Modelling of Radionuclide Transport along the Underground Access Structures of Deep Geological Repositories

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Technical Report 14-10

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The report was reviewed by Peter Robinson and Jürg Schneider, who provided valuable comments, for which the authors would like to express their gratitude.
Summary

The arrangement and sealing of the access routes to a deep geological repository for radioactive waste should ensure that any radionuclide release from the emplacement rooms during the post-closure phase does not by-pass the geological barriers of the repository system to a significant extent. The base case of the present study, where realistic values for the hydraulic properties of the seals and the associated excavation damage zones were assumed, assesses to what extent this is actually the case for different layout variants (ramp and shaft access and shaft access only). Furthermore, as a test of robustness of system performance against uncertainties related to such seals and the associated excavation damage zones, the present study also considers a broad spectrum of calculation cases including the hypothetical possibility that the seals perform much more poorly than expected and to check whether, consequently, the repository tunnel system and the access structures may provide significant release pathways.

The study considers a generic repository system for high-level waste (HLW repository) and a generic repository system for low- and intermediate-level waste (L/ILW repository), both with Opalinus Clay as the host rock. It also considers the alternative possibilities of a ramp or a shaft as the access route for material transport (waste packages, etc.) to the underground facilities. Additional shafts, e.g. for the transport of persons and for ventilation, are included in both cases.

The overall modelling approach consists of three broad steps:

1. The network of tunnels and access structures is implemented in a flow model, which serves to calculate water flow rates along the tunnels and through the host rock.
2. All relevant transport paths are implemented in a radionuclide release and transport model, the water flow rates being obtained from the preceding flow model calculations.
3. Individual effective dose rates arising from the radionuclides released from the considered repository system are finally evaluated using biosphere dose conversion factors.

The detailed modelling approaches used are to some extent rather simple and stylised, which is deemed acceptable for the purpose of the present study. In addition, all simplifications clearly lead to an overestimate of releases.

The results obtained for the HLW and for the L/ILW repository are generally similar. Quantitative differences arise from the size of the main facility, from the inventory and the properties of the emplaced waste, as well as from the concepts of how radionuclides are released from the different waste forms.

The results show that, for realistic parameter values, radionuclide release along the access structures of a deep geological repository is extremely low. Thus, they confirm the reference assumption that radionuclide release occurs predominantly through the host rock. Globally increasing the hydraulic conductivities that are assumed for the tunnel system and the seals (including the excavation damage zone along these underground structures) increases the calculated flows along all access routes, but the increase is found to level off with increasing hydraulic conductivity of seals and excavation damage zones, as flow becomes ultimately controlled by the limited capacity of the host rock to supply water. The dose rate maxima due to releases via the access structures show the same asymptotic behaviour as the flow, and remain low in all cases.
The calculated release rates along the access structures for cases where realistic hydraulic properties of the seals and the excavation damage zones were assumed are very low for all variants considered and, in particular, far less than the release rates from the host rock. It is thus concluded that the type of main access route to the underground facilities of a deep geological repository with properties as assumed for the present study is not relevant to its post-closure safety.

Finally, even for highly unfavourable parameter values for the hydraulic properties of the seals and the associated excavation damage zones, the calculated dose rates remain well below the regulatory protection criterion of 0.1 mSv per year, often by several orders of magnitude. This finding, and taking into account the fact that for these calculations a number of simplifications were made that clearly lead to an overestimate of releases, demonstrates the robustness of the repository systems considered in the present study with respect to variations of the hydraulic properties of the seals and of the associated excavation damage zones.
Zusammenfassung

Mit der Anordnung und der Versiegelung der Zugangsbauwerke zu einem geologischen Tiefenlager für radioaktive Abfälle soll sichergestellt werden, dass die Radionuklidfreisetzung aus den untertägigen Lagerkammern während der Nachverschlussphase praktisch ausschließlich über die geologische Barriere erfolgt. Der Basisfall der vorliegenden Studie, in welchem realistische Werte für die hydraulischen Eigenschaften der Versiegelungsbauwerke und der zugehörigen Auflockerungszonen verwendet werden, untersucht, inwiefern dies für verschiedene Auslegungsvarianten (Zugang über Rampe und Schächte und Zugang nur über Schächte) tatsächlich der Fall ist. Um die Robustheit des Systemverhaltens gegenüber möglichen Störeinflüssen und Ungewissheiten in Zusammenhang mit solchen Versiegelungsbauwerken und den zugehörigen Auflockerungszonen zu untersuchen, wird in vorliegender Studie zusätzlich ein breites Spektrum von Rechenfällen analysiert, einschließlich der hypothetischen Annahme, dass diese Bauwerke eine deutlich geringere hydraulische Barrierenwirkung aufweisen als erwartet, und um zu prüfen, ob deshalb die Zugangsbauwerke zu den Lagerkammern als bevorzugte Freisetzungspfade für Radionuklide aus einem geologischen Tiefenlager in Erscheinung treten könnten.


Das Vorgehen bei der Modellierung lässt sich in drei Schritte unterteilen:

1. Das Netzwerk an Untertagebauwerken und Zugangsbauwerken eines geologischen Tiefenlagers wird in einem hydraulischen Modell abgebildet, mit welchem die Wasserflüsse entlang dieser Bauwerke und durch das Wirtgestein für verschiedene Situationen berechnet werden.

2. Alle relevanten Transportpfade für Radionuklide werden, basierend auf den Ergebnissen der verschiedenen Situationen, in numerischen Transportmodellen abgebildet und jeweils eine Radionuklidfreisetzungsrate aus dem generischen Lagersystem berechnet.


Für die technische Umsetzung werden zahlreiche vereinfachende Annahmen getroffen, welche im Hinblick auf die übergeordnete Fragestellung jedoch als vertretbar betrachtet werden und welche zudem ausnahmslos zu einer Überschätzung der Freisetzungsarten führen.

Für beide Lagertypen werden qualitativ recht ähnliche Ergebnisse ermittelt. Quantitative Unterschiede zwischen den beiden Lagern lassen sich auf wenige Einflussfaktoren, namentlich auf die Grösse der Einlagerungsbereiche, auf die Eigenschaften der eingelagerten radioaktiven Abfälle sowie auf die Konzepte und Parameter zur Mobilisierung der Radionuklide aus den Abfällen zurückführen.

Die unter Verwendung von realistischen Parameterwerten für die hydraulischen Eigenschaften der Versiegelungsbauwerke und der zugehörigen Auflockerungszenen berechneten Freisetzungsaten aus den Zugangsbauwerken sind für alle betrachteten Varianten äusserst niedrig und deutlich geringer als die Freisetzungsraten aus dem Wirtgestein. Daraus wird gefolgert, dass die Art des Hauptzugangsbauwerks nach unter Tage für die in dieser Studie untersuchten Tiefenlager keine Bedeutung für deren Langzeitsicherheit hat.

Schliesslich liegen die berechneten Dosiswerte auch für sehr ungünstige Parameterwerte für die hydraulischen Eigenschaften der Versiegelungsbauwerke und der zugehörigen Auflockerungszenen deutlich unterhalb des behördlichen Schutzkriteriums von 0.1 mSv pro Jahr, in den meisten Fällen sogar um mehrere Grössenordnungen. Diese Resultate, zusammen mit der Tatsache, dass für diese Modellrechnungen zahlreiche Vereinfachungen gemacht wurden, welche allesamt die berechneten Freisetzungsaten überschätzen, zeigt deutlich die Robustheit der betrachteten geologischen Tiefenlager gegenüber möglichen Störeinflüssen und Ungewissheiten im Zusammenhang mit den hydraulischen Eigenschaften der Versiegelungsbauwerke und der zugehörigen Auflockerungszenen.
Résumé

Le dimensionnement et les dispositifs de scellement des voies d’accès d’un dépôt géologique pour déchets radioactifs doivent assurer qu’après la fermeture du site, le relâchement des radionucléides provenant des tunnels de stockage s’effectue principalement au travers de la barrière géologique. Pour la configuration de base de la présente étude, dans laquelle on a fixé des valeurs réalistes pour les propriétés hydrauliques des scellements et des zones perturbées par l’excavation qui leur sont proches, on analyse dans quelle mesure ce postulat est vérifié pour différentes architectures de dépôt (accès par le biais d’une descenderie et de puits d’une part, de puits seulement d’autre part). En outre, afin de tester la robustesse du système au regard des facteurs de perturbation et des incertitudes susceptibles d’affecter les scellements et les zones perturbées correspondantes, on a également analysé un large éventail de cas de calcul, y compris l’hypothèse selon laquelle l’efficacité des scellements en tant que barrière hydraulique se révèle très inférieure aux prévisions, ceci afin de vérifier si les accès au dépôt pourraient devenir des voies de relâchement préférentielles pour les radionucléides provenant du stockage géologique.

Ce questionnement est traité sur la base de calculs de transports de radionucléides provenant d’un site de stockage générique pour déchets de haute activité (stockage DHA) et d’un site de stockage générique pour déchets de faible et moyenne activité (stockage DFMA) situés tous deux dans les argiles à Opalinus. Dans ces calculs, tali la possibilité d’une descenderie que celle d’un puits sont étudiées et comparées comme des variantes équivalentes permettant l’acheminement des matériaux (colis de déchets, etc.) de la surface vers les ouvrages souterrains. Des puits supplémentaires, par exemple pour le transport des personnes et la ventilation, sont prévus dans chacune des variantes.

La démarche de modélisation peut être divisée en trois étapes:

1. Le réseau constitué, dans le dépôt géologique générique, par les ouvrages souterrains et les voies d’accès est représenté sous la forme d’un modèle hydraulique, qui permet pour chaque cas de calculer les écoulements d’eau le long de ces ouvrages en relation avec les flux dans la roche d’accueil.

2. Sur la base des résultats obtenus, pour chaque cas, on représente l’ensemble des cheminement de radionucléides sous la forme d’un modèle de transport numérique et on calcule un taux de relâchement des radionucléides issus du dépôt générique.

3. Ces taux de relâchement sont finalement traduits en dose effective individuelle à l’aide de facteurs de conversion biosphère, puis comparés aux objectifs de protection fixés par les autorités.

La démarche de modélisation repose pour une part sur des approches schématiques et simplifiées, qui demeurent toutefois plausibles au regard de la problématique générale à traiter et qui de plus conduisent dans tous les cas à une surévaluation des taux de relâchement.

Les résultats obtenus pour les deux types de dépôt sont, d’une manière générale, assez similaires. Les différences quantitatives constatées sont à mettre au compte d’un petit nombre de facteurs, à savoir la taille des modules de stockage, les propriétés des déchets radioactifs stockés, ainsi que les concepts et paramètres de mobilisation appliqués aux radionucléides provenant des déchets.
Les résultats montrent que, pour des paramètres de modélisation réalisistes, les taux de relâchement de radionucléides le long des voies d’accès au dépôt sont extrêmement bas. Ceci confirme l’hypothèse générale selon laquelle, dans un site de stockage géologique, le relâchement des radionucléides s’effectue en priorité au travers de la barrière géologique. Si l’on augmente progressivement la conductivité hydraulique le long de l’ensemble des ouvrages et accès souterrains (y compris dans la zone perturbée correspondante), les écoulements d’eau calculés le long de ces structures augmentent également. Toutefois, les taux d’écoulement n’augmentent pas à l’infini, mais se rapprochent d’une valeur limite, ceci étant dû au fait que le taux d’écoulement le long des ouvrages souterrains est finalement limité par le faible apport d’eau en provenance de la roche d’accueil. Les doses individuelles calculées montrent le même comportement asymptotique que les écoulements d’eau le long des ouvrages souterrains et restent faibles, même dans le cas de taux d’écoulements élevés.

Si l’on assigne des valeurs de paramètres réalisistes aux propriétés hydrauliques des scellements et des zones perturbées correspondantes, les taux de relâchement calculés pour les voies d’accès sont, pour toutes les configurations considérées, extrêmement faibles et bien inférieurs aux taux de relâchement au travers de la roche d’accueil. On en conclut que, pour les systèmes de stockage analysés dans cette étude, le type d’accès reliant la surface aux installations souterraines n’a pas d’incidence sur la sûreté à long terme.

Enfin, même si l’on fixe des valeurs de paramètres très défavorables pour les propriétés hydrauliques des scellements et des zones perturbées correspondantes, les doses calculées se situent bien en dessous de l’objectif de protection de 0.1 mSv par an fixé par les autorités – dans la plupart des cas elles lui sont inférieures de plusieurs ordres de grandeur. Ces résultats, combinés au fait que ces modélisations reposent sur des approches simplifiées qui, toutes, conduisent à une surévaluation des taux de relâchement, montrent clairement la robustesse des systèmes de stockage géologique considérés au regard de perturbations potentielles et incertitudes en relation avec les propriétés hydrauliques des scellements et des zones perturbées par l’excavation qui leur sont proches.
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1 Introduction

1.1 Background and aims

In Switzerland, the Nuclear Energy Law requires the disposal of all types of radioactive waste in deep geological repositories (KEG 2003). The Swiss Radioactive Waste Management Programme (Nagra 2008a) foresees two types of repositories: a high-level waste repository (HLW repository)\(^1\) for spent fuel (SF)\(^2\), vitrified high-level waste (HLW) and long-lived intermediate-level waste (ILW), and a repository for low- and intermediate-level waste (L/ILW repository)\(^3\). The procedure for selecting repository sites is specified in the concept part of the Sectoral Plan for Deep Geological Repositories\(^4\) (SGT, BFE 2008). The Sectoral Plan foresees a selection of sites in three stages, the third of which leads to a General Licence Application procedure that defines both the sites and the main features of the two repositories.

In SGT Stage 1, Nagra proposed geological siting regions for the HLW repository and the L/ILW repository based on safety and engineering feasibility criteria (Nagra 2008b). These proposals were later evaluated by the responsible federal authorities and their experts, who all came to a positive conclusion (ENSI 2010, KNE 2010, KNS 2010). In 2011, all proposed geological siting regions were formally approved by the Swiss Government (BFE 2011).

In SGT Stage 2, the overall objective is twofold: (i) to select at least two geological siting regions for each repository type for further geological investigations in SGT Stage 3; and (ii) to identify suitable locations for the surface facility in the geological siting regions identified in SGT Stage 1. In this context, it is important to show that flexibility exists in the siting of the surface facility, irrespective of the exact position of the underground facilities, which will be defined in detail following further geological investigations in SGT Stage 3.

Figs. 1.1-1 and 1.1-2 show example layouts of the L/ILW repository and the HLW repository with their respective main features, including the surface facilities and the underground facilities. The layouts are based on the scenario of a 50 year operation period for the five nuclear power plants in Switzerland and a collection period for radioactive waste resulting from medicine, industry and research up to the year 2050. In both example layouts, the main access from the surface facility is provided by a ramp ("Access tunnel" in the figures), which, among other purposes, serves as the main transport route for the radioactive waste to be emplaced underground.

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\(^1\) German: HAA-Lager.

\(^2\) According to current legislation, spent fuel is classified as radioactive waste.

\(^3\) German: SMA-Lager.

\(^4\) German: Sachplan geologische Tiefenlager (SGT)
Fig. 1.1-1: Example layout of the L/ILW repository with its main features. Not drawn to scale.

Fig. 1.1-2: Example layout of the HLW repository with its main features. Not drawn to scale.
As can be seen in Figs. 1.1-1 and 1.1-2, the use of a ramp as the main access route for radioactive waste to the underground facilities for both the HLW repository and the L/ILW repository contributes to the required flexibility in the siting of the surface facility, since it allows an offset of the surface facility with respect to the location of the underground facilities. However, besides the use of a ramp, an equally flexible solution is obtained by using a combination of shafts and (sub-) horizontal tunnels. Note that, regardless of the type of main access, additional underground access structures are also necessary. In the present example layouts, a ventilation shaft (VS) and an operations / construction shaft (CS) are indicated, along with the corresponding shaft head at the surface. In the following, the terms "underground access structure" or just "access structure" are used to refer to the ramp or shafts.

In the example layouts, all underground facilities are constructed in the host rock formation and form a network of tunnels, also referred to as (repository) tunnel system in the following. For repository closure, all underground structures are backfilled and, at selected locations, sealing elements (seals) are installed to limit potential water flow along the tunnel system. The underground access structures, i.e. the ramp and the shafts, are also sealed. As a result, any radionuclide release from the emplacement rooms during the post-closure phase of the deep geological repositories is expected to occur primarily in the vertical direction through the host rock. The repository tunnel system and the underground access structures are not expected to provide significant release pathways.

Nevertheless, to test the robustness of the post-closure performance of the repository systems, the present study considers the hypothetical possibility that the seals perform more poorly than expected. In such a case, increased water flow would occur through the tunnel system and the access routes, driven by natural hydraulic gradients. This would allow radionuclide release via the underground access structures in addition to the release pathways through the host rock. This report evaluates the consequences of this scenario for post-closure safety, based on flow and radionuclide transport calculations, which are carried out for both the HLW repository and the L/ILW repository.

In Project Opalinus Clay, the scenario of radionuclide release affected by the ramp and shafts was already evaluated with radionuclide transport modelling, assuming water flow generated by natural hydraulic gradients, tunnel convergence and repository-induced gas (see Sections 7.4.7, 7.4.8 and 7.4.9 of Nagra 2002a and, for modelling details, Sections 3.6, 3.7 and 3.8 of Nagra 2002b). This modelling work was later refined and consolidated in a follow-up report (Smith et al. 2004). The present study further extends and refines the earlier work by taking into account, for example, not only groundwater inflow from the host rock to the emplacement rooms, but also inflow to the entire repository tunnel system. It is also based on current concepts for the HLW and L/ILW repository architecture. The modelling approach and parameter values are chosen to err on the side of conservatism in the sense that dose rates are expected to be overestimates.

5 Such a situation could, in theory, occur (i) if there are undetected errors or defects during the construction of the seals, (ii) if later the sealing materials degrade unexpectedly or (iii) if the excavation damage zone (EDZ) in the host rock evolves in an unexpected and unfavourable manner. However, the planned quality control measures during construction and on-going extensive research to further strengthen the scientific understanding of the evolution of the repository system mean that the likelihood of such a situation occurring is very low.

6 An important difference compared with earlier concepts for repository architecture in the context of the present work is that the concepts now include dead-end emplacement rooms and dead-end disposal areas.
This study takes into account recommendations from the Swiss safety authorities as an outcome of their evaluation of Project Opalinus Clay (see Nagra 2008c). In particular, recommendation number 2.1.1-10 (see Section 2.1.1 of Nagra 2008c) suggests that Nagra should carry out further sensitivity analyses of radionuclide transport assuming less favourable hydraulic properties for the buffer in the SF / HLW emplacement rooms and for the backfilled underground access structures and seals. Thus, the focus of the study is on situations giving rise to far more substantial flows through the emplacement rooms, the repository tunnel system and the access structures than would be expected in reality. In this way, it forms the basis for potentially more detailed analyses that may be needed in support of the General Licence Applications in SGT Stage 3.

One particular aim of this study is to compare two variants for the main access route to the underground facilities: main access via a ramp and main access via a shaft. The inclusion of the alternative of main access via a shaft arose in the course of discussions on finding suitable sites for the surface facility of each repository in the course of SGT Stage 2. An official technical meeting with the regulatory authority ENSI and with SGT stakeholders was held on 5 July 2012 at the offices of ENSI. The general topic of the meeting was the state-of-the-art of sealing the access routes to the underground facilities of a deep geological repository. As a contribution to this discussion, Nagra presented an extension of the earlier analyses (mentioned above) in order to evaluate systematically the influence of the different types of access routes on post-closure safety. The work presented on 5 July 2012 was provisional and has since been refined and consolidated in the present report.

1.2 Overview

Fig. 1.2-1 presents an overview of the conceptual model for a scenario with radionuclide transport along the tunnel system and the underground access structures of a deep geological repository. It schematically illustrates the emplacement rooms with the emplaced waste, the tunnel system at repository level and the two principal types of access structure: a ramp and a shaft. All underground structures are backfilled and seals are installed at selected locations.

The underground structures at repository level are assumed to lie in a horizontal plane at a depth that places it approximately at the centre of the host rock. For the purposes of this study, the properties assigned to the host rock are based on those of Opalinus Clay, which is the only host rock under consideration for the HLW repository, and which is also a candidate host rock for the L/ILW repository. In the respective geological siting regions, Opalinus Clay is embedded between overlying and underlying low-permeability confining units, some of which are also considered potential host rocks for the L/ILW repository. However, in this modelling study, only the situation of an isolated host rock is considered.
Relatively permeable formations (aquifers) are assumed to lie beneath and above the host rock. The hydraulic head differs between these aquifers, resulting in a broadly vertical groundwater flow through the host rock (longer blue arrows in Fig. 1.2-1). Note that, in the present study, the access structures (ramp and shafts) both enter the host rock at its boundary with the overlying aquifer, which is assigned a lower hydraulic head value than the underlying aquifer. This is a pessimistic assumption with respect to radionuclide release via the access structures. Furthermore, this head value is assumed to be the same for all exit points of the access structures from the host rock.

In most of the scenarios considered in the present report, the seals and backfill materials are assumed not to fulfil their barrier functions entirely, thus allowing water flow and radionuclide transport along the repository tunnel system (shorter blue and green arrows). As a result, radionuclides are released via the access structures in addition to the radionuclide transport pathways through the host rock (longer green arrows).

Radionuclides that arrive at the boundaries of the host rock (also called release points) are assumed to be instantly transferred to the biosphere. From the radionuclide fluxes at the release points, a time-history of effective individual dose rate (hereafter referred to simply as dose rate) is calculated by multiplication with steady-state biosphere dose conversion factors. Calculations are, for illustrative purposes, extended up to 10^7 years. However, the emphasis in the discussion of the calculated dose rates is on the respective time frames for safety assessment, which have been reasoned to be 10^5 years for the L/ILW repository and 10^6 years for the HLW repository (Nagra 2008d).

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The selected approach is pessimistic compared with the alternative, hypothetical situation in which the overlying aquifer is assigned a higher hydraulic head than the underlying aquifer. In this alternative situation, water would be forced from the repository tunnel system into the host rock, and no advective transport of radionuclides along the repository tunnel system to the overlying aquifer would occur.
The overall modelling approach consists of three steps. Firstly, the network of tunnels (including the emplacement rooms) is implemented in a flow model and water flow rates along the tunnel system are calculated. Secondly, all relevant transport paths are implemented in a transport model, the water flow rates within the individual transport paths being obtained from the flow model calculations. Thirdly, dose rates are determined from the calculated radionuclide release rates at the exit points of the repository system under consideration using biosphere dose conversion factors. Detailed assumptions that are made in implementing this modelling approach are presented later in this report.

Owing to the ongoing preparation of the technical documentation for SGT Stage 2, input data for this modelling study may reflect the current state of knowledge or that of earlier milestones in the Swiss programme. The following list summarises the different sources used for various input data categories and provides the rationale for their selection.

- **Input parameters with respect to the dimensions and to the flow and transport properties of the host rock** are chosen from Nagra (2010), which is the latest approved milestone in the Swiss programme.

- **With respect to the biosphere**, the concept of steady-state biosphere dose conversion factors is applied and the reference values for a temperate climate in Nagra (2010) are used.

- **Repository configuration data** are obtained from the most recent cost studies 2011, which are based on the scenario of a 50 year operation period of the Swiss nuclear power plants (NPPs). Inventory data are taken from Nagra (2008d), the safety calculations of which are based on the same waste scenario. However, for technical reasons, SF and HLW inventory data are taken from Nagra (2010) and adapted to the waste scenario under consideration (see Section 2.5).

- **Concepts and input data with respect to nuclide release from the waste forms** are mainly taken from Nagra (2010). The only exception concerns the matrix dissolution rate of SF, for which the current state of knowledge is applied (see Section 2.5).

- **Flow and transport data for the tunnel system** are, where possible, either derived from parameters for the emplacement rooms in Nagra (2010), or reflect the current state of knowledge.

Complete input data sets are listed in Appendices A and B.

Several sets of calculation cases are defined to explore issues and uncertainties that are specific, or have a strong link, to the scenario of radionuclide transport via the underground access structures of a deep geological repository. Other uncertainties concerning, for example, geochemical retention in the engineered structures and the host rock, are investigated to a more limited extent. Repository-induced effects, such as transient flows driven by tunnel convergence and repository-generated gas, are not discussed in this report. However, the concepts and parameter ranges investigated in the present report are intended to be broad enough to at least bound the effects of such transient flows, which is shown in specific reports with back-reference to the present report.
1.3 Structure of this report

The remaining chapters of this report are organised as follows.

- Chapter 2 describes the considered HLW and L/ILW repository systems, including the radioactive waste types and the radionuclide inventory, as well as the engineered and natural barriers.

- Chapter 3 gives an overview of how flow and transport modelling and the evaluation of dose are carried out.

- Chapter 4 describes the various calculation cases, their aims and how they are implemented.

- Chapter 5 describes the results of the analyses of the calculation cases.

- Chapter 6 presents the conclusions.

