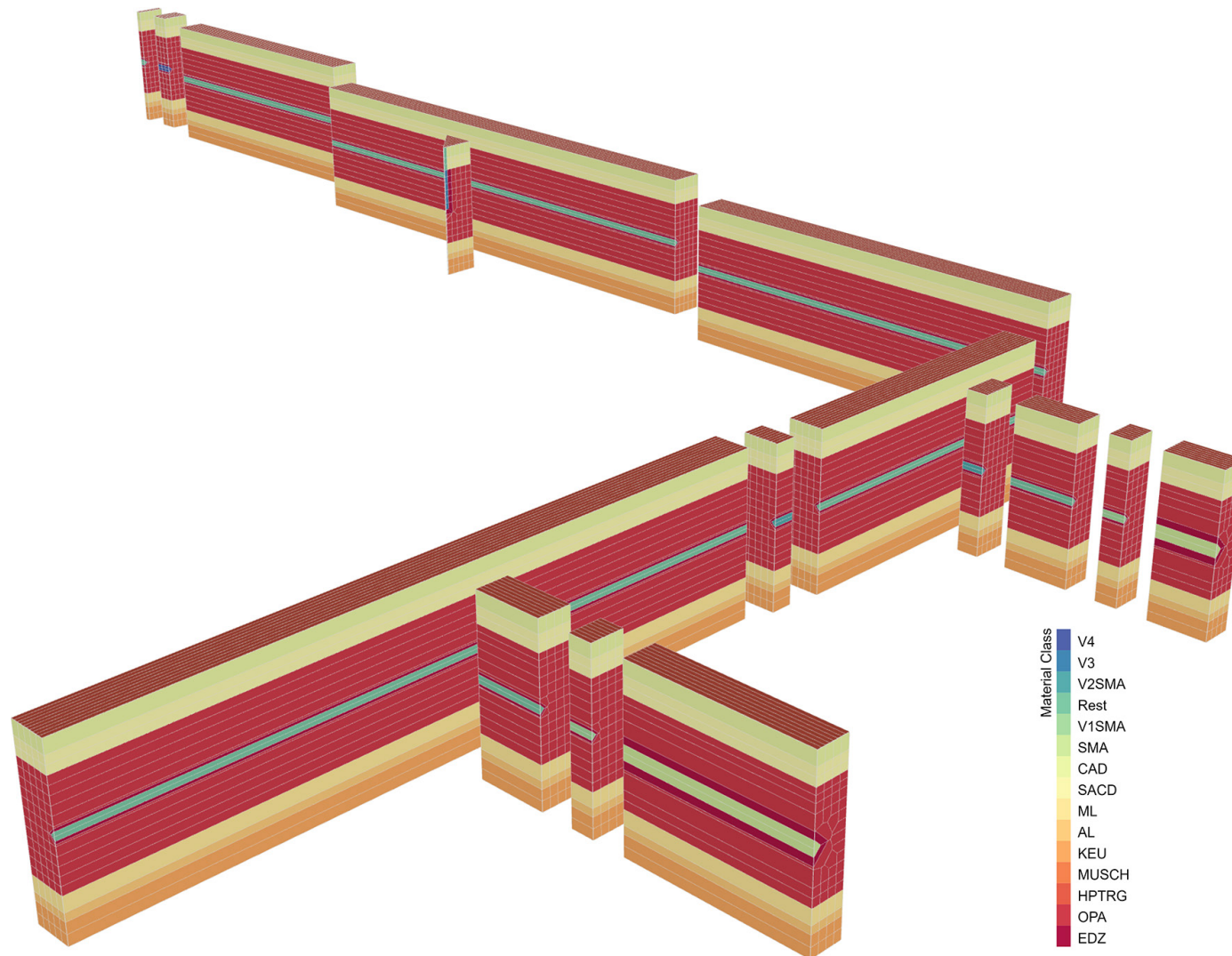


Fig. B-19: 3D view of the macroelement model for an L/ILW repository in JO

Tab. B-3: Geometric parameters of the macroelement model for an L/ILW repository in JO. Volumes refer to scaled properties

Name	Letter	Scale	Volume [m ³]	Cross-section [m ²]	Length [m]	Pore volume [m ³]	Porosity [-]	Material Name	Material Class	Width [m]	Elevation [m asl]
SMACA	A	7	251,103	152.2	235.7	50,221	0.20	SMACA	SMA	42.5	-50
SMAV1	B	7	10,138	48.3	30.0	3,041	0.30	SMAV1	V1SMA	42.5	-50
SMABR	C	7	33,790	53.6	90.0	11,827	0.35	SMABR	Rest	42.5	-50
SMAOV	D	2	89,072	49.1	907.6	33,710	0.38	SMAOV	Rest	50	-50
SMAV2	E	2	2,920	49.1	29.8	876	0.30	SMAV2	V2SMA	50	-60
SMPOV	F	2	41,859	49.1	426.5	26,033	0.62	SMPOV	Rest	50	-65
CENTR	M	2	83,885	49.1	854.7	59,988	0.72	CENTR	Rest	50	-20
SHAFT	N	1	9,552	91.9	103.9	3,038	0.3/0.35	V3/Shaft	V3/Rest	56	-30
SMPIC	O	1	12,175	152.2	80.0	2,435	0.20	SMPIC	SMA	42.5	-60
SMPV1	P	1	1,448	48.3	30.0	434	0.30	SMPV1	V1SMA	42.5	-60
SMPBR	Q	1	4,827	53.6	90.0	1,690	0.35	SMPBR	Rest	42.5	-60
SMPV2	e	1	1,485	49.5	30.0	446	0.30	SMPV2	V2SMA	50	-60
SMCOV	V	2	63,275	49.1	644.7	27,601	0.44	SMCOV	Rest	50	-50
ACTUN	W	1	30,522	63.6	480.0	10,683	0.35	ACTUN	Rest	50	0
V4	X	1	2,226	63.6	35.0	668	0.30	V4	V4	50	10
RAMP	Y	1	636	63.6	10.0	223	0.35	RAMP	Rest	50	10

L/ILW repository in NL

The comparison of siting regions for the HLW repository led Nagra to propose NL for the HLW repository. Thus, in principle, only the analysis of a combined repository is required for this siting region. Nonetheless, in Fig. B-20, a macroelement model of an L/ILW repository in NL is presented, based on the combined repository configuration with the HLW repository section removed.

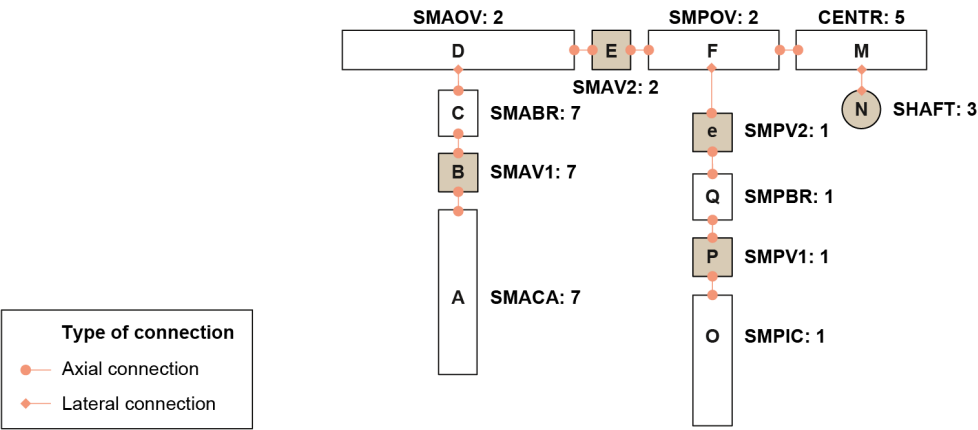


Fig. B-20: Schematic illustration of the macroelement model layout of an L/ILW repository in the NL siting region

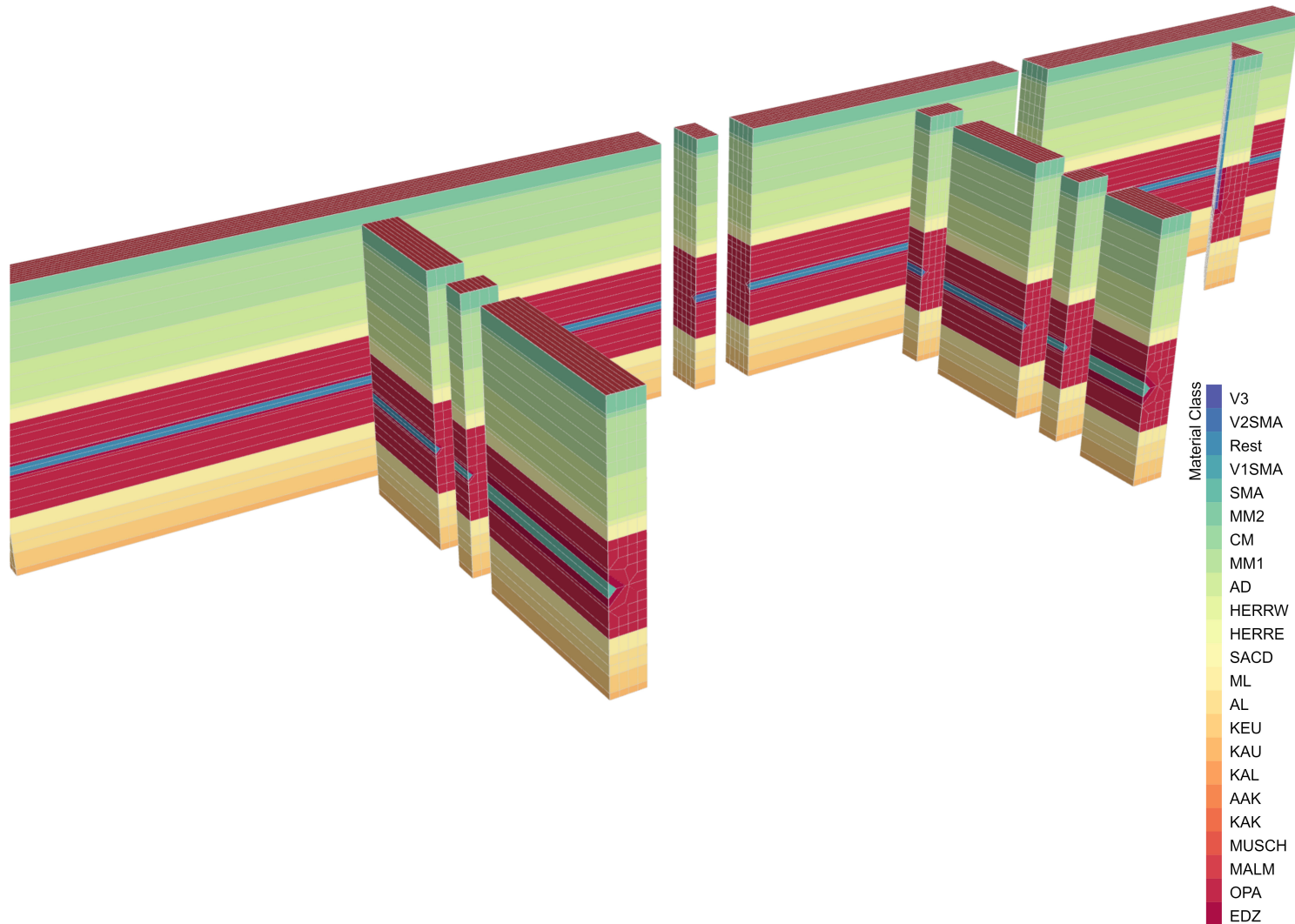


Fig. B-21: 3D view of the macroelement model for an L/ILW repository in NL

The model includes three access shafts, i.e., the operations, access and ventilation shafts, which is the same as in the combined repository. As described in Nagra (2023a), only two shafts are assumed for an L/ILW repository in the ZNO siting region, with the cross-section of the ventilation shaft enlarged to the same value as that of the operations shaft. Such a configuration could also be feasible for NL. However, for the site comparison, three shafts are assumed for both NL and ZNO on the grounds of conservatism, because a greater number of shafts potentially increases C-14 releases along the shafts.

The detailed geometrical parameters for each of the macroelements are the same as those listed in Tab. B-5 for a combined repository.

L/ILW repository in ZNO

The macroelement model for an L/ILW repository in ZNO is shown in Figs. B-23 and B-24, based on the site-specific repository configurations shown in Fig. B-22. Fig. B-23 illustrates the connections between macroelements, whereas Fig. B-24 shows the 3D geometry of the model.

The layout of the repository is quite similar to the L/ILW repository in JO and to the L/ILW section of a combined repository in NL. There are, however, differences in the length of the access tunnels and overall repository layout.

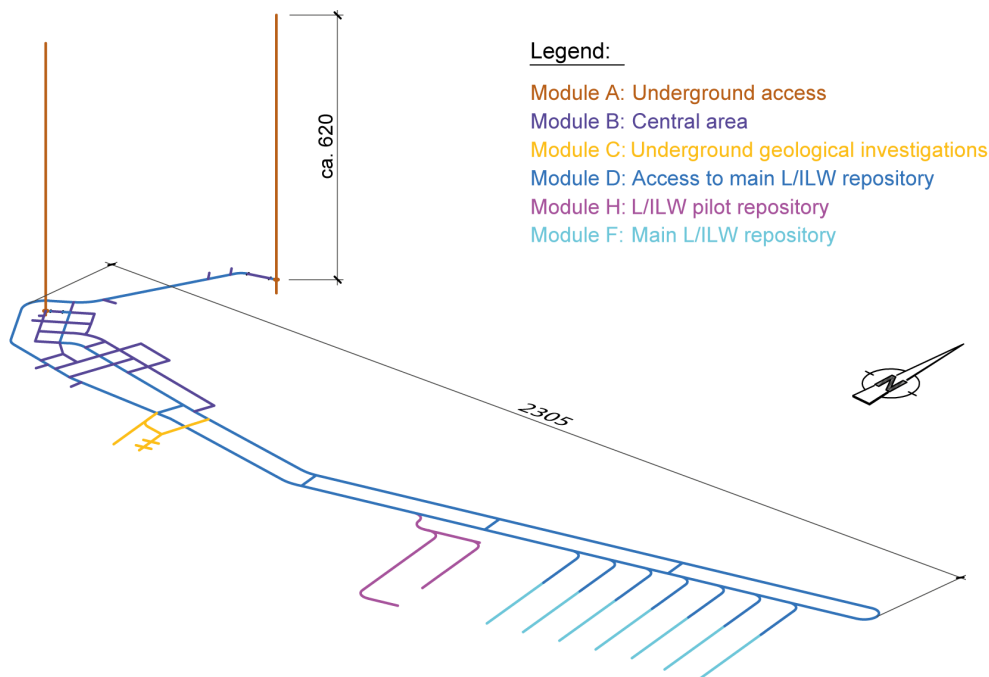


Fig. B-22: Configuration of an L/ILW repository in the ZNO siting region
(source: Fig. 8-3 in Nagra (2023a))

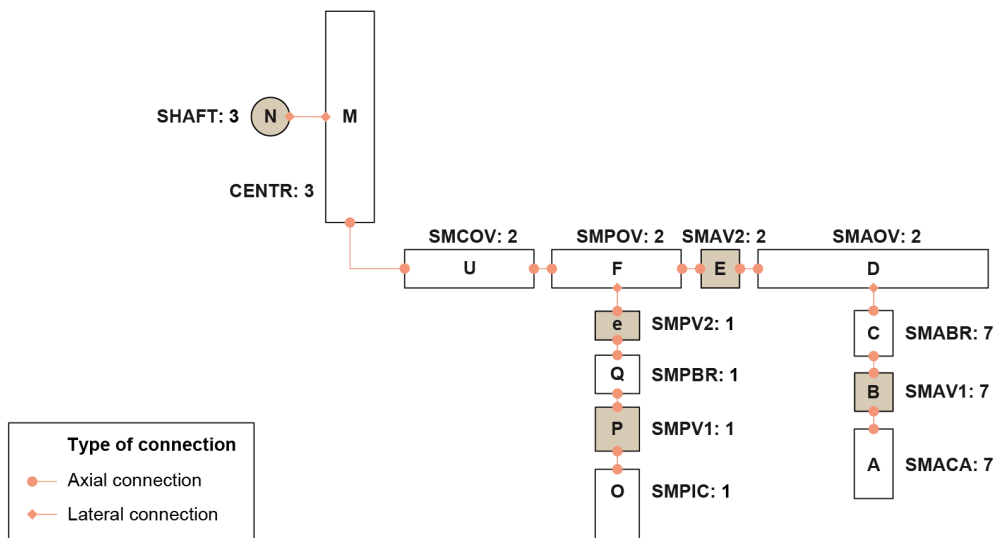


Fig. B-23: Schematic illustration of the macroelement model layout of an L/ILW repository in the ZNO siting region

The letters marking the macroelements are for modelling purposes that are not consistent with the module letters in Fig. B-22

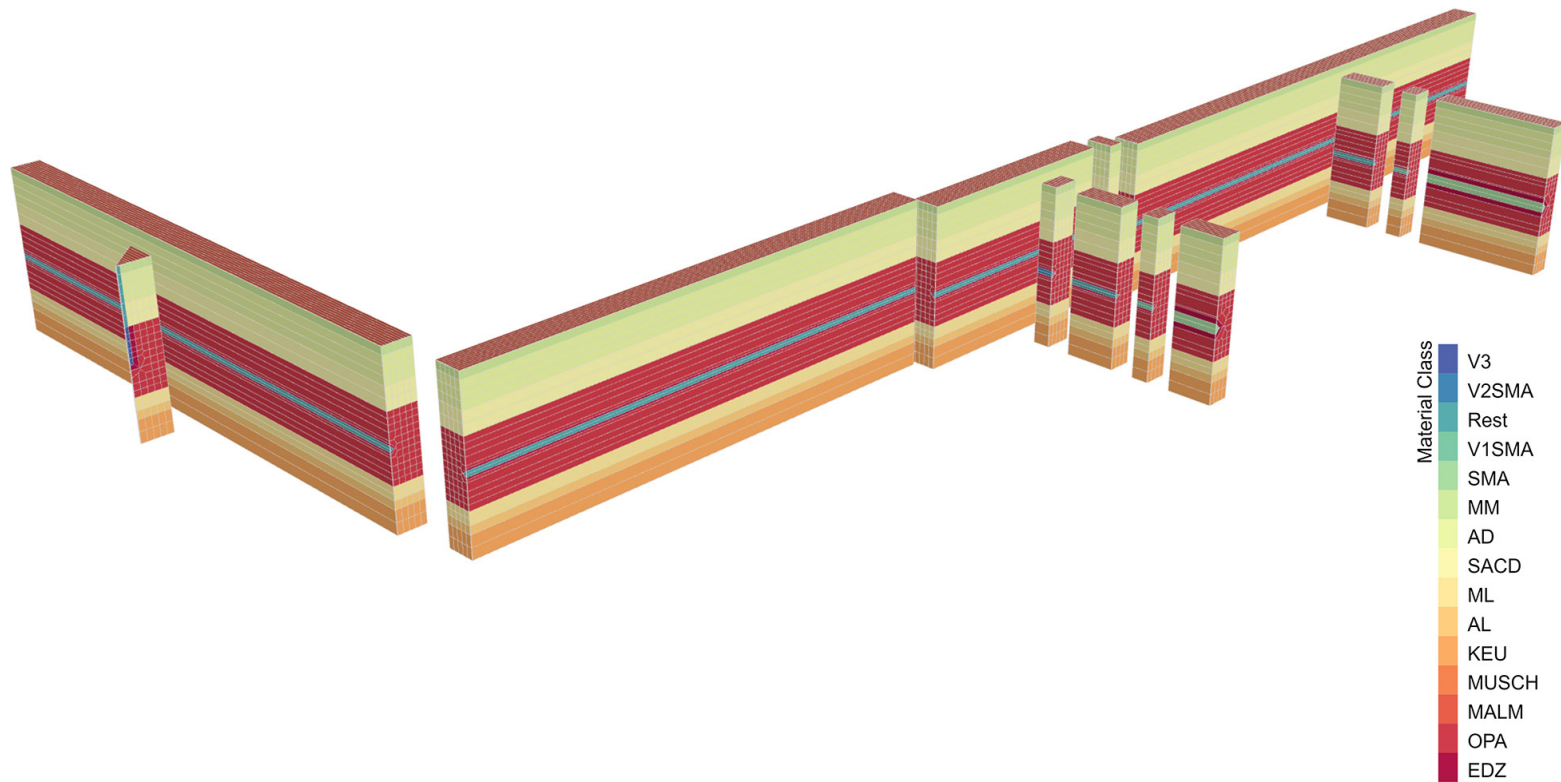


Fig. B-24: 3D view of the macroelement model for an L/ILW repository in ZNO

The detailed geometric set up in the model for the L/ILW single repository in ZNO is documented in Tab. B-4.