Further details on flow and transport modelling are provided in Appendices A and B, respectively. Appendix C provides more detailed analyses of selected results and also presents simplified analytical flow and transport models that are used to enhance understanding of the numerical results. Finally, Appendices D and E give lists of the abbreviations and of the most important mathematical symbols used in this report.
2 Description of the Repository Systems

2.1 Geological and hydrogeological settings

As mentioned in Section 1.2, the situation of a hydraulically isolated host rock is considered in this modelling study. The host rock is assumed to be saturated, homogeneous (with the exception of excavation disturbance; see Section 2.3) and isotropic porous medium. Interfaces with overlying and underlying rock formations are treated as fixed hydraulic head boundaries. The difference between the heads imposed at these boundaries gives rise to a steady, ambient flow through the host rock.

The properties assigned to the host rock are based on those of Opalinus Clay. An isotropic hydraulic conductivity is assumed, even though evidence exists for hydraulic anisotropy in Opalinus Clay. Anisotropy would have some impact on the amount of water that passes into, and out of, the tunnels in a vertical plane normal to the tunnel axis (see Sections A.2.1 and A.2.2). Nonetheless, the vertical ambient hydraulic gradient together with the large lateral extent of the repository compared with its vertical extent means that the overall flow through the host rock is predominantly vertical and is thus controlled mainly by the vertical component of hydraulic conductivity (as explained in Section C1.2, for high water flow rates, inflow to the repository tunnel system depends mainly on the size of the repository footprint together with the magnitude of the vertical, ambient flow). In line with Nagra (2010), the hydraulic conductivity of the host rock is set to $2 \times 10^{-14}$ m/s for the HLW repository and to $1 \times 10^{-13}$ m/s for the L/ILW repository. These values are typical of Opalinus Clay, perpendicular to its bedding planes, as it appears in the geological siting regions and reflect the fact that in some siting regions there may be less overburden in the case of the L/ILW repository than in the case of the HLW repository. The effects of a higher hydraulic conductivity in the host rock are investigated with a specific set of calculation cases (calculation cases related to hydraulic conductivity of the host rock described in Sections 4.3 and 5.2).

In the case of the HLW repository, the host rock is assumed to extend for 55 m above the repository horizon and 55 m below. The hydraulic head is set to 0 m and 110 m at the upper and lower boundaries of the host rock, respectively, which corresponds to a steady ambient hydraulic gradient of 1 with water flow directed upwards. For the L/ILW repository, the host rock is assumed to extend for 55 m above the repository horizon and 50 m below. The hydraulic head is set to 0 m and 105 m at the upper and lower boundaries, respectively, again corresponding to a steady ambient hydraulic gradient of 1 with water flow directed upwards. Note that the hydraulic head at the exit points of the access structures (ramp and shafts) is also set to 0 m for both repository types.

The steady ambient hydraulic gradient across the host rock is the ultimate driver for sustained advective flow through the tunnel system. If its magnitude is close to zero, then there is negligible flow along the tunnel system, regardless of the flow properties of the backfilling and sealing materials. An ambient hydraulic gradient of 1 is considered a pessimistic value for the geological siting regions with Opalinus Clay as a host rock. Transient hydrogeological phenomena (e.g. as a result of glacial processes) may cause relatively high ambient hydraulic gradients for limited periods during post-closure phase, the consequences of which are not covered by the stationary case. Such phenomena are outside the scope of the present report; a detailed discussion of potential transient hydrogeological phenomena in Opalinus Clay (albeit not dealing with radionuclide transport along the access structures) is given in Nagra (2003).

Radionuclide transport parameters for the host rock are summarised in Appendix B.2.
2.2 Repository configurations

The present modelling study is based on the reference configurations of the HLW repository and the L/ILW repository developed in the course of Nagra's 2011 cost study, which are based on the scenario of a 50 year operation period of the Swiss NPPs. The term configuration includes, in the present context, the repository architectures, as well as the tunnel dimensions, the planned backfilling and sealing of all underground structures, and the inventories of emplaced waste.

The radioactive materials to be disposed of in the two deep geological repositories consist of:

- **SF** in the form of fuel assemblies, which contain a large number of irradiated fuel rods (100 to 200). The fuel rods consist of stacks of cylindrical pellets within a zirconium alloy (Zircaloy) cladding, along with other structural materials such as steel alloys. The pellets are composed of ceramic uranium oxide (UO₂) or a blend of UO₂ and PuO₂ (MOX).
- **HLW**, in which radionuclides are incorporated in a homogenous borosilicate glass matrix within a thin stainless steel fabrication flask.
- **ILW** and **LLW**, which contain much lower activities than SF or HLW, and in which radionuclides are embedded within a cement matrix or, in some cases, within a bitumen, polystyrene or borosilicate glass matrix. The waste matrix is usually packed in steel drums and / or concrete containers.

SF assemblies and fabrication flasks with vitrified HLW are packed in disposal canisters in the surface facility. These disposal canisters are of about 5 (SF) and 3 (HLW) meters long and are about 1 m in diameter. Following transport of the disposal canisters to the underground facilities, they are emplaced in dead-end emplacement rooms that are between 300 and 1000 m in length and have a circular profile with an initial diameter of about 2.5 m. According to the current concept, the emplacement will be co-axial with respect to the room walls, thus requiring a pedestal of compacted bentonite blocks on which the disposal canisters will be placed. Immediately after emplacement, the respective room section is backfilled with highly compacted bentonite granules. The bentonite blocks and granules together form a protective mechanical and chemical buffer around the disposal canisters. A spacing of about 3 m is foreseen between individual canisters to limit temperature rise in the bentonite and in the host rock due to the residual thermal power of SF and HLW. After an emplacement room has been completely filled, a final seal consisting of highly compacted bentonite granules is installed (see Section 2.4). To increase the level of compartmentalisation in the repository, so-called intermediate seals will be installed at frequent intervals along the SF / HLW emplacement rooms. The effect of such intermediate seals on radionuclide transport along the repository tunnel system is investigated with a specific set of calculation cases (see Sections 4.3 and 5.2).

ILW is packed in concrete disposal containers of standard size in the surface facility. After transport to the underground facilities, the containers are stacked in dead-end emplacement rooms, which are supported by concrete lining. ILW is divided into two waste groups (ILW-1 and ILW-2), each emplaced in its own group of emplacement rooms. Some flexibility exists with regard to the dimensions of the ILW emplacement rooms. In this study, room profiles of about 8 m width are assumed for both groups. The remaining void spaces in the emplacement rooms are backfilled with a specifically designed mortar and finally the rooms are sealed. The current concept foresees a gas-permeable seal at the end of ILW emplacement rooms (see Section 2.4).
The concept of emplacement for the L/ILW repository is in many ways identical to that for the ILW part in the HLW repository. For instance, L/ILW is also divided into two categories (L/ILW-1 and L/ILW-2), each emplaced in separate emplacement rooms. One difference concerns the somewhat greater flexibility with respect to the size of emplacement rooms, since a broader range of geological conditions among the geological siting regions and candidate host rocks for the L/ILW repository is expected. For the present study, a room type of medium size is selected. It has a width of approximately 10 m and a height of approximately 13 m.

The underground facilities of the HLW repository and the L/ILW repository both comprise (see the example layouts in Figs. 1.1-1 and 1.1-2):

- the main facility with the emplacement rooms,
- a pilot facility containing representative amounts of the disposed radioactive waste,
- a test area, also referred to as the underground research laboratory (URL),
- a central area,
- the underground access structures (i.e. ramp and/ or shafts), and
- various types of seals at different locations within the underground tunnel system and the underground access structures.

In the present repository layouts, to minimise any possible interaction of the pilot facility with the remaining underground facilities (e.g. disturbance of observation measurements in the pilot facility due to construction activities in the main facility), there is no direct tunnel connection between the pilot facility and the other underground facilities within the host rock. In the present modelling study, the pilot facility is thus assumed to have no significant hydraulic effect on the main facility and is therefore not explicitly modelled. Nevertheless, its inventory is added to the inventory of the main facility.

Within the main facility, the emplacement rooms will be arranged in disposal areas\(^8\), the ultimate shape of which will be determined based on the in-situ geological conditions. In the present study, a regular alignment of emplacement rooms in disposal areas is assumed.

The use of a tunnel liner is expected for all types of underground structures. In the case of the SF / HLW emplacement rooms, the liner will be interrupted every 10\(^{th}\) canister position or so by an intermediate seal, where physical contact will occur between the bentonite backfill and the Opalinus Clay host rock. The lining of the underground structures is not explicitly modelled in the calculation cases presented in this document, but is implicitly considered through the modelling of the excavation damage zone (EDZ, see Sections 2.3 and 4.3.4).

The repository layout of the HLW repository and the planned backfilling and sealing of the underground structures are shown in Fig. 2.2-1, which is the basis for the flow and transport models developed later in this report. Fig. 2.2-2 gives the equivalent information for the L/ILW repository. In both repository layouts, three emplacement rooms in the main facilities are slightly shorter than the rest of the emplacement rooms in the main facility. For simplicity, however, all emplacement rooms in a main facility are assumed to have the same length: 200 m for emplacement rooms in the L/ILW main facility and 700 m for emplacement rooms in the HLW main facility.

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\(^8\) The term disposal area includes a certain distance from groups of emplacement rooms, whereas the term disposal room area neglects such distance. In this report, for reasons of simplicity, the term disposal area is also used for the latter.
Fig. 2.2-1: Layout of the backfilled and sealed HLW repository.

All underground structures, with the exception of the emplacement rooms and the sealing elements V1 and V3, are backfilled with a sand / bentonite mixture (see Tab. 2.4-1).

In the 2011 cost studies, a relatively small cross-sectional area was assumed for the ILW emplacement rooms. In the present study, a slightly larger cross-section is assumed, and so the lengths of the ILW emplacement rooms are not derived from Fig. 2.2-1, but taken from Nagra (2008d).

Fig. 2.2-2: Layout of the backfilled and sealed L/ILW repository.

The ventilation tunnel and the test facility are backfilled with crushed host rock (bright orange). All other underground structures, with the exception of the emplacement rooms and the sealing element V3, are backfilled with a sand / bentonite mixture (see Tab. 2.4-1).
The locations of the entry points to the repository access structures (ramp and shafts) at the repository level in these figures should be regarded as examples from a variety of possibilities. If the ramp, as the main transportation route for radioactive waste, is replaced by a third shaft, again a variety of locations for this third shaft is conceivable.

For simplicity, and in order to obtain an unbiased comparison between ramp and third shaft as the main access structure, this modelling study assumes that, for each repository type, (i) the entry point of the main access route into the central area is located relatively close to the main facility, which is pessimistic with respect to radionuclide release from the main facility; and (ii) the distance from the entry point of the respective access structure to its sealing element is equal for both options and entirely at repository level. This distance is set to a generic value of 200 m (see Figs. 2.2-1 and 2.2-2).

The branch tunnel to the third shaft is assumed to have the same dimensions and properties as the ramp. The third shaft itself is assumed to have the same geometric properties as the other shafts. This assumption may not be realistic if this third shaft were to serve as the main access structure, but it is nonetheless considered adequate in view of the wide range of hydraulic conductivity values investigated for the shaft sealing material.

In the flow and transport modelling, all underground structures are modelled as circular, straight tubes, with flow and transport properties that are assumed to be homogenous and isotropic. The equivalent radii of these tubes are generally derived from the clearance area of the individual tunnels, with the exception of the ILW and L/ILW emplacement rooms, where a 0.3 metre-thick lining is additionally taken into account. Tunnel convergence is generally neglected in view of the wide range of hydraulic conductivity values investigated. Short tunnel sections with special cross sections (locks, unloading areas etc.) are neglected or modelled with the dimensions of the longer neighbouring tunnels.

The underground structures considered in the modelling, their profile types, with notation according to the 2011 cost studies, and the calculated equivalent radii are given for each repository type in Tab. 2.2-1. General flow and transport properties in the tunnel system are presented in Section 2.6. Flow and transport parameters of the individual modelled tunnels can be obtained from the description of the flow and transport models in Appendices A and B.
Tab. 2.2-1: Modelled underground structures, profile types with notation according to the 2011 cost studies and calculated equivalent radii for the HLW repository and the L/ILW repository.

<table>
<thead>
<tr>
<th>Tunnel (profile type)</th>
<th>Equivalent radius [m]</th>
<th>Tunnel (profile type)</th>
<th>Equivalent radius [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operations tunnel, construction tunnel, cross-cut, central area, observation tunnel (D5/L)</td>
<td>2.55</td>
<td>Operations tunnel, construction tunnel, cross-cut, central area, observation tunnel (D5/L)</td>
<td>2.55</td>
</tr>
<tr>
<td>Construction shaft, ventilation shaft (S2)</td>
<td>3.00</td>
<td>Operations shaft, ventilation shaft (S2)</td>
<td>3.00</td>
</tr>
<tr>
<td>Ramp (A5)</td>
<td>3.18</td>
<td>Ramp (A5)</td>
<td>3.18</td>
</tr>
<tr>
<td>Branch-off emplacement rooms ILW (L)</td>
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<td>Branch-off emplacement rooms ILW (L)</td>
<td>2.55</td>
</tr>
<tr>
<td>Emplacement rooms ILW, including lining (K06)</td>
<td>5.31</td>
<td>Emplacement rooms L/ILW, including lining (K09)</td>
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<tr>
<td>Branch-off emplacement rooms SF / HLW (E)</td>
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<td></td>
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<tr>
<td>Emplacement rooms SF / HLW and seal V1 (F)</td>
<td>1.25</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.3 **Rock disturbance due to excavation**

The excavation of the underground structures will mechanically disturb the host rock in the vicinity of the underground structures. In particular, stress re-distribution due to excavation will lead to the formation of micro- and macro-scale fractures that will affect the hydraulic and transport properties of the rock close to the excavated structures. This disturbed rock zone can conceptually be split into an inner part, where the connectivity of fractures is such that the macroscopic hydraulic conductivity is significantly enhanced, and an outer part, where little change of the hydraulic conductivity is expected (see Nagra 2002c and Alcolea et al. 2014). The inner part is in the following referred to as excavation damage zone (EDZ).

After repository closure, it is expected that the excellent self-sealing capacity of Opalinus Clay, in combination with the swelling capacity of the backfill and sealing materials and the effects of tunnel convergence, will eventually result in EDZ flow and transport properties that are comparable to those of the undisturbed rock. Nevertheless, for the purposes of the present study, it is cautious to assign the inner EDZ a higher average hydraulic conductivity than the undisturbed rock. This accounts for the possibility that (i) the swelling pressure of the buffer and backfill materials and the effects of tunnel convergence do not fully restore the undisturbed hydraulic properties of the rock and / or (ii) this process is adversely influenced by the liner, which is planned to be removed only at the position of selected seals.

In most calculation cases, the EDZ is treated as a homogeneous, isotropic porous medium, forming an annular region 0.7 m thick around each of the underground openings. However, because some micro- and macro-scale fracturing may persist over time, it is appropriate, as an alternative conceptual model, to also represent the EDZ as a fractured porous medium. This is done with a specific set of calculation cases (see calculation cases addressing conceptualisation...
of the EDZ in Sections 4.3 and 5.2). Note that, in most calculation cases, it is assumed that the EDZ at the positions of the seals is not removed. This is conservative with respect to flow along the repository tunnel system, but is not in agreement with the current sealing concept, which foresees that the EDZ will be removed as far as possible.

The persistence of an EDZ may also affect vertical transport of radionuclides through the host rock towards the release points at the upper and lower boundaries. Consistently with Nagra (2010), this is accounted for by assuming reduced vertical transport lengths in the host rock. As a pessimistic approach and in accordance with Nagra (2010), the vertical extent of the SF / HLW emplacement rooms including the EDZ is estimated to be 5 m and the respective value for the ILW and the L/ILW emplacement rooms is taken to be 20 m.

General flow and transport properties of the EDZ are specified in Section 2.6. Values for the individual modelled tunnels are given in Appendices A and B.

### 2.4 Sealing elements

Sealing elements (also referred to as seals) provide a number of different operational and post-closure safety functions. For example, the seals constructed at the end of the ILW emplacement rooms protect the work force from waste that has already been emplaced during the operational phase and, at the same time, provide favourable chemical conditions inside the emplacement room after waste emplacement. Another example is presented by the seals of the disposal areas, which, among other purposes, provide hydraulic isolation of individual disposal areas from each other (compartmentalisation) in order to reduce unfavourable consequences of possible localised external or internal disturbances during the post-closure phase of a repository.

In the present context, the main function of the seals is the limitation of potential water flow through the tunnel system and the underground access structures. As a result, radionuclide release from the emplacement rooms during the post-closure phase is expected to occur primarily to the surrounding host rock.

Sealing elements consist of several components, including bulkheads, transition elements and the actual sealing component, which, according to the current concept, is made of bentonite or a sand / bentonite mixture. In the present modelling study, only the actual sealing component is considered and is, in the following, referred to as the seal or sealing element. For the other components, it is assumed that the respective tunnel sections are backfilled with the same material as the neighbouring non-seal tunnel sections.

The lengths of the different types of seal and the respective sealing materials are assumed to be the same for both repository types (as far as applicable), and are listed in Tab. 2.4-1. The assumed locations and the names of the individual seals are indicated in Figs. 2.2-1 and 2.2-2, although these figures do not account for the actual lengths of the individual sealing elements. Furthermore, they do not account for the intermediate seals inside the SF / HLW emplacement rooms; the properties of these seals are described in the context of the set of calculation cases that addresses their potential impact (see calculation cases addressing transport in the SF / HLW emplacement rooms and the role of intermediate seals in Sections 4.3 and 5.2).

General flow and transport parameters of the seals are given in Section 2.6. Information about the flow properties of the individual modelled seals are included in the description of the flow models in Appendix A. Transport properties of the individual seals are listed in Appendix B. As noted above, in most calculation cases, it is assumed that the EDZ at the position of the seals is not removed, which is not in agreement with the current sealing concept.
Tab. 2.4-1: Length and sealing material for the different seal types.

For the seal types V2 and V4, each seal is assumed in the model to consist of two sealing elements, 50 m in length, which, if implemented, would provide redundancy. However, for the V3 seal type (i.e. the shaft seal) only a single sealing element 40 m in length is modelled, since the assumed thickness of the host rock does not leave space for a redundant second sealing element.

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Sealing material</th>
<th>Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>Seal at the ends of SF / HLW emplacement rooms</td>
<td>Compacted bentonite</td>
<td>12 m</td>
</tr>
<tr>
<td>V2</td>
<td>Gas-permeable seal for entire disposal areas</td>
<td>Compacted sand / bentonite mixture with mass ratio 70/30</td>
<td>2 × 50 m</td>
</tr>
<tr>
<td>V3</td>
<td>Shaft seal</td>
<td>Compacted bentonite</td>
<td>40 m</td>
</tr>
<tr>
<td>V4</td>
<td>Gas-permeable seal for ramp</td>
<td>Compacted sand / bentonite mixture with mass ratio 70/30</td>
<td>2 × 50 m</td>
</tr>
<tr>
<td>V5</td>
<td>Gas-permeable seal for ILW and L/ILW emplacement rooms</td>
<td>Compacted sand / bentonite mixture with mass ratio 70/30</td>
<td>40 m</td>
</tr>
</tbody>
</table>

2.5 Radionuclide inventories and release data

As mentioned in the Introduction and in Section 2.2, the repository configurations considered are based on the scenario of a 50 year operation period for the five NPPs in Switzerland and a collection period for radioactive waste resulting from medicine, industry and research that extends up to the year 2050. Therefore, inventory data for ILW and L/ILW are taken from the safety calculations in Nagra (2008d), which are based on the same waste scenario.\(^9\)

For technical reasons, SF and HLW inventory data are taken from Nagra (2010), which are, however, based on a waste scenario that considers SF from the additional NPPs that were proposed at that time. For simplicity, the respective inventory data are scaled by the ratio between the number of SF disposal canisters in Nagra (2008d) and that in Nagra (2010) for each canister type.

The radionuclides considered in the modelling study are the same as reported in Appendix A3 in Nagra (2008d) and are listed in Appendix B, along with half-life values and decay chain parameters. The summed activities at the year 2050 for each type of SF / HLW disposal canister and each type of ILW and L/ILW emplacement room are also reported in Appendix B.

Input data and concepts with respect to radionuclide release from the waste forms are mainly taken from Nagra (2010). In particular, the time of complete containment is set to 10'000 years for SF and HLW and to 100 years for ILW and L/ILW. In terms of the fractional matrix dissolution rate of SF, however, a constant value of \(10^{-7}\) per year is applied, which reflects the current state of knowledge (Nagra 2013).

---

\(^9\) In particular, the so-called reference waste allocation to the two repository types (German: 'Referenzzuteilung') is used.
In this study, the interior of the emplacement rooms is modelled in a relatively abstract manner. That is to say, the disposal containers and canisters are not modelled explicitly. Rather, the radionuclides are assumed to be released homogenously into the emplacement rooms, which are assumed to be filled with backfill material only. More details on the treatment of the emplacement rooms in transport modelling are provided in Section 3.4.

2.6 General flow and transport parameters

Each underground structure is conceptualised as a circular and straight cylinder (tunnel) consisting of a homogeneous, isotropic medium, surrounded by a second annular region (EDZ) that also consists of a homogeneous, isotropic medium. These two parts are also referred to as (flow / transport) domains in later chapters. Furthermore, underground structures are each allocated to one of six different types (#1 to #6), according to their flow and transport properties (see Tab. 2.6-1).

In the following, reference flow and transport parameter values for the host rock, the underground structures and their EDZ are either taken or derived from values given in Nagra (2010), or otherwise reflect the current state of knowledge. Uncertainties in the flow and transport properties of the host rock and the underground structures (including their EDZ) are reflected in the selection of alternative conceptual models and/or parameter values for the calculation cases defined in Chapter 4.

2.6.1 Flow parameters

The values for the hydraulic conductivity $K$ and the transport-relevant porosity $n$ of the different types of underground structure (including the EDZ) are summarised in Tab. 2.6-1.\(^{10}\) This table also indicates the sources of some individual porosity values. Note that a difference in accessible porosity for anions and non-anions is assumed only for tunnels and shafts backfilled or sealed with compacted bentonite (tunnel types #1 and #3).

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\(^{10}\) The porosity values given in Tab. 2.6-1 are not fully consistent with the given dry bulk density values and the prescribed sand / bentonite mass ratios. However, these discrepancies are very small and have no significant impact on the overall results.
Tab. 2.6-1: Reference flow and transport data.
Underground structures are each allocated to one of six different tunnel types (#1 to #6). Values for anions are given in brackets.

<table>
<thead>
<tr>
<th>Tunnel type (backfill / sealing material)</th>
<th>Tunnel</th>
<th>EDZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>SF / HLW emplacement rooms and seal V1 (compacted bentonite)</td>
<td>1E-13 0.36 (0.05)²</td>
<td>1'E50 1E-12</td>
</tr>
<tr>
<td>Seals V2, V4, V5 (compacted sand / bentonite mixture 70/30)</td>
<td>1E-11 0.27³</td>
<td>480 1E-11</td>
</tr>
<tr>
<td>Shaft seal V3 (compacted bentonite)</td>
<td>1E-13 0.36 (0.05)²</td>
<td>1'E50 1E-12</td>
</tr>
<tr>
<td>Other tunnels (sand / bentonite mixture 70/30)</td>
<td>1E-9 0.3</td>
<td>450 1E-10</td>
</tr>
<tr>
<td>Other tunnels (crushed host rock)</td>
<td>1E-9 0.4</td>
<td>1'E50 1E-10</td>
</tr>
<tr>
<td>L/ILW and ILW emplacement rooms (mortar)</td>
<td>1E-6 0.2</td>
<td>not required 1E-10</td>
</tr>
</tbody>
</table>

¹ Senger & Ewing (2008), valid for an equivalent porous medium
² Nagra (2010)
³ Nagra (2008e)

### 2.6.2 Sorption and solubility limitation

Transport of radionuclides along the tunnel system is retarded by element-specific sorption on accessible solid grain surfaces. In line with the general modelling approach adopted in the provisional safety analyses for SGT Stage 2 (Nagra 2014), sorption is assumed to be fully reversible and to be linear (i.e. the amount sorbed onto a surface is proportional to the dissolved concentration in the surrounding fluid). Hence, a retardation coefficient $R^E$ of element $E$ in the different backfill and sealing materials of the tunnel system can be defined as:

$$R^E = 1 + \frac{K^E_A \cdot \rho_s}{\eta^E}$$  \hspace{1cm} (2.6-1)

$K^E_A$  sorption coefficient of element $E$ [m$^3$/kg]
$\rho_s$  dry bulk density of sorbing material [kg/m$^3$]
$\eta^E$  element-specific porosity [-]

The sorption coefficients $K^E_A$ for the backfill material of the SF / HLW emplacement rooms (bentonite) and for the host rock are taken from the modelling work reported in Nagra (2010).
Chemical conditions in the tunnels backfilled / sealed with bentonite or with a sand / bentonite mixture are assumed to be similar to those in the SF / HLW emplacement rooms. Thus, in the following paragraphs, retention parameters are derived from those of the bentonite buffer in the SF / HLW emplacement rooms in Nagra (2010). In particular, the same sorption coefficients are used. Likewise, the chemical conditions in the tunnels backfilled with crushed host rock and in the EDZs of all tunnels are assumed to be similar to those of the host rock, such that the sorption coefficients for the host rock can also be used for these repository elements. Note that, since a possible lining structure along the repository tunnel system is not considered in the calculation cases presented here (at least not explicitly), no sorption coefficients for the liner need to be derived.

The dry bulk density $\rho_s$ of compacted bentonite in the shaft seal (tunnel #3 in Tab. 2.6-1) is assumed to be 1.65 g/cm$^3$. This value reflects the current knowledge on shaft sealing, which is summarised in Gruner (2010). For simplicity, this value is also taken for the V1 seal and the bentonite backfill in the SF / HLW emplacement rooms (tunnel type #1)\textsuperscript{11}, as these will also be constructed with compacted bentonite (see Tab. 2.6-1).

For the horizontal seals V2, V4 and V5 (tunnel type #2 in Tab. 2.6-1) and for all other tunnels backfilled with a sand / bentonite mixture (tunnel type #4), only the bentonite is assumed to provide sorption capacity. The bulk dry density of sorbing material is therefore calculated according to:\textsuperscript{12}

$$\rho_s = \frac{\rho}{1 + x}$$ \hspace{1cm} (2.6-2)

- $\rho$ dry bulk density of sand / bentonite mixture [kg/m$^3$]
- $x$ sand / bentonite mass ratio (70/30 assumed for tunnels #2 and #4) [-]

For horizontal seals that consist of compacted sand / bentonite mixture (tunnel type #2), a value for $\rho$ of 1.6 g/cm$^3$ is assumed. This assumption is founded on the GAST experiment (Nagra 2012), for which a sand / bentonite mass ratio of 80/20 was used and which aimed at a slightly higher target density $\rho$ of 1.7 g/cm$^3$.

The tunnels of type #4 and #5 are not intended to provide any sealing function. Therefore, it is likely that the backfill material for these tunnels will not be compacted to the same extent as for tunnels of type #2 and #3. As a result, a somewhat lower dry bulk density $\rho$ of 1.5 g/cm$^3$ is assumed for both tunnel types in the context of this modelling study.

The dry bulk density assumed for undisturbed Opalinus Clay is also used for the EDZs of all tunnels.

\textsuperscript{11} Note that the value for dry bulk density of bentonite in the SF / HLW emplacement rooms is not taken from Nagra (2010), because the value in Nagra (2010) accounts for tunnel convergence, whereas tunnel convergence is generally disregarded in the present study.

\textsuperscript{12} Note that all backfilling and sealing activities are assumed to result in materials with homogenous properties.
Sorption in the cementitious backfill material of the ILW and L/ILW emplacement rooms is not considered. Consequently, the potential effects of cement degradation due to the comparatively high water flow rates along the L/ILW and ILW emplacement rooms in part of the calculation cases are addressed in a pessimistic manner.

Solubility limitation is conservatively neglected in the present study, mainly due to technical reasons (see Section 3.4.2).

2.6.3 Diffusion

The present modelling study focusses on situations where advective transport is the dominant transport process along the tunnel system. A wide range of hydraulic conductivities of the sealing and/or the backfill materials is investigated that extends from realistic to high (hypothetical) values. Conceptually, these high hydraulic conductivities are related to flow paths that have a well-connected pore space with large pores and negligible tortuosity. The pore diffusion coefficient for all radionuclides is therefore set to a value for small ions in free water and all radionuclides are assumed to have access to the respective total porosity of non-compacted backfill/sealing materials (see Tab. 2.6-1).

Note that this approach is conservative, since the selected transport modelling approach disregards diffusive exchange between the tunnels (including the EDZ) and the undisturbed surrounding host rock (see Section 3.3). Only diffusive exchange between the tunnel and its EDZ is considered, which are both modelled, in most cases, as homogenous porous media and which both contribute to advective transport.

In van Loon (2012), the maximum pore diffusion coefficient of radionuclides in free water is reported as $2 \times 10^{-9}$ m$^2$/s. This value is adopted for all materials within the tunnels, including the EDZ, regardless of the chemical group to which a radionuclide belongs. The effective diffusion coefficients used in transport modelling are obtained by multiplying this pore diffusion coefficient with the respective porosity values for the different materials.

2.6.4 Dispersion

Dispersion has two principal effects: (i) spreading of a radionuclide plume along a transport path and thus (ii) earlier arrival of a part of the plume at the end of the transport path. In the present modelling study, dispersion along a one-dimensional leg is expressed in terms of the Peclet number $Pe$, which is the ratio of the transport path length $L$ and the longitudinal dispersion coefficient $\alpha$ (see Nagra 2014):

$$Pe = \frac{L}{\alpha} \quad (2.6-3)$$

A reference value of $Pe = 10$ is used for all tunnels, including the EDZs.

This parameter is, however, relatively uncertain and it is a priori not clear whether a high Peclet number has beneficial or adverse effects on radionuclide release along the underground access structures. This is because dispersion generally reduces concentrations but earlier arrival at the upper boundary of the host rock may diminish the favourable effect of radioactive decay. System behaviour is still more complicated in the case of decay chains. Thus, a set of alternative values for the Peclet number is considered in separate analyses (see calculation cases addressing dispersion along the tunnel system in Sections 4.3 and 5.2).


3 Overall Modelling Approach

3.1 General

The Models and Codes Report for SGT Stage 2 (Nagra 2014) sets the basis for the present modelling study: it describes at length the generic concepts, the codes used and the corresponding general modelling approach for water flow and radionuclide transport in the multi-barrier systems of the HLW and L/ILW repositories as applied in the provisional safety analyses for SGT Stage 2.

This general modelling approach is, however, based on Nagra's Reference Scenario for a deep geological repository, in which the influence of the repository tunnel system and the underground access structures on radionuclide release from the barrier system during the post-closure phase is considered negligible. As illustrated in Fig. 1.2-1, radionuclide release in the alternative scenario considered in the present modelling study occurs through the undisturbed host rock above and below the emplacement rooms, as well as along the underground structures, including the ramp and shafts. Some modification of the general modelling approach is therefore required for the present scenario, as presented in this chapter.

The overall modelling approach consists of three broad steps:

1. The network of tunnels and access structures of a given repository system is implemented in a flow model, which serves to calculate water flow rates along the tunnels. Water flows need to be determined specifically for each repository configuration and each parameter combination. This leads to the definition of the calculation cases in Chapter 4. The flow modelling approach is described in Section 3.2.

2. All relevant transport paths are implemented in a radionuclide release and transport model, the water flow rates within the individual transport paths being obtained from the preceding flow model calculations. Note that information about which transport paths are relevant is also obtained from the preceding flow model calculations. Therefore, transport models are generally specific to each calculation case. The transport modelling approach is described in general terms in Section 3.3. A more detailed description of the approach to modelling radionuclide release from the emplacement rooms to the subsequent transport paths is given in Section 3.4.

3. Doses arising from the radionuclides released from the exit points of the considered repository system are finally evaluated, as described in Section 3.5.

The modelling approach presented in this chapter differs from earlier work on the present scenario, as presented in Nagra (2002a/b) and in Smith et al. (2004), in two main respects:

1. The current flow modelling approach and the corresponding computational code can handle (nearly) any repository configuration and allows inflow to any tunnel of the repository system, provided the tunnel lies entirely at repository level. It is therefore possible to account for all relevant underground structures when calculating water flow.

2. The use of the code PICNIC-TD for transport modelling allows an automatic and dynamic splitting of radionuclides released from the emplacement rooms to the subsequent transport pathways according to their respective advective / diffusive / dispersive transport capacities, rather than simply their advective transport capacity, which was the adopted approach in the earlier work.

Detailed numerical aspects of the application of the present flow and transport models using computational codes are covered in Section 3.6.
3.2 Flow modelling

For flow modelling purposes, the host rock, the emplacement rooms and the other underground structures (the latter two being surrounded by excavation damage zones, EDZs) are each modelled as a saturated, homogenous porous media with isotropic flow properties. In addition,

- flow is assumed to be governed by Darcy's law, and
- steady-state flow conditions are assumed.

Flow rates along the repository tunnel system are calculated by means of a resistor network approach, in which all underground structures are represented as continuous resistors, also termed legs. The continuous flow and head profile along the axis of each underground structure is calculated explicitly using an analytical approach. The legs, which are linked together at junctions, can be of two broad types:

- Dead-end legs, i.e. legs with one closed end and another end that connects to one or more further tunnel sections (e.g. legs representing emplacement rooms), or
- Open-ended legs, i.e. legs where both ends connect (i) to one or more further legs, or (ii) to points with a fixed head boundary (e.g. construction and operations tunnels, ramps, shafts and seals).

Both inflow of water into the tunnel system and flow of water along the tunnel system are considered in the calculation of the head profile along the legs. Note that any flow is ultimately driven by the hydraulic head differences between the tunnel system and the surrounding rock and that flow through the system of underground structures varies in proportion to the ambient hydraulic gradient, as does the flow through the host rock.

Each leg is conceptualised as a straight, circular tube (also called a tunnel) of homogeneous, isotropic material, surrounded by a further, annular homogeneous and isotropic region (the EDZ). In general, the EDZ is characterised by a markedly higher hydraulic conductivity compared with the undisturbed host rock (see Section 2.3).

Fig. 3.2-1 illustrates how the form of the flow field in a transverse section around a tunnel varies according to the difference between the head at a given point along the tunnel and the ambient head. In particular, the figure shows simulations of the flow around an SF / HLW emplacement room, assuming head values in the tunnel of 45 m (Test 1), 30 m (Test 2), 15 m (Test 3) and 0 m (Test 0). The ambient head value at repository level is 55 m.

This type of flow field, and its associated hydraulic head field, can be represented as the superposition of two parts (see Fig. 3.2-2):

1. The part of the flow field due to the ambient hydraulic gradient that would occur if the structure (the tunnel and its EDZ) did not act as a sink for water.
2. The part of the flow field due to the sink effect of the structure alone, in the absence of any ambient hydraulic gradient.
Fig. 3.2-1: Hydraulic head distributions (coloured regions) and flow lines around an SF / HLW emplacement room for increasing drawdown within the room in Tests 1, 2, 3 and 0 (see main text).

The figure also shows the position of a stagnation point above the emplacement room (if this exists) for each test calculation.
In this figure, the head $h$ [m] is equal to the sum of $h'$ [m], which is the head associated with the first component of flow (lower left figure), and $\tilde{h}$ [m], which is the head associated with the second flow component (lower right figure). $H_u$ [m] and $H_l$ [m] are the heads imposed at the upper and lower boundaries of the host rock, respectively. $H_A$ [m] is the ambient head at repository depth and $h(x)$ [m] is the hydraulic head along the tunnel, the axis of which is assumed to follow the $x$ [m] direction.
In any region not containing sources or sinks, the head distribution, as well as the distribution of the two components of head, is governed by Laplace's equation:

$$\nabla^2 h = \nabla^2 (h' + \bar{h}) = \nabla^2 h' = \nabla^2 \bar{h} = 0$$  \hspace{1cm} (3.2-1)

The splitting of the flow field into the two parts is allowed according to the uniqueness theorem, whereby real solutions of Laplace's equation within a bounded region where either Dirichlet or Neumann (gradient) boundary conditions apply are unique. Thus, if a solution to Laplace's equation can be found that satisfies the required boundary conditions by any means whatever (such as the splitting into two parts), then that solution is the correct one since only one solution exists.

In modelling radionuclide release and transport based on Nagra's Reference Scenario for a deep geological repository, only the first part (see the left-hand side of Fig. 3.2-2) is considered, since flow along the repository tunnel system is assumed negligible. In the present study, this first part is used in the determination of the net flow rates in the host rock below and above the emplacement rooms (Section 3.4). The quantity \( w_c \) depicted on the left-hand side of Fig. 3.2-2 is termed the flow capture width of the emplacement room. It denotes the width of a stream tube that is fully captured by the tunnel and its EDZ. The concept of the flow capture width is used in Section 3.4.2 and its evaluation for different tunnel geometries is described in Appendix A.2.

It is the second part of the flow field (see the right-hand side of Fig. 3.2-2) that gives rise to a net inflow to the underground structures and that is thus addressed by the resistor network approach. Flow enters the underground structure from all directions and gives rise to a varying flow \( Q \) [m\(^3\)s\(^{-1}\)] along the position \( x \) along the axial direction of an underground structure. This variation is given by:

$$\frac{dQ}{dx} = W \cdot K_{GEO} \left[ \frac{H_l - h(x)}{L_l} + \frac{H_u - h(x)}{L_u} \right]$$

$$= W \cdot K_{GEO} [H_A - h(x)] \left( \frac{1}{L_l} + \frac{1}{L_u} \right)$$  \hspace{1cm} (3.2-2)

where

- \( L_u, L_l \) vertical distances from the tunnel axis to the upper and lower boundaries of the host rock, respectively [m]\(^{13}\)
- \( K_{GEO} \) isotropic hydraulic conductivity of the host rock [m s\(^{-1}\)]
- \( W \) effective leg width [m]

The effective leg width is defined as the width of a section of a hypothetical planar feature at repository level that would capture the same flow as the actual underground structure (tunnel and EDZ), as illustrated in Fig. 3.2-3. The derivation of an appropriate value for \( W \) for each leg in a flow modelling network is also described in Appendix A.2 of the present report.

\(^{13}\) It is assumed that the dimensions of the modelled tunnels are small compared with the vertical distances from the tunnel to the host rock boundaries with fixed hydraulic head values.
Inflow to each leg is calculated according to Eq. 3.2-2. In this way, the flow and head distribution throughout the network can be calculated.

![Diagram](image)

*Fig. 3.2-3: Conceptual representation of the effective leg width $W$."

It is a limitation of the resistor network approach as described above that inflow can only be taken into account for structures that lie entirely in the repository horizon. Thus, inflow to the shafts cannot be modelled. However, as demonstrated in Appendix A, Section A.3.2, inflow to these relatively short features will be small, and in most cases much less than the total flow that passes through them. The ramp is modelled as a horizontal structure with inflow, but inflow to the ramp seal is not taken into account.

The resistor network approach as described above is implemented in the Resistor Network Code (Smith & Poller 2012), which is a more general implementation of the model developed in the framework of project Opalinus Clay for the HLW repository (Nagra 2002b). The new implementation allows a nearly arbitrary network of flow paths to be analysed while requiring a minimum effort to set up the flow network model.

*Fig. 3.2-4 shows a sketch of the flow model network for the L/ILW repository as presented in Fig. 2.2-2. The grouping of the emplacement rooms of the main facility into panels is carried out for the purposes of transport modelling (see Section 3.4). As noted in Chapter 2, the underground structures are each allocated to one of six different tunnel types (1 to 6), according to their flow and transport properties. The structures allocated to each type are shown in Fig. 3.2-4. Note that tunnel types 4 and 5 are identical from the point of view of flow modelling.*

Details about the geometric and flow parameters of the individual legs for both repository types are given in Appendix A.
Fig. 3.2-4: Flow model legs considered for the L/ILW repository in the variant with main access via ramp.

Note: for the variant where the main access route is a third shaft rather than a ramp, the ramp seal (tunnel type #2) is replaced by a shaft seal (tunnel type #3).

3.3 Transport modelling

For transport modelling purposes, the host rock, the emplacement rooms and the other underground structures (the two latter surrounded by an excavation damage zone, EDZ) are again each modelled as a saturated, homogenous porous media with isotropic flow and transport properties. In addition:

- radionuclide transport occurs due to advection in flowing water, hydrodynamic dispersion and molecular diffusion;
- diffusion is governed by Fick's laws and dispersion is modelled as a diffusion-like process, also governed by Fick's laws;
- radionuclide concentrations are not constrained by elemental solubility limits (see also the discussion of the mixing-tank approach in Section 3.4.2);
- radionuclides are retarded by linear, equilibrium sorption; and
- steady-state flow conditions and constant radionuclide retention properties are assumed (except in a specific set of calculation cases addressing alternative concepts for the hydraulic gradient, see Sections 4.3 and 5.2).
The transport and retention processes, including the governing equations, are described in more detail in Section 3.2.7 of Nagra (2014).

Transport modelling is carried out with the code PICNIC-TD (Nagra 2014) and is based on the concept of a network of one-dimensional transport pathways, again called legs. Every leg has an upstream end and a downstream end, with each end corresponding to a particular junction. Junctions can have several incoming and outgoing legs. Some junctions are connected to a source term, which is generated typically by another code, e.g. STMAN (see Section 3.4.1).

Each PICNIC-TD leg usually models a pair of spatially distinct domains: the flow domain and the adjacent medium, called the matrix in PICNIC-TD terminology (where flow may also occur). The flow domain may represent features with either circular or planar cross sections, with one-dimensional advective / dispersive and diffusive transport along the features and uniform concentration assumed normal to the flow direction. Advective / dispersive and diffusive transport is modelled in the matrix in the same way as transport in the flow domain, but with additional diffusive transport normal to the flow direction. Transport of radionuclides in the gas phase is not included in PICNIC-TD and is, in any case, not within the scope of this study.

In the context of the present study, a PICNIC-TD leg may represent a vertically orientated pathway in the undisturbed host rock, an individual underground structure or a group of parallel, identical underground structures. In the case of the underground structures, the PICNIC-TD flow domain represents the excavated and backfilled volume (the tunnel), and the matrix represents the EDZ. The tunnel takes the form of a straight, circular cylinder consisting of a homogeneous, isotropic medium. The matrix is an adjoining annular region, also consisting of a homogeneous, isotropic medium. One such leg and the transport processes occurring therein is presented in Fig. 3.3-1.

In the case of the host rock, the flow domain of the leg represents a vertical slice of the undisturbed host rock below or above the emplacement room; the matrix models the remainder of the undisturbed host rock. In this case, both domains have identical transport properties (for more details see Section 3.4.2). In the case of the underground structures, both the tunnel and the EDZ conduct water and allow advective / dispersive and diffusive transport in the $x$-direction. The tunnel radius is assumed to be sufficiently small compared with the length of the tunnel (and transverse dispersion and radial diffusion sufficiently fast) that nuclide concentrations in the water flowing within the tunnel can be assumed to be uniform in the radial direction, as required by PICNIC-TD. Radionuclides migrate between the tunnel and the EDZ by diffusion in the radial direction. Recall that the radial diffusion coefficient in the EDZ is set to a relatively high value, accounting for the possibility of transverse dispersion as well as radial diffusion (Section 2.6). Thus, radial concentration profiles in the EDZ are also approximately uniform in the radial direction.

As noted in Section 2.3, some micro- and macro-scale fracturing may persist over time in the EDZ and it is thus appropriate, as an alternative conceptual model, to also represent the EDZ as a fractured porous medium, as considered in a specific set of calculation cases (see calculation cases addressing the conceptualisation of the EDZ described in Sections 4.3 and 5.2).
Radionuclide release from the EDZ of a tunnel to the surrounding host rock is not modelled (except in the special case of the emplacement rooms, see Section 3.4.2). Besides being pessimistic with regard to radionuclide release along ramp and shafts, this simplification is based on the following considerations:

- If there is a relatively large drawdown of the hydraulic head within a tunnel, which may be the case in situations where the hydraulic conductivity of the access structures is relatively high, flow may in fact be inwardly directed all around the perimeter of the tunnel, thus precluding any significant release of radionuclides to the host rock (see Fig. 3.2-1, Tests 0, 2 and 3). In these situations, omitting radionuclide exchange between the tunnel and the surrounding host rock has no effect.

- For situations in which the total transport capacity of the tunnel system is relatively low, omitting radionuclide transport from the tunnel system to the host rock has little or no effect either, because the great majority of radionuclides enter the host rock directly from the emplacement rooms by diffusion. This is the case for Nagra’s Reference Scenario and for the base cases considered in this report.

There remains the further possibility that transport along the repository tunnel system is dominated by diffusion only. Consider for instance the hypothetical situation where the tunnels at repository depth are neither backfilled nor sealed, while perfect sealing is provided for the ramp and shafts. In this case, omitting radionuclide transport from the underground structures to the host rock may underestimate radionuclide release to the biosphere via the host rock, especially if radionuclide concentrations at repository depth are controlled by non-linear processes, such as solubility limitation, so that uniform concentrations develop throughout the repository tunnel system. However, the effect would be limited, being of the order of the ratio of the total repository footprint to that of the emplacement rooms.
From the resistor network calculations, a single flow value for a tunnel and the surrounding EDZ is obtained. For transport modelling, however, the flow component in each domain (tunnel and EDZ) needs to be determined. This is done by considering the product of the hydraulic conductivity and the cross-section of each domain, termed the areal transmissivity. The total flow is then attributed to the two domains in proportion to their areal transmissivities.

The networks of legs considered in transport modelling are broadly similar to those used for flow modelling. However, for computational reasons, the transport networks only contain those underground structures that are accessible to radionuclides by means of advective transport. Thus, only legs that are located at the downstream end of a flow path (sequence of legs) that originates in an emplacement room are included. Other legs, including legs that have two down-stream ends (i.e. a water divide somewhere in the middle of the legs) are not explicitly included in the transport network. However, the inflow of water from these structures is implicitly taken into account (see the blue arrows in Fig. 3.3-2).

The aforementioned approach is again pessimistic with respect to radionuclide release along ramp and shafts. It does, however, require transport models that are specific to the different flow situations arising in each calculation case. Therefore, transport networks are generated automatically from the case-specific flow modelling results. Fig. 3.3-2 is an example of such transport model layout, based on the flow modelling results of calculation case SA4 for the L/ILW repository (as defined in Chapter 4).

At each junction, PICNIC-TD requires the specification of the flow in each of the legs to which the junction is connected. If the flows do not balance and, in particular, if the outflow exceeds the inflow, then the model / code implicitly assumes that there is an additional incoming flow (see blue arrows in Fig. 3.3-2).
In PICNIC-TD, flows must be modelled as being constant along each leg. By contrast, in the flow model based on the resistor network approach, the calculated water flow (i) either increases monotonically in the flow direction, (ii) or there is a flow divide somewhere within the leg, on either side of which flow increases monotonically.\textsuperscript{15} For legs of the first type, the value of the flow rate at the downstream end is the highest value that the flow rate takes within such a leg. It is this value that is used in the PICNIC-TD transport modelling calculations. A proof given in Appendix B, Section B.1 formally demonstrates the conservatism of this approach when calculating transport of a single radionuclide. Legs of the second type are not included explicitly in transport modelling, since they are not accessible to radionuclides by means of advective transport (see above).

PICNIC-TD allows different possibilities for the handling of radionuclide transfer between connected legs at junctions, as illustrated in Fig. 3.3-3 for legs with circular geometry. For the present modelling study, it is in general assumed that all flow and associated radionuclides leaving the EDZ and the tunnel of the upstream legs are routed through (and mixed at) the junction. Radionuclides entering a downstream leg from a junction pass into the tunnel of that leg first and must diffuse into the EDZ before being transported parallel to the tunnel along the EDZ (i.e. the situation depicted in the right-hand part of Fig. 3.3-3).\textsuperscript{16}

\textsuperscript{15} In the case of the legs representing the shafts and also the ramp seal, inflow from the host rock to these legs is not included in the flow model. Thus, flow along these legs is constant in the flow model.

\textsuperscript{16} This may not be realistic for junctions where two identical tunnels meet. The effect of this approach is however considered small in light of the potential effects of radial diffusion and transverse dispersion in the EDZ fracture network along the relatively long tunnels (if this length is compared with the radial extension of the EDZ of the tunnel).
To reduce the computational effort for transport modelling, the emplacement rooms of the main facilities are grouped into panels (e.g. Panels 1 and 2 in Fig. 3.3-2). Radionuclides are released from the panels to the repository tunnel system by advection / dispersion and diffusion. They may also be released from the emplacement rooms into the host rock by diffusion and also by advection / dispersion if the net flow rate from the host rock to the emplacement rooms is not too large. The treatment of radionuclide release and transport in the panels and from the panels to their surroundings is described in Section 3.4.2.

Radionuclides leaving an SF / HLW or L/ILW emplacement room are released via a branch tunnel to the respective operations tunnel, and release to the operations tunnel is distributed along its length. However, since this distribution cannot be represented explicitly due to the grouping of emplacement rooms into panels, transport along the operations tunnel is conservatively neglected for all radionuclides, including those that originate from another panel further upstream. This approach is illustrated by the oval shapes in Fig. 3.3-2 (designated by 'P1-1' and 'P2-1'), which are modelled as single junctions in the PICNIC-TD models.

3.4 Radionuclide release to and from the emplacement rooms

3.4.1 Radionuclide source term

In Section 2.5 it was pointed out that in this study, the interior of the emplacement rooms is modelled in a rather abstract manner. This means that the radionuclides are assumed to be released homogenously into the emplacement rooms, which are filled with backfill material only. To further simplify the calculation of the source term:

- no distinction is made between tunnels containing SF and those containing HLW; and
- no distinction is made between tunnels containing L/ILW that belongs to waste group L/ILW-1, and those containing L/ILW that belongs to waste group L/ILW-2.

The chemical conditions within and around the emplacement rooms are assumed to be unaffected by the water flow along the emplacement rooms that is implicit in the present scenario. Therefore, containment time, waste dissolution rates and congruent release rates of radio-nuclides are modelled as in the Reference Scenario. Further details concerning radionuclide release from the waste forms is given in Section 2.5.