Tab. B-4: Geometric parameters of the macroelement model for an L/ILW repository in ZNO. Volumes refer to scaled properties

Name	Letter	Scale	Volume [m³]	Cross-section [m²]	Length [m]	Pore volume [m³]	Porosity [-]	Material Name	Material Class	Width [m]	Elevation [m asl]
SMACA	A	7	251,103	152.2	235.7	50,221	0.20	SMACA	SMA	42.5	-270
SMAV1	B	7	10,138	48.3	30.0	3,041	0.30	SMAV1	V1SMA	42.5	-270
SMABR	C	7	33,790	53.6	90.0	11,827	0.35	SMABR	Rest	42.5	-270
SMAOV	D	2	116,816	49.1	1190.3	43,420	0.37	SMAOV	Rest	50	-270
SMAV2	E	2	2,920	49.1	29.8	876	0.30	SMAV2	V2SMA	50	-255
SMPOV	F	2	39,912	49.1	406.7	26,381	0.66	SMPOV	Rest	50	-245
CENTR	M	3	148,597	49.1	1009.4	64,974	0.44	CENTR	Rest	50	-200
SHAFT	N	3	43,283	91.9	156.9	14,310	0.3/0.35	V3/Shaft	V3/Rest	56	-200
SMPIC	O	1	12,175	152.2	80.0	2,435	0.20	SMPIC	SMA	42.5	-245
SMPV1	P	1	1,448	48.3	30.0	434	0.30	SMPV1	V1SMA	42.5	-245
SMPBR	Q	1	4,827	53.6	90.0	1,690	0.35	SMPBR	Rest	42.5	-245
SMPV2	e	1	1,485	49.5	30.0	446	0.30	SMPV2	V2SMA	50	-245
SMCOV	U	2	88,641	49.1	903.2	33,559	0.38	SMCOV	Rest	50	-220

Combined repository in NL

The macroelement model for a combined repository in the NL siting region, with HLW and L/ILW repository sections sharing a common central area with three access shafts, is shown in Figs. B-26 and B-27, based on the site-specific repository configurations shown in Fig. B-25. Fig. B-26 illustrates the connections between the macroelements, whereas Fig. B-27 shows the overall geometry of the model. The macroelements representing the L/ILW and HLW emplacement drifts and caverns (including those of the pilot repositories) are connected to V1 seal macroelements, which are in turn connected to branch tunnel macroelements. These are connected, via a series of macroelements, to a macroelement representing the three shafts, with their V3 seals.

Several simplifications are applied in this model. For example, the cross-sectional areas of the different tunnels are averaged to provide an equivalent cross-section for the corresponding macroelement.

The detailed geometrical parameters for each of the macroelements are listed in Tab. B-5.

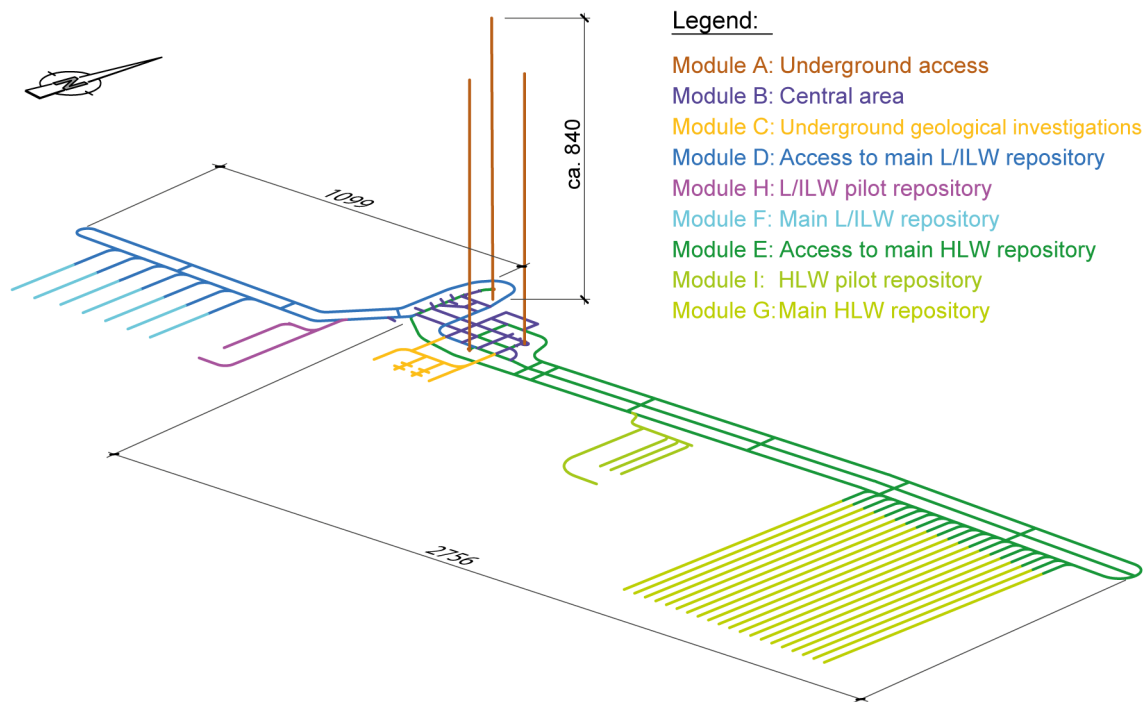


Fig. B-25: Configuration of a combined repository for L/ILW and HLW in the NL siting region
(source: Fig. 7-1 in Nagra (2023a))

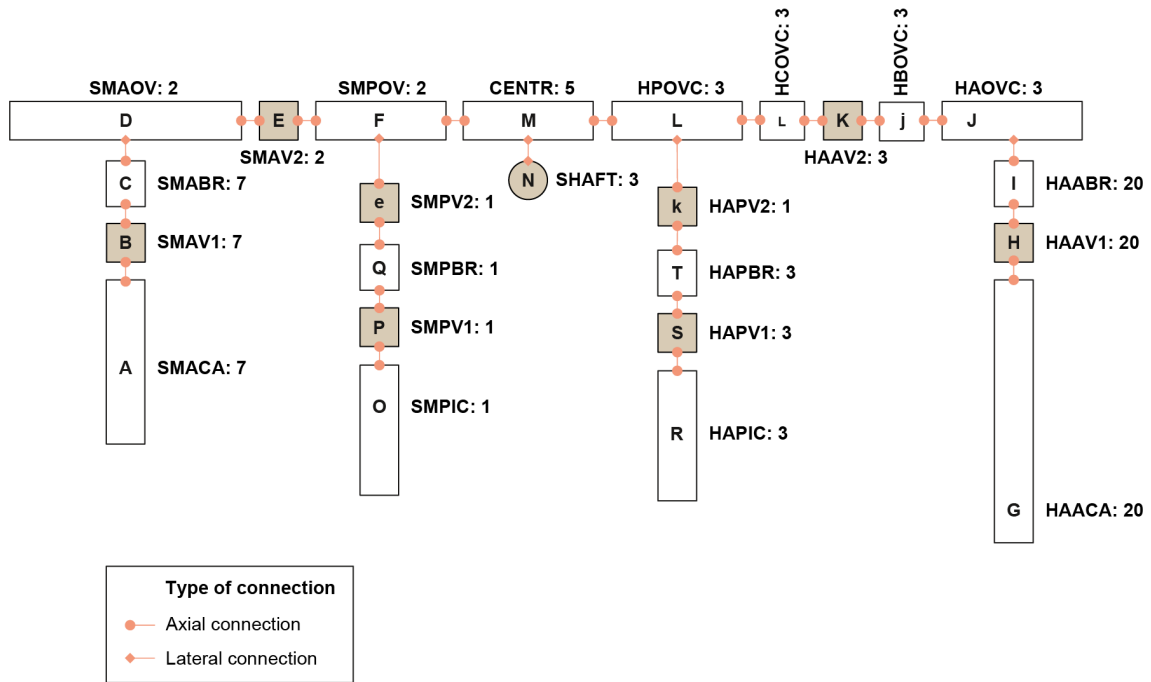


Fig. B-26: Schematic illustration of the macroelement model layout of a combined repository for L/ILW and HLW in the NL siting region

The letters marking the macroelements are for modelling purposes are not consistent with the module letters in Fig. B-25

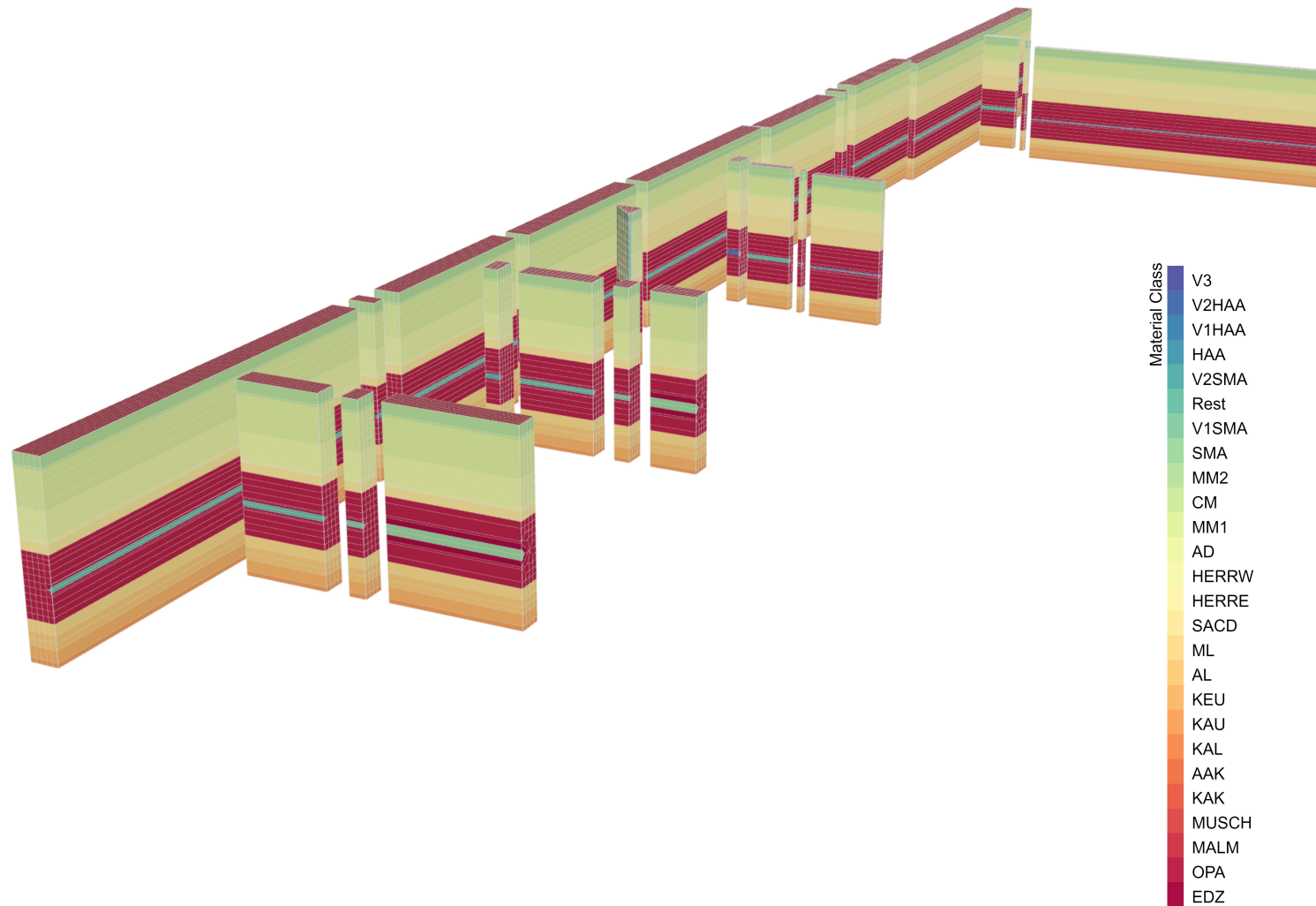


Fig. B-27: 3D view of the macroelement model for a combined repository for L/ILW and HLW in NL

Tab. B-5: Geometric parameters of the macroelement model of a combined L/ILW and HLW repository in NL. Volumes refer to scaled properties

Name	Letter	Scale	Volume [m³]	Cross-section [m²]	Length [m]	Pore volume [m³]	Porosity [-]	Material Name	Material Class	Width [m]	Elevation [m asl]
SMACA	A	7	251,103	152.2	235.7	50,221	0.20	SMACA	SMA	42.5	-401
SMAV1	B	7	10,138	48.3	30.0	3,041	0.30	SMAV1	V1SMA	42.5	-404
SMABR	C	7	56,317	53.6	150.0	19,711	0.35	SMABR	Rest	42.5	-405
SMAOV	D	2	79,330	49.1	808.3	30,300	0.38	SMAOV	Rest	50	-405
SMAV2	E	2	2,920	49.1	29.8	876	0.30	SMAV2	V2SMA	50	-409
SMPOV	F	2	40,431	49.1	412.0	24,049	0.59	SMPOV	Rest	50	-411
HAACA	G	20	113,609	6.6	860.0	28,402	0.25	HAACA	HAA	20	-472
HAAV1	H	20	1,321	6.6	10.0	396	0.30	HAAV1	V1HAA	20	-454
HAABR	I	20	105,377	52.7	100.0	36,882	0.35	HAABR	Rest	20	-451
HAOVC	J	3	146,843	49.2	995.2	56,533	0.38	HAOVC	Rest	50	-449
HBOVC	j	3	57,847	49.2	392.0	20,246	0.35	HBOVC	Rest	50	-430
HAAV2	K	3	4,450	49.2	30.2	1,335	0.30	HAAV2	V2HAA	50	-432
HCOVC	l	3	59,330	49.2	402.1	22,466	0.38	HCOVC	Rest	50	-434
HPOVC	L	3	87,512	49.2	593.1	47,325	0.54	HPOVC	Rest	50	-424
CENTR	M	5	112,003	49.1	456.5	76,073	0.68	CENTR	Rest	50	-417
SHAFT	N	3	57,279	91.9	207.7	19,254	0.3/0.35	V3/Shaft	V3/Rest	56	-417
SMPIC	O	1	13,697	152.2	90.0	2,739	0.20	SMPIC	SMA	42.5	-411
SMPV1	P	1	1,448	48.3	30.0	434	0.30	SMPV1	V1SMA	42.5	-411
SMPBR	Q	1	8,045	53.6	150.0	3,422	0.43	SMPBR	Rest	42.5	-411
SMPV2	e	1	1,485	49.5	30.0	446	0.30	SMPV2	V2SMA	50	-411
HAPIC	R	3	3,170	6.6	160.0	793	0.25	HAPIC	HAA	20	-445
HAPV1	S	3	198	6.6	10.0	59	0.30	HAPV1	V1HAA	20	-440
HAPBR	T	3	15,806	52.7	100.0	7,612	0.48	HAPBR	Rest	20	-438
HAPV2	k	1	1,485	49.5	30.0	446	0.30	HAPV2	V2HAA	50	-435

B.2.3 Macroelement models for scenarios with faults

The alternative safety scenario “undetected fault” (Section 4.2.2) and the “what-if?” cases for “undetected fault with elevated transmissivity” (Section 4.3.1.1) and “fault reactivation by geological processes or repository-induced effects” (Section 4.3.1.2) all consider a vertical fault that intersects the L/ILW emplacement caverns or the HLW emplacement drifts and extends vertically across the entire thickness of the CRZ. This fault is assumed to be orientated either perpendicular or parallel to the cavern or drift axes. The different configurations of the fault with respect to the emplacement caverns and drifts are shown together in Fig. 4-4.

Consistent with the assumptions made for transport in the liquid phase, in cases where the fault is perpendicular to the cavern or drift axes, the fault is assumed to pass through the centre of these structures. Either all the caverns or all the drifts are assumed to be intersected by the fault. These cases can be covered by inserting a fault element in the middle of the macroelement of either the L/ILW emplacement caverns or HLW emplacement drifts. Fig. B-28 illustrates a macroelement model with a fault crossing perpendicular to the L/ILW caverns. The fault macroelement is shown in red.

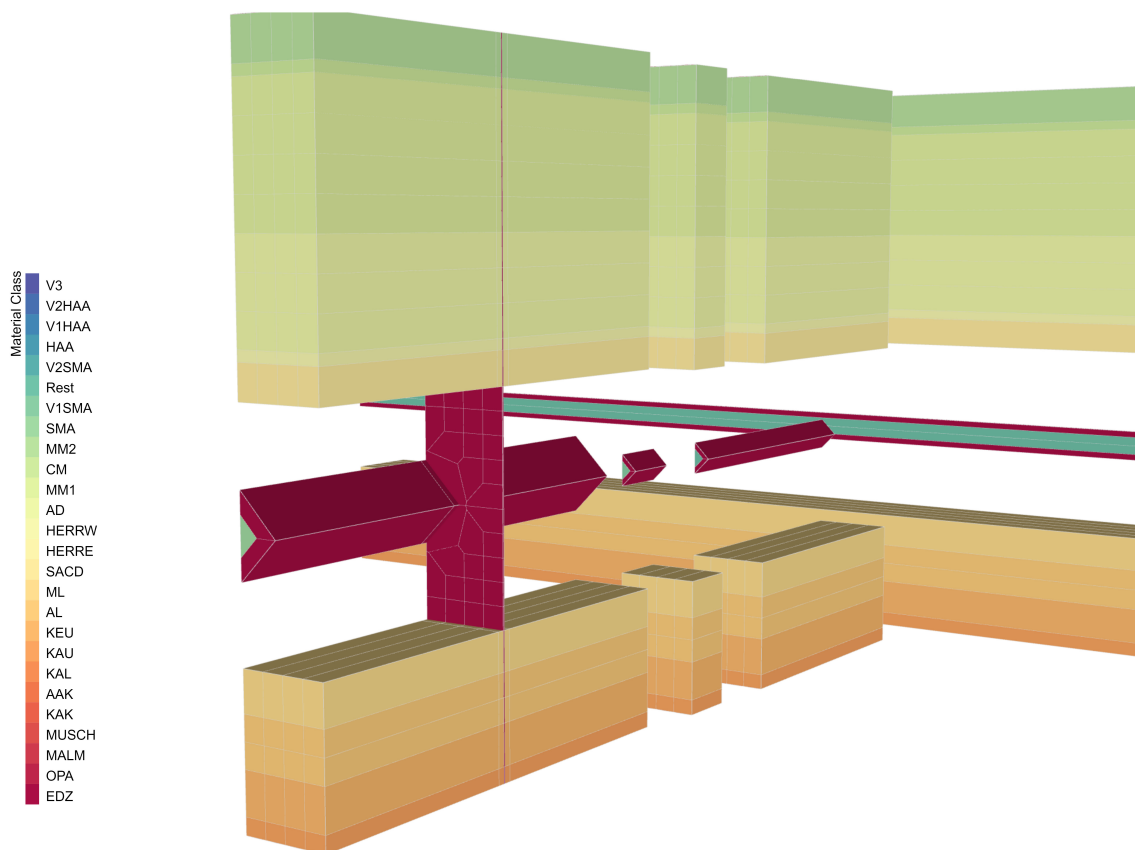


Fig. B-28: Example of a macroelement model with a fault crossing perpendicular to the L/ILW emplacement caverns. For better visibility, OPA is not shown

Consistent with the assumptions made for transport modelling in the liquid phase, in cases where the fault is parallel to the cavern or drift axes, the fault is assumed to pass along the centre of one of the caverns or drifts. The whole length of the cavern or drift is affected by the fault. These cases are represented, as illustrated in Fig. B-29, by introducing an additional macroelement representing the affected emplacement cavern or drift, shown in red in the figure. Another macroelement represents the unaffected caverns or drifts. Both macroelements are connected through the V1 seal and branch tunnel to the access tunnel macroelement.