In the present study, the code family STMAN is used for calculating radioactive decay and ingrowth during the time of complete containment (e.g. in SF and HLW canisters) and for calculating instant and congruent release from all waste forms into the backfill material of the emplacement rooms. Nagra (2014) presents an overview of the capabilities of STMAN. Since STMAN is designed to model radial transport from the emplacement room into the host rock, a marginal diffusive transport barrier is included around the waste forms in the STMAN model. More details of the STMAN model used for calculating the source term for the PICNIC-TD transport models are given in Section 3.6.
3.4.2 Mixing-tank approach

Inflow from the host rock to the emplacement rooms and water flow along the emplacement rooms are largest near the branch tunnels, since the hydraulic head decreases along the repository tunnel system. Hence, the conditions for radionuclides to be released from the waste forms and to be transported within the emplacement rooms may vary considerably along as well as among the emplacement rooms. A detailed transport model would be needed to account for this variability in full. In the present study, however, a simplified approach based on a mixing-tank concept has been adopted.

Definition of mixing tanks

Each single emplacement room is in this study represented as a mixing tank, i.e. the buffer or backfill material of each emplacement room is assumed not to provide any barrier to radionuclide transport. Hence, radionuclide concentrations within each room are uniform. This approach is pessimistic with regard to radionuclide release from the emplacement room to the repository tunnel system, as is shown in a separate analysis (see calculation cases addressing transport in the SF / HLW emplacement rooms and the role of intermediate seals described in Sections 4.3 and 5.2). It is also convenient because it allows an automatic and dynamic splitting of radionuclides released in the emplacement room to the connected pathways (which comprise the host rock and the branch tunnels) according to their respective total advective / dispersive and diffusive transport capacity, as explained below.

As mentioned in Section 3.3, the SF / HLW and L/ILW emplacement rooms themselves are grouped into panels (e.g. Panels 1 and 2 in Fig. 3.3-2). As a result, an entire panel is treated as a single mixing tank, which simplifies transport modelling considerably.

Application of source terms

Because no information about the location of individual SF and HLW disposal canisters is available today and since, in any case, the emplacement rooms are modelled as mixing tanks, the source terms obtained with STMAN for the different SF and HLW waste types are summed up and proportionally assigned to the panels. The same approach is chosen for the two L/ILW waste groups.\textsuperscript{17} Note that the ILW tunnels for the two ILW waste groups are not grouped into a single panel. Rather, they are referred to as two separate panels in the following.

The source term obtained with STMAN (or the part of it assigned to the panel under consideration) is assumed to enter the transport network at the downstream junction at the end of the PICNIC-TD leg representing the emplacement rooms of the panel (e.g. the junctions P1-3 and P2-3 in Fig. 3.3-2). The selection of the downstream junction rather than the upstream junction makes no difference to the results, given that the leg is treated as a mixing tank with uniform concentrations throughout.

\textsuperscript{17} This linear approach is justified, since non-linear processes such as solubility limitation are disregarded in the present study. Furthermore, the omission of non-linear processes allows a relatively simple modelling strategy.
Treatment of emplacement rooms and associated tunnels

The mixing-tank approach is implemented by representing all the emplacement rooms of a panel using a single PICNIC-TD leg (panel leg, see e.g. Fig. 3.3-2). This leg has the dimensions and properties of a single emplacement room (see Tab. 2.6-1, tunnel types #1 and #6), except for (i) a very high diffusive transport capacity assigned to the backfill material to mimic mixing conditions, and (ii) a pore volume and, in the case of SF / HLW panels, a sorption capacity corresponding to all $N$ emplacement rooms of the panel.$^{18,19}$

A second leg, connected in series to the panel leg, represents all the $N$ emplacement room seals of a panel. Similarly, a third leg, connected in series to the second, represents all $N$ branch tunnels that connect the sealed emplacement rooms to the operations tunnel (see Fig. 3.3-2).

Each of these three legs has two domains: the backfilled room, seal or branch tunnel is represented by the flow domain of the respective PICNIC-TD leg and the EDZ by the matrix of the leg. In general, the transport properties and the dimensions of these legs are the same as for a leg representing a single tunnel. However, the transport capacities of these legs are modified by setting the PICNIC-TD model parameter CSA (the leg cross sectional area) to the cross sectional area of an individual tunnel multiplied by the number of emplacement rooms, $N$. This ensures that these legs provide for the transport capacity of all the emplacement rooms, seals and branch tunnels in the respective panel.

The water flow leaving a panel and entering the seals, $Q_p$ [m$^3$ s$^{-1}$], is taken from the flow modelling results. To this end, the water flow rates at the downstream ends of the $N$ individual emplacement rooms of a panel $Q_j$ are summed:

$$Q_p = \sum_{j=1}^{N} Q_j$$ (3.4-1)

The water flows through the legs representing the $N$ seals of the panel $Q_s$ [m$^3$ s$^{-1}$] and the $N$ branch tunnels to the panel $Q_b$ [m$^3$ s$^{-1}$] are calculated in a similar manner. Note that $Q_b > Q_s > Q_p$ due to inflow from the host rock.

Treatment of host rock above and below a panel

The leg representing all emplacement rooms of a panel is directly connected not only to the leg representing the emplacement room seals, but also to two further PICNIC-TD legs representing, respectively:

- the undisturbed host rock above the panel; and
- the undisturbed host rock below the panel.

$^{18}$ Since the volumes occupied by the disposed waste forms are neglected, the pore volume and the sorption capacity of the emplacement room backfill are slightly overestimated.

$^{19}$ Recall that sorption in the cementitious backfill material of the ILW and L/ILW emplacement rooms is not considered, and that solubility limitation is disregarded for all types of emplacement room (see Section 2.6.2).
This model set-up is illustrated in Fig. 3.4-1. Each of these two host rock legs is again assigned two domains, an inner domain and an outer domain. The inner domain of the leg represents $N$ vertical slices of the undisturbed host rock below or above the emplacement rooms; the outer domain models the remainder of the undisturbed host rock. Unlike legs representing a tunnel and its EDZ, both domains of the host rock legs share the same flow and transport properties.

The inner domain of the host rock leg is represented by the flow domain of the PICNIC-TD leg and the outer domain by the matrix. The legs themselves are assigned a rectangular geometry (rather than the cylindrical geometry used to represent the emplacement rooms and underground access tunnels). Radionuclides released from the emplacement rooms to the host rock first enter the inner domain of the host rock legs, from where they can subsequently diffuse to the outer domain. Thus, the leg representing the emplacement room panel is directly connected to the inner domains of the host rock legs, but not to the outer domains. The outer domains of the two host rock legs are connected separately (i.e. as depicted in the left-hand part of Fig. 3.3-3).

Fig. 3.4-1: Transport modelling approach for a repository panel, showing the panel junction with the source term connected to the legs representing the emplacement rooms, the host rock and the seals / branch tunnels of a panel.
The width of the inner domain is set to half of the external surface area of the emplacement room (including its EDZ), i.e. \(2b = 0.5 \cdot \pi \cdot w\), where \(w\) [m] is the diameter of the tunnel including the EDZ (see Fig. 3.2-2). This ensures that radionuclide transfer from the emplacement rooms to the rock by diffusion is represented by the proper contact area. The total width of both domains is set to the emplacement room separation, \(d\) [m]. The PICNIC-TD model parameter CSA (the leg cross sectional area) for the host rock legs is set by multiplying the width of the inner domain by the depth \(l\) and by the number of emplacement rooms, \(N\).\(^{20}\) The total depth of the legs in the direction of the emplacement room axis is equal to the length of the emplacement room, \(l\) [m]. For defining the length of the host rock legs, the vertical extent of the emplacement rooms, including potentially disturbed areas, is taken into account (see Section 2.3).

As noted in Section 3.2 (see Fig. 3.2-2 and also the top part of Fig. 3.4-1), the flow field through and around an emplacement room in a vertical plane normal to the axis of the room can be represented as the superposition of two parts:

1. The part of the flow field due to the ambient hydraulic gradient that would occur if the emplacement room (including its EDZ) did not act as a sink of water.
2. The part of the flow field due to the sink effect of the emplacement room alone, in the absence of any ambient hydraulic gradient.

Considering all \(N\) emplacement rooms in a panel, the second part of the flow field gives rise to an inflow \(Q_p\) to the rooms, which is evaluated using the resistor network flow model and Eq. 3.4-1, above. The first part of the flow field, illustrated by the bottom left part of Fig. 3.2-2, includes a stream tube within which all the water passes into and out of the panel rooms and their EDZs, carrying groundwater at a flow rate \(Q\) [m\(^3\) s\(^{-1}\)].

If, as is usually the case in the present study, the hydraulic conductivity of the EDZ is assumed to be much larger than that of the host rock, and also assuming that the rooms are not too close to the lower or upper boundaries of the rock or the adjacent rooms, the width \(w_c\) [m] of this stream tube away from the convergence / divergence caused by the emplacement room (see Fig. 3.2-2) is approximately equal to twice the EDZ diameter. The quantity \(w_c\) is termed the flow capture width of the emplacement room (see Appendix A, Section A.2.1).

For \(N\) emplacement rooms, \(Q\) is thus given by:

\[
Q = N \cdot K_{GEO} \cdot w_c \cdot L \cdot \frac{H_l - H_u}{L_l + L_u} = 2 \cdot N \cdot K_{GEO} \cdot w \cdot L \cdot \frac{H_l - H_u}{L_l + L_u} \tag{3.4-2}
\]

where \(L\) [m] is the length of an emplacement room and other parameters are defined above or in Section 3.2. For modelling purposes, \(Q\) is assumed to be carried entirely by the inner domains of the host rock legs.\(^{21}\)

Superimposing the first and second parts of the flow field, and further assuming that:

- the inflow, \(Q_p\), is supplied equally by the rock above and below the panel (a reasonable assumption as the rooms are roughly centrally located in the host rock), and
- this inflow originates entirely from within the inner domain

\(^{20}\) The general approach adopted for defining the parameter CSA in PICNIC-TD calculations is described in Section 3.5.5 in Nagra (2014).

\(^{21}\) Note that the capture width \(w_c = 2 \cdot w\) is always less than the width of the inner host rock domain \((2b = 0.5 \cdot \pi \cdot w)\).
The upwardly directed flow in the inner domain of the leg representing the host rock below the panel, $Q_i$ [m$^3$ s$^{-1}$], is given by:

$$Q_i = Q + 0.5 \cdot Q_p$$  \hspace{1cm} (3.4-3)

In the inner domain of the leg representing the host rock above the panel, the upwardly directed flow, $Q_u$ [m$^3$ s$^{-1}$], is given by:

$$Q_u = Q - 0.5 \cdot Q_p$$  \hspace{1cm} (3.4-4)

It can be seen that, if $Q < 0.5 \cdot Q_p$, flow in the inner domain of both legs is directed towards the emplacement rooms, thus advective release to the host rock will not occur. This is clearly realistic for large net inflow values, $Q_p$, because, in this case, a groundwater drawdown cone forms in the rock around the emplacement room, meaning that the flow all around its perimeter is inwardly directed and no advective release of radionuclides to the host rock can occur. Radionuclides may, however, still reach the host rock by diffusion (and dispersion) if flow to the emplacement rooms is not too strong.

In the outer domain, the flow (directed upwards), $Q_m$ [m$^3$ s$^{-1}$], consists of that part of the ambient flow that is not assigned to the inner domain:

$$Q_m = N \cdot K_{GEO} \cdot (d - w_e) \cdot L \cdot \frac{H_i - H_u}{L_i + L_u}$$  \hspace{1cm} (3.4-5)

### 3.5 Evaluation of doses

In the present study, radionuclides that arrive at the boundaries of the host rock and at the exit points of the ramp and the shafts (also called release points) are assumed to be instantly transferred to the biosphere. Effective dose rates are calculated by (i) multiplying the time-dependent radionuclide fluxes at the release points by biosphere dose conversion factors and then by (ii) summing up the dose contributions of the individual radionuclides at different release points. The complete set of safety-relevant radionuclides for the respective repository types (including decay chains) is considered in the transport models.

The concept of biosphere dose conversion factors is based on the premise that the entire biosphere is in a steady-state condition, including radionuclide inputs from the repository system. This approach is pessimistic in the sense that it neglects accumulation of individual radionuclides in different compartments of the biosphere, which may occur very slowly. The biosphere dose conversion factors applied in the present study are the reference values for a temperate climate given in Nagra (2010). An overview of the underlying biosphere assessment model is presented in Nagra (2002b).
In most cases, the resulting maximum dose rates within the respective time frames for safety assessment are considered for the evaluation of the modelling results. This includes the comparison of these values resulting from different calculation cases, as well as an assessment of these values against regulatory protection criteria. According to the Swiss Federal Nuclear Safety Inspectorate (ENSI) in its guideline ENSI-G03/e (ENSI 2009), the following protection criteria apply to deep geological repositories in the post-closure phase:

**Protection Criterion 1:** For each future evolution classified as likely, the release of radionuclides may not lead to an individual dose exceeding 0.1 mSv per year.

**Protection Criterion 2:** Future evolutions classified as less likely that are not considered under protection criterion 1 may not, taken together, constitute an additional individual radiological risk of health detriment exceeding one in a million per year.

Although the scenario of radionuclide release along the underground access structures of a deep geological repository is certainly unlikely, the present study does not form part of a safety case. Therefore, no quantitative value is assigned to the probability of this scenario and no assessment against Protection Criterion 2 is made. Rather, calculated dose rate maxima are compared with the dose limit of 0.1 mSv per year specified in Protection Criterion 1.

In addition, the calculated dose rate maxima can be compared with the level of insignificant dose rate, set at 0.01 mSv/a by the International Atomic Energy Agency (IAEA 2011). From this value it is judged that dose rates as low as $10^{-7}$ mSv/a clearly have no radiological meaning. This is reflected in the results presented later in the report by the use of background shading for dose rates below $10^{-7}$ mSv/a.

### 3.6 Numerical aspects

The resistor network approach is implemented in the Resistor Network Code, version 1.2. The calculation of flow values is exact and thus no numerical parameters need to be specified. The code performs some error checks during execution, more details of which can be found in Appendix A and in Smith & Poller (2012).

Transport modelling is carried out using the code family STMAN, version 5.9, for calculating the source term and the code PICNIC-TD, version 1.4, for calculating radionuclide transport through the repository tunnel system, the access structures and the host rock. Details of numerical aspects of STMAN 5.9 are presented in Nagra (2014) and references therein. Nagra (2014) also provides an overview of PICNIC-TD, along with references to other relevant documents.

Radionuclide release and transport from the L/ILW repository is analysed with one STMAN run and one PICNIC-TD run for each calculation case. For some calculation cases, the HLW repository source terms and the corresponding transport analyses for are defined and carried out separately for SF, HLW and ILW; in such cases there are thus three STMAN runs and three PICNIC-TD runs for each case. The results are then superimposed to obtain the release rates from the entire HLW repository. The approach is justified because solubility limitation is not included in the calculations; the governing equations for radionuclide release and transport are then linear, allowing the superposition of solutions.
Since an STMAN model requires a specific modelling domain structure, the model is set up as follows:

- The model domain comprises (i) the waste forms themselves, (ii) a narrow water-filled reservoir into which the radionuclides are released from the waste forms (this can be thought of, e.g. as the water-filled void space inside a breached SF / HLW disposal canister), and (iii) a weak diffusive barrier, with a nominal thickness of 0.1 m.
- At the outer boundary of the diffusive barrier, a zero-concentration boundary condition is applied. The radionuclide flux across this boundary provides the source term for transport modelling.

In the case of PICNIC-TD, each leg comprises an inner domain representing the backfilled / sealed emplacement rooms, underground tunnels or access structures and an outer domain for the associated EDZs. As described in Section 3.3, radially uniform conditions are assumed in each domain. This assumption is made for the sake of consistency in the treatment of the two domains, since PICNIC-TD cannot account for any radial concentration gradients in the inner domain. It is also justified in light of the potential effects of radial diffusion and transverse dispersion in the EDZ fracture network and in the tunnel backfill. Note that individual tunnels are in all cases long compared with their radii and compared with the thicknesses of their EDZs, favouring radial mixing by diffusion and transverse dispersion.

Where the properties of the two domains are highly dissimilar, treating both domains as fully mixed may be non-conservative, e.g. in a situation in which advective transport is predominantly in the EDZ, with relatively slow, radial diffusion between the EDZ and the tunnel backfill. Such a situation is, however, bounded by the alternative calculation case with a fractured EDZ, where diffusive exchange between tunnel and EDZ is precluded (see Sections 4.3.2 and 5.2.2). From a technical point of view, radially uniform concentrations in the EDZ are obtained by using a single radial layer to represent the matrix of the respective leg. Note that, since the number of layers in the matrix is a global parameter in PICNIC-TD, the outer domain of the host rock legs is also modelled with a single layer.

Due to the fact that transport models need to be specific for each calculation case, the input files for PICNIC-TD are generated automatically according to the results of the corresponding flow calculation. This is done using scripts, written in the Python language. Many other tasks are also carried out using Python scripts, as far as possible.

Using the default values for the solver accuracy parameters used to control the time-stepping, the computing time for a PICNIC-TD calculation range from a few minutes to a few hours (if the complete set of safety-relevant radionuclides is used).
4 Calculation Cases

4.1 General
The following sections describe the calculation cases for the HLW repository and the L/ILW repository analysed in the present study. The main calculation cases described in Section 4.2 address the main topic of this report, namely flow and transport through the repository tunnel system and access structures, considering uncertainties in the hydraulic properties of these features, and also the design alternative of replacing the ramp by a third shaft. Additional, complementary calculations addressing issues that are also of some relevance to this study are described in Section 4.3.

Generally, a calculation case is defined through the specification of a repository system (HLW or L/ILW), its configuration and layout (including the derived flow and transport leg networks), and a set of hydraulic conductivities and other parameter values for the repository system. The calculation cases are defined and implemented in such a way that they tend to overestimate radionuclide release along the ramp and shafts. In addition to the pessimistic parameters presented in the following sections and in Section 2.6, there are a number of pessimistic assumptions that are made in modelling the calculation cases. These have already been mentioned in Chapter 3, the potentially most significant are:

- the omission of water inflow to the repository shafts and to the ramp seal, which results in higher inflows to, and hence releases from, the emplacement rooms (see Sections 4.2 and A5.2);
- the omission of radionuclide release from the repository tunnel system to the surrounding host rock, although release to the host rock from the emplacement rooms is considered (see Sections 3.3 and 3.4);
- the treatment of emplacement rooms (and panels of emplacement rooms) as mixing tanks, with no consideration of transport times either along the emplacement rooms, or in front of a panel (see Section 3.4); and
- the omission of sorption in the cementitious backfill material of the ILW and L/ILW emplacement rooms (see Section 3.4).

Also pessimistic is the omission of solubility limitation in the emplacement rooms, although its influence on the results is expected to be low for the calculation cases presented.

The implementation of flow and transport modelling for the various calculation cases is described in detail in Appendices A and B.

4.2 Main calculation cases

4.2.1 Overview and base cases
The main calculation cases are listed in Tab. 4.2-1, together with case-specific hydraulic conductivity values, which are in most cases the dominant parameters. Each case-specific set of hydraulic conductivity values is given a unique name (BC, SA1, SA2, etc.). A calculation case name is obtained by concatenating the repository system type (HLW or L/ILW) and the name of the set of hydraulic conductivities (e.g. HLW_BC), although often in the following, a case is referred to as simply, e.g. BC for the HLW repository.
Tab. 4.2-1: Main calculation cases and characteristic hydraulic conductivity values for different tunnel types and for the host rock.

<table>
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<th>Tunnel #1 and shafts #3</th>
<th>Tunnel #2</th>
<th>Tunnels #4 and #5</th>
<th>Tunnel #6</th>
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<td>KDZ3</td>
<td>K2-V5</td>
<td>KDZ2-V5</td>
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Overriding system analyses (SA)

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<th>Tunnel #2</th>
<th>Tunnels #4 and #5</th>
<th>Tunnel #6</th>
<th>Host rock</th>
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Quality of horizontal seals (QHS)

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<th>Tunnels #4 and #5</th>
<th>Shafts #3</th>
<th>Tunnel #6</th>
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<tr>
<td>QHS2</td>
<td>as QHS1</td>
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<td>1E-11 (EDZ only)</td>
<td>as BC</td>
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</tr>
<tr>
<td>QHS1_3S</td>
<td>as QHS1 but with a third shaft instead of a ramp (see Appendix A.1)</td>
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<td></td>
</tr>
<tr>
<td>QHS2_3S</td>
<td>as QHS2 but with a third shaft instead of a ramp (see Appendix A.1)</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

Note: Hydraulic conductivity values are in [m s\(^{-1}\)].


A base case (BC) and several sets of variant calculation cases are presented for each repository type. In addition, for each repository type, a further base case BC_3S is defined for the variant layout with a third shaft instead of a ramp. Fig. 4.2-1 shows the flow network for case HLW_BC, where legs are coloured to indicate the hydraulic conductivities of the tunnels and their EDZs. The low hydraulic conductivities of the SF / HLW emplacement rooms and of the repository seals are apparent from the light blue colours of the corresponding legs.
Fig. 4.2-1: Flow network for case \textit{HLW\_BC}, where legs are coloured to indicate the hydraulic conductivities of the tunnels (upper figure) and their EDZs (lower figure).

The base cases represent the situation in which radionuclide release from the emplacement rooms during the post-closure phase occurs predominantly vertically orientated through the host rock (the Reference Scenario). Flow from the emplacement rooms to the repository tunnel system in the base cases is very low and, as described in Section 5.1.1, flow from the emplacement rooms in case \textit{HLW\_BC} is so low that the resistor network flow modelling approach becomes invalid. In reality, in the base cases, diffusion will be the dominant transport process in the near field and radionuclide release along the tunnel system will be negligible. These cases do not, therefore, strictly speaking, belong to the present scenario and have only indicative character, i.e. they are used as a reference against which to compare flow and transport affected by the repository tunnel system.
The sets of variant cases are described further in the following sections.

4.2.2 Overriding system analyses

Six calculation cases are defined (SA1 to SA6) for each repository type with progressively increasing hydraulic conductivity values throughout the repository tunnel system and access structures. For example, the assumed hydraulic conductivity values for the EDZ of the SF / HLW emplacement rooms range from $10^{-11}$ m/s (SA1) to $10^{-6}$ m/s (case SA6). Note that most of the parameter values for SA2 to SA6 are consistent neither (i) with the quality of backfilling and scaling of the emplacement rooms and access structures that is currently expected can be achieved, nor (ii) with the expected behaviour of the EDZ. They are to be understood as hypothetical cases, defined exclusively in the context of the present overriding system analyses.

SA4 to SA6 in particular are considered rather extreme cases. The hydraulic conductivities assumed in the parameter set SA4 are, for example, clearly hypothetical, with the hydraulic conductivities of the bentonite seals, the backfill of the SF / HLW emplacement rooms and their associated EDZs being four orders of magnitude above the base-case values. The parameter set SA4 is, however, of particular interest for the present study, since the assumed hydraulic conductivities, as well as those in SA5 and SA6, are sufficiently high that radionuclide transport along the repository tunnel system and access structures contributes more to overall peak dose than does transport through the host rock, at least when the base case values for host rock hydraulic conductivity are assumed (see Chapter 5.1, Fig. 5.1-5). The complementary calculation cases described in Section 4.3 are thus based on the parameter set SA4.

4.2.3 Quality of horizontal seals and the option of a shaft in place of the ramp

Five calculation cases are defined that explore (i) the consequences of (sub-) horizontal seals (including the ramp seal) that perform more poorly than expected, and (ii) the question of whether in such cases a shaft as the main access route would perform markedly better than a ramp from the point of view of radionuclide release along the underground access structures of the repository systems. Based on the reference layout, case QHS1 assumes that the hydraulic conductivity of all horizontal seals and their respective EDZs is increased with respect to the BC (note that the seal of the inclined ramp is also considered a horizontal seal). Fig. 4.2-2 shows the flow networks for cases HLW_BC and HLW_QHS1, where legs are coloured to indicate the hydraulic conductivities of the EDZs. Case QHS2 additionally assumes a more permeable EDZ in the shafts. For the variant layout with a third shaft instead of a ramp (extension _3S), analogous calculation cases BC_3S, QHS1_3S and QHS2_3S are defined.
Fig. 4.2-2: Flow networks for cases $HLW_{BC}$ (upper figure) and $HLW_{QHS1}$ (lower figure), where legs are coloured to indicate the hydraulic conductivities of the EDZs.
4.3 Complementary calculation cases

As mentioned in Section 4.2.2, the parameter set SA4 is of particular interest for the present study, since water flow along the repository tunnel system is sufficiently high that radionuclide release via the access structures contributes more to overall peak dose than does transport through the host rock. The complementary calculation cases described in the following sections are therefore based on the parameter set SA4.