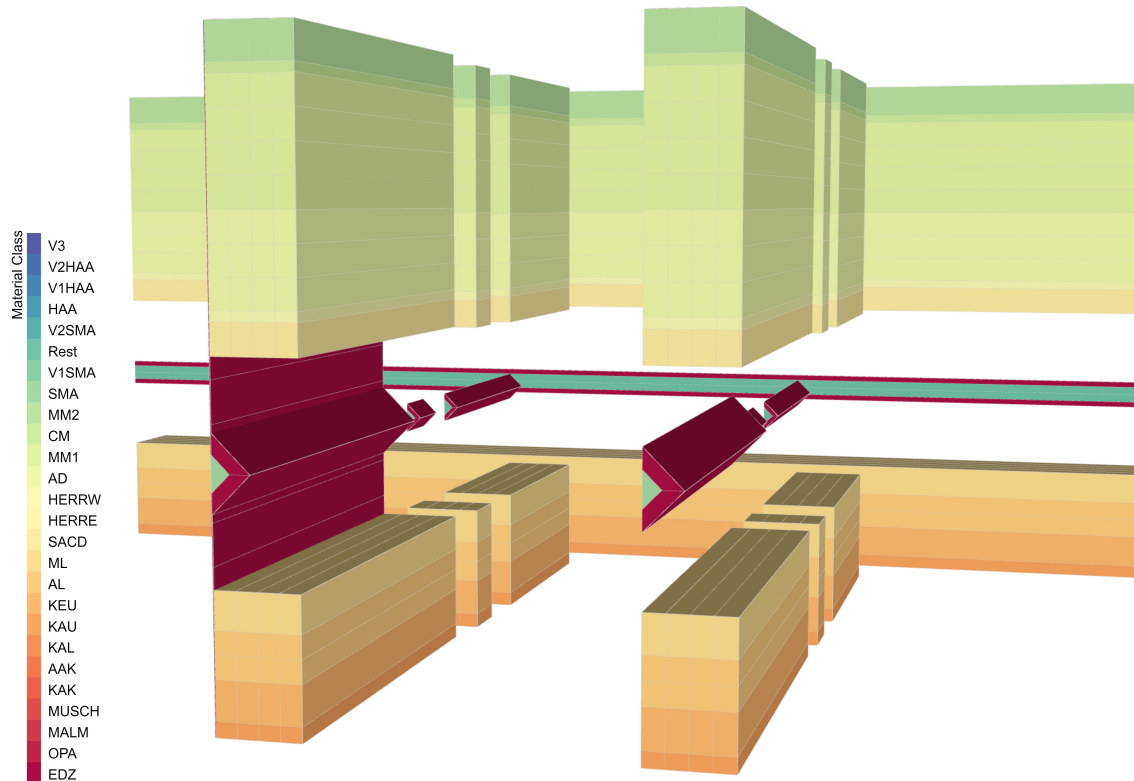


Fig. B-29: Example of a macroelement model with a fault parallel to the L/ILW caverns. For better visibility, OPA is not shown.

For the calculation case assuming an undetected fault in a single HLW repository for the alternative safety scenario, three site-specific models for the HLW repository in three siting regions are individually set up based on the placement given in Nagra (2023a). The following Tab. B-6 and Tab. B-7 provide information about the geometric parameters for the macroelement model for an HLW repository in JO and ZNO, respectively. The geometrical parameters for the HLW repository model for NL are the same as those listed in Tab. B-5 for a combined repository. The fault is then added to the model accordingly as described above.

Tab. B-6: Geometric parameters of the macroelement model for an HLW repository in JO. Volumes refer to scaled properties

Name	Letter	Scale	Volume [m³]	Cross-section [m²]	Length [m]	Pore volume [m³]	Porosity [-]	Material Name	Material Class	Width [m]	Elevation [m asl]
HAACA	G	20	114,270	6.6	865.0	28,567	0.25	HAACA	HAA	20	15
HAAV1	H	20	1,321	6.6	10.0	396	0.30	HAAV1	V1HAA	20	30
HAABR	I	20	115,914	52.7	110.0	40,570	0.35	HAABR	Rest	20	30
HAOVC	J	3	176,507	49.2	1196.2	68,579	0.39	HAOVC	Rest	50	30
HAAV2	K	3	4,450	49.2	30.2	1,335	0.30	HAAV2	V2HAA	50	20
HPOVC	L	3	60,813	49.2	412.1	39,365	0.65	HPOVC	Rest	50	10
CENTR	M	2	83,885	49.1	854.7	59,988	0.72	CENTR	Rest	50	-20
SHAFT	N	1	9,552	91.9	103.9	3,038	0.3/0.35	V3/Shaft	V3/Rest	56	-30
HAPIC	R	3	3,270	6.6	165.0	817	0.25	HAPIC	HAA	20	12
HAPV1	S	3	198	6.6	10.0	59	0.30	HAPV1	V1HAA	20	15
HAPBR	T	3	17,387	52.7	110.0	6,086	0.35	HAPBR	Rest	20	17
HAPV2	k	1	1,485	49.5	30.0	446	0.30	HAPV2	V2HAA	50	17
HCOVC	U	3	74,162	49.2	502.6	31,058	0.42	HCOVC	Rest	50	-5
ACTUN	W	1	30,522	63.6	480.0	10,683	0.35	ACTUN	Rest	50	0
V4	X	1	2,226	63.6	35.0	668	0.30	V4	V4	50	10
RAMP	Y	1	636	63.6	10.0	223	0.35	RAMP	Rest	50	10

Tab. B-7: Geometric parameters of the macroelement model for an HLW repository in ZNO. Volumes refer to scaled properties

Name	Letter	Scale	Volume [m³]	Cross-section [m²]	Length [m]	Pore volume [m³]	Porosity [-]	Material Name	Material Class	Width [m]	Elevation [m asl]
HAACA	G	20	114,270	6.6	865.0	28,567	0.25	HAACA	HAA	20	-320
HAHV1	H	20	1,321	6.6	10.0	396	0.30	HAHV1	V1HAA	20	-280
HAABR	I	20	115,914	52.7	110.0	40,570	0.35	HAABR	Rest	20	-275
HAOVC	J	3	177,990	49.2	1206.2	67,398	0.38	HAOVC	Rest	50	-270
HAHV2	K	3	4,450	49.2	30.2	1,335	0.30	HAHV2	V2HAA	50	-255
HPOVC	L	3	60,813	49.2	412.1	36,983	0.61	HPOVC	Rest	50	-245
CENTR	M	3	148,597	49.1	1009.4	64,974	0.44	CENTR	Rest	50	-200
SHAFT	N	3	43,283	91.9	156.9	14,310	0.3/0.35	V3/Shaft	V3/Rest	56	-200
HAPIC	R	3	3,270	6.6	165.0	817	0.25	HAPIC	HAA	20	-265
HAPV1	S	3	198	6.6	10.0	59	0.30	HAPV1	V1HAA	20	-255
HAPBR	T	3	17,387	52.7	110.0	6,086	0.35	HAPBR	Rest	20	-250
HAPV2	k	1	1,485	49.5	30.0	446	0.30	HAPV2	V2HAA	50	-250
HCOVC	U	3	127,498	49.2	864.1	51,535	0.40	HCOVC	Rest	50	-220

App. C Parameter assumptions in the radiological consequence analysis

This appendix documents the most important assumptions for the parameter set used in the radiological consequence analysis.

C.1 Effective diffusion coefficients

The effective diffusion coefficients given in the database (Glaus et al. 2024) are for the reference temperature (25 °C). These need to be corrected to the local temperature of the rock units for the transport simulations.

Based on the effective diffusion coefficient, $D_e^{T_0}$, at a reference temperature T_0 , its value can be corrected to account for the actual (absolute) temperature, T , of the rock by means of the Arrhenius law:

$$D_e^T = D_e^{T_0} \cdot \exp \left[-\frac{E_A}{R} \left(\frac{1}{T} - \frac{1}{T_0} \right) \right] \quad [\text{C-1}]$$

where E_A is an activation energy of 20 ± 5 kJ/mol and R is the universal gas constant (8.314 J/(mol.K)).

The temperature of the rock units is calculated based on their depths. The corrected effective diffusion coefficients are assigned to the individual rock units in the model. For the diffusion in the near-field, the temperature at the mid-depth of the Opalinus Clay is used for the correction. The full set of the corrected effective diffusion coefficients can be found in the digital appendix (Enclosure C: inSituDe.html).

Moreover, for the simulation of C-14 transport in the gas phase, since the porewater diffusion coefficient in the TOUGH3 model is a global parameter for all the relevant transport media, the effective diffusion coefficient of organic C-14 in the Opalinus Clay given in the diffusion database (Glaus et al. 2024) is used to define the effective diffusion coefficient in the Opalinus Clay. The effective diffusion coefficients of the near-field materials and the upper and lower confining geological units are then scaled according to their porosity, which leads to an overestimation of the effective diffusion coefficient in the upper confining geological units.

In the simulation of radionuclide transport in the liquid phase, the radionuclide-specific accessible porosity given in the diffusion database (Glaus et al. 2024) is taken into account for the diffusive transport process. In contrast, for the model concerning two-phase flow for the C-14 methane, the porosity of geological units is considered, which is more relevant to the advective two phase flow.

C.2 Strategy of treating parameter uncertainty

As noted at the start of Chapters 6 and 7, when analysing the reference safety scenario both for the site comparison and in support of the safety case for a combined repository, a reference calculation case is analysed first, followed by probabilistic simulations and pessimistic deterministic cases. In the reference case, where there is quantified uncertainty in the properties of the repository features, rates of processes and other model parameters, best estimates are generally assumed. Other uncertainties are generally handled using conservative assumptions. For some parameters with currently poorly quantified uncertainty, pessimistic bounding values are conservatively considered in the reference case. Tab. C-1 documents briefly the strategy of treating the parameter uncertainty in the reference calculation case and in the probabilistic simulations. Detailed information for each individual parameter can be found under “Master table” in the digital App. H. Tab. C-2 explains the handling of parameter correlations in the probabilistic simulations.

Tab. C-1: Parameter setting and the corresponding decision basis for the reference case and for probabilistic simulations

Parameter Type	In the reference case	In the probabilistic simulations	Decision basis
Physical constants (such as gas constant)	Best estimate	Fixed value	Literature
Radionuclide decay chains and half lives	Best estimate	Fixed value	MIRAM-RBG database (Nagra 2023c)
Nearfield			
Dimensions of the emplacement rooms (backfill materials)	Best estimate	Fixed value	Provisional repository design (Nagra 2023a)
Size of the altered zones of bentonite	Conservative estimate	Fixed value	Performance assessment (Nagra 2024q)
Properties of the altered zones of bentonite	Conservative estimate	Fixed values	(Nagra 2014b)
Dissolution rate of SF and RP-HLW	Best estimate	Varied probabilistically	Performance assessment (Curti 2022, Johnson et al. 2023)
Canister containment time	Conservative estimation	Fixed values	Provisional canister design (Nagra 2024a)
Instantaneous release fraction of SF and L/ILW	Best estimate	Fixed best estimate (Exception: simulation concerning C-14 methane)	Performance assessment (Johnson et al. 2023)
Congruent C-14 release from the waste	Best estimate	Varied probabilistically	Performance assessment (Nagra 2024r, Nagra 2024k)
Rate of gas generation	Best estimate	Varied probabilistically	Performance assessment (Nagra 2024k)
RN-specific diffusion, sorption and solubility limits of bentonite	Best estimate	Varied probabilistically	Assessment basis (Glaus et al. 2024), (Marques Fernandes et al. 2024, Hummel et al. 2023)
RN-specific sorption of cementitious near-field	Best estimate	Varied probabilistically	Assessment basis (Tits & Wieland 2023)
RN-specific diffusion of cementitious near-field	Best estimate	Fixed value	Assessment basis (Tits & Wieland 2023)
(RN-specific) accessible porosity of bentonite	Best estimate	Fixed value	Assessment basis (Glaus et al. 2024)
Density of near-field materials	Best estimate	Fixed value	Consistent with performance assessment (Nagra 2024k)

Tab. C-1: continued

Parameter Type	In the reference case	In the probabilistic simulations	Decision basis
Nearfield cont.			
Thermal and mechanical parameters of the near-field materials	Best estimate	Fixed value	Consistent with performance assessment (Nagra 2024k)
Repository layout	Best estimate according to design	Fixed value	Provisional repository design (Nagra 2023a)
Size, hydraulic properties and sorption properties of EDZ, incl. conductivity and porosity	Best estimate according to performance assessment	Varied probabilistically, correlated with the Opalinus Clay	Consistent with performance assessment (Nagra 2024g)
Diffusion properties of EDZ	Best estimate	Fixed value	(Poller et al. 2014)
Geosphere			
RN-specific effective diffusion coefficient	Best estimate	Varied probabilistically	Assessment basis (Glaus et al. 2024)
Thicknesses of rock units in the CRZ	Best estimate	Varied probabilistically	Assessment basis (Nagra 2024 <i>in prep.</i>)
Hydraulic conductivity and two-phase-flow-relevant parameters of geological units and repository components	Best estimate	Varied probabilistically	Assessment basis (Nagra 2024e) and performance assessment (Nagra 2024k)
(RN-specific) porosity of the geological units in the CRZ	Best estimate	Varied probabilistically	Assessment basis (Glaus et al. 2024)
RN-specific sorption coefficient of the geological units in the CRZ	Best estimate	Varied probabilistically	Assessment basis (Marques Fernandes et al. 2024)
Anisotropy factor of the diffusive and advective transport properties	Best estimate	Fixed value	Assessment basis (Nagra 2024e)
Rock density of the geological units in the CRZ	Best estimate	Varied probabilistically	Assessment basis (Nagra 2024e)
Biosphere			
Biosphere dose conversion factor (BDCF)	Conservative assumption	Fixed value	Biosphere assessment (Nagra 2024i)

Tab. C-2: Correlations between the input parameters in the sampling for the probabilistic simulations

Considered correlation	Methodology in the sampling
Water-mediated radionuclide transport modelling	
Radionuclide-accessible porosity except Cl and I (non-anion)	A joint normalised random value for scaling the value for the accessible porosity
Radionuclide-accessible porosity for Cl and I (anion)	A joint normalised random value for scaling the value for the accessible porosity
Effective diffusion coefficient of Cl and I	A joint normalised random value for scaling the value for the effective diffusion coefficient
Hydraulic conductivity of the Opalinus Clay and EDZ	The conductivity is scaled from the sampled conductivity of the Opalinus Clay
Radionuclide-accessible porosity of the EDZ	The porosity is scaled from the sampled porosity (for non-anion) of the Opalinus Clay
Transport modelling considering two-phase flow	
Gas production rate of different gas-producing materials	A joint normalised random value for all metals for scaling the value for the corrosion/degradation rate of individual metals
Porosity of the Opalinus Clay and EDZ	A constant site-specific value for scaling the value for the rock porosity
Permeability of the Opalinus Clay and EDZ	A constant value for scaling the value for the permeability
Van Genuchten parameter P_0 and permeability	The gas-entry-pressure-relevant Van Genuchten parameter P_0 is calculated from the sampled permeability with the Leverett functional relationship

App. D Description of codes for the analysis of radiological consequences

D.1 VPAC

VPAC, or *Versatile Performance Assessment Code*, is an integrated computer code that simulates groundwater flow and nuclide release and transport in a saturated, heterogeneous 2D or 3D porous media. The porous media can represent the repository near-field, the surrounding geosphere, or both. Discrete water-conducting features (faults) need to be modelled explicitly as homogeneous porous media. The general features of the code are documented in detail in Holocher et al. (2008).

VPAC is, in principle, suitable for calculating nuclide release and transport for all repository barriers considered in the present report. Its strength lies in its ability to model complicated geometrical settings, but at the cost of the separate preparation of a (detailed) numerical mesh and of comparatively long model run times. For rather simple water flow and solute transport problems, the use of VPAC may not be the best choice. In practice, therefore, its use is limited to L/ILW near-field release, retention and transport calculations.

The 2D or 3D VPAC model domain can include any spatially distinct features of the engineered barriers or of the geological barrier. All these features are conceptualised as homogeneous porous media and their properties are specified through so-called “material classes”.

The processes represented explicitly in VPAC are:

- saturated groundwater flow, where the hydraulic conductivity can be time-dependent;
- release of nuclides (radionuclides and stable isotopes) from the waste matrix, which can be a specified function of time (see below);
- radioactive decay and ingrowth, with an unlimited number of radionuclides and unlimited decay chain lengths;
- advection, dispersion and diffusion of nuclides, with diffusion coefficients that can be time-dependent;
- nuclide-specific linear sorption equilibrium between aqueous and solid phases, with sorption coefficients that can be time-dependent; and
- element-specific solubility limitation²⁷.

Nuclides are released instantaneously and/or gradually, in a time-dependent manner, to the model domain. Optionally, a containment time prior to release can be specified. Nuclide release occurs congruently with dissolution or corrosion of the waste matrices at user-defined and time-dependent rates and with user-specified geometries of the waste matrices. Possible geometries are slab geometry, cylinder geometry and spherical geometry.

The verification tests performed for this code are documented in Holocher et al. (2008).

²⁷ Solubility limitation is, however, conservatively omitted in VPAC safety assessment calculations of the L/ILW repository near-field.

D.2 STMAN suite of codes

STMAN is a family of three computer codes that model the release of nuclides from different waste packages and subsequent 1D radial transport through the engineered barriers. The three codes are:

- SPENT, which is applicable to directly disposed of spent fuel (SF);
- STRENG, which is applicable to vitrified high-level waste (RP-HLW); and
- STALLION, which is applicable to long-lived intermediate-level waste (ILW) and to low- and intermediate-level waste (L/ILW)²⁸.

STMAN has been enhanced iteratively following its initial development, based on experience gained through its application in several Nagra projects. Successive versions of STMAN have been documented in a series of user guides, release notes and technical notes on the mathematical model provided by the developer. The current version of STMAN Version 5.10 is used in the radiological consequence analysis in the present report (Robinson 2022).

Radionuclide transport calculations are carried out easily and quickly using STMAN. The code provides accurate numerical solutions for simple geometrical problem settings. Note that, in many cases, simplified geometrical representations of more complex systems are adequate for the purposes of safety assessment, especially given the uncertainties in the values assigned to the input parameters.

For the near-field of an HLW repository (or the HLW section of a combined repository), a single canister (SPENT and STRENG) is usually modelled. The output is then scaled to the number of canisters. Up to three subdomains can be distinguished:

- the waste package, including the water-filled space to which nuclides are first released;
- an optional surrounding annular region of buffer material, through which nuclides are transported by radial diffusion and which can be divided into an arbitrary number of concentric subregions, each having its own specific transport properties; and
- an optional host rock unit, which is a 1D linear abstraction of the host rock surrounding the waste package and the buffer material.

All subdomains are conceptualised as homogeneous porous media.

²⁸ Since STALLION is no longer used for the modelling of the L/ILW near-field, this part of the code is not described further in the present report

Processes explicitly included in STMAN are:

- a period of complete containment, e.g., in an HLW disposal canister;
- release of nuclides (radionuclides and stable isotopes) from the waste matrix, which can be time-dependent;
- radioactive decay and ingrowth, with an unlimited number of radionuclides and unlimited decay chain lengths;
- 1D radial diffusion of nuclides from the waste package through the buffer material (if present) to the host rock (if present), with diffusion coefficients in the buffer material that can be time-dependent;
- advective/dispersive/diffusive transport of nuclides in the 1D linear representation of the surrounding host rock;
- nuclide-specific linear sorption equilibrium between the liquid and solid phases, with sorption coefficients that can be time-dependent; and
- element-specific solubility limits, with solubility limits that can be time-dependent.

There are two broad options available to the user regarding the interface between the buffer material and the host rock:

- (1) to specify a boundary condition, of which two types are available; and
- (2) to use the optional host rock unit.

The second of these is the option generally applied in the present report.

With regard to option (1), the simplest type of boundary condition is a fixed concentration condition, for which the value is usually conservatively set to zero. Alternatively, a mixing-cell boundary condition can be used. This type of boundary condition assumes that the diffusive nuclide flux across the interface between the buffer material and the host rock is balanced by an advective nuclide flux in the host rock. The concentration in the mixing cell (i.e., at the interface between the buffer material and the host rock) is then set dynamically by the code to maintain the balance. The water entering the mixing cell from upstream in the host rock can have a user-specified nuclide concentration or can carry a user-specified nuclide flux. In the latter case, the user-specified nuclide flux is read from a separate input file. The groundwater flow rate in the host rock can also be specified by means of a separate input file.