4.3.1 Dispersion along the tunnel system

As noted in Section 2.6.4, the Peclet number, which is the parameter quantifying longitudinal hydrodynamic dispersion for transport along the repository tunnel system is set to 10 in the main calculation cases. Its value is, however, relatively uncertain and it is a priori not clear whether a high Peclet number has beneficial or adverse effects on radionuclide release along the underground access structures. Thus, a set of alternative values for the Peclet number is considered in a series of calculations cases based on the case SA4:

- **SA4_Dvl**: very low longitudinal dispersion along tunnel system (Pe = 100)
- **SA4_Dl**: low longitudinal dispersion along tunnel system (Pe = 30)
- **SA4_Dh**: high longitudinal dispersion along tunnel system (Pe = 3)
- **SA4_Dvh**: very high longitudinal dispersion along tunnel system (Pe = 1)

4.3.2 Conceptualisation of the EDZ

As noted in Section 2.3, the disturbed rock zone can be considered as having an inner part, where the connectivity of fractures is such that the permeability is significantly enhanced, and an outer part, where no such effect is expected. In most calculation cases, the inner part (i.e. the EDZ) is treated as a homogeneous, isotropic porous medium, forming an annular region 0.7 m thick around each of the underground openings (Fig. 4.3-1a, below). However, because some micro- and macro-scale fracturing in the EDZ may persist over time, it is appropriate, as an alternative conceptual model, to also represent the EDZ as a fractured porous medium. Radionuclides could, in principle, also reach the outer part of the disturbed rock zone.

In the variant case **SA4_EDZ1**, transport in the EDZ is assumed to occur along a single fracture, assumed to run along the interface between the inner and the outer part of the disturbed rock zone (Fig. 4.3-1b). Details of the corresponding modelling approach are as follows:

- Each tunnel and its EDZ are modelled with two separate legs, which are connected only at their respective ends. The flow value is distributed between the two legs the same way it is distributed between the two domains of a single leg in the main calculation cases (Section 3.3).
- The tunnel leg is modelled the same way as the "tunnel domain" described in Section 3.3, with the exception that no matrix is assigned to the tunnel leg.
- The EDZ leg is modelled as a planar flow channel surrounded by a diffusion-accessible matrix (Fig. 4.3-1c). The properties of the matrix are the same as those of undisturbed host rock.
- Based on the assumption that the flow channel runs along the interface between the inner part and the outer part of the disturbed rock zone, the matrix penetration depth is set to the thickness of the EDZ, i.e. to 0.7 m. The lateral extent of the leg is set to the circumference of the EDZ at the location of the interface, i.e. to \(2 \cdot (r + 0.7 \text{ m}) \cdot \pi\).
In Nagra (2010), a hypothetical situation is considered in which radionuclides, having entered a discrete geosphere fracture, may irreversibly sorb onto colloids already present in the discrete fracture. These colloids are precluded by their size and / or charge from entering the adjacent rock matrix. A bounding approach was adopted in Nagra (2010) to model this situation in which matrix diffusion was switched off. The same approach is adopted in variant case $SA4\_EDZ1b$ of the present modelling study, where matrix diffusion in the EDZ legs is precluded.

In another variant case, $SA4\_EDZ2$, it is assumed that the EDZ is entirely removed at the position of the seals. The flow model for this variant case is adjusted accordingly. Again, a variant case $SA4\_EDZ2b$ is modelled, in which the matrix is assumed not to be accessible to radionuclides. In practice, the complete removal of the EDZ will not be possible. The expected situation is, however, well bounded by the two assumptions of complete removal and of non-removal.

Fig. 4.3-1: Different conceptualisations of the EDZ used in $SA4$ (a); and $SA4\_EDZ1$ and $SA4\_EDZ2$ (b); modelling the EDZ as a single planar fracture with matrix (c).
4.3.3 Transport in the SF / HLW emplacement rooms and the role of intermediate seals

In the modelling approach for the main calculation cases, each SF / HLW emplacement room is considered a mixing tank, i.e. the backfill or buffer material of the emplacement room is assumed not to provide any transport barrier to radionuclides within the room. This pessimistic assumption may highly overestimate radionuclide release from the SF / HLW emplacement rooms to the repository tunnel system for two reasons:

- flow along the SF / HLW emplacement rooms increases non-linearly and is thus relatively high only in the neighbourhood of the seal,
- the reference concept foresees the construction of intermediate seals along the emplacement rooms every 11th canister position or so to provide an additional level of compartmentalisation.

The degree of overestimation using the mixing-tank approach and the role of the intermediate seals are investigated in the complementary cases described below.

A possible implementation of an intermediate seal is illustrated in Fig. 4.3-2. According to this figure, the liner is removed along a section of the emplacement room about 10 m in length. Within this section, the length of the effective sealing element is about 4 m. For simplicity, only the length of the effective sealing element is considered in the present study, which is pessimistic in that it will tend to underestimate the effectiveness of the intermediate seal. A further pessimistic assumption is that the EDZ is not removed around the effective sealing element, although at least partial removal would be carried out in practice.

Based on the reference length of an SF / HLW emplacement room of 700 m, these are each divided into:

- 8 non-seal sections, and
- 7 seal sections.

The SF canister pitch (length of an SF disposal canister plus the separation between canisters) is about 8 m and there are 10 such canisters in each non-seal section. Thus, each non-seal section has a length of $10 \times 8 \, \text{m} + 4 \, \text{m} = 84 \, \text{m}$ (note: $84 \, \text{m} \times 8 + 4 \, \text{m} \times 7 = 700 \, \text{m}$).

The legs representing the host rock are subdivided accordingly, with a leg above the repository horizon and a leg below the horizon for each seal and non-seal section. The flow model is adapted accordingly to provide flow values for the shorter, horizontal legs and the narrower, vertical host-rock legs. The assignment of flow values to the various domains of the host-rock legs follows the methodology described in Section 3.4.2.

The source term is divided into eight and is applied at the upstream junction of each seal section, as well as at the upstream junction of the final tunnel seal (i.e. at the downstream ends of the individual non-seal sections).

A set of calculation cases is defined, again based on $SA4$, in which advective / dispersive transport dominates radionuclide release from an emplacement room. In the first case of this set ($SA4_SA4$), the parameter values of case $SA4$ are applied to both seal and non-seal sections along the emplacement rooms. The transport results of this calculation case are intended to give a first approximation of the effect of using a mixing tank as part of the standard modelling approach. Note that the flows in case $SA4_SA4$ are the same as those in case $SA4$ in the remaining parts of the tunnel system.
In the remaining calculation cases, the hydraulic parameters for the seal sections and their respective EDZs are progressively reduced using the values for tunnel type #1 (see Tab. 4.2-1). The names of the calculation cases are $SA4_{-}SA3$, $SA4_{-}SA2$ and $SA4_{-}SA1$. For example, in case $SA4_{-}SA1$, hydraulic parameter values for the seal sections are taken to be those for tunnel type 1 in case $SA1$.

4.3.4 Transport along a liner

The current repository concept foresees the construction of a cementitious tunnel liner around all underground structures. Although the equilibration of the geomechanical conditions in the post-closure phase is expected to result in low hydraulic conductivity of the backfill / sealing material and the EDZ, it may also result in brittle deformation of the liner. In addition, if water flow along the liner was high, its sorption capacity would potentially degrade over time.

The thickness of the liner will depend on the tunnel type and the geomechanical conditions. The following estimates are based on the radius of the relatively long operations / construction tunnels in the present flow models of about 2.5 m, for which a reasonable liner thickness is about 0.20 m. Assuming an effective hydraulic conductivity of the fractured liner of $10^{-7}$ m/s (10 times higher than the value assumed for the L/ILW emplacement room backfill), the flow through the liner for a unit hydraulic gradient (hydraulic conductivity times cross-sectional area) is about $3 \times 10^{-7}$ m$^3$/s, which is in the order of the total flow through the operations tunnel and its EDZ for a unit gradient in case $SA4$. Therefore, the results of the bounding case $SA4_{-}EDZ1b$ may also be considered as bounding case for transport along a fractured liner with negligible sorption capacity. Similarly, the case $SA4_{-}EDZ2b$ is transferable to the situation in which the liner is removed at seal positions.
4.3.5 Hydraulic conductivity of the host rock

A single calculation case $SA4_a$ is defined, based on the calculation case $SA4$, but with the hydraulic conductivity of the host rock for the HLW repository increased to $10^{-13} \text{ m/s}$ from the base case value of $2 \times 10^{-14} \text{ m/s}$ and the hydraulic conductivity of the host rock for the L/ILW repository increased to $10^{-12} \text{ m/s}$ from the base case value of $10^{-13} \text{ m/s}$.

4.3.6 Physical and geochemical retention

Four further calculation cases are defined to illustrate reduced physical and geochemical retention in the repository barrier system. All of these cases assume the same flows in the host rock and in the repository tunnel system as case $SA4$:

- $SA4_b$: pessimistic (i.e. higher) effective diffusion coefficients in the host rock;
- $SA4_d$: reduced sorption coefficients in the SF / HLW near field and the geosphere;
- $SA4_f$: increased dissolution rates of the SF matrix and the cladding (incl. structural materials); and
- $SA4_g$: reduced (1'000 year) SF and HLW canister lifetime.

Cases $SA4_b$ and $SA4_d$ are calculated for both repository types, but $SA4_f$ and $SA4_g$ are applicable only to the HLW repository. The specific parameter values used in $SA4_b$ and $SA4_d$, where these differ from $SA4$, are the same as those used in the corresponding calculation cases in Nagra (2010). In case $SA4_f$, dissolution rates of the SF matrix and the cladding are increased by a factor of 100.
5 Results and Discussion

5.1 Main calculation cases

5.1.1 Base cases

Flow calculations for the base cases give flow rates from the repository emplacement rooms that are extremely low, with Darcy velocities that are in the order of micrometres per year or less (see Appendix C). The validity of the resistor network approach for these and other calculation cases is discussed in Appendix A.3. The modelling approach is shown to be fully adequate for all calculation cases except for HLV BC, where the exact values calculated may be unreliable. In view of these findings, calculated radionuclide release rates exiting via the ramp and shaft in the base case transport calculations for the HLW repository are to be viewed as indicative only.

The evolution of dose rate with time for a HLW repository due to releases from the SF / HLW emplacement panels and the ILW emplacement rooms is shown in the upper graph of Fig. 5.1-1 for the HLW base case. The lower graph shows the dose rates due to releases from the emplacement panels of the L/ILW repository. Note that the vertical shaded region in this and other dose rate figures indicates the time frame for safety assessment, which is $10^6$ years for the HLW repository and $10^5$ years for the L/ILW repository. Furthermore, the fact that dose rates as low as $10^{-7}$ mSv a$^{-1}$ clearly have no radiological meaning is reflected in the figure by a horizontal shaded region.

Since the sealing and backfilling of the repository tunnel system and the access structures are assumed to be highly effective, release rates in both these calculations are dominated by the transport paths through the host rock. The upper graph shows that the maximum dose rates are due to releases from the SF / HLW panels and are more than three orders of magnitude below the 0.1 mSv a$^{-1}$ regulatory guideline. $^{22}$ The maximum dose rates due to the ILW emplacement rooms are around three orders of magnitude lower still. The relative contributions of SF and HLW are discussed in Appendix C, where it is shown that the maximum dose rate due to SF is about an order of magnitude higher than that due to HLW. The maximum dose rates for the L/ILW repository within its time frame for safety assessment are more than five orders of magnitude below the regulatory guideline. The relative contributions of different radionuclides to the evolution of dose rate in this and other cases for the HLW repository and also for the L/ILW repository are discussed in Appendix C.

5.1.2 Overriding system analyses

Flow modelling results

Flow modelling results for the base cases and the overriding system analyses for the HLW and the ILW repository, in terms of the total flows from the waste emplacement panels (i.e. groups of emplacement rooms; see Figs. 4.2-1 and 4.2-2) and in terms of the flows exiting the repository via the ramp and shafts (construction / operations $^{23}$ and ventilation shafts) are shown in Figs. 5.1-2 and 5.1-3.

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$^{22}$ Note that this result compares well with the maximum dose rate calculated in the Reference Case of project Opalinus Clay (4.8 x $10^{-5}$ mSv/a, see Nagra 2002a), which also assumed the situation of an isolated host rock.

$^{23}$ Note that in all presented results for the L/ILW repository, the operations shaft is denoted CS.
Fig. 5.1-1: Evolution of dose rate in calculation case $\text{HLW}_{\text{BC}}$ (upper graph) and $\text{L/ILW}_{\text{BC}}$ (lower graph).

Background shading in this and similar figures is used to indicate (i), that dose rates of $10^{-7}$ mSv/a or lower have no radiological meaning and (ii), the time frames for safety assessment of $10^6$ years for the HLW repository and $10^5$ years for the L/ILW repository.

R/S: total release via ramp and shafts. HR: total release via host rock.
Fig. 5.1-2: Summary of key flows calculated for the HLW repository in the overriding system analyses (SA) and in the base case (BC).

Fig. 5.1-3: Summary of key flows calculated for the L/ILW repository in the overriding system analyses (SA) and in the base case (BC).

R/S: ramp and shafts. VS: ventilation shaft. CS: operations shaft.
The calculated flows are similar for the two repository types, especially the flows exiting the repositories via the ramp and shafts. This is unsurprising, since the repository layouts, the backfill and sealing materials as well as the assumed geological environments are comparable.

Flow values along the ramp and up the two shafts are in the order of $0.001 \text{ to } 1 \text{ m}^3\text{a}^{-1}$, which is consistent with those evaluated for the HLW repository in earlier Nagra studies (see e.g. Figure 3.1 of Smith et al. 2004). Although there are significant differences in the model and parameter values used in the present study and in previous studies, this broad consistency in the results provides some support for their plausibility.

Globally increasing the hydraulic conductivity in the tunnel system (i.e. going from $BC \rightarrow SA1 \rightarrow SA2 \rightarrow \ldots \rightarrow SA6$) increases all the calculated flows, but the increase is seen to level off with increasing hydraulic conductivity ($SA5$ results are quite similar to those for $SA6$), since the inflow to the repository is ultimately limited by the low hydraulic conductivity of the rock. In any given case, the flows up the two shafts are similar to each other. In the base case ($BC$) and in case $SA1$, they are less than the flow along the ramp, although in other cases they are greater. The flows along the ramp are virtually identical in case $SA1$ and in the $BC$, since the hydraulic conductivity of the ramp ($K4$ in Tab. 4.2-1) and its seal ($K2-V4$) are identical in these two cases. The hydraulic conductivity of the shafts is, however, higher in $SA1$ compared with the base case, resulting in higher shaft flows in $SA1$.

To further illustrate the "levelling-off" effect, asymptotic values for the total flow from the repository (i.e. the sum of flows along the ramp and shafts) and for flow from the repository emplacement rooms or panels in the case of a very high hydraulic conductivity in the tunnel system are presented in Appendix C.

Transport modelling results

The impact of assigning higher hydraulic conductivities to the repository tunnel system, including the repository seals is illustrated by comparing the transport modelling results of cases $HLW\_SA4$ and $LILW\_SA4$ with those of the corresponding base cases (Fig. 5.1-4). It can be seen that the dose rates due to releases via the host rock transport pathway are a little lower in $HLW\_SA4$ and $LILW\_SA4$ if compared with the base case. The reduction is due to the diversion of part of the releases from the emplacement rooms to the repository tunnel system.

With the exception of the ventilation shaft, which is not accessible to radionuclides in both base cases, releases via the shafts and ramp give maximum dose rates that are higher than those due to releases via the host rock. The peak dose rates, however, remain well below the regulatory guideline (around three orders of magnitude for the HLW repository and almost four orders of magnitude for the L/ILW repository). In the case of the HLW repository, the greatest contribution to the peak dose is from the ramp, followed by the construction shaft, followed by the host rock and finally the ventilation shaft. In the case of the L/ILW repository, the peak dose rates due to releases from the two shafts are similar, and higher than that due to ramp release, which is in turn higher than that due to release via the rock.\footnote{It should be noted that this ordering of the peak dose rates is highly specific to the modelled repository layout and may thus be different for alternative arrangements of the underground structures within the central area. It is, however, judged that the overall results would be quite similar (see Appendix C).}
Fig. 5.1-4: Evolution of dose rate in calculation cases *HLW_SA4* (upper graph) and *L/ILW_SA4* (lower graph), each compared with the corresponding base case.

**BC**: base case. **HR**: host rock. **CS**: construction / operations shaft. **VS**: ventilation shaft.
These maxima for the ramp and shafts occur after a few tens of thousands to about one hundred thousand years post closure, following which the dose rates due to releases via all these structures eventually decline to levels lower than those due to releases via the host rock.

As noted earlier, the hydraulic conductivities assumed in the $SA4$ cases are clearly hypothetical, with, for example, the hydraulic conductivities of the bentonite seals, SF / HLW emplacement rooms and their associated EDZs being four orders of magnitude above the more realistic base-case values. Nevertheless, the case is of particular interest, since the assumed hydraulic conductivities, as well as those in $SA5$ and $SA6$, are sufficiently high that transport along the repository tunnel system and access structures contributes more to overall peak dose than does transport through the host rock (Fig. 5.1-5).

The parameter set $SA4$ is also comparable in its parameter values to the "what if?" case of a HLW repository studied in the follow-up report to Project Opalinus Clay by Smith et al. (2004), where an EDZ hydraulic conductivity of $10^{-8}$ m s$^{-1}$ was also assumed for the SF / HLW emplacement rooms. The peak dose rate due to release via the host rock in this "what if?" case was similar to that calculated in the present study for $HLW_{SA4}$, being somewhat over $10^{-5}$ mSv a$^{-1}$ in both cases. On the other hand, the peak dose rate due to release via the single shaft of the earlier study was similar to that via the host rock, and thus lower than those via the construction shaft in the present study. Furthermore, the peak dose rate due to release via the ramp was 2 to 3 orders of magnitude lower in the earlier study compared with the present study, being in the order of $10^{-7}$ mSv a$^{-1}$ in the earlier study. It should be noted, however, that differences in the dose rates due to releases via the repository tunnel system and access structures are unsurprising, given the differences e.g. in the assumed repository layout, the models used to calculate flows (which in the earlier study included only inflows from the host rock to the emplacement rooms) and the modelling approach used to calculate near-field release.

Fig. 5.1-5 presents the calculated maximum dose rates for all the base cases and all the $SA$ calculation cases for the HLW repository and the L/ILW repository within the respective time frames for safety assessment (10$^6$ years for the HLW repository and 10$^5$ years for the L/ILW repository). In order to display most of the calculated maxima within the assessment time frames, the $y$-axis for the L/ILW repository has been extended to dose levels that are far too low to have any radiological significance.

The dose rate maxima due to shaft and ramp releases follow the same trend as the flows along these paths: generally increasing with growing hydraulic conductivity values in the tunnel system, but levelling off at very high hydraulic conductivity values. Conversely, for the HLW repository, the dose rate maxima for release from the host rock decrease with higher hydraulic conductivity values in the tunnel system. This is because the more the flow in the host rock is diverted into the tunnel system, the less radionuclide release there is to the host rock. For the L/ILW repository, the dose rate maxima for release from the host rock are generally quite insensitive to the hydraulic conductivity values in the tunnel system. This is, however, because the peak dose rates for releases from the host rock is determined by an initial diffusive pulse of C-14 in organic form, for which advective / dispersive transport along the tunnel system is not relevant.

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25 The results of this "what if?" case were also discussed in Figure 6.2-3 of Nagra (2010).

26 It should be noted that some of the maximum dose rates (especially those for the L/ILW repository) are achieved long after the respective time frames for safety assessment.
Fig. 5.1-5: Maximum dose rates calculated for the HLW repository (upper graph) and the L/ILW repository (lower graph) within the respective time frames for safety assessment in the overall system analyses (SA) and in the base cases.

For the more realistic hydraulic conductivity values within the tunnel system (SA1 and SA2), dose rates due to releases via the ramp and shafts are markedly less than those due to releases from the host rock. Only for unrealistically high hydraulic conductivity values within the tunnel system and the EDZ (SA4 to SA6) are dose rates due to ramp and shaft releases larger than those from the host rock. However, even in these cases, the dose rates are low, remaining below $10^{-3}$ mSv per year for both repository types, $10^{-3}$ mSv per year being two orders of magnitude below the Swiss regulatory Protection Criterion 1.

The results of the overriding system analyses (flow and transport modelling) are further discussed in Appendix C.

5.1.3 Quality of the horizontal seals and the option of a shaft in place of the ramp

Flow modelling results

Figs. 5.1-6 and 5.1-7 show some key flow values for different tunnels of the HLW and L/ILW repositories calculated for the base cases and for calculation cases that illustrate the importance of the quality of the horizontal seals, and that illustrate the effects of replacing the ramp by a third shaft. In Case QHS1, which considers the reference layout with a ramp, the hydraulic conductivities of the horizontal seals (depicted in green in the case of a L/ILW repository in Fig. 3.2-4), and the SF / HLW emplacement rooms and their EDZs are increased by two orders of magnitude with respect to the base case (BC). This has a negligible impact on the flows up the shafts. However, the flows from the waste emplacement rooms and along the ramp (the ramp seal being taken as horizontal) are significantly increased. Case QHS2 again considers the reference layout. However, in addition to increasing the hydraulic conductivities of the horizontal seals, of the SF / HLW emplacement rooms and of their EDZs, the hydraulic conductivities of the shaft EDZs are also increased by an order of magnitude. Compared with case QHS1, this leads to a significant increase in the flows up the shafts, but has a negligible impact on flow along the ramp.

The same figures also show these key flow values for the corresponding cases with a third shaft (cases BC_3S, QHS1_3S and QHS2_3S). In all cases, replacing the ramp by a third shaft has little impact on the flow up the other two shafts. The flow up the third shaft is, however, significantly less than the flow up the ramp. This is mainly because in cases QHS1 and QHS2 the shafts and their EDZs are assigned a far lower hydraulic conductivity than those of the ramp (e.g. $10^{-13}$ m s$^{-1}$ for the shaft sealing material compared with $10^{-11}$ ms$^{-1}$ for the ramp sealing material in the base cases). Thus, for the assumed layout and the parameter set used in QHS1, the repository is more effectively sealed when the ramp is replaced by a shaft, also leading to lower flows from the emplacement panels. On the other hand, in those cases where the hydraulic conductivity of the shaft EDZ is increased by only a factor of 10 (QHS2 and QHS2_3S), the effect of replacing the ramp by a third shaft is relatively minor.
Fig. 5.1-6: Summary of key flows calculated for a HLW repository in the analysis of the base cases and of calculation cases addressing the quality of the horizontal seals (QHS1 and QHS2) and the option of a third shaft in place of the ramp (QHS1\_3S and QHS2\_3S).

Fig. 5.1-7: Summary of key flows calculated for a L/ILW repository in the analysis of the base cases and of calculation cases addressing the quality of the horizontal seals (QHS1 and QHS2) and the option of a third shaft in place of the ramp (QHS1_3S and QHS2_3S).

Transport modelling results

Figs. 5.1-8 shows the calculated maximum dose rates for the same set of QHS calculation cases and for the base cases for the HLW and L/ILW repositories. In all cases, the maximum dose rates due to releases from the host rock dominate over those due to releases from the ramp and the shafts. Releases via ramp and shafts are generally very low. The y-axis for the L/ILW repository has been extended to dose levels that are far too low to have any radiological significance in order to illustrate model behaviour in all of these cases.

As expected from the flow results, the maximum dose rate for the reference layout with a ramp due to flow along the ramp is little affected if the hydraulic conductivity of the shaft EDZs is increased in addition to the hydraulic conductivity of the horizontal seals. The maximum dose rates due to the releases via the shafts increase, but only if the shaft is accessible to radionuclides by advective transport, which is not the case for the ventilation shaft (VS) in cases QHS1 and QHS2 for the HLW repository and in case QHS1 for the L/ILW repository. For the variant layout with a third shaft, the maximum dose rates resulting from releases via the third shaft are clearly less than those via the ramp.

In summary, if a relatively poor quality of horizontal sealing elements (including the ramp seal) is assumed, while the vertical seals (i.e. those for the shafts) still perform as expected, the variant layout with the ramp performs slightly less favourably than the layout with a third shaft. However, in both variants, the calculated release rates along the access structures are very low and, in particular, far less than the release rates from the host rock.

5.2 Complementary calculation cases

As mentioned in Section 4.2.2, the parameter set SA4 is of particular interest for the present study, since water flow along the repository tunnel system is sufficiently high that radionuclide release via the access structures contributes more to overall peak dose than does transport through the host rock. The complementary calculation cases described in the following sections are therefore based on the parameter set SA4.

5.2.1 Dispersion along the tunnel system

Fig. 5.2-1 shows the evolution of dose rates for the SA4 cases for the HLW repository and the L/ILW repository; and for calculation cases in which the Peclet number is varied up and down from its reference value of Pe = 10:

- **SA4_Dvl**: very low longitudinal dispersion along tunnel system (Pe = 100).
- **SA4_DL**: low longitudinal dispersion along tunnel system (Pe = 30).
- **SA4_Dh**: high longitudinal dispersion along tunnel system (Pe = 3).
- **SA4_Dvh**: very high longitudinal dispersion along tunnel system (Pe = 1).