The option with the host rock (2) is motivated by the need to obtain satisfactory estimates of nuclide releases across the interface between the buffer material and the host rock in cases where diffusive transport in the rock is significant, and nuclides are therefore transported not only from the buffer to the rock but also vice versa. The layer is thus sometimes also referred to as the *diffusive host rock layer*, although advective transport in the host rock can be taken into account. Generally, the same transport processes as in the buffer material are modelled in the host rock layer, although solubility limitation is conservatively disregarded. Moreover, the host rock layer is represented by a 1D linear (Cartesian) geometry, whereas the buffer is represented by a 1D cylindrical geometry. The surface area between the buffer and the host rock is set equally to the outer surface area of the buffer material. The host rock layer has a specified length and the boundary condition at the far end is one of zero concentration.

The verification tests performed for this code are documented in Robinson (2022).

D.3 PICNIC-TD

All geosphere retention and transport calculations are carried out with PICNIC-TD. PICNIC-TD is a computer code that models transport of dissolved nuclides through one or more porous, water-saturated 1D linear transport pathways. Multiple pathways can be connected to form a network model. These transport pathways are called legs in PICNIC-TD. Each leg can be parameterised such that it represents either a homogeneous porous medium or a discrete water-conducting flow feature, with an adjacent porous rock matrix.

PICNIC-TD is well-suited to problems in which radionuclide transport can be considered to occur predominantly along a homogeneously mediated flow path. In most cases, the assumption of one-dimensional linear flow paths is a significant simplification of reality, e.g., due to the non-uniform distribution of radioactive waste in the repository. However, for post-closure safety assessment, which is often based on simplifications and unfavourable assumptions (especially at early stages of repository planning), the assumption of one-dimensional and linear transport is considered adequate if, at the same time, spatially averaged properties of the model domain are used.

Successive versions of PICNIC-TD (and its predecessor PICNIC) have been documented in a series of user guides, test reports and release notes provided by the developer. The mathematical model for the most recent version of PICNIC-TD (Version 1.5.1) and the verification test cases are described in the User Guide (Robinson & Chittenden 2022). Processes explicitly included in PICNIC-TD 1.5.1 are:

- radioactive decay and ingrowth, with an unlimited number of radionuclides and unlimited decay chain lengths;
- one-dimensional advective/dispersive/diffusive solute transport through the flow feature of a leg;
- diffusive transfer of nuclides between the flow feature and the adjacent matrix (if present);
- diffusive transport of nuclides in the matrix perpendicular to the direction of flow and advective/dispersive/diffusive transport of nuclides in the matrix parallel to the direction of flow; and
- nuclide-specific equilibrium sorption between liquid and solid phases.

From Version 1.3 on, PICNIC-TD has been capable of handling non-linear as well as linear sorption equilibrium between liquid and solid phases for single nuclides or groups of nuclides. Only linear equilibrium sorption is, however, modelled in the dose calculations in the present report.

Every leg of PICNIC-TD has an upstream end and a downstream end, referred to as a junction, where it can, or cannot, be connected to further legs or other model features. In particular, a junction can have one or more incoming or outgoing legs. However, some have no incoming legs, but are connected to a source term (typically an STMAN or VPAC output), while others have no outgoing legs, but produce a result (e.g., release rates to the biosphere). Legs can optionally produce additional diagnostic outputs (e.g., total mass) for positions within a leg.

Two types of geometry can be handled in PICNIC-TD: planar flow features (e.g., faults) and cylindrical flow features (e.g., tubular structures, such as veins or tunnels). A limited region or porous material (rock matrix) can also be included around these flow features. For the present radiological consequence analysis, layers of sedimentary rock within the CRZ are modelled as planar flow features without a matrix. In calculation cases that include a fault, this is also represented as a planar feature, but with a surrounding rock matrix.

D.4 TOUGH3-EOS75r

TOUGH3-EOS75R is an extended version of module EOS7R of the TOUGH3 family of codes (Jung et al. 2018). The processes covered by the original EOS7R are the following:

- movement of gas and liquid phases and the partitioning of up to two radionuclides (Rn1 and Rn2) between the available phases;
- heat transport;
- advective fluid flow in each phase under pressure, viscous, and gravity forces according to the multiphase extension of Darcy's law, which includes relative permeability and capillary pressure effects;
- diffusive mass transport of all the phases; and
- radioactive decay.

Based on EOS7R, the following modifications have been made specifically in order to meet the purposes of the present analysis of radiological consequences:

- the main gas component is changed to hydrogen (rather than "air"), the corresponding properties of which are taken from module EOS5;
- Rn1 and Rn2 are treated as independent components (no Rn2 ingrowth due to decay of Rn1), such that both could represent C-14 as methane, with Rn1 representing C-14 from the L/ILW disposal area and Rn2 representing C-14 from the HLW disposal area; and
- the main program of TOUGH3 was extended to include optional scaling factors for diffusive flow, advective flow and heat flow for each connection to cope with material and process-specific anisotropy.

These processes and modifications fully cover the modelling needs for the present project stage. Furthermore, because TOUGH3 models two-phase flow processes in three dimensions, flow and transport along the repository tunnel system and through the CRZ can be fully considered.

For quality assurance purposes, the modified code has been reviewed by the Lawrence Berkeley National Laboratory (LBNL), which is the original developer of TOUGH3. The EOS75R code has undergone a systematic verification test carried out by the original developer of EOS7R and proved to deliver reliable simulation results (Zhang et al. *in prep.*).

App. E Reliability of geometrical abstractions

Benchmarking investigations have been carried to test the reliability of the geometric abstractions made in the present analysis of radiological consequences and to ensure consistency between the various model studies. The benchmarking investigations for radionuclide transport in the liquid phase are discussed in Nagra (2024p). The present appendix focusses benchmarking for the macroelement approach described in Section 5.2 for gas-mediated radionuclide migration. In particular, the geometric simplification inherent in the macroelement approach is assessed by comparing its results with those of a detailed performance assessment model.

E.1 Model setup

The detailed performance assessment model used for benchmarking is illustrated in Fig. E-1 and the simplified macroelement representation of the same system is shown in Fig. E-2.

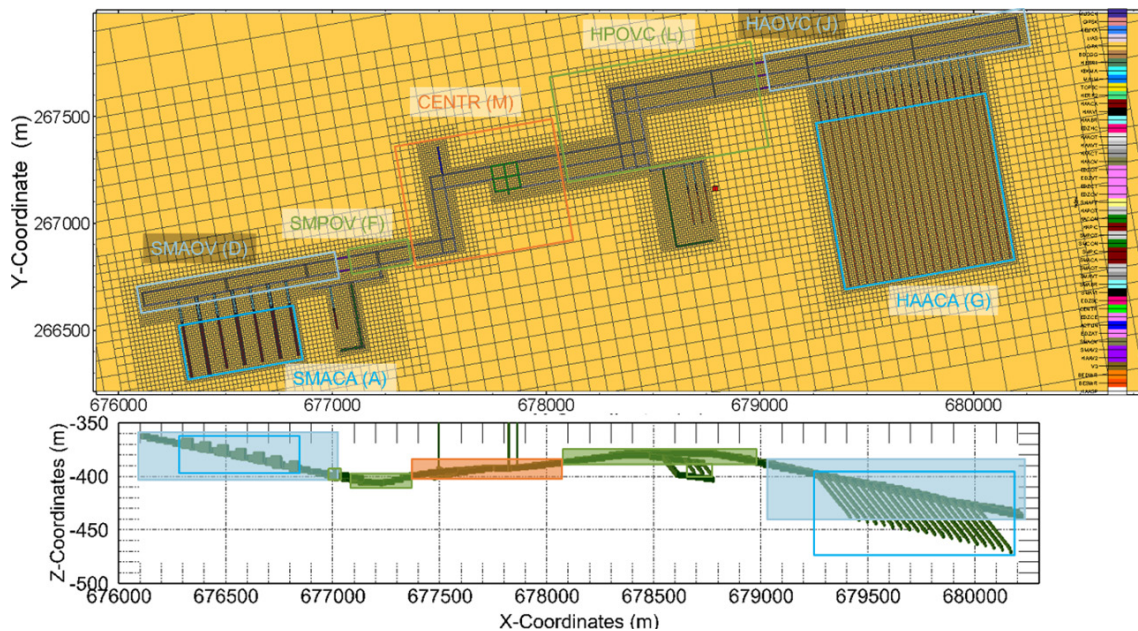


Fig. E-1: Cross-section and plan view of the detailed performance assessment model for a combined repository, showing the main repository structures

For the purposes of this benchmarking exercise, several adjustments to the macroelement model used in the main analysis of radiological consequences were implemented:

- The finite element grid of the detailed performance assessment model has been used to configure the cross-sectional areas of the macroelements. The porous volumes of these elements have been scaled to match those of the detailed performance assessment model.
- All underground repository structures have a rectangular shape, with the exception of the emplacement caverns in the main and pilot L/ILW emplacement caverns, where a square shape has been implemented.

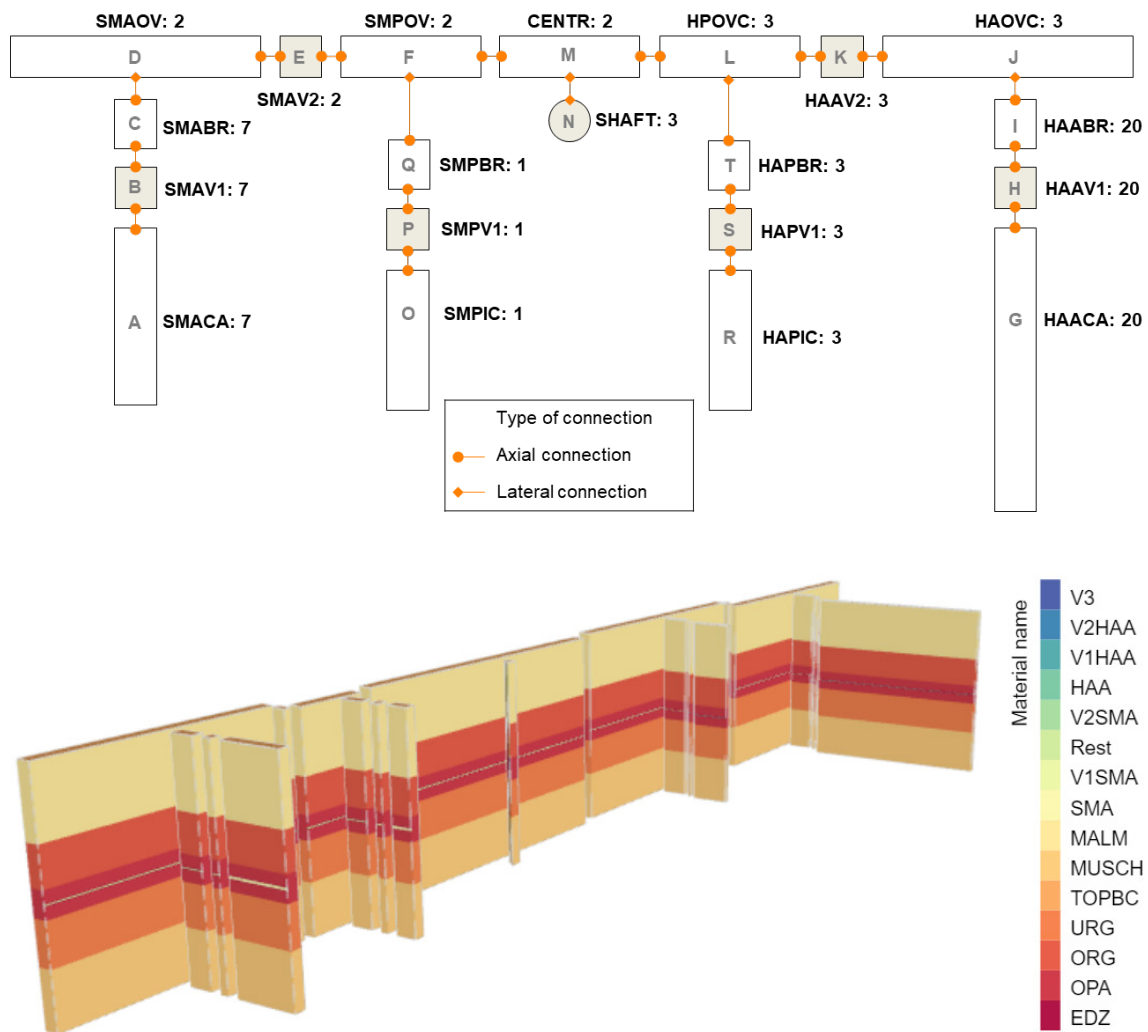


Fig. E-2: Top: Layout of the macroelement model; macroelements with grey filling represent sealing elements. Bottom: 3D illustration of the full structure of the macroelement model, including emplacement rooms for L/ILW and HLW, operations and access tunnels, the central area and shaft. The areas marked in different coloured rectangles are represented in the model as individual macroelements. Since the hydrostatic pressure is an important factor for gas behaviour, the averaged elevation of the area shown in the figure is set as the elevation of the macroelements

- In the detailed performance assessment model, an EDZ is implemented above and below each underground repository structure, with a thickness of 2.5 metres. The EDZ is generally not represented next to the lateral sides of the structures, with the exception of the L/ILW emplacement caverns (main disposal area only), along with their V1 seals and branch tunnels, which have been assigned 2-metre-thick lateral EDZs. In the macroelement model, EDZs surround all the repository underground structures and are assigned a thickness of 2.25 metres. However, the porous volume is scaled to be consistent with that of the detailed performance assessment model.
- The stratigraphy of the aquifers at the top and bottom of the model (the Malm and Muschelkalk aquifers) have been represented in the macroelement model, consistent with their representation in the detailed performance assessment model.

- The same gas source term has been used in the detailed performance assessment model and in the macroelement model. Note, however, that, unlike the calculations in the main analyses of radiological consequences, gas generation in the access and operations tunnels due to corrosion of metal reinforcement has not been taken into account in this benchmarking study.
- Also, unlike the calculations in the main analyses of radiological consequences, gas diffusion is disregarded in this benchmarking study.
- The initial equilibration phase modelled in the main analyses of radiological consequence is omitted in the benchmarking study.
- There are some negligible differences in the thermal and hydraulic parameter values used in the two models, arising from scaling effects.

E.2 Parametrisation

The parameter values used in the macroelement model for the benchmark study are listed in Tab. E-1 to Tab. E-3.

Tab. E-1: Geometrical properties of macroelements and their corresponding repository structures

Name	Letter	Scale	Volume [m ³]	Cross-section [m ²]	Length [m]	Pore volume [m ³]	Porosity [-]	Material	Material class	Width [m]	Elevation [m asl]
SMACA	A	7	165,000	100.0	235.7	42,158	0.26	SMACA	SMA	42.5	-380
SMAV1	B	7	10,500	50.0	30.0	2,936	0.28	SMAV1	V1SMA	42.5	-380
SMABR	C	7	31,500	50.0	90.0	4,520	0.14	SMABR	Rest	42.5	-380
SMAOV	D	2	94,000	50.0	940.0	14,336	0.15	SMAOV	Rest	50	-380
SMAV2	E	2	3,000	50.0	30.0	424	0.14	SMAV2	V2SMA	50	-400
SMPOV	F	2	30,000	50.0	300.0	11,696	0.39	SMPOV	Rest	50	-405
HAACA	G	20	216,250	12.5	865.0	33,908	0.16	HAACA	HAA	20	-435
HAAV1	H	20	2,500	12.5	10.0	294	0.12	HAAV1	V1HAA	20	-420
HAABR	I	20	27,500	12.5	110.0	10,692	0.39	HAABR	Rest	20	-415
HAOVC	J	3	183,500	50.0	1223.3	24,140	0.13	HAOVC	Rest	50	-410
HAAV2	K	3	4,500	50.0	30.0	548	0.12	HAAV2	V2HAA	50	-390
HPOVC	L	3	179,500	50.0	1196.7	31,606	0.18	HPOVC	Rest	50	-380
CENTR	M	2	135,500	50.0	1355.0	22,521	0.17	CENTR	Rest	50	-395
SHAFT	N	3	32,885	25.0	438.5	12,805	0.39	V3,shORG,shMAL	V3,Rest,Rest	50	-395
SMPIC	O	1	8,000	100.0	80.0	2,044	0.26	SMPIC	SMA	42.5	-400
SMPV1	P	1	1,500	50.0	30.0	419	0.28	SMPV1	V1SMA	42.5	-400
SMPBR	Q	1	4,500	50.0	90.0	646	0.14	SMPBR	Rest	42.5	-400
HAPIC	R	3	6,188	12.5	165.0	970	0.16	HAPIC	HAA	20	-395
HAPV1	S	3	375	12.5	10.0	44	0.12	HAPV1	V1HAA	20	-390
HAPBR	T	3	4,125	12.5	110.0	1,604	0.39	HAPBR	Rest	20	-385

Tab. E-2: Thermohydraulic and two-phase flow parameters of the material classes for the host rock, EDZ, seals and backfill

	OPALINUS CLAY	EDZ	V1HAA	V1SMA	V2HAA	V2SMA	V3	Rest	SMA	HAA
drok [kg/m³]	2650	2650	2650	2650	2650	2650	2650	2650	2650	2700
por [-]	0.12	0.14	*	*	*	*	*	*	*	*
per1 [m²]	1E-20	1E-19	5E-19	5E-18	5E-18	5E-18	5E-19	1E-15	1E-15	1E-20
per2 [m²]	1E-20	1E-19	5E-19	5E-18	5E-18	5E-18	5E-19	1E-15	1E-15	1E-20
per3 [m²]	2E-21	2E-20	5E-19	5E-18	5E-18	5E-18	5E-19	1E-15	1E-15	1E-20
A [-]	5	5	1	1	1	1	1	1	1	1
cwet [W/m/K]	1.55	2.1	1.3	2.1	2.1	2.1	2.1	2.1	2.1	1.3
spht [J/kg/K]	946.5	1000	299.78	1000	1000	1000	1000	1000	1000	268.9
com [1/Pa]	1.70E-09	1.70E-09	1.00E-09	1.00E-09	1.00E-09	1.00E-09	1.00E-09	1.00E-09	1.00E-09	2.50E-09
expan [1/K]	3.47E-05	3.47E-05	1.50E-05	1.50E-05	1.50E-05	1.50E-05	3.47E-05	1.50E-05	1.50E-05	2.50E-05
cdry [W/m/K]	1.55	1.5	0.3	0.4	0.4	0.4	2.1	0.4	0.4	0.3
Slr_krel [-]	0.5	0.25	0.3	0.3	0.3	0.3	0.01	0.3	0.3	0.01
Sgr_krel [-]	0	0	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
n [-]	1.6	1.67	2.5	2.5	2.5	2.5	1.82	2.5	2.5	1.82
P0 [Pa]	3.40E+07	2.00E+06	4.00E+03	4.00E+03	4.00E+03	4.00E+03	1.80E+07	4.00E+03	4.00E+03	1.80E+07
Pmax [Pa]	1.00E+09	1.00E+08	1.00E+09	1.00E+07	1.00E+07	1.00E+07	1.00E+09	1.00E+07	1.00E+07	1.00E+09
Tref [°C]	-	-	-	-	-	-	-	-	-	-
Slr_pcap [-]	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

* Porosity is defined macroelement/structure-specific, see geometry table.

Tab. E-3: Thermohydraulic and two-phase parameters of the used material classes for the confining geological units (ORG/URG), aquifers and boundaries

The parameters of the confining geological units are weighted by the average thicknesses of the respective subunits denoted in grey.

Thickness [m]	198	93	10	46	149	31	50	0	54	135	242	1
	MUSCH*	GIPSK	KEUKA	LIAS	URG	BDOGG	HERR1	HERR2	KBKMA	ORG	MALM	TOPBC**
drok [kg/m ³]	2670	2670	2670	2670	2670	2670	2600	2600	2600	2616	2670	2670
por [-]	0.12	0.11	0.11	0.11	0.11	0.13	0.1	0.1	0.09	0.10	0.09	0.09
per1 [m ²]	1E-14	5E-20	1E-18	2E-20	1.0E-19	5E-20	9E-20	3E-19	1E-20	4.9E-20	1E-14	1E-14
per2 [m ²]	1E-14	5E-20	1E-18	2E-20	1.0E-19	5E-20	9E-20	3E-19	1E-20	4.9E-20	1E-14	1E-14
per3 [m ²]	1E-14	5E-20	1E-18	2E-20	3.6E-20	5E-20	9E-20	3E-19	1E-20	2.1E-20	1E-14	1E-14
A [-]	1	1	1	1	2.925	1	1	1	1	2.378	1	1
cwet [W/m/K]	4.021	2.143	2.143	2.143	2.143	2.203	3.211	3.211	3.211	2.980	3.211	2.203
spht [J/kg/K]	905.5	995	995	995	995	995	905.5	905.5	905.5	926.1	905.5	995
com [1/Pa]	1.00E-09	1.70E-09	1.70E-09	1.70E-09	1.70E-09	1.70E-09	1.00E-09	1.00E-09	1.00E-09	1.16E-09	1.00E-09	1.70E-09
expan [1/K]	3.47E-05	1.70E-05	1.70E-05	1.70E-05	1.70E-05	1.70E-05	3.50E-05	3.50E-05	3.50E-05	3.09E-05	3.47E-05	1.70E-05
cdry [W/m/K]	4.021	2.143	2.143	2.143	2.143	2.203	3.211	3.211	3.211	2.980	3.211	2.203
Slr_krel [-]	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Sgr_krel [-]	0	0	0	0	0	0	0	0	0	0	0	0
n [-]	1.67	2	2	2	2	2	1.9	1.9	1.9	1.92	2	2

Tab. E-3: continued

Thickness [m]	198	93	10	46	149	31	50	0	54	135	242	1
	MUSCH*	GIPSK	KEUKA	LIAS	URG	BDOGG	HERR1	HERR2	KBKMA	ORG	MALM	TOPBC**
P0 [Pa]	1.80E+07	1.80E+07	1.80E+07	1.80E+07	1.80E+07	1.80E+07	1.30E+07	1.30E+07	1.30E+07	1.41E+07	5.00E+06	1.80E+07
Pmax [Pa]	1.00E+09	1.00E+10	1.00E+10	1.00E+10	1.00E+10	1.00E+10	1.00E+09	1.00E+09	1.00E+09	3.07E+09	1.00E+08	1.00E+10
Tref [°C]	-	-	-	-	-	-	-	-	-	-	-	-
Slr_pcap [-]	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

* Bottom boundary condition

** Top boundary condition

E.3 Results

Temperature, pressure and saturation at selected locations are chosen as indicators for comparison between the results of the detailed performance assessment model and the macroelement model (these are also the main indicators identified in Nagra (2024k)).

Fig. E-3 illustrates a very good agreement of the three indicators in different observation points between the detailed performance model and the macroelement model. The following points are noted:

- The two models show good agreement between calculated pressures in the pilot and main emplacement caverns of the L/ILW repository, in the sealing system and in the central area; the peak pressures calculated with the two models differ by less than 0.1 MPa.
- Some discrepancies between the models are found regarding the pressure caused by the heat output from the HLW repository. The temperature in the HLW emplacement drifts of the pilot repository is overestimated by the macroelement model, because the drifts are represented in that model using symmetry considerations that implicitly assume an infinite series of such drifts, and thus underestimate the loss of heat to the host rock.
- Differences between the two models in the peak temperatures in both the main and pilot repository emplacement drifts are also caused by the way in which the thermal source term is distributed within the drifts; in the detailed performance assessment model, the thermal source term is partitioned and these parts are placed in every second numerical element, whereas the macroelement model distributes the thermal source term uniformly along each drift.
- The temperatures of the V1 seals of the HLW emplacement drifts are underestimated by the macroelement model, because the heat transfer between the host rock surrounding the emplacement drifts and the sealing system is not considered in this model.
- There is overall good agreement of in the evolution of gas saturation and in the evolution of gas flow calculated using the two models, the latter being of key importance to the fate of C-14 in gaseous form.

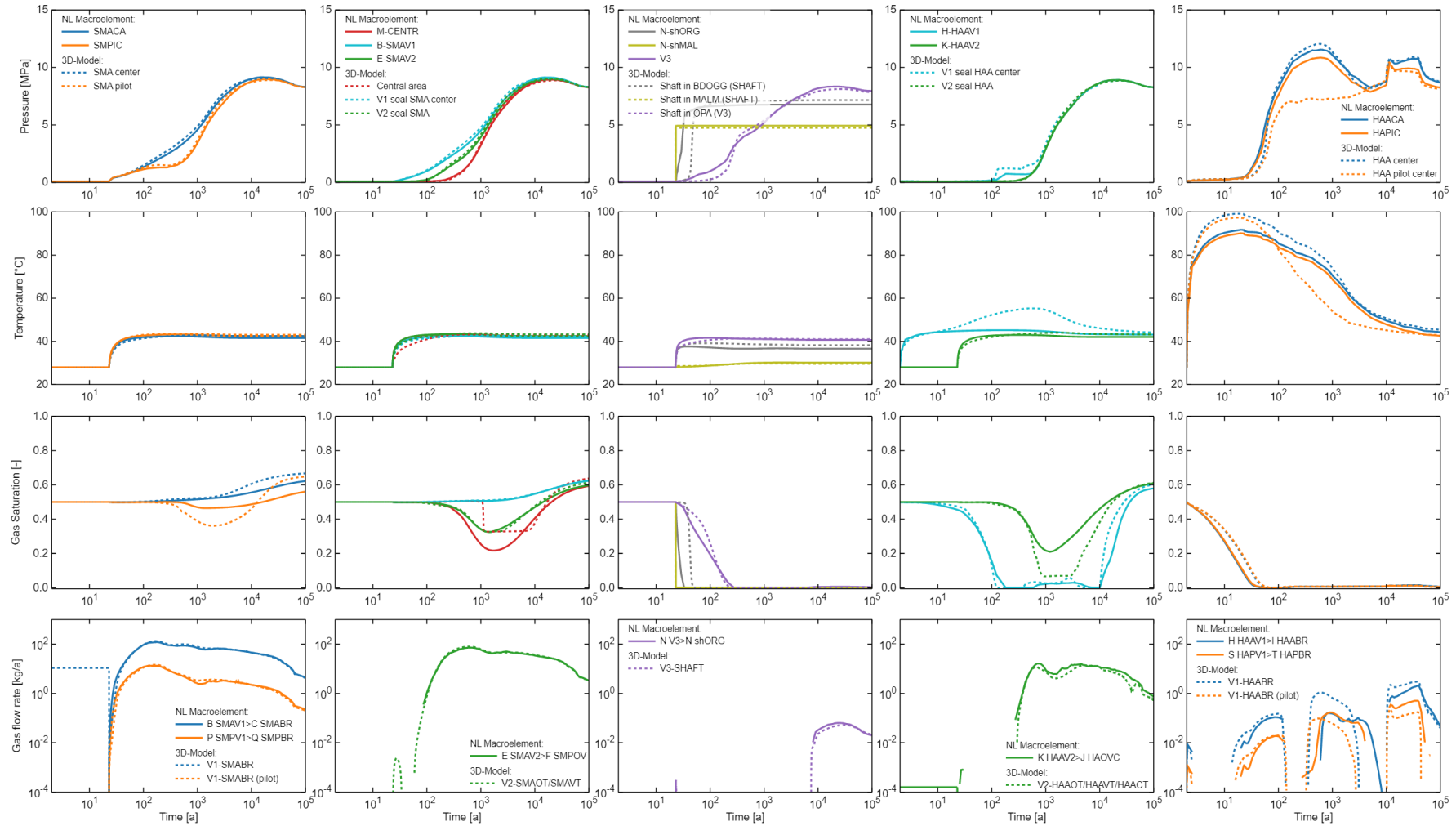


Fig. E-3: Pressure (first row), temperature (second row), gas saturation (third row) and gas flows (fourth row) evaluated at different locations within the repository using the detailed performance assessment model and the macroelement model

The total gas volume and hydrogen mass within the modelled system are taken as additional indicators for benchmarking. Fig. E-4 shows the good agreement of these indicators calculated with the two models.

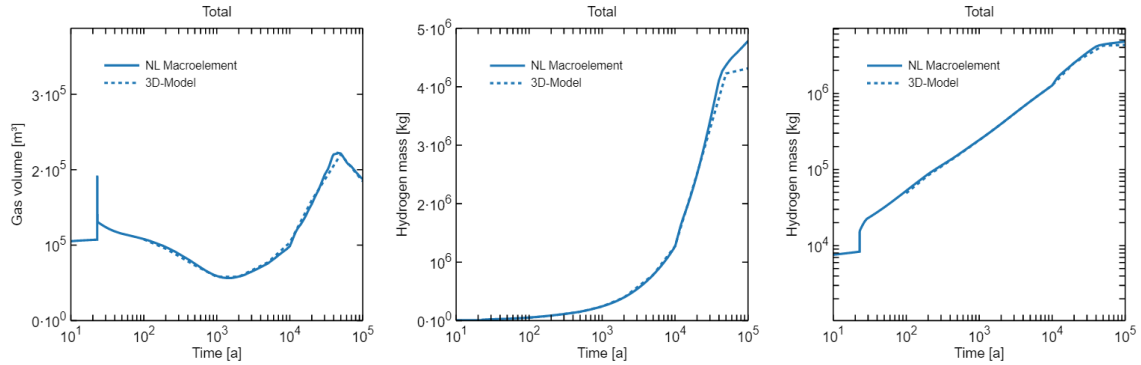


Fig. E-4: Total gas volume (left plot) and hydrogen mass (centre and right plots) present in the system. The right plot shows the same data as the centre plot, but with a logarithmic scale for the y-axis

Overall, this benchmark study provides confidence that, despite the strong geometrical simplifications made to it, the macroelement model can produce reliable results, similar to those of the detailed meshed performance assessment model.

App. F Quality assurance of simulations

The radiological consequence analysis in this report has been carried out in compliance with Nagra's Quality Management System (QMS). The QMS defines specific working procedures that include general quality assurance measures such as external reviews, as well as quality assurance measures specific to individual activities. These specific measures are documented in quality assurance (QA) guidelines. There are four quality assurance guidelines that refer to safety assessment modelling. The following sections describe the procedures carried out in the current radiological consequence analysis in accordance with the QA guidelines.

F.1 Guideline #1: Use of computer codes for safety analysis

Verification tests performed for each of the codes used for the analysis of radiological consequences are referred to in App. D; see also Guidelines #2 and #3, below. Moreover, Nagra's benchmark studies to assess the reliability of geometrical abstractions, see App. E, provide additional confidence in the quality of the simulations performed in the analysis of radiological consequences.

The large number of calculation cases, each of which involves the running of several computer codes, requires a system of software tools that enables the calculations to be executed and documented efficiently and in such a manner that all quality requirements are met. The system of software tools developed for this purpose consists of:

- a parameter database, referred to as the “Master Table”, to manage the data used in input files of all calculations, including data clearance and references;
- a table of calculation cases and model runs, which defines the sets of parameter values for individual calculation cases, and allows the generation of corresponding input files;
- a pre-processor to automatically generate set-up files, which are a first step in the generation of input files for the main codes, interpreting the above-mentioned Master Table and the table of calculation cases and model runs;
- a scripted simulation chain that sequentially performs all operations needed to complete one or a series of calculation cases: generation of the code-specific input files (pre-processing scripts), initiation and execution of the simulation jobs with the simulation codes on a batch job schedule, which allows the tracking of the status of each job;
- automated post-processing routines, converting the main results into a unified data format and generating derived results (indicators, dose conversion etc.); and
- an electronic input data and result application (EDR), which stores results and other model-run data in an interactive electronic database.

The “Master Table” mentioned above provides human-readable, synthetic input for the modelling study within the framework of the consequence analysis. This Master Table is a file containing the parameter names, their description, their reference values and, for probabilistic calculations, a value range (upper and lower bounds) and the specification of a probability density function. For probabilistic calculations, parameter groups can also be defined to handle parameter correlations, e.g., the effective diffusion coefficients of radionuclides should have similar values if the corresponding elements have similar chemical properties. Moreover, the Master Table provides a justification (reference to source document or computational method) for all the parameter values that have been entered, as well as for the corresponding value ranges.

The workflow linking the various software tools to manage the execution and documentation of calculation cases and individual model runs is shown in Fig. F-1.

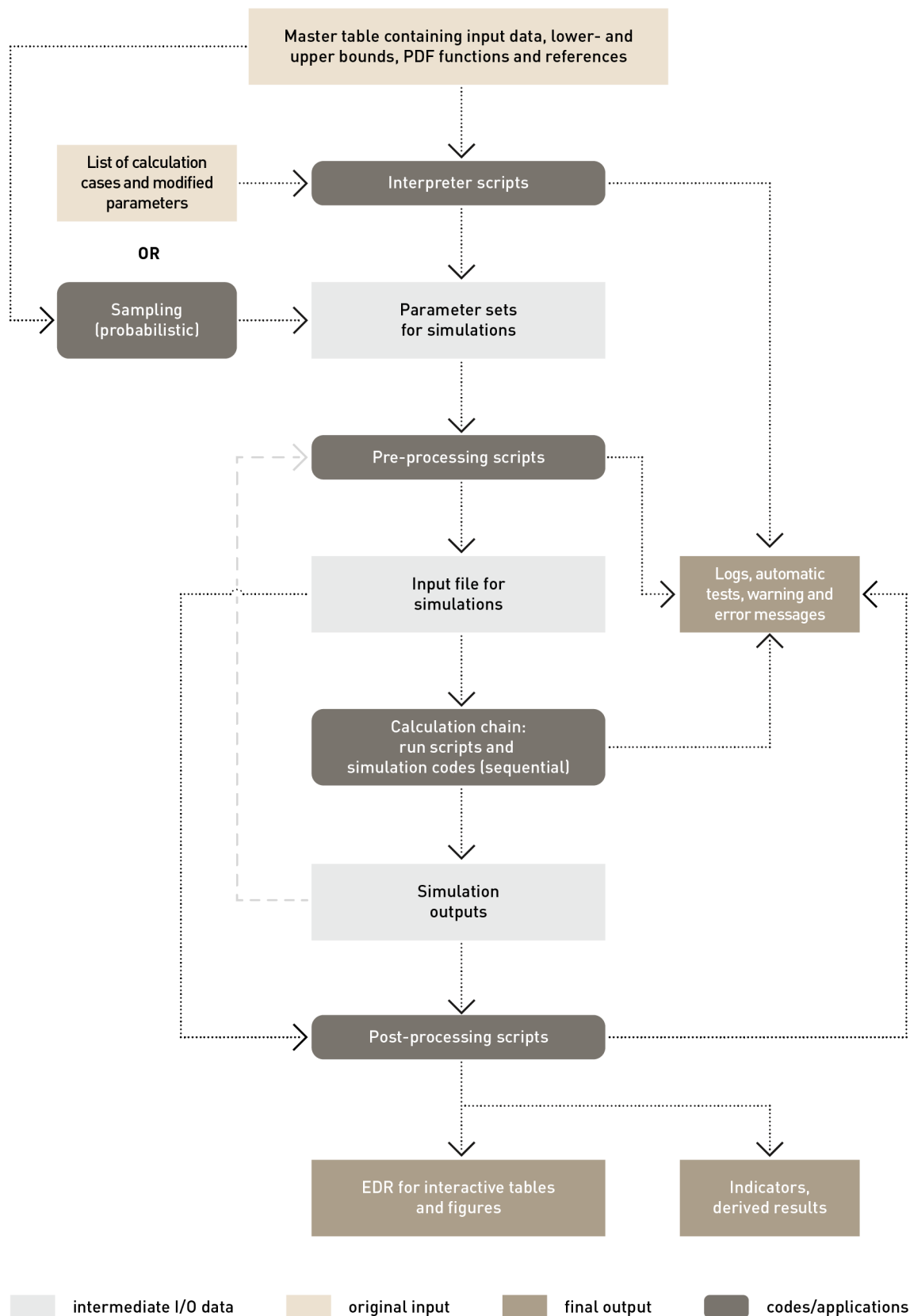


Fig. F-1: Overview of the system of software tools to manage the execution and documentation of calculation cases and individual model runs

The software scripts and the simulation chain scripting the different sequences of one or several calculation cases (sandy yellow rectangles in Fig. F-1) must be carefully checked. During their development, and each time they have been updated, a verification has been performed. All other elements of the system shown in Fig. F-1 (i.e., scripts, and routines) are subject to:

- QA of the software, usually consisting of unit tests during its development and a third-party review after its completion; and
- a systematic verification of the outputs generated by the software and their conformity with the corresponding input files.

The functioning of log-file generation, automatic consistency checks, generation of warning messages and process terminations (error handling) are also controlled. Thus, for example, the interpreter scripts of the Master Table are verified by systematically comparing the input parameters defined in the Master Table (input of processing step) with the generated parameter files (output of processing step, here as “JavaScript” data) on one or a selection of sample cases, usually including the reference case. The verification of the intermediate input-output files (grey elements in Fig. F-1) and final outputs (EDR, indicators, etc., shown in brown element in Fig. F-1) is then systematically performed for this selection of cases.

The EDR generation scripts apply data operations to the results (e.g., extraction of maxima of time series) to generate figures and tables. As for other scripts, these data operations are tested individually by performing unitary tests. When a direct input-output correspondence is not possible, a further method to check the quality of individual and model-chain calculations is to verify overall balances. For example, it is possible to verify whether the evolution of the total activity of each nuclide, summed over all modelled components (e.g., all near-field and geosphere models), plus the activity that leaves the modelled barrier system, matches the total activity that should be globally present, taking into account radioactive decay and ingrowth.

F.2 Guideline #2: Acquisition and development of safety analysis codes

This guideline specifies the principal requirements on, and quality assurance measures for, safety analysis codes, i.e., the codes used in the analysis of radiological consequences (App. D). The codes for the radionuclide transport in the liquid phase have all been developed specifically for Nagra and have been applied in several previous project stages. Some minor developments have been made to the STMAN and PICINIC-TD codes, which have undergone new formal releases, in which release notes have been compiled for QA purposes. However, the VPAC code, used for the L/ILW near-field calculations, has not undergone any further development since the last project stage.

As mentioned in Section 5.2.2 and App. D.4, a special version of the TOUGH3 code for two-phase flow has been developed specifically for simulating the transport of C-14 methane. As part of the QA for this version, the module has been systematically checked by the Lawrence Berkeley National Laboratory (LBNL), the original developer of the TOUGH3 code family.

F.3 Guideline #3: Maintenance of computer codes for safety analysis

A logbook is maintained for each code, where quality assurance measures and their results are recorded and where information, such as version number and functionality, is clearly documented. Specific checks are undertaken when the code has been modified or further developed. The checks are usually performed using the defined standard calculations for verification (also after reinstallation or recompilation). Furthermore, the developers of the codes are involved as maintenance support for the analysis of radiological consequences.

F.4 Guideline #4: Test procedures for safety analysis modelling

Test procedures include the checking of conceptual models, of mathematical models (e.g., equations, initial and boundary conditions), of numerical solution techniques, of input data and of results. This involves plausibility checks (e.g., comparison with information from other post-closure safety assessment studies and comparison with results from other analyses or other calculation cases) and can additionally require independent calculations (simplified or equally complex). It may also involve tests of convergence of the solution as discretisation in space and time is refined (solution verification).

The quality assurance procedure for the analysis of radiological consequences is jointly undertaken by Nagra and the contractor that has carried out the modelling work (CSD Engineers). For the modelling work, the focus of the QA is on the input data (sandy yellow rectangles in Fig. F-1) and the final output data (brown elements in Fig. F-1). The quality assurance workflow consists of the following steps:

- Nagra defines the general modelling approach (e.g., probabilistic or deterministic calculations, simulation cases to be considered, etc.).
- The contractor proposes the use of codes and drafts the conceptual simulation model.
- Nagra checks and approves the use of the conceptual simulation model.
- Based on the conceptual simulation model, the contractor prepares the format of the “Master Tables”, with all necessary case descriptions and input parameters.
- Nagra fills the “Master Tables” with available data. An internal double check is performed by Nagra. In addition, Nagra’s data clearance system ensures the agreement and consistency between the data producers and the users.
- The contractor takes over the “Master Tables” and the reference documents sent by Nagra and performs a further check to minimise the possibility of errors.
- The contractor performs the model runs based on the parameters and cases in the “Master Tables”. As part of this step, the QA check on the tables, log files, output files, etc., is performed.
- Nagra takes over the EDR and carries out a second-round plausibility check.
- The results (data and figures) needed for the present report are produced directly by the quality-assured EDR. If figures and tables in the report are produced using any additional processing, a further check is carried out to ensure the consistency between the data produced by the modelling and the data and figures appearing in the report.

If any quality issues are detected in the process, the above steps are literally repeated.