Doses rates due to releases from the host rock are the same in all these cases. The dose rates due to releases from the ramp and shafts, and the subsequent maxima, appear earlier as Peclet number is reduced (longitudinal dispersion along the tunnel system is increased). The maxima themselves are virtually the same in all cases, except in case SA4_Dvh for the L/ILW repository, which is higher than the other cases for the L/ILW repository by almost 40%.
Fig. 5.1-8: Maximum dose rates calculated for a HLW repository (upper graph) and for a L/ILW repository (lower graph) in the base cases and in the analysis of calculation cases addressing the quality of the horizontal seals (\textit{QHS1} and \textit{QHS2}) and the option of a third shaft in place of the ramp (\textit{QHS1\_3S} and \textit{QHS2\_3S}).

Fig. 5.2-1: Evolution of dose rate in the SA4 calculation cases for the HLW repository (upper graph) and the L/ILW repository (lower graph) and for calculation cases in which the Peclet number is varied up and down from its reference value of 10.

R/S: ramp and shafts. HR: host rock. For details on the individual cases, see Section 4.3.1.
Thus, it can be concluded that longitudinal dispersion along the tunnel system has a minor effect on the dose rate maximum of case $SA4$, increasing it by a few tens of percent at most, and then only if very high longitudinal dispersion along the tunnel system is assumed.

5.2.2 Conceptualisation of the EDZ

Fig. 5.2-2 shows the evolution of dose rates for the $SA4$ cases for the HLW repository and the L/ILW repository, in which the EDZ is treated as a homogeneous, isotropic porous medium, and for calculation cases illustrating alternative conceptualisations of the EDZ:

- $SA4_{EDZ1}$: transport in the EDZ is assumed to occur along a single fracture, assumed to be running along the interface between the inner and the outer part of the disturbed rock zone.
- $SA4_{EDZ1b}$: same as $SA4_{EDZ1}$, except that matrix diffusion in the EDZ legs is precluded, to account for the possibility of colloid facilitated radionuclide transport.
- $SA4_{EDZ2}$: the fractured EDZ is entirely removed at the position of the seals (flow model adjusted accordingly).
- $SA4_{EDZ2b}$: same as $SA4_{EDZ2}$, except that matrix diffusion in the EDZ legs is precluded, to account for the possibility of colloid facilitated radionuclide transport.

Dose rates due to releases from the host rock are practically the same in all these cases. The dose rates due to releases from the ramp and shafts, and the corresponding maxima, appear earliest in the two cases where matrix diffusion in the EDZ legs is precluded ($SA4_{EDZ1b}$ and $SA4_{EDZ2b}$). If transport in the EDZ is assumed to occur along a single fracture, the dose rates due to releases from the ramp and shafts, and the corresponding maxima, appear earlier than in $SA4$. If, in addition, this fractured EDZ is entirely removed at the position of the seals, the doses rates due to releases from the ramp and shafts, and the corresponding maxima, appear later than in $SA4$. Nevertheless, the maxima themselves are similar in most cases, although, in case $SA4_{EDZ1b}$ for the L/ILW repository, the maximum dose rate is higher by a factor of about 2 than in the corresponding $SA4$ case.

In summary, the conceptualisation of the EDZ and possible technical measures to reduce the extent of the EDZ at the positions of seals affect the dose rate maximum by around a factor of 2 at most.

5.2.3 Transport in the SF / HLW emplacement rooms and the role of intermediate seals

Fig. 5.2-3 shows the evolution of dose rate in the calculation case $SA4$ for the HLW repository and in calculation case $SA4_{SA4}$, which illustrates an alternative conceptualisation of radionuclide transport along the SF / HLW emplacement rooms. In case $SA4$, radionuclide transport times along the emplacement rooms are disregarded (mixing-tank approach). In contrast, in case $SA4_{SA4}$, radionuclide transport along the emplacement rooms is modelled explicitly, with the rooms divided into seal and non-seal sections but with the parameter values of case $SA4$ that are applied to both section types.

The figure shows that pulse release to the repository tunnel system from the emplacement rooms that is observed in $SA4$ at the assumed SF / HLW canister breaching time is both spread in time and diminished in magnitude in $SA4_{SA4}$. Dose rates due to releases from the ramp and shafts and due to release from the host rock are, however, similar in the two cases (although dose rates due to ramp and shaft releases are slightly lower in $SA4_{SA4}$).
Fig. 5.2-2: Evolution of dose rate in the SA4 calculation cases for the HLW repository (upper graph) and the L/ILW repository (lower graph) and for calculation cases illustrating alternative conceptualisations of the EDZ.

R/S: ramp and shafts. HR: host rock. For details on the individual cases, see Section 4.3.2.
Fig. 5.2-3: Evolution of dose rate in the SA4 calculation case for the HLW repository and for calculation case SA4_SA4, which illustrates an alternative conceptualisation of transport along the SF / HLW emplacement rooms.

R/S: ramp and shafts. HR: host rock. For details on the individual cases, see Section 4.3.3.

The set-up of the further cases SA4_SA3, SA4_SA2, and SA4_SA1 is the same as that of SA4_SA4, except that the hydraulic conductivities for the seal sections and their respective EDZs are progressively reduced using the values for tunnel type #1 that were used in the calculation cases SA3, SA2 and SA1, respectively (see Tab. 4.2-1). Fig. 5.2-4 shows the calculated maximum dose rates in these cases and in SA4_SA4. The reduction in hydraulic conductivities for the sections with intermediate seals leads to a reduction in the maximum dose rates due to releases from the ramp and shafts of more than one order of magnitude.

In summary, an alternative, less pessimistic conceptualisation of transport along the SF / HLW emplacement rooms leads to a reduction in the calculated maximum dose rate, at least in the present example (SA4), where the performance of the backfill and seals in the rest of the repository tunnel system is markedly poorer than expected.

5.2.4 Transport along a liner

As explained in Section 4.3.4, the results of the bounding case SA4_EDZ1b may also be considered as bounding case for transport along a fractured liner with negligible sorption capacity. Similarly, the case SA4_EDZ2b is transferable to the situation in which the liner is removed at seal positions. Thus, referring to the results in Section 5.2.2, the possibility of transport along a liner affects the dose rate maximum by around a factor of 2 at most.
Fig. 5.2-4: Maximum dose rates calculated for a HLW repository in the \textit{SA4} calculation case for the HLW repository and for further calculation cases illustrating an alternative conceptualisation of transport along the SF / HLW emplacement rooms.

R/S: ramp and shafts. HR: host rock. For details on the individual cases, see Section 4.3.3.

\section*{5.2.5 Hydraulic conductivity of the host rock}

\textbf{Flow modelling results}

Figs. 5.2-5a and 5.2-5b show the flow results of the analysis of sensitivity to the hydraulic conductivity in the host rock. Increasing the hydraulic conductivity of the rock ($10^{-13}$ m/s for the HLW repository and $10^{-12}$ for the L/ILW repository in case \textit{SA4 a} compared with $2 \times 10^{-14}$ m/s for the HLW repository and $10^{-13}$ m/s for the L/ILW repository in case \textit{SA4}) increases the flow up the shafts and along the ramp, and also the flow from HLW Panel 2 and from the ILW emplacement rooms. The flows from HLW Panel 1 and from L/ILW Panels 1 and 2 are, however, reduced.

Note that a higher flow up the shafts and along the ramp implies a higher hydraulic head at repository level (for the same hydraulic conductivities in the tunnel system), i.e. more similar to the ambient head at repository depth. Thus, although the higher hydraulic conductivity of the host rock can lead to higher inflows to the underground structures, reduced flow along underground structures can also occur in some circumstances, as a result of changes in the flow directions within the tunnel system. Overall, however, the effects on flow in the repository tunnel system are small (less than one order of magnitude).
Fig. 5.2-5a: Summary of key flows calculated for the HLW repository in the analysis of the impact of hydraulic conductivity of the host rock.

SA4: increased hydraulic conductivity (orange bars); SA4: reference hydraulic conductivity (blue bars) (see also Section 4.3.5).

CS: construction shaft. VS: ventilation shaft.
Fig. 5.2-5b: Summary of key flows calculated for the L/ILW repository in the analysis of the impact of hydraulic conductivity of the host rock.

SA4_a: increased hydraulic conductivity (orange bars); SA4: reference hydraulic conductivity (blue bars) (see also Section 4.3.5).

CS: operations shaft. VS: ventilation shaft.
Transport modelling results

Fig. 5.2-6 shows the evolution of dose rate for these two calculation cases. The peak dose rate due to radionuclide release through the host rock is increased in the case of the higher hydraulic conductivity in the host rock by around two orders of magnitude for the L/ILW repository and by less than an order of magnitude for the HLW repository. The peak dose rate due to radionuclide release along ramp and shafts is also increased in the case of the HLW repository, but reduced for the L/ILW repository, though by less than an order of magnitude in both cases. In L/ILW case SA4_a, the increase in host rock hydraulic conductivity results in the host rock becoming the transport pathway that gives the highest dose rate within the time frame for safety assessment, whereas the repository tunnel system remains the dominant transport pathway for the HLW repository. This behaviour of the L/ILW repository is due to the radionuclide Cs-137, which reaches its maximum dose rate within the time frame for safety assessment for higher water flow in case SA4_a (see Appendix C, Figs. C2-3 and C2-4).

Overall, it is concluded that, for the hydraulic properties of the repository tunnel system assumed in these cases, increasing the hydraulic conductivity of the host rock has minor effects on flow out of the repository via the ramp and shafts and on the corresponding dose rates, although the host rock becomes the dominant transport pathway contributing to peak dose rate in the case of the L/ILW repository.

5.2.6 Physical and geochemical retention

Fig. 5.2-7 shows the evolution of dose rate in case SA4 compared with case SA4_b, which assumes more pessimistic (i.e. higher) effective diffusion coefficients in the host rock. All flows are the same as in case SA4. For the HLW repository, the peak dose rate due to the host rock transport path occurs earlier in SA4_b compared with SA4 and is slightly higher. For the L/ILW repository, the peak dose rate is both earlier and significantly higher in SA4_b compared with SA4, the difference in the magnitude of the peak being almost three orders of magnitude.

Reduced sorption coefficients in the near field and the geosphere (case SA4_d) give evolutions of dose rates that are indistinguishable from those of case SA4 for both repository types, since dose rates are in any case dominated by radionuclides for which no sorption is assumed (see Appendix C, Section C.2).

Fig. 5.2-8 shows the evolution of dose rate in case SA4 compared with case SA4_f (increased dissolution rates of the SF matrix and the cladding) and SA4_g (SF and HLW canister lifetime reduced to 1'000 years). These cases are applicable only to the HLW repository. The effects of canister lifetime on peak dose rates are minor. However, increasing the dissolution rates of the SF matrix and cladding gives peak dose rates that are higher by about one order of magnitude compared with case SA4.

In summary, of the physical and chemical retention parameters investigated, the values assigned to the effective diffusion coefficients for the host rock and the dissolution rates of the SF matrix and the cladding can have a significant effect on peak dose rates, whereas the effects of canister lifetime are small over the range of variation considered. Peak dose rate remains more than one order of magnitude below the regulatory protection criterion in all cases evaluated in this section.
Fig. 5.2-6: Evolution of dose rate in the $SA4$ (reference hydraulic conductivity) and $SA4_a$ (increased hydraulic conductivity) calculation cases for the HLW repository (upper graph) and the L/ILW repository (lower graph), which illustrates the effects of increased host rock hydraulic conductivity.

R/S: ramp and shafts. HR: host rock. For details on the individual cases, see Section 4.3.5.
Fig. 5.2-7: Evolution of dose rate in the SA4 calculation cases for the HLW repository (upper graph) and the L/ILW repository (lower graph) and for calculation cases SA4_b, which illustrates the effects of increased effective diffusion coefficients in the host rock.

R/S: ramp and shafts. HR: host rock. For details on the individual cases, see Section 4.3.6.
Fig. 5.2-8: Evolution of dose rate in the SA4 calculation case for the HLW repository and for calculation cases SA4_f and SA4_g illustrating, respectively, the effects of increased SF matrix and cladding dissolution rates and reduced canister lifetime. R/S: ramp and shafts. HR: host rock. For details on the individual cases, see Section 4.3.6.

5.3 Summary of results

The results of the main calculation cases presented in Section 5.1 of this chapter illustrate the impact on flows within and from a deep geological repository and on the resulting dose rate maxima of (i), globally increasing hydraulic conductivity in the tunnel system and (ii), assuming a degraded performance of the horizontal seals and also replacing the ramp by a third shaft.

Key observations are:

- Globally increasing the hydraulic conductivity in the tunnel system increases all the calculated flows, but the increase is found to level off with increasing hydraulic conductivity. The dose rate maxima due to shaft and ramp releases follow the same general trend as the flows along these paths: generally increasing with growing hydraulic conductivity values in the tunnel system, but levelling off at very high hydraulic conductivity values. In all cases, maximum dose rates are well below the regulatory protection criterion.

- No advective release to the host rock occurs in the cases with the highest hydraulic conductivities assigned to the tunnel systems. This is illustrated in Fig. 3.2-1, Test 0, which is representative for this situation and which shows inflow from the host rock into a tunnel at all positions around the tunnel-host rock interface.

- Increasing the hydraulic conductivities of the horizontal seals and the EDZs relative to the base-case values has a negligible impact on the flows up the shafts. However, the flows from the waste emplacement rooms and along the ramp are significantly increased.
• If the hydraulic conductivity of the shaft EDZ is also increased, the flows up the shafts are significantly increased, but this has a negligible impact on flow along the ramp or on the maximum dose rate due to releases via the ramp. The maximum dose rates due to the releases via the shafts increase, but only if the shaft is accessible to radionuclides by advective transport.

• If a relatively poor quality of horizontal sealing elements (including the ramp seal) is assumed, while the vertical seals (i.e. those for the shafts) still perform as expected, the variant layout with the ramp performs slightly less favourably than the layout with a third shaft. However, in both variants, the calculated release rates along the access structures are very low and, in particular, far less than the release rates from the host rock.

The results of complementary calculation cases based on parameter set $SA4$ have been presented in Section 5.2 of this chapter. For these, some key observations are:

• Longitudinal dispersion along the repository tunnel system has a minor effect on the calculated dose rate maximum of case $SA4$, increasing it by a few tens of percent at most, and then only if very high longitudinal dispersion along the tunnel system is assumed.

• Alternatives to the reference conceptualisation of the EDZ and possible technical measures to reduce the extent of the EDZ at the positions of seals affect the dose rate maximum by around a factor of 2 at most. The same conclusion can be drawn for radionuclide transport along the lining of the repository tunnel system.

• Alternatives to the reference conceptualisation of the SF / HLW emplacement rooms as mixing tanks, in which transport along the SF / HLW emplacement rooms is explicitly modelled, give a reduction in the calculated maximum dose rate, at least in the present example (case $SA4$), in which the performance of the backfill and seals in the rest of the repository tunnel system is markedly poorer than expected.

• Increasing the host rock hydraulic conductivity with respect to its values in case $SA4$ has minor effects on flow out of the repository via the ramp and shafts and on the corresponding dose rates.

• Of the physical and chemical retention parameters investigated, the values assigned to the effective diffusion coefficients for the host rock and the dissolution rates of the SF matrix and the cladding can have significant effects on peak dose rates, whereas the effects of canister lifetime are small over the range of variation considered.

In all cases, the peak dose rate remains below the regulatory protection criterion, generally by several orders of magnitude, in spite of the generally conservative assumptions made in this modelling study.
6 Conclusions

When a deep geological repository for radioactive waste shall be closed, all underground structures will be backfilled and, at selected locations, seals will be installed to limit potential water flow along the subsurface tunnel system. The underground access structures, typically consisting of shafts and a ramp, will also be sealed after a certain observation period. As a result, radionuclide release from the emplacement rooms during the post-closure phase is expected to occur primarily through the host rock. In order to assess to what extent this is actually the case for different layout variants (ramp and shaft access as opposed toshaft access only), a base case with realistic parameter values for the hydraulic properties of the seals and the associated excavation damage zones has been defined and analysed. As a test of robustness of system performance against uncertainties related to such seals and the associated excavation damage zones, the present study also considers a broad spectrum of calculation cases including the hypothetical possibility that the seals perform very much more poorly than expected and to check whether, consequently, the repository tunnel system and the underground access structures may provide significant release pathways.

The modelling approaches used are to some extent rather simplified and stylised, which has been deemed acceptable for the purpose of the present study. Some simplifications in particular are judged to be rather conservative, e.g. the neglecting of transport times either along the emplacement rooms or in front of a panel, as well as the omission of radionuclide release from the repository tunnel system to the surrounding host rock in cases with little flow along the repository tunnel system. Overall, the simplifications made clearly lead to an overestimation of releases.

Generally, the results obtained for the L/ILW repository are qualitatively similar to those for the HLW repository. This is unsurprising, since the repository layouts, the backfill and sealing materials as well as the assumed geological environments are comparable. Quantitative differences arise from the size of the main facility, from the inventory and the properties of the emplaced waste, as well as from the concepts of how radionuclides are released from the different waste forms.

The results show that, for realistic parameter values, radionuclide release along the access structures of a deep geological repository is extremely low. Thus they confirm the reference assumption that radionuclide release occurs predominantly through the host rock. Globally increasing the hydraulic conductivities that are assumed for the tunnel system and the seals (including the excavation damage zone along these underground structures) increases all the calculated flows, but the increase is found to level off with increasing hydraulic conductivity, as flow becomes ultimately controlled by the limited capacity of the host rock to supply water. The dose rate maxima due to releases via the access structures show the same asymptotic behaviour as the flow, and remain low in all cases.

If a relatively poor quality of horizontal sealing elements (including the ramp seal) is assumed, while the vertical seals (i.e. those for the shafts) still perform as expected, the variant layout with the ramp performs slightly less favourably than the layout with a third shaft. However, in both variants, the calculated release rates along the underground access structures are very low and, in particular, far less than the release rates from the host rock. It is thus concluded that the type of main access route to the underground facilities of a deep geological repository is not relevant to its post-closure safety.
Finally, even for highly unfavourable parameter values for the hydraulic properties of the seals and the associated excavation damage zones, the calculated dose rates remain well below the regulatory protection criterion of 0.1 mSv per year, often by several orders of magnitude. This finding, and taking into account the fact that in the models used for these calculations a number of simplifications were made that clearly lead to an overestimate of releases, demonstrates the robustness of the repository systems considered in the present study with respect to variations of the hydraulic properties of the seals and of the associated excavation damage zones.
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A Resistor Network Flow Modelling

A.1 Flow model network structures

A.1.1 Geometrical simplifications

The layouts of the HLW and L/ILW repositories and the planned backfilling and sealing of the emplacement rooms and access structures are shown in Figs. 2.2-1 and 2.2-2 of Section 2.2. To convert these layouts to a flow model network structure, the following simplifying assumptions are made:

- effects of tunnel curvature on inflow to a tunnel section are disregarded;
- short tunnel sections with special cross sections (locks, unloading areas etc.) are neglected or incorporated in the neighbouring tunnels;
- all SF / HLW emplacement rooms are assumed to have the same length; and
- all L/ILW emplacement rooms are also assumed to have the same length.

Figs. A1-1 and A1-2 show the flow model network structure for the HLW repository. For clarity, the SF / HLW part of the flow model layout and the remainder of the layout are shown separately in the two figures, but are combined in the flow model itself. The blue dashed lines in the two figures show where the partial network structures presented in each figure join. Fig. A1-3 shows the flow model network structure for the L/ILW repository. Waste emplacement panels (i.e. groups of emplacement rooms) defined for the purposes of transport modelling are also shown in Figs. A1-1 (SF / HLW panels) and A1-3 (L/ILW panels).

In the flow modelling approach implemented in the Resistor Network Code, inflow from the host rock can only be calculated for those tunnel sections that are entirely in the repository plane. Because of this limitation, the ramp is modelled as if, below the V4 seal, it were a horizontal feature, with inflow calculated accordingly. No inflow is modelled to either the V4 seal at the upper end of the ramp or to the vertical, V3 shaft seals. As demonstrated in Appendix A, Section A.3.2, inflow to the shaft seals will be relatively small, and in most cases much less than the total flow that passes through them.

In the case of a HLW repository, the host rock is assumed to extend for 55 m above the repository horizon and 55 m below. The hydraulic head is set to 0 and to 110 m at the upper and lower boundaries of this zone, respectively. For the L/ILW repository, the host rock is assumed to extend for 55 m above the repository horizon and 50 m below. The hydraulic head is set to 0 and to 105 m at the upper and lower zone boundaries, respectively. In both cases, these heads correspond to an undisturbed hydraulic gradient of 1, with water flow directed upwards.
Fig. A1-1: Flow model for SF / HLW part of the HLW repository.

The blue dashed line in this figure corresponds to the blue dashed line in Fig. A1-2.
Fig. A1-2: Flow model for the test facility and the ILW part of the HLW repository.

The leg labelled k/t corresponds to either the ramp seal (k) or the seal of a third shaft (t). The blue dashed line in this figure corresponds to the blue dashed line in Fig. A1-1.
Fig. A1-3: Flow model for the L/ILW repository.

The leg labelled z/w corresponds to either the ramp seal (z) or the seal of a third shaft (w).
A.1.2  **Leg-specific parameter values**

Each HLW repository leg is assigned a label (a, b, c, … etc.) to identify the flow model parameter values that are assigned to it. Similar labels are also assigned to each leg of the L/ILW repository. Note that each label is defined for a specific repository type, i.e. the properties of a HLW leg with a given label are not necessarily the same as those of the L/ILW leg with the same label.

The flow models require the specification of the lengths and radii (tunnel and EDZ) for each leg. The corresponding data for the HLW repository are given in Tab. A1-1, where the column "leg type" provides labels (a, b, c, etc.) that map the data in each row of the table to the legs in the network structures shown in Figs. A1-1 and A1-2. Similarly, Tab. A1-2 provides data for the L/ILW repository corresponding to the network structure shown in Fig. A1-3. In both tables, the column "radius" refers to the tunnel component of a leg. For the column "ratio of EDZ radius to tunnel radius", EDZ radii are based on the assumption that the EDZ is 0.7 m thick in all tunnels and shafts. Tunnel radii for any given tunnel profile type are taken from Tab. 2.2-1. Tunnel lengths are based on the layouts shown in Figs. 2.2-1 and 2.2-2 and, for the seals, in Tab. 2.4-1.

For each leg to which inflow is allowed, an effective leg width is also required. The calculation of effective leg width is described in Section A.2. Where the structure corresponding to the leg is close to other structures, the effective leg width is set equal to the spacing of the structures, or some other measure of typical structure separation. These are the values given in the "tunnel spacing" column. As noted above, inflow is not calculated for vertical structures (the shafts) and also not calculated for the V4 seal of the ramp. Hence, an effective leg width is not required for these structures, as indicated by "no inflow" in the "tunnel spacing" column in Tabs. A1-1 and A1-2.