App. G Description of the probabilistic model setup and the sensitivity measures

G.1 Monte-Carlo simulation

As mentioned in Section 3.4, the Monte-Carlo simulation method is used for the radiological consequence analysis and sensitivity analysis. The Monte-Carlo simulation method is a technique to propagate the uncertainty in model inputs to uncertainty in model outputs. To perform a Monte-Carlo simulation, an input parameter domain is first defined according to the ranges of values assigned to each uncertainty input parameter. Thereafter, combinations of input parameter values are generated randomly based on the individual probability density distribution functions (PDFs) of each parameter by using Latin Hypercube sampling. The model is then run repeatedly in a set of so-called “realisations” until an adequate number of parameter combinations has been sampled. In the probabilistic analyses of this report, 4000 “realisations” are performed. Finally, the results from all the realisations are aggregated and analysed.

G.2 Sensitivity analysis

Sensitivity analysis examines the sensitivity of the output of a model to variations in its input. Consistent with common international practice, a stepwise approach is adopted, applying sensitivity analysis methods of increasing complexity and computational cost until a suitable method for the problem at hand has been identified (Smith et al. 2019). As shown in Fig. G-1, the first step is to use a graphical approach, whereby scatter plots are constructed showing, for each realisation, a selected performance or safety indicator (e.g., maximum dose rate) vs. the corresponding value for an input parameter, which is varied between realisations. If, as is often the case, a monotonic relationship is found between the input parameters and the indicator, the next step is to apply linear and rank-based methods to quantify and compare sensitivities (see App. G.2.1 and G.2.2). However, there may be some instances where this is not the case and correlations are less simple, as in the example on the bottom left of Fig. G-1. Here, a variance-based method, e.g., the modified EASI method (Plischke 2010) with cosine transformation (Plischke 2012), as described in App. G.2.3, is appropriate. In the following sections, the measures used in the present analysis are briefly introduced. The example on the bottom right of Fig. G-1, which requires the use of so-called “density-based methods”, is not encountered in practice in the present analysis of radiological consequences.

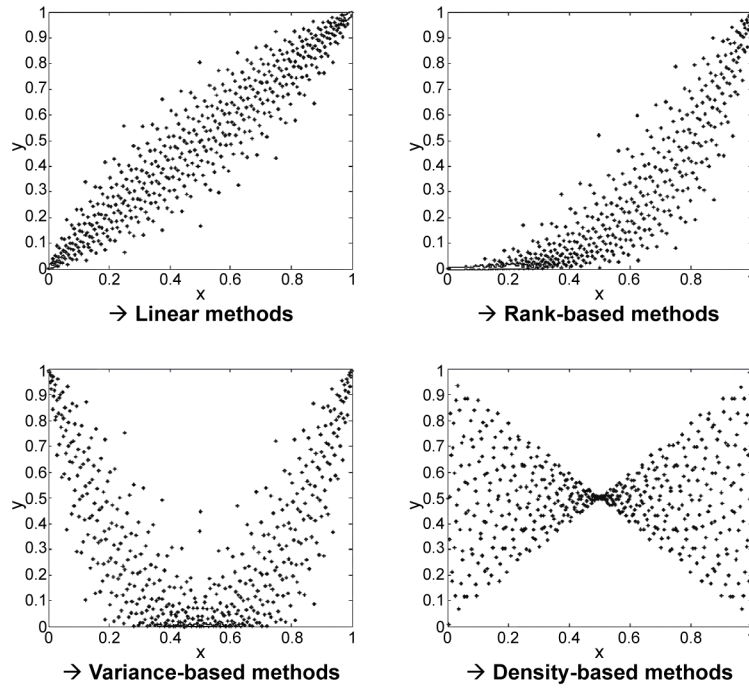


Fig. G-1: Summary of classes of probabilistic global sensitivity analysis methods and the use of scatter plots to identify which are needed

G.2.1 Pearson correlation coefficient as a sensitivity measure

The Pearson correlation coefficient is the most widely used correlation statistic for linearly related variables. The following formula is used to calculate this coefficient:

$$r_{xy} = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^n (y_i - \bar{y})^2}} \quad [\text{G-1}]$$

where r_{xy} is the Pearson correlation coefficient between input parameter x and output parameter y , n is the number of Monte-Carlo realisations, x_i and y_i are the values of input and output parameters in the i_{th} realisation, and $\bar{x}$, $\bar{y}$ are the mean of the input and output, respectively.

G.2.2 Spearman correlation coefficient as sensitivity measure

The Spearman correlation coefficient (Iman & Conover 1982) is defined as the Pearson correlation coefficient between the rank numbers of input parameter x_i and output parameter y_i in Eq. G-1:

$$r_{rg} = \frac{\sum_{i=1}^n (rgx_i - \bar{rgx})(rgy_i - \bar{rgy})}{\sqrt{\sum_{i=1}^n (rgx_i - \bar{rgx})^2} \sqrt{\sum_{i=1}^n (rgy_i - \bar{rgy})^2}} \quad [\text{G-2}]$$

where rg are the rank numbers of the input and output parameters. The Spearman correlation coefficient indicates how well the relationship between two variables can be described using a monotonic function.

G.2.3 Variance-based “Modified EASI sensitivity measure”

The EASI algorithm (Plischke 2010) is a Fourier-based technique for performing variance-based methods of global sensitivity analysis for the computation of first-order effects (sensitivity of individual parameters without considering the interactions between the input parameters). In the present radiological consequence analysis, a modified EASI algorithm is used to investigate the parameter sensitivity (Plischke 2012). The mathematical process for calculating the sensitivity measure is introduced briefly in this section.

The variance-based sensitivity measure is defined by:

$$S_j = \frac{\text{Var}[Y/X_j]}{\text{Var}[Y]} \quad [\text{G-3}]$$

where $E[Y/X_j]$ is the conditional expectation of Y (array of the probabilistic modelling results) with given X_j (array of the sample of input parameters for the probabilistic modelling), $\text{Var}[\cdot]$ denotes the variance of the data.

The algorithm to estimate S_j from given pairs of data consists of the following three steps.

1. Sort the output data (Y) using the input data (X_j) as a key.
2. Compute the first few coefficients of the sorted output data using a suitable orthogonal transformation.

For the analysis of radiological consequences, the discrete cosine transformation is used for this second step. This transformation has good energy concentration/compaction properties, which means that the first few coefficients provide a fair reconstruction of the original signal. The weights for the j_{th} coefficient of the discrete cosine transformation are given by:

$$w_{i,j} = \sqrt{\frac{2}{n}} \cos\left(\frac{\pi(2i-1)j}{2n}\right), i = 1, \dots, n; j = 1, \dots, n-1 \quad [\text{G-4}]$$

and the above-mentioned coefficient is then:

$$c_j = \sum_{i=1}^n w_{i,j} y_{\psi(i)} \quad [\text{G-5}]$$

where $y_{\psi(i)}$ is the rearranged result parameter.

3. Form the quotient between the sum of squares of these coefficients and the variance of Y .

In this third step, the conditional expectation is calculated. As the data are reordered in the first step, the input is now increasingly ordered. If there is a functional correlation between input and output, the (rearranged) output signal can be approximated by half a cosine wave (i.e., approximately linear) and its higher harmonics. Hence, the functional correlation is expressed by replacing the coefficients of the higher frequencies by 0, $c = (c_0, c_1, c_2, \dots, c_m, 0, \dots, 0)$, thus keeping only those which are in resonance with the input signal. For a harmonic regression metamodel, inverse discrete cosine transformation must be applied to these filtered coefficients $c_j, j = 1, \dots, M$. According to the recommendation in Plischke (2012), $M = 7$ is applied in the sensitivity analysis performed in the present report.

The final variance-based sensitivity measure can then be calculated as:

$$S_j = \frac{1}{(n-1)Var[Y]} \sum_{j=1}^{M=7} C_j^2 \quad [G-6]$$

In practice, instead of computing the variance of Y directly, the sum of squared coefficients for it can be used, and Equation (G-6) will then be replaced by:

$$S_j = \frac{\sum_{j=1}^{M=7} C_j^2}{\sum_{j=1}^{n-1} C_j^2} \quad [G-7]$$

G.3 Judgement of the significance of parameter sensitivity

A minimum meaningful value or criterion for each of the sensitivity measures defined in Sections G.2.1 to G.2.3 can be derived using a so called “dummy parameter”, with randomly generated values. The criterion, termed the “threshold of significance”, is applied to each output parameter considered in the sensitivity analysis. In the test, the sensitivity measures are calculated between the “dummy parameter” and the result parameter. These sensitivity measures then provide the criterion for judging if an input parameter shows sensitivity.

Additionally, based on the system understanding, a qualitative judgement can be made of the reasonableness of the parameter sensitivities and correlations indicated by various graphical and analytical methods.

Some of the weak correlations, while still above the threshold of significance, are not readily interpretable. These correlations can be due to numerical artefacts associated with random sampling, but, since they only concern weakly correlated parameters, the reliability of sensitivity measures in identifying the most sensitive parameters is unaffected.

App. H Data Appendix

H.1 Safety-relevant radionuclides considered in the consequence analysis

Tab. H-1: Safety-relevant radionuclides considered in the consequence analysis

Element	RN	Relevant for the waste type		
		SF	RP-HLW	L/ILW
Ac	Ac-227	✓	✓	✓
Ag	Ag-108m	✓	✓	✓
Al	Al-26			✓
Am	Am-241	✓	✓	✓
	Am-242m	✓	✓	✓
	Am-243	✓	✓	✓
C	C-14	✓		✓
Ca	Ca-41	✓		✓
Cf	Cf-249	✓	✓	✓
	Cf-251	✓	✓	✓
Cl	Cl-36	✓		✓
Cm	Cm-242	✓	✓	✓
	Cm-243	✓	✓	✓
	Cm-244	✓	✓	✓
	Cm-245	✓	✓	✓
	Cm-246	✓	✓	✓
	Cm-247	✓	✓	✓
	Cm-248	✓	✓	✓
Cs	Cs-135	✓	✓	✓
	Cs-137	✓	✓	✓
Fe	Fe-60			✓
Hg	Hg-194			✓
Ho	Ho-166m	✓	✓	
I	I-129	✓	✓	✓
Mo	Mo-93	✓	✓	✓
Nb	Nb-91			✓
	Nb-93m	✓	✓	✓
	Nb-94	✓	✓	✓
Ni	Ni-59	✓		✓
	Ni-63	✓	✓	✓

Tab. H-1: continued

Element	RN	Relevant for the waste type		
		SF	RP-HLW	L/ILW
Np	Np-237	✓	✓	✓
Pa	Pa-231	✓	✓	✓
Pb	Pb-202			✓
	Pb-210	✓	✓	✓
Pd	Pd-107	✓	✓	
Po	Po-209			✓
	Po-210	✓	✓	✓
Pu	Pu-238	✓	✓	✓
	Pu-239	✓	✓	✓
	Pu-240	✓	✓	✓
	Pu-241	✓	✓	✓
	Pu-242	✓	✓	✓
Ra	Ra-226	✓	✓	✓
	Ra-228	✓	✓	✓
Se	Se-79	✓	✓	✓
Si	Si-32			✓
Sm	Sm-151	✓	✓	
Sn	Sn-121m	✓	✓	
	Sn-126	✓	✓	✓
Sr	Sr-90	✓	✓	✓
Tc	Tc-99	✓	✓	✓
Th	Th-228	✓	✓	✓
	Th-229	✓	✓	✓
	Th-230	✓	✓	✓
	Th-232	✓	✓	✓
Ti	Ti-44			✓
U	U-232	✓	✓	✓
	U-233	✓	✓	✓
	U-234	✓	✓	✓
	U-235	✓	✓	✓
	U-236	✓	✓	✓
	U-238	✓	✓	✓
Zr	Zr-93	✓	✓	✓

H.2 Initial inventory of the waste for the modelling

For the HLW repository and the HLW section of a combined repository, the inventory in representative canisters is considered as the source term for the radiological consequence analysis. There are three types of SF canisters and two types of RP-HLW. For the L/ILW, there are two waste types distinguished by their composition. The following table provides a brief description of the HLW canister and waste types, the numbers of canisters and where this information can be found in the MIRAM-RBG database.

Tab. H-2: HLW canister types and the numbers of each type considered in the radiological consequence analysis

Name	Number of canisters	Description	Nomenclature in MIRAM-RBG
BWR-ELB	891	SF from boiling water reactor	L-950601, M-950601
PWR-UO2 ELB ²⁹	699	SF from pressurised water reactor without MOX fuel	KKB UO2, KKG UO2
PWR-MOX ELB	345	SF from the pressurised water reactor with MOX fuel	KKB UO2, KKG UO2, KKB MOX, KKG MOX
RP-HLW-1 ³⁰	145	RP-HLW from La Hague	J-Z-005000 (CSD-V)
RP-HLW-2 ³¹	65	RP-HLW from Sellafield	J-Z-005002 (VR-SL)

²⁹ There are 694 disposal canisters of the type PWR-UO2. However, because some other waste types (“J-P-002024” from PSI Hot Laboratory and “J-P-950001” from the PSI Diorit II Reactor) are expected to require further 5 PWR canisters, these are accounted for in the analysis of radiological consequences by assuming a further 5 PWR-UO2 canisters, bringing the total to 699.

³⁰ In the radiological consequence analysis, the number of the canisters is set to 436

³¹ In the radiological consequence analysis, the number of the canisters is set to 196

Tab. H-3: Mean inventory of one BWR-ELB of post-closure safety-relevant radionuclides and stable isotopes of SF (Nagra 2023c)

Radionuclide	Fuel matrix [Bq]	Structural materials [Bq]	Instantly released inventory [Bq]
$^{14}\text{C}_{\text{anorg}}$	0	0	6.24×10^8
$^{14}\text{C}_{\text{org}}$	4.04×10^{10}	8.49×10^{10}	6.33×10^8
^{36}Cl	9.95×10^8	2.02×10^9	1.30×10^8
^{41}Ca	3.22×10^8	1.10×10^8	0
^{59}Ni	1.01×10^9	1.71×10^{11}	0
^{63}Ni	1.09×10^{11}	1.79×10^{13}	0
^{79}Se	6.66×10^9	2.35×10^4	3.35×10^7
^{90}Sr	1.68×10^{15}	8.74×10^9	8.39×10^{11}
^{93}Zr	1.62×10^{11}	2.00×10^{10}	0
^{91}Nb	1.49×10^6	1.22×10^7	0
$^{93\text{m}}\text{Nb}$	1.46×10^{11}	1.65×10^{10}	0
^{94}Nb	1.89×10^8	1.17×10^{10}	0
^{93}Mo	7.21×10^7	3.28×10^8	0
^{99}Tc	1.22×10^{12}	4.83×10^7	1.22×10^8
^{107}Pd	1.08×10^{10}	9.76×10^4	1.08×10^6
$^{108\text{m}}\text{Ag}$	3.64×10^8	1.54×10^4	0
$^{121\text{m}}\text{Sn}$	8.74×10^{11}	9.03×10^{10}	0
^{126}Sn	2.32×10^{10}	1.52×10^5	2.32×10^7
^{129}I	2.40×10^9	1.56×10^4	9.66×10^7
^{135}Cs	4.01×10^{10}	1.41×10^5	9.06×10^8
^{137}Cs	2.53×10^{15}	1.09×10^{10}	5.78×10^{13}
^{151}Sm	1.30×10^{13}	6.25×10^7	0
$^{166\text{m}}\text{Ho}$	8.21×10^7	2.24×10^3	0
^{210}Pb	2.98×10^5	6.41×10^4	0
^{210}Po	3.54×10^5	4.28×10^2	0
^{226}Ra	5.51×10^5	2.51×10^5	0
^{228}Ra	9.61×10^3	3.44×10^3	0
^{227}Ac	2.78×10^6	4.78×10^4	0
^{228}Th	2.57×10^9	7.76×10^3	0
^{229}Th	3.39×10^5	1.20×10^4	0
^{230}Th	5.88×10^7	3.71×10^4	0
^{232}Th	1.13×10^4	1.76×10^3	0
^{231}Pa	3.77×10^6	2.96×10^3	0
^{232}U	2.50×10^9	3.20×10^3	0
^{233}U	5.57×10^7	2.39×10^3	0
^{234}U	1.22×10^{11}	8.94×10^3	0
^{235}U	9.51×10^8	2.20×10^3	0

Tab. H-3: continued

Radionuclide	Fuel matrix [Bq]	Structural materials [Bq]	Instantly released inventory [Bq]
^{236}U	2.31×10^{10}	7.76×10^3	0
^{238}U	2.07×10^{10}	2.81×10^4	0
^{237}Np	3.05×10^{10}	1.78×10^4	0
^{238}Pu	2.30×10^{14}	4.87×10^8	0
^{239}Pu	2.05×10^{13}	1.33×10^8	0
^{240}Pu	4.17×10^{13}	1.92×10^8	0
^{241}Pu	7.04×10^{14}	5.61×10^9	0
^{242}Pu	2.12×10^{11}	2.51×10^6	0
^{241}Am	2.74×10^{14}	2.06×10^9	0
$^{242\text{m}}\text{Am}$	5.62×10^{11}	4.53×10^6	0
^{243}Am	2.37×10^{12}	3.35×10^7	0
^{243}Cm	6.04×10^{11}	6.23×10^6	0
^{244}Cm	5.82×10^{13}	1.05×10^9	0
^{245}Cm	5.70×10^{10}	9.68×10^5	0
^{246}Cm	2.10×10^{10}	4.40×10^5	0
^{247}Cm	8.98×10^4	1.98×10^3	0
^{251}Cf	3.21×10^5	1.93×10^3	0
Stable isotopes	Fuel matrix [mol]	Structural materials [mol]	Instantly released inventory [mol]
C	8.83	1.68×10^1	2.73×10^{-1}
Cl	2.25×10^{-1}	4.15×10^{-1}	0
Ca	1.78	5.50×10^{-1}	0
Ni	7.61×10^{-1}	3.13×10^2	0
Se	1.74	0	8.77×10^{-3}
Sr	1.07×10^1	0	5.35×10^{-3}
Zr	9.70×10^1	7.89×10^3	0
Nb	1.93×10^{-2}	1.22	0
Mo	7.18×10^1	3.82×10^{-1}	0
Pd	3.68×10^1	0	3.68×10^{-3}
Ag	2.13	0	0
Sn	9.69×10^{-1}	8.97×10^1	9.70×10^{-4}
I	1.01	0	0
Cs	2.32×10^1	0	0
Sm	7.97	0	0
Ho	5.12×10^{-3}	0	0
Pb	8.69×10^{-3}	4.60×10^{-1}	0

Tab. H-4: Mean inventory of one PWR-UO₂-ELB of post-closure safety-relevant radionuclides and stable isotopes of SF (Nagra 2023c)

Radionuclide	Fuel matrix [Bq]	Structural materials [Bq]	Instantly released inventory [Bq]
¹⁴ C _{anorg}	0	0	4.41×10^8
¹⁴ C _{org}	2.85×10^{10}	3.69×10^{10}	4.55×10^8
³⁶ Cl	5.27×10^8	9.36×10^8	2.18×10^8
⁴¹ Ca	2.14×10^8	5.04×10^7	0
⁵⁹ Ni	7.68×10^8	4.30×10^{10}	0
⁶³ Ni	7.34×10^{10}	4.04×10^{12}	1.17×10^4
⁷⁹ Se	5.76×10^9	1.33×10^4	2.95×10^7
⁹⁰ Sr	1.48×10^{15}	3.88×10^{10}	8.38×10^{11}
⁹³ Zr	1.40×10^{11}	1.18×10^{10}	1.56×10^7
⁹¹ Nb	1.40×10^6	4.39×10^7	0
^{93m} Nb	1.23×10^{11}	1.23×10^{10}	1.46×10^7
⁹⁴ Nb	1.58×10^8	5.55×10^9	0
⁹³ Mo	6.18×10^7	2.11×10^8	0
⁹⁹ Tc	1.04×10^{12}	3.11×10^7	2.08×10^8
¹⁰⁷ Pd	9.17×10^9	5.36×10^4	9.17×10^5
^{108m} Ag	2.85×10^8	1.22×10^4	3.08×10^5
^{121m} Sn	7.73×10^{11}	6.84×10^{10}	0
¹²⁶ Sn	2.00×10^{10}	8.78×10^4	2.00×10^7
¹²⁹ I	1.95×10^9	8.33×10^3	2.15×10^8
¹³⁵ Cs	3.58×10^{10}	9.02×10^4	2.10×10^9
¹³⁷ Cs	2.14×10^{15}	6.12×10^9	1.36×10^{14}
¹⁵¹ Sm	1.31×10^{13}	4.20×10^7	0
^{166m} Ho	6.82×10^7	7.54×10^2	0
²¹⁰ Pb	2.78×10^5	1.75×10^4	2.84×10^1
²¹⁰ Po	2.89×10^5	2.78×10^2	2.77×10^1
²²⁶ Ra	6.31×10^5	5.38×10^4	6.71×10^1
²²⁸ Ra	8.79×10^3	8.77×10^2	0
²²⁷ Ac	2.68×10^6	9.58×10^3	5.22×10^1
²²⁸ Th	3.50×10^9	2.05×10^3	0
²²⁹ Th	3.31×10^5	2.42×10^3	1.57
²³⁰ Th	5.42×10^7	9.76×10^3	5.27×10^3
²³² Th	9.16×10^3	5.27×10^2	0
²³¹ Pa	3.61×10^6	8.80×10^2	9.10×10^1
²³² U	3.41×10^9	1.30×10^3	0
²³³ U	5.05×10^7	7.33×10^2	2.98×10^2
²³⁴ U	1.23×10^{11}	7.06×10^3	1.12×10^7

Tab. H-4: continued

Radionuclide	Fuel matrix [Bq]	Structural materials [Bq]	Instantly released inventory [Bq]
²³⁵ U	9.15×10^8	7.84×10^2	6.81×10^4
²³⁶ U	2.22×10^{10}	3.85×10^3	2.01×10^6
²³⁸ U	1.53×10^{10}	1.61×10^4	1.36×10^6
²³⁷ Np	3.28×10^{10}	1.03×10^4	3.94×10^5
²³⁸ Pu	2.87×10^{14}	3.70×10^8	2.09×10^{10}
²³⁹ Pu	1.83×10^{13}	8.33×10^7	1.56×10^9
²⁴⁰ Pu	3.31×10^{13}	1.09×10^8	3.16×10^9
²⁴¹ Pu	6.65×10^{14}	3.72×10^9	2.58×10^{10}
²⁴² Pu	1.80×10^{11}	1.34×10^6	2.00×10^7
²⁴¹ Am	2.63×10^{14}	1.42×10^9	2.23×10^{10}
^{242m} Am	7.45×10^{11}	3.91×10^6	0
²⁴³ Am	2.25×10^{12}	1.92×10^7	0
²⁴³ Cm	6.99×10^{11}	4.73×10^6	0
²⁴⁴ Cm	6.45×10^{13}	6.49×10^8	5.43×10^9
²⁴⁵ Cm	7.98×10^{10}	8.59×10^5	0
²⁴⁶ Cm	2.60×10^{10}	3.09×10^5	0
²⁴⁷ Cm	1.38×10^5	6.08×10^2	0
²⁵¹ Cf	7.11×10^5	5.96×10^2	0
Stable isotopes	Fuel matrix [mol]	Structural materials [mol]	Instantly released inventory [mol]
C	6.43	1.06×10^1	1.99×10^{-1}
Cl	1.80×10^{-1}	2.44×10^{-1}	0
Ca	1.45	3.24×10^{-1}	0
Ni	5.64×10^{-1}	2.96×10^2	0
Se	1.12	0	5.64×10^{-3}
Sr	6.05	0	3.03×10^{-3}
Zr	5.99×10^1	4.65×10^3	0
Nb	2.26×10^{-2}	1.68	0
Mo	4.98×10^1	2.25×10^{-1}	0
Pd	3.48×10^1	0	3.48×10^{-3}
Ag	2.37	0	0
Sn	8.21×10^{-1}	5.28×10^1	8.21×10^{-4}
I	8.86×10^{-1}	0	0
Cs	1.70×10^1	0	0
Sm	6.34	0	0
Ho	4.04×10^{-3}	0	0
Pb	7.04×10^{-3}	2.71×10^{-1}	0

Tab. H-5: Mean inventory of one PWR-MOX-ELB of post-closure safetyrelevant radionuclides and stable isotopes of SF (Nagra 2023c)

Radionuclide	Fuel matrix [Bq]	Structural materials [Bq]	Instantly released inventory [Bq]
$^{14}\text{C}_{\text{anorg}}$	0	0	3.09×10^8
$^{14}\text{C}_{\text{org}}$	2.00×10^{10}	3.16×10^{10}	3.12×10^8
^{36}Cl	4.29×10^8	7.63×10^8	1.08×10^8
^{41}Ca	1.59×10^8	4.10×10^7	0
^{59}Ni	5.56×10^8	5.38×10^{10}	0
^{63}Ni	5.13×10^{10}	4.86×10^{12}	0
^{79}Se	4.46×10^9	1.08×10^4	2.24×10^7
^{90}Sr	8.92×10^{14}	2.69×10^{10}	4.46×10^{11}
^{93}Zr	1.02×10^{11}	9.62×10^9	0
^{91}Nb	1.56×10^6	3.70×10^7	0
$^{93\text{m}}\text{Nb}$	9.20×10^{10}	9.71×10^9	0
^{94}Nb	1.77×10^8	5.07×10^9	0
^{93}Mo	6.24×10^7	1.72×10^8	0
^{99}Tc	8.40×10^{11}	2.53×10^7	8.40×10^7
^{107}Pd	1.04×10^{10}	4.37×10^4	1.04×10^6
$^{108\text{m}}\text{Ag}$	2.82×10^8	9.99×10^3	0
$^{121\text{m}}\text{Sn}$	6.47×10^{11}	5.03×10^{10}	0
^{126}Sn	1.88×10^{10}	7.13×10^4	1.88×10^7
^{129}I	1.83×10^9	7.20×10^3	1.47×10^8
^{135}Cs	3.81×10^{10}	7.71×10^4	1.67×10^9
^{137}Cs	1.52×10^{15}	4.25×10^9	6.87×10^{13}
^{151}Sm	1.44×10^{13}	3.32×10^7	0
$^{166\text{m}}\text{Ho}$	7.00×10^7	1.01×10^3	0
^{210}Pb	2.36×10^5	3.24×10^4	0
^{210}Po	2.62×10^5	2.41×10^2	0
^{226}Ra	4.86×10^5	1.44×10^5	0
^{228}Ra	6.93×10^3	1.34×10^3	0
^{227}Ac	1.83×10^6	1.41×10^4	0
^{228}Th	2.00×10^9	2.57×10^3	0
^{229}Th	2.98×10^5	6.16×10^3	0
^{230}Th	5.09×10^7	5.26×10^4	0
^{232}Th	7.49×10^3	7.90×10^2	0
^{231}Pa	2.40×10^6	1.29×10^3	0
^{232}U	1.94×10^9	1.45×10^3	0
^{233}U	4.44×10^7	1.09×10^3	0
^{234}U	1.20×10^{11}	2.17×10^4	0

Tab. H-5: continued

Radionuclide	Fuel matrix [Bq]	Structural materials [Bq]	Instantly released inventory [Bq]
²³⁵ U	5.43×10^8	1.06×10^3	0
²³⁶ U	1.20×10^{10}	4.09×10^3	0
²³⁸ U	1.30×10^{10}	1.38×10^4	0
²³⁷ Np	2.63×10^{10}	1.88×10^4	0
²³⁸ Pu	3.34×10^{14}	3.04×10^8	0
²³⁹ Pu	2.51×10^{13}	7.13×10^7	0
²⁴⁰ Pu	6.96×10^{13}	9.30×10^7	0
²⁴¹ Pu	6.94×10^{14}	2.29×10^9	0
²⁴² Pu	3.94×10^{11}	1.08×10^6	0
²⁴¹ Am	5.26×10^{14}	1.07×10^9	0
^{242m} Am	2.34×10^{12}	3.48×10^6	0
²⁴³ Am	5.01×10^{12}	1.50×10^7	0
²⁴³ Cm	1.16×10^{12}	3.27×10^6	0
²⁴⁴ Cm	1.01×10^{14}	3.78×10^8	0
²⁴⁵ Cm	2.95×10^{11}	6.11×10^5	0
²⁴⁶ Cm	7.30×10^{10}	2.02×10^5	0
²⁴⁷ Cm	4.75×10^5	9.19×10^2	0
²⁵¹ Cf	2.29×10^6	8.86×10^2	0
Stable isotopes	Fuel matrix [mol]	Structural materials [mol]	Instantly released inventory [mol]
C	6.49	8.54	2.01×10^{-1}
Cl	1.83×10^{-1}	2.02×10^{-1}	0
Ca	1.49	2.68×10^{-1}	0
Ni	5.66×10^{-1}	2.17×10^2	0
Se	1.12	0	5.63×10^{-3}
Sr	5.79	0	2.90×10^{-3}
Zr	5.92×10^1	3.85×10^3	0
Nb	2.50×10^{-2}	1.10	0
Mo	5.07×10^1	1.87×10^{-1}	0
Pd	3.84×10^1	0	3.84×10^{-3}
Ag	2.66	0	0
Sn	8.82×10^{-1}	4.37×10^1	8.83×10^{-4}
I	9.53×10^{-1}	0	0
Cs	1.75×10^1	0	0
Sm	6.66	0	0
Ho	4.34×10^{-3}	0	0
Pb	7.25×10^{-3}	2.25×10^{-1}	0

Tab. H-6: Mean inventory of post-closure safety-relevant radionuclides and stable isotopes of reprocessed high-level waste (RP-HLW) per canister (each containing 3 steel flasks with vitrified HLW) of types: RP-HLW-1 (Areva) and RP-HLW-2 (BNFL)

Radionuclide	RP-HLW-1 [Bq]	RP-HLW-2 [Bq]
⁶³ Ni	1.25×10^{11}	2.29×10^{11}
⁷⁹ Se	5.75×10^{10}	5.65×10^{10}
⁹⁰ Sr	1.75×10^{15}	1.44×10^{15}
⁹³ Zr	3.01×10^{11}	3.54×10^{11}
^{93m} Nb	2.85×10^{11}	3.37×10^{11}
⁹⁴ Nb	2.92×10^8	3.82×10^8
⁹³ Mo	2.18×10^8	2.59×10^8
⁹⁹ Tc	2.90×10^{12}	2.68×10^{12}
¹⁰⁷ Pd	1.95×10^{10}	2.37×10^{10}
^{108m} Ag	5.51×10^8	9.61×10^8
^{121m} Sn	9.45×10^{11}	1.00×10^{12}
¹²⁶ Sn	1.08×10^{11}	1.51×10^{11}
¹²⁹ I	9.51×10^7	4.62×10^5
¹³⁵ Cs	8.53×10^{10}	1.04×10^{11}
¹³⁷ Cs	2.77×10^{15}	2.93×10^{15}
¹⁵¹ Sm	2.46×10^{13}	3.06×10^{13}
^{166m} Ho	1.88×10^8	2.91×10^8
²¹⁰ Pb	2.72×10^5	1.10×10^6
²¹⁰ Po	2.69×10^5	1.09×10^6
²²⁶ Ra	4.27×10^5	1.71×10^6
²²⁸ Ra	2.88×10^4	9.81×10^4
²²⁷ Ac	4.12×10^6	7.52×10^6
²²⁸ Th	3.03×10^6	5.66×10^5
²²⁹ Th	1.44×10^5	3.27×10^5
²³⁰ Th	1.27×10^7	4.93×10^7
²³² Th	2.88×10^4	9.81×10^4
²³¹ Pa	4.46×10^6	8.05×10^6
²³² U	2.91×10^6	4.56×10^5
²³³ U	1.71×10^7	8.55×10^6
²³⁴ U	2.26×10^8	2.34×10^8
²³⁵ U	1.72×10^6	1.22×10^6
²³⁶ U	2.93×10^7	8.58×10^6

Tab. H-6: continued

Radionuclide	RP-HLW-1 [Bq]	RP-HLW-2 [Bq]
²³⁸ U	3.45×10^7	2.51×10^7
²³⁷ Np	5.46×10^{10}	3.09×10^{10}
²³⁸ Pu	5.68×10^{11}	7.20×10^{11}
²³⁹ Pu	6.16×10^{10}	5.43×10^{10}
²⁴⁰ Pu	1.37×10^{12}	5.24×10^{11}
²⁴¹ Pu	4.44×10^{11}	1.61×10^{11}
²⁴² Pu	3.96×10^8	1.62×10^8
²⁴¹ Am	2.41×10^{14}	2.97×10^{14}
^{242m} Am	6.16×10^{11}	8.05×10^{11}
²⁴³ Am	4.97×10^{12}	2.03×10^{12}
²⁴² Cm	5.09×10^{11}	6.65×10^{11}
²⁴³ Cm	3.57×10^{11}	1.75×10^{12}
²⁴⁴ Cm	2.83×10^{13}	1.04×10^{13}
²⁴⁵ Cm	5.80×10^{10}	2.70×10^{10}
²⁴⁶ Cm	4.85×10^9	2.33×10^9
²⁴⁷ Cm	1.39×10^4	5.62×10^3
²⁴⁸ Cm	3.19×10^4	1.19×10^4
²⁴⁹ Cf	2.92×10^5	9.10×10^4
²⁵¹ Cf	1.71×10^4	5.18×10^3
Stable isotope	RP-HLW-1 [mol]	RP-HLW-2 [mol]
Ni	1.10×10^2	3.52×10^1
Se	2.43	3.13
Zr	2.38×10^2	1.69×10^2
Nb	4.47×10^{-2}	4.65×10^{-1}
Mo	9.63×10^1	1.20×10^2
Pd	3.93×10^1	4.46×10^1
Ag	2.61	3.17
Sn	1.54	1.48
Pb	2.02×10^{-2}	4.41×10^{-2}

Tab. H-7: Total inventory of radionuclides relevant to post-closure safety in L/ILW emplacement caverns

Radionuclide	L/ILW (LILW1) [Bq]	L/ILW (LILW2) [Bq]	L/ILW (total) [Bq]
$^{14}\text{C}_{\text{anorg}}$	5.42×10^{12}	4.83×10^{12}	1.03×10^{13}
$^{14}\text{C}_{\text{org, Congr. rel.}}$	3.80×10^{13}	5.96×10^{11}	3.86×10^{13}
$^{14}\text{C}_{\text{org}}$	5.00×10^{12}	2.55×10^{12}	7.55×10^{12}
^{26}Al	5.87×10^9	6.23×10^8	6.50×10^9
^{32}Si	7.15×10^{11}	9.59×10^8	7.16×10^{11}
^{36}Cl	9.45×10^{11}	3.18×10^{10}	9.76×10^{11}
^{41}Ca	4.84×10^{11}	1.30×10^9	4.86×10^{11}
^{44}Ti	4.53×10^{13}	3.66×10^{10}	4.53×10^{13}
^{60}Fe	4.64×10^8	0	4.64×10^8
^{59}Ni	2.12×10^{14}	6.16×10^{12}	2.18×10^{14}
^{63}Ni	2.55×10^{16}	3.42×10^{14}	2.59×10^{16}
^{79}Se	3.23×10^{10}	3.54×10^8	3.26×10^{10}
^{90}Sr	1.24×10^{15}	4.14×10^{13}	1.28×10^{15}
^{93}Zr	7.34×10^{12}	8.82×10^{11}	8.22×10^{12}
^{91}Nb	9.75×10^{11}	8.69×10^7	9.75×10^{11}
$^{93\text{m}}\text{Nb}$	1.06×10^{13}	8.61×10^{11}	1.14×10^{13}
^{94}Nb	2.76×10^{13}	5.22×10^{10}	2.76×10^{13}
^{93}Mo	2.95×10^{12}	6.97×10^9	2.96×10^{12}
^{99}Tc	4.22×10^{12}	5.06×10^{11}	4.73×10^{12}
$^{108\text{m}}\text{Ag}$	7.13×10^{14}	7.65×10^{10}	7.13×10^{14}
^{126}Sn	5.88×10^{10}	1.64×10^{11}	2.23×10^{11}
^{129}I	2.25×10^9	1.86×10^8	2.44×10^9
^{135}Cs	4.09×10^{10}	2.59×10^9	4.35×10^{10}
^{137}Cs	1.56×10^{15}	1.09×10^{14}	1.66×10^{15}
^{194}Hg	6.59×10^{12}	2.46×10^8	6.59×10^{12}
^{202}Pb	1.26×10^{11}	2.14×10^6	1.26×10^{11}
^{210}Pb	4.74×10^{11}	3.95×10^{10}	5.13×10^{11}
^{209}Po	1.33×10^{10}	9.34×10^8	1.42×10^{10}
^{210}Po	4.74×10^{11}	3.92×10^{10}	5.13×10^{11}
^{226}Ra	4.99×10^{11}	5.25×10^{10}	5.52×10^{11}
^{228}Ra	4.60×10^9	1.07×10^{10}	1.53×10^{10}
^{227}Ac	1.31×10^7	1.68×10^8	1.81×10^8
^{228}Th	6.21×10^9	1.20×10^{10}	1.82×10^{10}
^{229}Th	6.41×10^6	7.90×10^6	1.43×10^7
^{230}Th	5.67×10^7	1.37×10^7	7.04×10^7

Tab. H-7: continued

Radionuclide	L/ILW (LILW1) [Bq]	L/ILW (LILW2) [Bq]	L/ILW (total) [Bq]
²³² Th	4.76×10^9	1.11×10^{10}	1.59×10^{10}
²³¹ Pa	1.19×10^7	4.03×10^6	1.59×10^7
²³² U	1.63×10^9	1.41×10^9	3.04×10^9
²³³ U	1.08×10^9	3.53×10^7	1.12×10^9
²³⁴ U	6.83×10^{10}	1.51×10^{10}	8.34×10^{10}
²³⁵ U	2.97×10^9	4.84×10^8	3.45×10^9
²³⁶ U	3.87×10^9	3.10×10^8	4.18×10^9
²³⁸ U	9.41×10^{10}	9.58×10^9	1.04×10^{11}
²³⁷ Np	1.92×10^{11}	2.25×10^9	1.94×10^{11}
²³⁸ Pu	7.88×10^{13}	6.73×10^{12}	8.56×10^{13}
²³⁹ Pu	1.60×10^{13}	4.11×10^{12}	2.01×10^{13}
²⁴⁰ Pu	2.28×10^{13}	3.43×10^{12}	2.62×10^{13}
²⁴¹ Pu	1.37×10^{14}	2.37×10^{13}	1.60×10^{14}
²⁴² Pu	9.83×10^{10}	9.57×10^9	1.08×10^{11}
²⁴¹ Am	1.51×10^{14}	1.80×10^{13}	1.69×10^{14}
^{242m} Am	7.74×10^{10}	2.71×10^8	7.76×10^{10}
²⁴³ Am	6.35×10^{11}	5.41×10^8	6.36×10^{11}
²⁴² Cm	6.39×10^{10}	2.24×10^8	6.41×10^{10}
²⁴³ Cm	6.15×10^{10}	8.54×10^7	6.15×10^{10}
²⁴⁴ Cm	4.54×10^{12}	1.52×10^{12}	6.06×10^{12}
²⁴⁵ Cm	9.08×10^9	1.68×10^7	9.10×10^9
²⁴⁶ Cm	2.82×10^9	3.87×10^6	2.83×10^9
²⁴⁷ Cm	1.42×10^4	0	1.42×10^4
²⁴⁸ Cm	9.89×10^4	0	9.89×10^4
²⁴⁹ Cf	2.71×10^6	2.07×10^3	2.72×10^6
²⁵¹ Cf	1.56×10^5	0	1.56×10^5

C-14 in the waste originates either from contaminated materials or from activated materials (mainly metals and fuel pellets) and is also present in some other waste types, e.g., in RP-HLW. The C-14 in contaminated L/ILW waste packages, along with other radionuclides, is assumed to be instantaneously released from the waste package in both organic and inorganic form. The C-14 in the activated metals is assumed to be mainly released congruently during metal corrosion, with the corresponding metal corrosion rate, giving rise to a time-dependent C-14 source term, which is calculated using data in Nagra (2024r) and in Diomidis et al. (2023). Fig. H-1 shows the resulting time-dependent release rate of organic C-14, which is considered as source term in the radiological consequence analysis. The inorganic C-14 is assumed to be dissolved in the liquid phase. Most of the inorganic C-14 release is assumed to be instantaneous Nagra (2024r), with the exception that the inorganic C-14 in vitrified HLW (RP-HLW) is assumed to be released with the glass dissolution rate given in Curti (2022).