Hydraulic conductivities are also required for the tunnel and EDZ components of each leg. Since they are case-dependent, they are indicated by the labels K1, K2, etc., with the actual value corresponding to each label given in Tab. 4.2-1 of the main part of this report.
<table>
<thead>
<tr>
<th>Leg type</th>
<th>Tunnel profile type</th>
<th>Length [m]</th>
<th>Radius [m]</th>
<th>Tunnel spacing [m]</th>
<th>Ratio of EDZ radius to tunnel radius</th>
<th>Hydraulic conductivity</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>F</td>
<td>700</td>
<td>1.25</td>
<td>40</td>
<td>1.56</td>
<td>K1</td>
<td>KDZ1</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SF/HLW emplacement rooms.</td>
</tr>
<tr>
<td>b</td>
<td>F</td>
<td>12</td>
<td>1.25</td>
<td>40</td>
<td>1.56</td>
<td>K1-V1</td>
<td>KDZ1-V1</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>V1 seals.</td>
</tr>
<tr>
<td>c</td>
<td>E</td>
<td>35</td>
<td>2.27</td>
<td>40</td>
<td>1.31</td>
<td>K4</td>
<td>KDZ4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Branch tunnels. The distance from the centre of the V1 seal to the operations tunnel is about 43 m. 37 m (rounded to 35 m) is obtained if half the length of the V1 seal is then subtracted.</td>
</tr>
<tr>
<td>e</td>
<td>L</td>
<td>45</td>
<td>2.55</td>
<td>53</td>
<td>1.27</td>
<td>K4</td>
<td>KDZ4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Sections of operations tunnel between emplacement rooms. From Fig. A2-2, the distance along the operations tunnel from the first emplacement room to the last is 1'020 m. There are N = 23 emplacement rooms. 1'020/(N-1) = 46 m (rounded to 45 m).</td>
</tr>
<tr>
<td>f</td>
<td>D5</td>
<td>505</td>
<td>2.55</td>
<td>53</td>
<td>1.27</td>
<td>K4</td>
<td>KDZ4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Section of construction tunnel between cross tunnel and V2 seal. The length of the V2 seal is neglected in estimating the leg length.</td>
</tr>
<tr>
<td>g</td>
<td>L</td>
<td>45</td>
<td>2.55</td>
<td>53</td>
<td>1.27</td>
<td>K4</td>
<td>KDZ4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Section of the operations tunnel between the V2 seal to the first emplacement room. The length of the V2 seal is neglected in estimating the leg length.</td>
</tr>
<tr>
<td>h</td>
<td>L</td>
<td>70</td>
<td>2.55</td>
<td>69</td>
<td>1.27</td>
<td>K4</td>
<td>KDZ4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Section of the operations tunnel between the V2 seal to the central area.</td>
</tr>
<tr>
<td>j</td>
<td>A5</td>
<td>200</td>
<td>3.18</td>
<td>35</td>
<td>1.22</td>
<td>K4</td>
<td>KDZ4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Distance from the entry point of access structure (ramp or 3rd shaft) to its sealing element is set equal to a generic value of 200 m. Tunnel spacing based on presumed distance to parallel access route to pilot facility.</td>
</tr>
<tr>
<td>k</td>
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<td>No inflow</td>
<td>1.22</td>
<td>K2-V4</td>
<td>KDZ2-V4</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2 × V4 seal.</td>
</tr>
<tr>
<td>m</td>
<td>A5</td>
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<td>3.18</td>
<td>69</td>
<td>1.22</td>
<td>K4</td>
<td>KDZ4</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Tunnel section in central area.</td>
</tr>
<tr>
<td>Leg type</td>
<td>Tunnel profile type</td>
<td>Length [m]</td>
<td>Radius [m]</td>
<td>Tunnel spacing [m]</td>
<td>Ratio of EDZ radius to tunnel radius</td>
<td>Tunnel section in central area.</td>
<td>Comments</td>
</tr>
<tr>
<td>----------</td>
<td>---------------------</td>
<td>------------</td>
<td>------------</td>
<td>-------------------</td>
<td>--------------------------------------</td>
<td>--------------------------------</td>
<td>----------</td>
</tr>
<tr>
<td>n</td>
<td>A5</td>
<td>95</td>
<td>3.18</td>
<td>69.2</td>
<td>1.22</td>
<td>KD4</td>
<td>Tunnel section in central area.</td>
</tr>
<tr>
<td>p</td>
<td>L</td>
<td>70</td>
<td>2.55</td>
<td>69.2</td>
<td>1.27</td>
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<td>Tunnel section in central area.</td>
</tr>
<tr>
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<td>2.55</td>
<td>69.2</td>
<td>1.27</td>
<td>KD4</td>
<td>Tunnel section in central area.</td>
</tr>
<tr>
<td>r</td>
<td>D5</td>
<td>35</td>
<td>2.55</td>
<td>69.2</td>
<td>1.27</td>
<td>KD4</td>
<td>Tunnel section in central area.</td>
</tr>
<tr>
<td>s</td>
<td>D5</td>
<td>20</td>
<td>2.55</td>
<td>69.2</td>
<td>1.27</td>
<td>KD4</td>
<td>Tunnel section in central area.</td>
</tr>
<tr>
<td>t</td>
<td>S2</td>
<td>40</td>
<td>3.00</td>
<td>69.2</td>
<td>1.22</td>
<td>K4</td>
<td>V3 (shaft) seal.</td>
</tr>
<tr>
<td>u</td>
<td>D5</td>
<td>120</td>
<td>2.55</td>
<td>63.1</td>
<td>1.27</td>
<td>KD4</td>
<td>Cross tunnel between operations and construction tunnels.</td>
</tr>
<tr>
<td>v</td>
<td>L</td>
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<td>2.55</td>
<td>63.1</td>
<td>1.27</td>
<td>K2-V2</td>
<td>Parts of operations tunnel on either side of cross tunnel.</td>
</tr>
<tr>
<td>w</td>
<td>L</td>
<td>25</td>
<td>2.55</td>
<td>63.1</td>
<td>1.27</td>
<td>KD4</td>
<td>Tunnel section in central area.</td>
</tr>
<tr>
<td>x</td>
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<td>3.18</td>
<td>69.2</td>
<td>1.22</td>
<td>K4</td>
<td>Tunnel section in central area.</td>
</tr>
<tr>
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<td>69.2</td>
<td>1.22</td>
<td>K4</td>
<td>Tunnel section in central area.</td>
</tr>
<tr>
<td>z</td>
<td>D5</td>
<td>120</td>
<td>2.55</td>
<td>69.2</td>
<td>1.27</td>
<td>KD4</td>
<td>Tunnel section in central area.</td>
</tr>
<tr>
<td>a</td>
<td>L</td>
<td>45</td>
<td>2.55</td>
<td>69.2</td>
<td>1.27</td>
<td>KD4</td>
<td>Tunnel section in central area.</td>
</tr>
<tr>
<td>b</td>
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<td>69.2</td>
<td>1.27</td>
<td>L2-V2</td>
<td>Parts of operations tunnel on either side of cross tunnel.</td>
</tr>
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<td>K4</td>
<td>Tunnel section in central area.</td>
</tr>
<tr>
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<td>69.2</td>
<td>1.13</td>
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<td>Tunnel section in central area.</td>
</tr>
<tr>
<td>e</td>
<td>L</td>
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<td>2.55</td>
<td>69.2</td>
<td>1.27</td>
<td>K2-V5</td>
<td>Branch tunnel to ILW emplacement rooms. The distance from the operations tunnel to the centre of the V5 seal is 120 m.</td>
</tr>
<tr>
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<td>L</td>
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<td>2.55</td>
<td>69.2</td>
<td>1.27</td>
<td>K4</td>
<td>Section of operations tunnel for ILW emplacement.</td>
</tr>
<tr>
<td>g</td>
<td>L</td>
<td>90</td>
<td>2.55</td>
<td>69.2</td>
<td>1.27</td>
<td>K4</td>
<td>Section of operations tunnel for ILW emplacement.</td>
</tr>
<tr>
<td>Leg type</td>
<td>Tunnel profile type</td>
<td>Length [m]</td>
<td>Radius [m]</td>
<td>Tunnel spacing [m]</td>
<td>Ratio of EDZ radius to tunnel radius</td>
<td>Hydraulic conductivity</td>
<td>Comments</td>
</tr>
<tr>
<td>----------</td>
<td>---------------------</td>
<td>------------</td>
<td>-----------</td>
<td>-------------------</td>
<td>-------------------------------------</td>
<td>----------------------</td>
<td>----------</td>
</tr>
<tr>
<td>ii</td>
<td>L</td>
<td>75</td>
<td>2.55</td>
<td>69</td>
<td>1.27</td>
<td>K4 KDZ4</td>
<td>Section of operations tunnel for ILW emplacement adjacent to ILW V2 seal. The length of the V2 seal is neglected in estimating the leg length.</td>
</tr>
<tr>
<td>jj</td>
<td>L</td>
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<td>2.55</td>
<td>69</td>
<td>1.27</td>
<td>K4 KDZ4</td>
<td>Tunnel section in central area adjacent to ILW V2 seal. The length of the V2 seal is neglected in estimating the leg length.</td>
</tr>
<tr>
<td>kk</td>
<td>A5</td>
<td>95</td>
<td>3.18</td>
<td>69</td>
<td>1.22</td>
<td>K4 KDZ4</td>
<td>Tunnel section in central area.</td>
</tr>
<tr>
<td>ll</td>
<td>A5</td>
<td>80</td>
<td>3.18</td>
<td>69</td>
<td>1.22</td>
<td>K4 KDZ4</td>
<td>Tunnel section in central area.</td>
</tr>
<tr>
<td>mm</td>
<td>D5</td>
<td>30</td>
<td>2.55</td>
<td>69</td>
<td>1.27</td>
<td>K4 KDZ4</td>
<td>Tunnel section in central area.</td>
</tr>
<tr>
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<td>D5</td>
<td>20</td>
<td>2.55</td>
<td>69</td>
<td>1.27</td>
<td>K4 KDZ4</td>
<td>Tunnel section in central area.</td>
</tr>
<tr>
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<td>D5</td>
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<td>69</td>
<td>1.27</td>
<td>K4 KDZ4</td>
<td>Tunnel section in URL.</td>
</tr>
<tr>
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<td>2.55</td>
<td>69</td>
<td>1.27</td>
<td>K4 KDZ4</td>
<td>Tunnel section in URL.</td>
</tr>
<tr>
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<td>69</td>
<td>1.27</td>
<td>K4 KDZ4</td>
<td>Tunnel section in URL.</td>
</tr>
<tr>
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<td>125</td>
<td>2.55</td>
<td>69</td>
<td>1.27</td>
<td>K4 KDZ4</td>
<td>Tunnel section in URL.</td>
</tr>
<tr>
<td>ss</td>
<td>D5</td>
<td>85</td>
<td>2.55</td>
<td>69</td>
<td>1.27</td>
<td>K4 KDZ4</td>
<td>Tunnel section in URL.</td>
</tr>
<tr>
<td>tt</td>
<td>D5</td>
<td>70</td>
<td>2.55</td>
<td>69</td>
<td>1.27</td>
<td>K4 KDZ4</td>
<td>Tunnel section in URL.</td>
</tr>
<tr>
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<td>2.55</td>
<td>69</td>
<td>1.27</td>
<td>K4 KDZ4</td>
<td>Tunnel section in URL.</td>
</tr>
<tr>
<td>vv</td>
<td>D5</td>
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<td>2.55</td>
<td>69</td>
<td>1.27</td>
<td>K4 KDZ4</td>
<td>Tunnel section in URL.</td>
</tr>
<tr>
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<td>69</td>
<td>1.27</td>
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<td>Part of observation tunnel.</td>
</tr>
<tr>
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<td>D5</td>
<td>430</td>
<td>2.5</td>
<td>69</td>
<td>1.27</td>
<td>K4 KDZ4</td>
<td>Part of observation tunnel.</td>
</tr>
<tr>
<td>yy</td>
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<td>2.55</td>
<td>69</td>
<td>1.27</td>
<td>K4 KDZ4</td>
<td>Tunnel section in central area.</td>
</tr>
</tbody>
</table>

Notes: See Appendix A.2 for details:

1 Based on blue area in Fig. A2-3.
2 Based on green area in Fig. A2-3.
3 Set equal to equivalent leg width, as defined by Eq. A2-32. For this leg, it is assumed that neighbouring structures do not influence water inflow.
<table>
<thead>
<tr>
<th>Leg type</th>
<th>Tunnel profile type</th>
<th>Leg properties</th>
<th>Tunnel radius [m]</th>
<th>Tunnel spacing [m]</th>
<th>Ratio of EDZ radius to tunnel radius</th>
<th>Hydraulic conductivity</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>K09</td>
<td>200</td>
<td>6.27</td>
<td>85</td>
<td>1.11</td>
<td>K6 KDZ6</td>
<td>L/ILW emplacement rooms.</td>
</tr>
<tr>
<td>b</td>
<td>L</td>
<td>40</td>
<td>2.55</td>
<td>85</td>
<td>1.25</td>
<td>K2-V5 KDZ2-V5</td>
<td>V5 seals.</td>
</tr>
<tr>
<td>c</td>
<td>L</td>
<td>85</td>
<td>2.55</td>
<td>85</td>
<td>1.27</td>
<td>K4 KDZ4</td>
<td>Branch tunnels. The distance from the centre of the V5 seal to the operations tunnel is 105 m. 85 m is obtained if half the length of the V1 seal is then subtracted.</td>
</tr>
<tr>
<td>d</td>
<td>L</td>
<td>45</td>
<td>2.55</td>
<td>28^1</td>
<td>1.27</td>
<td>K4 KDZ4</td>
<td>Section of the operations tunnel between the V2 seal to the first emplacement room. The length of the V2 seal is neglected in estimating the leg length.</td>
</tr>
<tr>
<td>e</td>
<td>L</td>
<td>45</td>
<td>2.55</td>
<td>28^1</td>
<td>1.27</td>
<td>K4 KDZ4</td>
<td>Length taken to be the length of f, divided by 2 (and rounded to 45).</td>
</tr>
<tr>
<td>f</td>
<td>L</td>
<td>85</td>
<td>2.55</td>
<td>28^1</td>
<td>1.27</td>
<td>K4 KDZ4</td>
<td>Sections of operations tunnel between emplacement rooms. The distance along the operations tunnel from the first emplacement room to the last is 595 m. There are N = 8 emplacement rooms. 595/(N-1) = 85 m.</td>
</tr>
<tr>
<td>g</td>
<td>D5</td>
<td>10</td>
<td>2.55</td>
<td>28^1</td>
<td>1.27</td>
<td>K5 KDZ5</td>
<td>Blind end of construction tunnel.</td>
</tr>
<tr>
<td>h</td>
<td>D5</td>
<td>60</td>
<td>2.55</td>
<td>28^1</td>
<td>1.27</td>
<td>K4 KDZ4</td>
<td>Cross tunnels between operations and construction tunnels.</td>
</tr>
<tr>
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<td>D5</td>
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<td>2.55</td>
<td>28^1</td>
<td>1.27</td>
<td>K5 KDZ5</td>
<td>Construction tunnel section between cross tunnels.</td>
</tr>
<tr>
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<td>28^1</td>
<td>1.27</td>
<td>K5 KDZ5</td>
<td>Section of construction tunnel between cross tunnel and V2 seal. The length of the V2 seal is neglected in estimating the leg length.</td>
</tr>
<tr>
<td>m</td>
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<td>K2-V2 KDZ2-V2</td>
<td>2 × V2 seal.</td>
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<tr>
<td>Leg type</td>
<td>Tunnel profile type</td>
<td>Length [m]</td>
<td>Radius [m]</td>
<td>Tunnel spacing [m]</td>
<td>Ratio of EDZ radius to tunnel radius</td>
<td>Hydraulic conductivity</td>
<td>Comments</td>
</tr>
<tr>
<td>----------</td>
<td>---------------------</td>
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<td>1.27</td>
<td>K5 KDZ5</td>
<td>Tunnel section in central area adjacent to construction tunnel V2 seal. The length of the V2 seal is neglected in estimating the leg length.</td>
</tr>
<tr>
<td>p</td>
<td>L</td>
<td>60</td>
<td>2.55</td>
<td>50</td>
<td>1.27</td>
<td>K4 KDZ4</td>
<td>Tunnel section in central area adjacent to operations tunnel V2 seal. The length of the V2 seal is neglected in estimating the leg length.</td>
</tr>
<tr>
<td>q</td>
<td>L</td>
<td>255</td>
<td>2.55</td>
<td>50</td>
<td>1.27</td>
<td>K4 KDZ4</td>
<td>Tunnel section in central area.</td>
</tr>
<tr>
<td>r</td>
<td>L</td>
<td>50</td>
<td>2.55</td>
<td>50</td>
<td>1.27</td>
<td>K4 KDZ4</td>
<td>Tunnel section in central area.</td>
</tr>
<tr>
<td>s</td>
<td>L</td>
<td>10</td>
<td>2.55</td>
<td>50</td>
<td>1.27</td>
<td>K4 KDZ4</td>
<td>Tunnel section in central area.</td>
</tr>
<tr>
<td>t</td>
<td>D5</td>
<td>35</td>
<td>2.55</td>
<td>50</td>
<td>1.27</td>
<td>K5 KDZ5</td>
<td>Tunnel section in central area.</td>
</tr>
<tr>
<td>u</td>
<td>D5</td>
<td>200</td>
<td>2.55</td>
<td>50</td>
<td>1.27</td>
<td>K5 KDZ5</td>
<td>Tunnel section in central area.</td>
</tr>
<tr>
<td>v</td>
<td>D5</td>
<td>520</td>
<td>2.55</td>
<td>50</td>
<td>1.27</td>
<td>K5 KDZ5</td>
<td>Tunnel section in URL.</td>
</tr>
<tr>
<td>w</td>
<td>S2</td>
<td>40</td>
<td>3.00</td>
<td>No inflow</td>
<td>1.23</td>
<td>K3 KDZ3</td>
<td>V3 (shaft) seals.</td>
</tr>
<tr>
<td>x</td>
<td>L</td>
<td>130</td>
<td>2.55</td>
<td>50</td>
<td>1.27</td>
<td>K4 KDZ4</td>
<td>Tunnel section in central area.</td>
</tr>
<tr>
<td>y</td>
<td>D5</td>
<td>280</td>
<td>2.55</td>
<td>50</td>
<td>1.27</td>
<td>K4 KDZ4</td>
<td>Observation tunnel.</td>
</tr>
<tr>
<td>z</td>
<td>A5</td>
<td>100</td>
<td>3.18</td>
<td>No inflow</td>
<td>1.22</td>
<td>K2-V4 KDZ2-V4</td>
<td>2 × V4 seal.</td>
</tr>
<tr>
<td>aa</td>
<td>A5</td>
<td>200</td>
<td>3.18</td>
<td>1.22</td>
<td>K4 KDZ4</td>
<td>Distance from the entry point of access structure (ramp or 3rd shaft) to its sealing element is set equal to a generic value of 200 m.</td>
<td></td>
</tr>
<tr>
<td>bb</td>
<td>L</td>
<td>35</td>
<td>2.55</td>
<td>50</td>
<td>1.27</td>
<td>K4 KDZ4</td>
<td>Tunnel section in central area.</td>
</tr>
<tr>
<td>cc</td>
<td>L</td>
<td>65</td>
<td>2.55</td>
<td>50</td>
<td>1.27</td>
<td>K4 KDZ4</td>
<td>Tunnel section in central area.</td>
</tr>
<tr>
<td>dd</td>
<td>L</td>
<td>10</td>
<td>2.55</td>
<td>50</td>
<td>1.27</td>
<td>K4 KDZ4</td>
<td>Tunnel section in central area.</td>
</tr>
<tr>
<td>ee</td>
<td>L</td>
<td>25</td>
<td>2.55</td>
<td>50</td>
<td>1.27</td>
<td>K5 KDZ5</td>
<td>Tunnel section in central area.</td>
</tr>
<tr>
<td>Leg type</td>
<td>Tunnel profile type</td>
<td>Length [m]</td>
<td>Radius [m]</td>
<td>Tunnel spacing [m]</td>
<td>Ratio of EDZ radius to tunnel radius</td>
<td>Hydraulic conductivity</td>
<td>Comments</td>
</tr>
<tr>
<td>----------</td>
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<td>-------------------------------------</td>
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<tr>
<td>ff</td>
<td>L</td>
<td>15</td>
<td>2.55</td>
<td>50</td>
<td>1.27</td>
<td>K4</td>
<td>KDZ4</td>
</tr>
<tr>
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<td>L</td>
<td>120</td>
<td>2.55</td>
<td>50</td>
<td>1.27</td>
<td>K4</td>
<td>KDZ4</td>
</tr>
<tr>
<td>hh</td>
<td>L</td>
<td>30</td>
<td>2.55</td>
<td>50</td>
<td>1.27</td>
<td>K4</td>
<td>KDZ4</td>
</tr>
<tr>
<td>ii</td>
<td>L</td>
<td>60</td>
<td>2.55</td>
<td>28</td>
<td>1.27</td>
<td>K4</td>
<td>KDZ4</td>
</tr>
<tr>
<td>jj</td>
<td>L</td>
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<td>2.55</td>
<td>28</td>
<td>1.27</td>
<td>K4</td>
<td>KDZ4</td>
</tr>
</tbody>
</table>

Notes: See Appendix A.2 for details:
1 Based on blue area in Fig. A2-4.
2 Based on green area in Fig. A2-4.
3 Set equal to equivalent leg width, as defined by Eq. A2-32. For this leg, it is assumed that neighbouring structures do not influence water inflow.
A.2 Flow capture width and effective leg width

The concepts of flow capture width, \( w_c \), and effective leg width, \( W \), are introduced in Section 3.2. Both parameters are related to the flow field within and around a tunnel and its EDZ. In the following, it is explained how values are assigned to these parameters in the flow and transport calculations, beginning with flow capture width in Section A.2.1, followed by effective leg width in Section A.2.2.

A.2.1 Flow capture width

In the present study, it is generally the case that the hydraulic conductivities of the EDZs around the emplacement rooms and around the other tunnels of the repository tunnel systems are much larger than that of the undisturbed host rock. As a result, the ambient flow within the host rock will converge upstream of these features, pass through them, and then diverge again downstream (see e.g. Fig. 3.2-2).

The flow capture width is the term used for the width of a stream tube that passes into and out of the EDZ, before convergence or after divergence, since it can be used to express the amount of water that passes through (or is "captured" by) the EDZ for a known ambient flow. The following presents a derivation of this capture width for the special case of a circular tunnel or emplacement room with an EDZ in a homogeneous and isotropic rock (as applied in the present study). The result shows that setting the capture width to twice the tunnel diameter (including EDZ) is appropriate in this case.

Although not used in the present study, the more general case of the capture width for an elliptical structure in both isotropic and anisotropic media is then also derived. In all cases considered, the following assumptions are made:

- the rock outside the EDZ is homogeneous;
- flow is incompressible and described by Darcy's law, which means that potential flow theory can be applied;
- the tunnel or emplacement room (including any EDZ, and referred to simply as the tunnel in the following) has a much higher hydraulic conductivity than the rock, such that the outer boundary of the tunnel can be considered an equipotential;
- a steady and uniform ambient flow is present at large distances from the tunnel; and
- the flow direction is normal to the axis of the tunnel.

The description is organised as follows:

1. Introduction of the concepts of potential flow and of complex potential; and application to flow past a circular tunnel.
2. Derivation of an expression for capture width for a circular tunnel in an isotropic rock.
3. Introduction of the concept of conformal mapping and how this can be used to calculate potential flow past an elliptical tunnel.
4. Derivation of an expression for capture width for an elliptical tunnel in an isotropic rock.
5. Extension to the situation of an anisotropic rock.
Complex potential and flow past a circular tunnel

In fluid dynamics, potential flow describes the velocity field as the gradient of a scalar function: the velocity potential. Applications of potential flow include the flow field for aerofoils and water waves, as well as the present application of groundwater flow. In potential flow theory, the complex potential $f [m^2/s]$ is defined, where:

$$ f = \phi + i\psi \tag{A2-1} $$

and where $\phi [m^2/s]$ and $\psi [m^2/s]$ are, respectively, the velocity potential and the stream function. $\phi$ and $\psi$ satisfy the Cauchy-Riemann equations, and hence $f$ is analytic in the $xy$-plane:

$$ \frac{\partial \phi}{\partial x} = \frac{\partial \psi}{\partial y} \tag{A2-2} $$

and

$$ \frac{\partial \phi}{\partial y} = - \frac{\partial \psi}{\partial x} \tag{A2-3} $$

Both $\phi$ and $\psi$ also satisfy Laplace's equation. Lines of constant $\psi$ are streamlines and lines of constant $\phi$ are known as equipotential lines. They are orthogonal to each other. In systems where the hydraulic head satisfies Laplace's equation, the hydraulic head $h$ is proportional to the velocity potential.

Steady flow with ambient velocity $V_\infty [m/s]$ in the positive $y$-direction around a circular, highly conductive tunnel of radius $a [m]$, with its centre at the origin of an $xy$-coordinate system, expressed as a complex potential, is:

$$ f = -V_\infty i \left( z + \frac{a^2}{z} \right) \tag{A2-4} $$

where

$$ z = x + iy \tag{A2-5} $$

The fluid velocity, which is a vector with components $V_x [m/s]$ and $V_y [m/s]$ is obtained from:

$$ \frac{df}{dz} = V_x - iV_y = -V_\infty \left( 1 - \frac{a^2}{z^2} \right) \tag{A2-6} $$

That this potential and the corresponding velocity field have the required properties can be seen as follows. At large distances from the cylinder (i.e. as $z \to \infty$):

$$ V_x \to 0 \tag{A2-7} $$

and

$$ V_y \to V_\infty \tag{A2-8} $$
i.e. the influence of the tunnel becomes small and the flow returns to ambient. Furthermore, from Eq. A2-4, $\phi$ and $\psi$ are given by:

$$\phi = V_\infty y \left( 1 - \frac{a^2}{r^2} \right)$$  \hspace{1cm} (A2-9)

and

$$\psi = -V_\infty x \left( 1 + \frac{a^2}{r^2} \right)$$  \hspace{1cm} (A2-10)

where $r = \sqrt{x^2 + y^2}$ is the radial distance from the centre of the tunnel. Thus, as required for a highly conductive tunnel, the velocity potential ($\phi$) is a constant (zero) along the outer surface of the tunnel.

### Capture width for a circular tunnel in an isotropic rock

In an isotropic, homogeneous rock in which water flow obeys Darcy's law, this flow can be described by potential flow theory. As illustrated on the left-hand side of Fig. A2-1, potential flow through a highly conductive tunnel in such a rock in a plane normal to the tunnel axis converges as it approaches the tunnel and diverges as it leaves. The capture width $w_c$ of the tunnel may be defined as the width of the streamtube that the tunnel intercepts at large distances from the tunnel. The boundaries of this streamtube are the streamlines that touch the outer surface of the tunnel at mid-height, i.e. at $x = \pm a$, $y = 0$. From Eq. A2-10, the value of the stream function along these streamlines is equal to $\pm 2V_\infty a$, and the streamlines are described by:

$$x = \pm 2a \frac{r^2}{a^2 + r^2}$$  \hspace{1cm} (A2-11)

At large distances from the tunnel (i.e. for $r \gg a$):

$$x \rightarrow \pm 2a$$  \hspace{1cm} (A2-12)

i.e. the streamlines become straight and parallel, and have a separation of $4a$ – this is the capture width $w_c$.