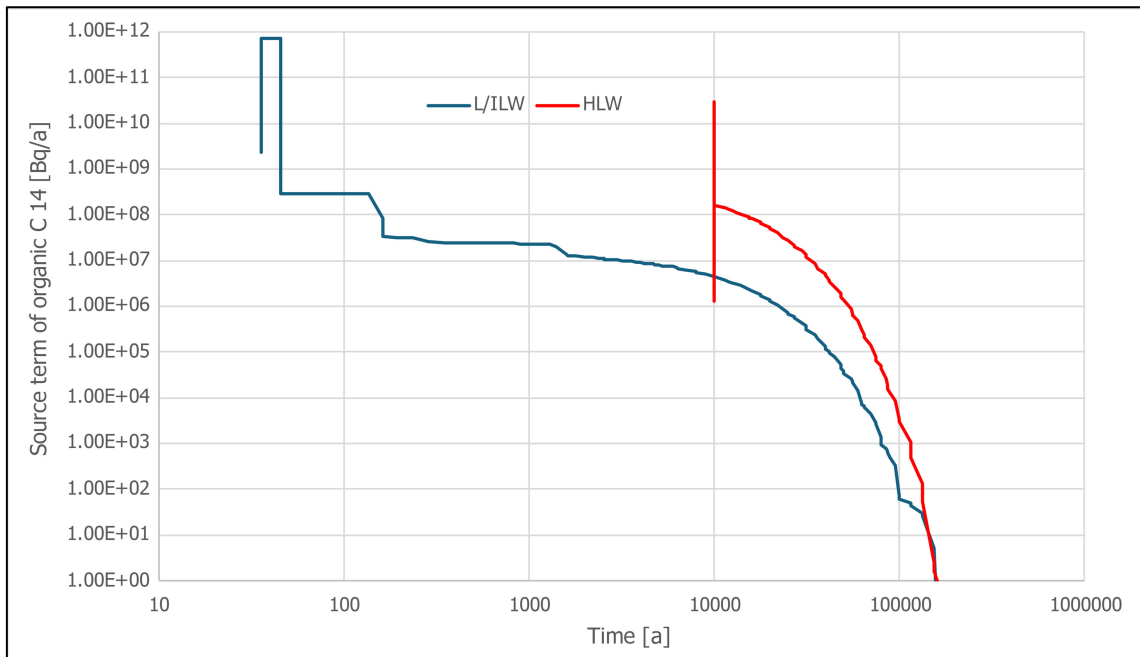


Fig. H-1: Time-dependent organic C-14 source terms

H.3 Parameter table for modelling radionuclide migration in the liquid phase

Full details of the input parameters, including reference values, upper and lower bounds (if varied), distribution (e.g. uniform/log-uniform/log-normal) and origin of the data are given in the digital appendix (Enclosure A: [parameterTableLiquidPhase.html](#)) to this report. The parameters and their characterisation are compiled in html files (termed “master table”).

H.4 Parameter table for modelling the two-phase migration of C-14 methane

Full details of the input parameters, including reference values, upper and lower bounds (if varied), distribution (e.g. uniform/log-uniform/log-normal) and origin of the data are given in the digital appendix (Enclosure B: parameterTableTwoPhase.html) to this report. The parameters and their characterisation are compiled in html files (termed “master table”). In addition, Tab. H-8 and Tab. H-9 give an overview on material and system parameters defined in the master table indicating if and where they are varied or not in probabilistic analyses. Furthermore, Tab. H-10 summarises the material parameters for the reference case.

Material parameters in the full master table (digital appendix) are a combination of the parameter type listed in Tab. H-8 and the material class listed in Tab. H-10. For example, por_OPA refers to the porosity of the Opalinus Clay and por_SMA refers to the porosity of the L/ILW caverns.

The porosity (por) and permeability (k) of EDZ are coupled to respective parameters of the Opalinus Clay via constant factors eta_por_EDZ and eta_k_EDZ. All other variable material parameters of the EDZ are tied to the Opalinus Clay with a constant factor of 1.

Van Genuchten gas entry pressure is varied with permeability according to the Leverett functional relationship.

Variation of corrosion/degradation rates:

- KorrDegRates_Szenario reflects a uniform distribution between 0 and 1. Depending on the sampled value, corrosion and degradation rates of all metals and organic materials will be interpolated between the lower (0) and upper (1) bounds in the following manner.
- Log-linear interpolation between the lower (0) and upper (1) bounds of the corrosion/degradation rates.
- In case the lower bound of the corrosion/degradation rate is zero, semi-log-linear interpolation between the lower bound (0), the reference value (0.5) and the upper bound (1) is applied. This applies to all organic materials.
- In case both lower bound and reference values of the corrosion/degradation rates are zero, linear interpolation between the lower (0) and the (1) upper bounds is applied. This applies to copper and lead.
- With variation of corrosion/degradation rates, both gas generation and congruent C-14 release from activated metals are varied.

Variation of IRF of activated metals:

- The IRF_C14_Szenario reflects a uniform distribution between 0 and 1 that is sampled independently from the corrosion/degradation rates from the KorrDegRates_Szenario. Depending on the sampled value, the IRF of all metals will be linearly interpolated between the lower (0) and upper (1) bounds.

C-14 release from contaminated materials is assumed to occur instantaneously and is not varied.

Tab. H-8: Master table summary for material parameters

Material parameters: thermohydraulic and two-phase parameters				
Parameter	Unit	Name	Host rock/EDZ/confining units	Tunnels/seals
Grain density	kg/m ³	drok	Varied	Not varied
Porosity	-	por	Varied	Varied
Permeability (vertical)	m ²	k	Varied	Varied
Water saturated (isotropic) heat conductivity	W/m/K	cwet	Not varied	Varied
Specific heat capacity	J/kg/K	spht	Not varied	Not varied
Pore compressibility	1/Pa	com	Not varied	Not varied
Thermal expansivity	1/K	expan	Not varied	Not varied
Dry (isotropic) heat conductivity	W/m/K	cdry	Not varied	Not varied
Van Genuchten residual liquid saturation for relative permeability	-	Slr_krel	Not varied	Not varied
Van Genuchten residual gas saturation for relative permeability	-	Sgr_krel	Not varied	Not varied
Van Genuchten shape parameter	-	n	Varied/not varied/not varied	Varied
Van Genuchten gas entry pressure	Pa	P0	Varied	Varied
Van Genuchten maximum capillary pressure	Pa	Pmax	Not varied	Not varied
Van Genuchten residual liquid saturation for capillary pressure	-	Slr_pcap	Not varied	Not varied
Anisotropy for flow/advection	-	A_Flow	Not varied	Not varied
Anisotropy for diffusion	-	A_Diffu	Not varied	Not varied
Anisotropy for heat conduction	-	A_Heat	Varied/varied/not varied	Not varied

Tab. H-9: Master table summary for system parameters

System parameters			
Parameter	Unit	Name	Variation
Diffusion coefficient for C-14 in liquid phase	m ² /s	De_C14_l_25	Varied
Diffusion coefficient for C-14 in gas phase	m ² /s	D_C14_g	Not varied
Diffusion coefficient for H ₂ in liquid phase	m ² /s	De_H2_l_25	Varied
Diffusion coefficient for H ₂ in gas phase	m ² /s	D_H2_g	Not varied
Variability of thickness of CRZ	m	Mvar_*	Varied
Surface elevation	m asl	OKTerrain	Not varied
Containment time for HLW (for C-14)	a	t_E_HAA	Not varied
Containment time for L/ILW (for C-14)	a	t_E_SMA	Not varied
Duration of operational phase for HLW	a	t_B_HAA	Not varied
Duration of operational phase for L/ILW	a	t_B_SMA	Not varied
Corrosion/degradation rates	-	KorrDegRate_Szenario	Varied
Instant release fraction (IRF) for C-14 release from activated metals	-	IRF_C14_Szenario	Varied
Temperature during operational phase	°C	T_B	Not varied
Relative humidity during operational phase	%	rh	Varied
Initial liquid saturation of tunnels/seals	-	Sl_0_TS	Not varied
Initial liquid saturation of HLW emplacement drifts	-	Sl_0_HAA	Not varied
Initial liquid saturation of L/ILW emplacement caverns	-	Sl_0_SMA	Not varied
Density of water for calculation of hydrostatic pressure	kg/m ³	rho	Not varied
Gravity	m ² /s	g	Not varied
Atmospheric pressure	Pa	atmP	Not varied
Geothermal gradient	K/m	gradientT	Not varied
Surface temperature	°C	surfaceT	Not varied

Tab. H-10: Thermohydraulic and two-phase parameters of OPA, EDZ, seals and backfill material classes for the reference case (equal for all siting regions)

	V1HAA	V1SMA	V2HAA	V2SMA	V3	V4	Rest	SMA	HAA	OPA	EDZ
drok [kg/m ³]	2700	2700	2700	2700	2700	2700	2700	2650	2700	2700	2700
por [-]	0.30	0.30	0.30	0.30	0.30	0.30	0.35	0.20	0.25	0.11	0.15
k [m ²]	1.0E-20	5.0E-18	1.0E-20	5.0E-18	1.0E-20	1.0E-20	1.0E-15	9.7E-15	3.0E-20	1.0E-21	6.0E-21
A_Flow [-]	1	1	1	1	1	1	1	1	1	5	1
cwet [W/m/K]	1.3	1.3	1.3	1.3	1.3	1.3	1.3	2.5	1.3	2.1	1.7
sphr [J/kg/K]	964	920	964	920	964	964	920	920	964	946.5	995
com [1/Pa]	3.0E-09	1.0E-09	3.0E-09	1.0E-09	3.0E-09	3.0E-09	1.0E-09	5.0E-10	3.0E-09	2.3E-09	3.9E-09
expan [1/K]	2.5E-05	1.5E-05	2.5E-05	1.5E-05	2.5E-05	2.5E-05	1.5E-05	1.5E-05	2.5E-05	1.7E-05	1.7E-05
cdry [W/m/K]	0.35	0.4	0.35	0.4	0.35	0.35	0.4	0.4	0.35	1.36	1.36
Slr_krel [-]	0	0.2	0	0.2	0	0	0.3	0.05	0	0.5	0
Sgr_krel [-]	0	0	0	0	0	0	0	0	0	0	0
n [-]	1.67	2.5	1.67	2.5	1.54	1.54	2.5	2	1.54	1.67	1.67
P0 [Pa] *	2.2E+07	4.0E+03	2.2E+07	4.0E+03	2.2E+07	2.2E+07	4.0E+03	2.1E+05	1.0E+07	4.8E+07	2.0E+07
Pmax [Pa]	1.0E+10	1.0E+08	1.0E+10	1.0E+08	1.0E+10	1.0E+10	1.0E+08	1.0E+08	1.0E+10	1.0E+10	1.0E+10
Slr_pcap [-]	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
A_Diffu [-]	1	1	1	1	1	1	1	1	1	5	1
A_Heat [-]	1	1	1	1	1	1	1	1	1	1.75	2

* 20 °C is taken as reference temperature to account for temperature dependence of capillary pressure due to changes in surface tension.

H.5 Electronic input data and results application (EDR)

The EDR stores output files and post-processed results. Together with a couple of interactive features, it provides a convenient platform for the discussion and verification of results. The EDR provides full flexibility to create any graph of radionuclide fluxes as functions of time or bar plots with maximum radionuclide fluxes from the stored results. Various options allow different calculation cases or different transport paths to be selected. The radionuclide fluxes may be plotted in units of activity, moles or effective dose rates (in which case the EDR multiplies calculated fluxes by the BCDs). The EDR further allows a quick understanding of differences between results. Finally, the generated figures and tables can be exported for use in reports or further analyses.

App. I Conformance with regulatory guidance

Tab. I-1: Regulatory statements in ENSI 33/649 (ENSI 2018), ENSI Guideline G03 (ENSI 2023) and the associated explanatory report (ENSI 2020a) that are relevant to the analysis of radiological consequences and their handling in the present report

Note that the original statements are in German.

Regulatory statement	Handling in this report
ENSI 33/649, Section 4.4 <i>Die Modellberechnungen sind auf standortspezifische Parameter und Konzepte zu stützen und mit experimentellen Daten zu belegen.</i>	Site-specific datasets and model concepts are used in the modelling for this report. Model concepts are documented in App. B Site-specific data can be found in App. H.
ENSI 33/649 Section 4.4 Letter b <i>Beschreibung der Wirkung und Robustheit der technischen und natürlichen Barrieren. Das Rückhaltevermögen des Barrierensystems ist durch Berechnungen aufzuzeigen.</i>	The barrier performance is analysed and demonstrated by using the complementary indicators (radiotoxicity and hypothetical dose rate) in Chapter 6 and 7.
ENSI 33/649 Section 4.4, Letter b <i>Dabei sind auch die standortvergleichsrelevanten Auswirkungen gekoppelter Prozesse (THMC) und der Gasbildung und -ausbreitung auf die technischen und natürlichen Barrieren sowie auf den Radionuklidtransport zu berücksichtigen.</i> ENSI G03/d, Section 9.3 <i>Die Auswirkungen von Bau und Betrieb auf die Langzeitsicherheit sind im Sicherheitsnachweis für die Nachverschlussphase zu berücksichtigen.</i>	THMC and gas processes are considered in the model assumption and configuration used in the radiological consequence analysis (Chapter 5 and App. H).
ENSI 33/649 Section 4.4 <i>Die in den Sicherheitsanalysen verwendeten Modelle (einschliesslich Rand- und Anfangsbedingungen sowie Parameter mit ihren Quellen) und die erhaltenen Resultate sind nachvollziehbar zu dokumentieren.</i> Letter g: <i>Begründung, warum die verwendeten Konzeptualisierungen und Rechenmodelle auf die vorliegende Situation anwendbar sind. Die Bedeutung von Vereinfachungen in den Konzeptualisierungen und Rechenmodellen gegenüber den natürlichen Gegebenheiten ist zu erläutern.</i>	The models used in the safety analyses are documented in Chapter 5 and App. B, including justifications for assumptions. Data and their sources are provided in App. H. The significance of simplifications in the conceptualisations and calculation models is addressed in App. A.

Tab. I-1: continued

Regulatory statement	Handling in this report
ENSI G03/d <i>Die Sicherheitsanalyse hat mindestens die folgenden Elemente zu umfassen: [...] systematische Sensitivitäts- und Unsicherheitsanalyse zur Ermittlung des Einflusses von Unsicherheiten in den Daten, Prozessen und Modellen auf die Berechnungsergebnisse.</i> ENSI 33/649, Section 4.4, Letter e <i>Ausgehend vom Referenzfall sind auch Berechnungen durchzuführen, welche für eine Kombination mehrerer sicherheitsrelevanter Parameter zugleich den jeweils ungünstigen Eckwert zugrunde legen. Die Auswahl der betrachteten Fälle ist zu begründen. Der Variationsbereich der möglichen Freisetzung radioaktiver Stoffe in die Biosphäre und des Dosismaximums aller Szenarien ist zu ermitteln.</i> Letter h: <i>Durchführen einer systematischen Sensitivitätsanalyse, um aufzuzeigen, inwiefern Änderungen in den Parameterwerten die Berechnungsergebnisse beeinflussen.</i>	Probabilistic simulations and systematic sensitivity analysis are performed for the reference safety scenario and analysed by graphical means and by the evaluation of a range of sensitivity measures. These probabilistic simulations are complemented by deterministic calculation cases, in which selected sensitive parameters (identified by the sensitivity analysis) are set to pessimistic bounding values. These are accompanied by the analysis of “combined pessimistic cases”, in which all sensitive parameters are assigned pessimistic bounding values.
ENSI 33/649, Section 4.4 Letter j: <i>Verwendung eines einheitlichen Biosphärenmodells für die Nordschweiz. Die sicherheitstechnische Bedeutung von alternativen Biosphärenszenarien ist zu berücksichtigen. Dazu sind umhüllende Szenarien von möglichen Entwicklungen insbesondere der Gebietsmorphologie und des Klimas zu betrachten.</i>	In the consequence analysis in support of both the site comparison and the safety case for a combined repository, the individual dose (dose rate) is generally calculated by multiplying the reference BDCFs by the radionuclide release rates to the biosphere, although the impact of using the alternative BDCFs is also investigated.
ENSI 33/649, Section 4.6: <i>Aufgrund der strengerer Anforderungen an die geologischen Barrieren und des längeren Betrachtungszeitraums für ein HAA-Lager ist in einem ersten Schritt der Standort für das HAA-Lager zu wählen. Im zweiten Schritt wird der Standort für das SMA-Lager gewählt.</i>	The radiological consequence analysis in support for the site comparison follows these steps as stipulated (see Chapter 6).
ENSI 33/649 Section 5.2 <i>Zusätzlich soll in der Sicherheitsanalyse für den gewählten Standort der zeitliche Verlauf der radiologischen Toxizität der eingelagerten Abfälle aufgezeigt werden.</i>	Radiotoxicity is used as complementary safety indicators for analysis in Chapters 6 and 7.

Tab. I-1: continued

Regulatory statement	Handling in this report
ENSI G03/d <i>Für den Sicherheitsnachweis ist ein Nachweiszeitraum von bis zu einer Million Jahre festzulegen. Die zeitliche Entwicklung des radiologischen Gefährdungspotenzials der eingelagerten Abfälle und die Prognostizierbarkeit der geologischen Langzeitentwicklung sind zu berücksichtigen.</i> <i>In der Sicherheitsanalyse sind Dosisberechnungen bis zum Zeitpunkt der maximalen radiologischen Auswirkungen des geologischen Tiefenlagers durchzuführen, mindestens jedoch bis zum Ende des Nachweiszeitraums.</i>	The time period for assessment extends up to 100,000 years post-closure for an L/ILW repository and up to one million years for an HLW repository or a combined repository. The timeframe covered by the calculations is extended, where necessary, to 10⁷ years for releases from the HLW repository section of a combined repository and to 10⁶ years for releases from the L/ILW repository section.
Explanatory report for G03/d: <i>Falls probabilistische Berechnungen verwendet werden, sollen unrealistische Parameterkombinationen vermieden werden.</i> <i>Zusätzlich soll eine Risikoverdünnung vermieden werden.</i> ENSI 33/649, Section 4.4, Letter e: <i>Gegenseitige physikalische Abhängigkeiten von Parametern sind entsprechend zu berücksichtigen.</i>	In carrying out the probabilistic analyses for the present report, correlations between the input parameters are considered to avoid unrealistic parameter combinations. The treatment of parameter correlations in probabilistic simulations are documented in App. C.2. According to Section 3.4.1, risk dilution is not an issue in the present probabilistic approach.
ENSI 33/649, Section 5.2: <i>Die Sicherheitsanalyse des Standortvergleichs (siehe Kap. 4.4) für den gewählten Standort wird entsprechend vertieft und mit umfassenden Szenarien- und Risikoanalysen gemäss Richtlinie ENSI-G03 ergänzt. Insbesondere wird für die in Kap. 4.4 aufgeführten Punkte b) «Wirkung und Robustheit der technischen und natürlichen Barrieren», e) «Szenarienanalyse mit einer umfassenden FEP Analyse» und h) «Sensitivitätsanalyse» ein höherer Detaillierungsgrad erwartet. Die möglichen radiologischen Auswirkungen zukünftiger Entwicklungen sind durch umhüllende Varianten aufzuzeigen. Wo Ungewissheiten bestehen, sind in der Sicherheitsanalyse die maximalen radiologischen Konsequenzen durch die Berechnung umhüllender Varianten oder durch konservative Annahmen abzuschätzen. Der Einfluss von Ungewissheiten auf die berechneten Ergebnisse ist systematisch aufzuzeigen, und die daraus gezogenen Schlüsse für die Langzeitsicherheit sind darzulegen.</i>	A systematic set of radiological consequence analysis (incl. dose calculations and analysis of barrier performance) is performed for the selected site, along with additional, hypothetical “what-if?” cases (see Chapter 4 and 7).

Tab. I-1: continued

Regulatory statement	Handling in this report
ENSI 33/649, Section 5.2: <i>Um die Robustheit eines Systems zu illustrieren, können auch sogenannte «What if»-Fälle verwendet werden. Dabei werden Phänomene unterstellt bzw. Parameter angenommen, die ausserhalb des Bereichs liegen, der aufgrund wissenschaftlicher Ergebnisse als möglich erachtet wird. Bei «What if»-Fällen geht es also nicht darum, realistische Fälle zu analysieren, sondern einen vertieften Einblick in das Verhalten des Lagersystems unter extremen Bedingungen zu erhalten</i>	
ENSI 33/649, Section 5.2: <i>Für alle Arten von numerischen Modellen und Berechnungen (z. B. Radionuklidenausbreitung, Gasausbreitung, gekoppelte thermo-hydraulisch-mechanische Prozesse) ist ein konsistenter Datensatz zu verwenden.</i>	The dataset used in the performance assessment and radiological consequence analysis is consistent (App. H).