---

27 An analytical solution for the streamlines around a circular feature with a hydraulic conductivity different from that of the surrounding medium is given, e.g. by Eq. 21 in Zhao et al. (1999), which references the earlier work of Phillips (1991). Zhao et al. (1999) also note that the limiting value of the "flow-focussing factor" (equivalent to the ratio of the capture width to the diameter of the circular feature) is equal to two when the ratio of hydraulic conductivity inside the feature to that outside the feature approaches infinity.
Fig. A2-1: Capture width $w_c$ for a circular tunnel in the $xy$-plane (left), mapping of the circle to an ellipse using the Joukowski transformation and capture width $w_e$ for an ellipse in the $uv$-plane (right).

The distance above or below the tunnel, where the tunnel exerts an influence on the flow (i.e. produces a convergence of the streamlines) can be estimated using Eq. A2-11. The width of the streamtube that is captured by the tunnel asymptotically approaches the capture width at increasing distances above and below the tunnel, as the bounding streamlines become increasingly parallel and vertical. From Eq. A2-11, the width of the streamtube is already 80% of the capture width at just one tunnel radius above the highest point of the tunnel or below the lowest point, i.e. when $r/a = \sqrt{(0.8/(1 - 0.8))} = 2$. By the same reasoning, the width of the streamtube is 90% of the capture width when $r/a = 3$, i.e. at one tunnel diameter above the highest point of the tunnel or below the lowest point; and 99% of the capture width when $r/a = 10$.\(^{28}\)

**Conformal mapping and the Joukowski transformation**

A conformal map is a map of one two-dimensional space to another that preserves angles. If a function satisfies Laplace's equation over one particular space, and is transformed via a conformal map to another space, the transformation also satisfies Laplace's equation. For this reason, any function that is defined by a potential can be transformed by a conformal map and still remain governed by a potential. By choosing an appropriate mapping, it is often possible to transform a geometry for which a solution is known into a geometry for which no solution is known, but which may be of more practical interest.

In the following, potential flow around an ellipse in two dimensions is analysed with conformal mapping, using a particular transformation of the complex plane; one that transforms the circle to an ellipse (Fig. A2-1).

\(^{28}\) These observations are relevant in that they indicate that the effects of the location and properties of the host rock boundaries above and below the repository on capture width will be small provided that these boundaries are more than a few tunnel diameters away from the repository horizon.
The transformation used for this application is termed the Joukowski transformation:

\[ w = u + iv = z + \frac{b^2}{z} \]  

(A2-13)

where \( u \) and \( v \) are the coordinates of a point in the transformed complex plane and \( b \) is a constant (we assume that \( b < a \)). A circle of radius \( a \) in the xy-plane, centred at the origin, is described by the line:

\[ z = ae^{i\theta} \]  

(A2-14)

where \( \theta \) varies from 0 to \( 2\pi \). From Eq. A2-13, the corresponding line in the uv-plane is:

\[ \bar{w} = \bar{u} + i\bar{v} = \left( a + \frac{b^2}{a} \right) \cos \theta + i \left( a - \frac{b^2}{a} \right) \sin \theta \]  

(A2-15)

From Eq. A2-15:

\[ \frac{\bar{u}^2}{\left( a + \frac{b^2}{a} \right)^2} + \frac{\bar{v}^2}{\left( a - \frac{b^2}{a} \right)^2} = 1 \]  

(A2-16)

Thus, the circle is transformed to an ellipse with a major axis of length \( c \) [m] in the \( u \)-direction:

\[ c = 2 \left( a + \frac{b^2}{a} \right) \]  

(A2-17)

and a minor axis of length \( d \) [m] in the \( v \)-direction:

\[ d = 2 \left( a - \frac{b^2}{a} \right) \]  

(A2-18)

Note that the sum of these axes is equal to twice the diameter of the circle:

\[ c + d = 4a \]  

(A2-19)

**Capture width of an elliptical tunnel in an isotropic rock**

The Joukowski transformation can be used to map the flow around a circular tunnel in the \( xy \)-plane (depicted on the left-hand side of Fig. A2-1) to the flow around an elliptical tunnel in the \( uv \)-plane (depicted on the right-hand side of Fig. A2-1). The major and minor axes of the ellipse are given by Eqs. A2-17 and A2-18.

Note that, from Eq. A2-13, at large distances from the cylinder (i.e. as \( z \to \infty \)):

\[ w \to z \]  

(A2-20)

This implies that the capture width of the ellipse, \( w_e \) [m], in the \( uv \)-plane is the same as the capture width of the circle in the \( xy \)-plane, and is equal to \( 4a \). Thus, from Eq. A2-19:

\[ w_e = 4a = c + d \]  

(A2-21)
The capture width of the elliptical tunnel is equal to the sum of its major and minor axes.29

**Extension to situation with anisotropic rock**

If the hydraulic conductivity of the rock varies with the direction in which it is measured, then the rock is anisotropic. In the case of two-dimensional flow, if the \( u v \) coordinate system in the flow plane is set up in such a way that the coordinate directions coincide with the principal directions of anisotropy, the hydraulic conductivity in the principal directions can be specified as \( K_u [\text{m/s}] \) and \( K_v [\text{m/s}] \). The Darcy velocity, which is a vector with components \( V_u [\text{m/s}] \) and \( V_v [\text{m/s}] \), can then be written:

\[
V_u = -K_u \frac{\partial h}{\partial u} \tag{A2-22}
\]

and

\[
V_v = -K_v \frac{\partial h}{\partial v} \tag{A2-23}
\]

where \( h [\text{m}] \) is the hydraulic head.

If the groundwater is assumed to be incompressible and free of sinks / sources, then:

\[
\frac{\partial V_u}{\partial u} + \frac{\partial V_v}{\partial v} = 0 \tag{A2-24}
\]

From Eqs. A2-22 to A2-24:

\[
\frac{\partial}{\partial u} \left( K_u \frac{\partial h}{\partial u} \right) + \frac{\partial}{\partial v} \left( K_v \frac{\partial h}{\partial v} \right) = 0 \tag{A2-25}
\]

If it is further assumed that the rock is homogeneous:

\[
K_u \frac{\partial^2 h}{\partial u^2} + K_v \frac{\partial^2 h}{\partial v^2} = 0 \tag{A2-26}
\]

Defining an anisotropy factor \( \gamma \) as:

\[
\gamma = \frac{K_v}{K_u} \tag{A2-27}
\]

---

29 Note that for the special case of the circular tunnel \( c = d = 2a \).
and the operator $\nabla^2$ as:

$$\nabla^2 = \frac{\partial^2}{\partial u^2} + \frac{\partial^2}{\partial v'^2}$$  \hfill (A2-28)$$

where:

$$v' = \frac{v}{\sqrt{\gamma}}$$  \hfill (A2-29)$$

Eq. A2-26 can be written:

$$\nabla^2 h = 0$$  \hfill (A2-30)$$

Thus, by transforming from the $uv$ to the $uv'$ coordinate system, the distribution of hydraulic head in an anisotropic rock can be described by Laplace's equation and the corresponding groundwater flow can be described by potential flow theory, allowing the results from the previous sections to be employed.

The coordinate transformation converts a circle in the $uv$ plane in an anisotropic rock into an ellipse in the isotropic $uv'$ plane, or an ellipse in the anisotropic $uv$ plane into a different ellipse in the isotropic $uv'$ plane. In particular, an ellipse with an axis of length $d$ [m] in the $v$ direction of the $uv$ plane is transformed to an ellipse with an axis of length $d' = d / \sqrt{\gamma}$ in the $v'$ direction of the $uv'$ plane. Because the rock in the $uv'$ plane is isotropic, from the result Eq. A2-21, the capture width of the ellipse is equal to the sum of its major and minor axes. Thus, if the ellipse has an axis of length $c$ [m] in the $u$ direction, its capture width in the $uv'$ plane is $c + d'$. If flow is in the positive $v$ direction (as depicted on the right-hand side of Fig. A2-1), then this capture width is also the capture width in the $uv$ plane, i.e.:

$$w_e = c + d' = c + \frac{d}{\sqrt{\gamma}} = c + d \frac{K_u}{K_v}$$  \hfill (A2-31)$$

If the hydraulic conductivity normal to the direction of ambient flow is very small ($K_u \to 0$), then $w_e \to c$, i.e. the capture width tends towards the tunnel width. This is expected, since the flow approaching the tunnel cannot converge and the flow leaving the tunnel cannot diverge, in the way depicted in Fig. A2-1, i.e. streamlines will remain parallel and unaffected by the presence of the tunnel. On the other hand, if the height of the tunnel becomes very small ($d \to 0$), then again $w_e \to c$, since the outer boundary of the tunnel is an equipotential, and, if the tunnel profile becomes flattened then, by symmetry, the only value that this potential can take is the ambient potential at tunnel depth. Thus, no convergence or divergence of streamlines will take place. Finally, if the rock is isotropic ($K_u = K_v$), the capture width is equal to the sum of the major and minor axes of the elliptical tunnel, which is the result given by Eq. A2-21.
A.2.2 Effective leg width

The effective leg width, $W \, [m]$, of an underground structure is defined as the width of a section of a hypothetical horizontal planar feature at repository level that captures the same flow as that structure (tunnel and EDZ), as illustrated in Fig. 3.2-3 of Section 3.2. This parameter is used in the resistor network approach to calculate the inflow from the host rock to the structure, or equivalently the variation of flow rate along the structure, according to Eq. 3.2-2.

Mathematical definition

An expression for the effective leg width $W$, valid for an isotropic rock and for tunnels that are widely spaced, is derived in Appendix C of Smith & Poller (2012). More generally, where there are multiple underground structures in close proximity to one another, such that neighbouring structures may restrict the flow into any single structure, the expression for effective leg width used in the present study is:

$$W = \min\{D, \omega\}$$  \hspace{1cm} (A2-32)

where $D \, [m]$ is the spacing of the structures in the case of parallel structures, or some other measure of typical structure separation (see Tab. A1-1 and A1-2), and $\omega \, [m]$ is a quantity termed the equivalent leg width, given by Eq. C-16 of Smith & Poller (2012):

$$\omega = 2\pi \frac{L_L L_u}{L_L + L_u} \ln \left( \frac{2}{\pi a} \left( \frac{L_L + L_u}{L_L + a} \right) \sin \left( \pi \frac{L_L}{L_L + a} \right) \right)$$  \hspace{1cm} (A2-33)

In this equation, $L_L \, [m]$ and $L_u \, [m]$ are, respectively, the distances from the repository level to the lower and upper boundaries of the host rock and $a \, [m]$ is the radius of the tunnel, including its EDZ.

Setting the effective leg width in this way involves an implicit assumption that the vertical extent of the tunnels is negligible compared with the thickness of the host rock and with the separation distance between neighbouring tunnels. The approach has been tested in numerical simulations of flow to parallel tunnels ($dQ/dx$) as the tunnel spacing $D$ is varied. The results, which are shown in Fig. A2-2, indicate that the effective leg width, as calculated analytically according to Eq. A2-32, tends to overestimate the net flow rate to each tunnel (when substituted into Eq. 3.2-2). The largest difference between the numerical simulations and the analytical result is observed for values of $D$ close to the equivalent leg width $\omega$. The difference becomes much smaller for small as well as for large values of $D$.

Since inflow occurs from all directions, the equivalent leg width will be different for an anisotropic rock than for the isotropic rock assumed here. However, as noted in Section 2.1, the vertical ambient hydraulic gradient together with the large lateral extent of the repository compared with its vertical extent means that the overall flow through the host rock is predominantly vertical and is thus controlled mainly by the vertical component of hydraulic conductivity (as explained in Section C1.2, for high water flow rates, inflow to the repository tunnel system depends mainly on the size of the repository footprint together with the magnitude of the vertical, ambient flow). Furthermore, given that hydraulic anisotropy of Opalinus Clay is estimated to be in the order of factor 5 to 10, the effect of anisotropy cannot be substantial and is in any case bounded by an alternative calculation case, in which the isotropic conductivity is enhanced by the same factor (see Sections 4.2 and 5.3).
Values for the high-level waste repository

In the case of the HLW repository, the effective leg width for the ramp is set equal to the assumed spacing between the ramp to the main part of the repository and the section of the ramp to the pilot facility (35 m). The effective leg width for the SF / HLW emplacement rooms is set equal to the spacing between these rooms (40 m). For all other horizontal legs, suitable measures of the spacing between the corresponding structures are calculated by:

- dividing the repository into a number of areas;
- in each area calculating the total length of legs; and
- dividing each area by the total length of legs in that area.

The areas defined for the HLW repository are shown in Fig. A2-3.
Fig. A2-3: Layout of the backfilled and sealed HLW repository, showing areas used in the calculation of effective leg widths.

The blue area is approximately 126'000 m². The total length of legs in the blue area (see data in Tab. A1-1) is equal to the length of legs $22\times e + f + g + u + x = 2'345$ m. A typical tunnel spacing in this area is thus taken to be $126'000 \text{ m}^2 / 2'345 \text{ m} = 53$ m.

The green area is around 220'000 m². The total length of legs in the green area (see data in Tab. A1-1) is equal to the length of legs $h + m + p + q + r + s + y + z + aa + bb + cc + dd + 2\times ee + 2\times ff + gg + hh + ii + jj + kk + ll + mm + nn + oo + pp + qq + rr + ss + tt + uu + vv + ww + yy = 3'190$ m. A typical tunnel spacing in this area is thus taken to be $220'000 \text{ m}^2 / 3'190 \text{ m} = 69$ m.

**Values for the low- and intermediate-level waste repository**

In the case of the L/ILW repository, the effective leg width for the emplacement rooms is set equal to the room separation (85 m). The effective leg width for the ramp is calculated is set equal to the equivalent leg width, calculated using Eq. A2-32. For all other horizontal legs, suitable measures of the spacing between the corresponding structures are calculated per area as in the case of the HLW repository. The areas defined for the L/ILW repository are shown in Fig. A2-4.
Fig. A2-4: Layout of the backfilled and sealed L/ILW repository, showing areas used in the calculation of effective leg widths.

The blue area is roughly 42'500 m². The total length of legs in the blue area (see data in Tab. A1-2) is equal to the length of legs \(d + 7\times f + g + 2\times h + j + k + ii + jj = 1'535\) m. A typical tunnel spacing in this area is thus taken to be 42'500 m² / 1'535 m = 28 m.

The green area is approximately 108'000 m². The total length of legs in the red area (see data in Tab. A1-2) is equal to the length of legs \(n + p + q + r + 2\times s + t + u + v + x + y + bb + cc + dd + ee + ff + gg + hh = 2'145\) m. A typical tunnel spacing in this area is thus taken to be 108'000 m² / 2'145 m = 50 m.

### A.3 Validity of the resistor network approach

#### A.3.1 Internal checks carried out by the Resistor Network Code

The Resistor Network Code (Smith & Poller 2012) incorporates checks that the code is applicable to the network at hand and that the calculated network flows are correct. The latter is checked by calculating the inflows and outflows at each junction from the various legs connected to it, and ensuring that they sum to zero (to a good approximation). The former is checked by estimating the flow through the rock parallel to each leg and checking that it is small compared with the flow through the leg itself, as explained further in the following paragraphs.

In the flow modelling carried out using the resistor network approach, inflow to each leg is obtained by solving Laplace's equation in two dimensions in a plane normal to the leg axis, i.e. it is assumed that horizontal flow in the rock parallel to the structure axis is negligible (much less than the radial flow towards the tunnel). If horizontal flow in the rock were accounted for (using a full 3-D flow model), flow in the rock approaching the leg from below would be diverted towards the downstream (lower head value) end of the leg. Thus, flow in the leg at its upstream end would be reduced, and flow at the downstream end would be increased.

As shown in Appendix D of Smith & Poller (2012), the Darcy velocity in the rock parallel to the leg axis is much less than the magnitude of the Darcy velocity radial to the leg, provided:
\[ K_{\text{geo}} \ll \frac{1}{4\pi y^2} (K + (y^2 - 1)K_{\text{EDZ}}) \left( \frac{1}{L_t} + \frac{1}{L_u} \right) \]

(A3-1)

In this equation, \( K_{\text{geo}} \) [m\(^2\)/s], \( K \) [m\(^2\)/s] and \( K_{\text{EDZ}} \) [m\(^2\)/s] are, respectively, the hydraulic conductivities of the host rock; and of the tunnel and EDZ components of the leg. \( L_t \) [m] and \( L_u \) [m] are, respectively, the distances from the repository level to the lower and upper boundaries of the host rock, \( W \) [m] is the effective leg width (see Appendix A.2). \( y \) is the ratio of the outer radius of the EDZ to the outer radius of the tunnel.

The condition (Eq. A3-1), which is taken to be a test of the validity of the resistor network approach, has been applied to all the calculation cases analysed in the present study. If the condition is taken to be satisfied provided the ratio of the right-hand side of the inequality to the left-hand side is greater than 10, the condition is met for all calculation cases, except in the case \( \text{HLW}_{\text{BC}} \), where the ratio for the SF / HLW emplacement rooms and their seals (leg types "a" and "b") is 3.6.

Thus, the resistor network modelling approach is fully adequate for most, but not all, of the calculation cases considered. However, the parameter values assumed in \( \text{HLW}_{\text{BC}} \) imply that diffusion will, in reality, be the dominant transport process in the near field and radionuclide release along the tunnel system will be negligible. This case does not, therefore, strictly speaking, belong to the present scenario and has only indicative character.

### A.3.2 Omission of inflow to shafts

Owing to limitations of the resistor network approach as described in Section 3.2 and Smith & Poller (2012), inflow to the repository shafts is not modelled. The justification for this simplification is that the inflow to these relatively short features will be small, and in most cases much less than the total flow that passes through them. This is demonstrated in the following paragraphs, where an approximate solution is first derived for the flow to a dead-end shaft, where the only inflow comes from the host rock. The calculated flow along such a shaft is then compared with the flows from a repository tunnel system via the shafts, calculated using the flow models described in Section A.1.

No analytical solution is available for a cylindrical shaft with a constant circular cross section along its length within a uniform linear flow field. Rather, in this section the shaft is modelled as half of a long, slender and homogeneous ellipsoid, as depicted in Fig. A3-1.
The ellipsoid is assigned an effective conductivity $K_{shaft}$ [m/s], which accounts for both the shaft backfill and the surrounding EDZ:

$$K_{shaft} = K + (r^2 - 1)K_{EDZ} \quad (A3-2)$$

The Darcy flow, $q$ [m s$^{-1}$], along the major axis of such an ellipsoid in a uniform ambient flow field with hydraulic gradient, $i$, is given by an expression presented on p. 428 of Carslaw & Jaeger (1959):

$$q = K_{shaft}i/\left[1 + \frac{b^2}{l^2} \left(\frac{K_{shaft}}{K_{GEO}} - 1\right) \left(\ln \left(\frac{2l}{b}\right) - 1\right)\right] \quad (A3-3)$$

where $b$ [m] is the radius of the minor axis of the ellipsoid and $l$ [m] is its length (twice the shaft length). The flow from the shaft where it intersects the upper boundary of the host rock is given by:

$$Q = \pi b^2 q = \pi b^2 K_{shaft}i/\left[1 + \frac{b^2}{l^2} \left(\frac{K_{shaft}}{K_{GEO}} - 1\right) \left(\ln \left(\frac{2l}{b}\right) - 1\right)\right] \quad (A3-4)$$

In order to set a value for $b$, consider the limiting case when $K_{shaft} = K_{GEO}$. The only inflow to the actual (cylindrical) shaft from the rock in this case will be at its base and equal to $\pi r^2 K_{shaft}i$. From Eq. A3-4, this same flow is obtained in the case of the ellipsoid if:

$$b = r \quad (A3-5)$$

The resulting inflows to the two additional shafts (ventilation and construction) from the rock are plotted in Fig. A3-2 (blue open circles for HLW repository and red open circles for L/ILW repository), using the parameter values of the overriding system analyses (SA) and the base cases (BC). The combined flows along the two shafts for the same cases calculated with
the Resistor Network Code are also shown (blue squares for HLW repository and red squares for L/ILW repository). Inflows from the rock are much less than the flows from the repository tunnel system, except in the base cases and in cases SA1, where they are of the same order of magnitude. However, in these cases the hydraulic conductivities of the shaft seals and their EDZs, and hence the overall flows along the shafts, are relatively low.

Fig. A3-2: Inflow to, and flows along, the repository shafts (see main text for further explanation).

It should be noted that the actual inflows from the rock to the shafts will be even less than those calculated using Eq. A3-4. This is because flow reaching the base of a shaft from the repository tunnel system will increase the hydraulic head at the base of the shaft compared with the case of a dead-end shaft. This increased head will reduce inflow from the rock.

If the hydraulic conductivity of the shaft seal is very low (comparable to that of the rock), it is this low conductivity together with the ambient hydraulic gradient that limits the flow of water along the shaft, irrespective of where this water originates from (i.e. directly from the rock to the shaft or from the repository tunnel system). This is because there is only a certain amount of water that can be conveyed along the shaft, given that the head at the base of the shaft cannot be higher than the ambient head in the rock at repository depth. In fact, the flows along the shafts calculated by the Resistor Network Code are well approximated by the product of the ambient hydraulic head gradient multiplied by the hydraulic conductivity of the shaft seal, \( K_{\text{shaft}} \), in cases where the hydraulic conductivity of the shaft seal is very low (BC, SA1, SA2), indicating the head at the base of the shaft is close to the ambient head in the rock (see the green dashed line in Fig. A3-2). However, application of Eq. A3-4 shows that, at least in the base case and case SA1, the overall flow along the shafts will, in reality, include a significant component that comes directly from the rock in addition to the component from the repository tunnel system. Including flow that comes directly from the rock would reduce the flow that comes from the repository tunnel system. Therefore, omission of the flow that comes directly from the rock is a cautious modelling simplification in the context of the scenario of radionuclide release via the ramp and shafts.
Fig. A3-2 also shows that, if the hydraulic conductivity of the shaft seal is relatively high, then it is the low hydraulic conductivity of the rock around the repository tunnel system that constrains the flow reaching the shaft: the asymptotic values shown by the solid blue (HLW repository) and red (L/ILW repository) lines in Fig. A3-2 are explained in detail in Appendix C. In these cases, inflow to the shafts directly from the rock is relatively small.

It can be concluded that, in the base cases and in cases SA1, the flow along the shafts may, in reality, be due to a large extent to inflow from the rock around (or directly below) the shaft. The flow to the shafts from the repository tunnel system may be significantly overestimated by the Resistor Network Code, but is in any case very low and overestimation is conservative in the context of the scenario of radionuclide release via the ramp and shafts. On the other hand, in all other cases, the inflow to the shafts from the host rock is much less than that from the repository tunnel system.
B Radionuclide Transport Modelling

B.1 Assigning flow values to PICNIC-TD legs

In the code PICNIC-TD, flows are modelled as being constant along each leg. By contrast, with the flow models based on the resistor network approach, either flow increases monotonically in the flow direction, or there is a flow divide somewhere within the leg, on either side of which flow increases monotonically. For legs of the first type, the value of the flow rate at the downstream end is the highest value that the flow rate takes within such a leg. It is this value that is used in the PICNIC-TD transport modelling calculations. The following proof formally demonstrates the conservatism of this approach when calculating transport of a single radionuclide. Legs of the second type are not included explicitly in transport modelling, since they are not accessible to radionuclides by means of advective transport.

For spatially varying flow, the steady-state transport equation for a single radionuclide along a leg with length $L$ is:

$$\frac{d}{dx} \left[ q(x)c(x) - D_e \frac{dc(x)}{dx} \right] + \varepsilon \lambda c(x) = 0$$

(B1-1)

where $c(x)$ [mol/m$^3$] is the radionuclide concentration, $q(x)$ [m/s] is the Darcy velocity, which is assumed to be either constant or an increasing function of the space variable $x$, $D_e$ [m$^2$/s] is the effective diffusion coefficient$^{30}$, $\varepsilon$ is the leg porosity and $\lambda$ [s$^{-1}$] is the decay constant of the single radionuclide.

For the present purposes, it is assumed that equation (B1-1) is subject to the following conditions at the upstream and downstream boundaries of the leg:

$$c(0) = c_0 \quad \text{and} \quad c(L) = 0$$

(B1-2)

If $q_c = q(L)$ is the maximal value of the Darcy velocity at the downstream boundary of the leg, then the corresponding transport equation solved by PICNIC-TD is:

$$\frac{d}{dx} \left[ q_c \tilde{c}(x) - D_e \frac{d\tilde{c}(x)}{dx} \right] + \varepsilon \lambda \tilde{c}(x) = 0$$

(B1-3)

with the boundary conditions:

$$\tilde{c}(0) = c_0 \quad \text{and} \quad \tilde{c}(L) = 0$$

(B1-4)

Conservatism of the adopted approach requires that:

$$\bar{F}_L \geq F_L$$

(B1-5)

---

$^{30}$ The effect of dispersion is not considered in this model.
for any function \( q(x) \) that increases with \( x \), where \( \bar{F}_L \) [mol/m\(^2\)/s] and \( F_L \) [mol/m\(^2\)/s] are fluxes defined by:

\[
F_L = -D_e \left( \frac{d\tilde{C}(x)}{dx} \right)_{x=L} \quad \text{and} \quad \bar{F}_L = -D_e \left( \frac{d\tilde{C}(x)}{dx} \right)_{x=L} \quad (B1-6)
\]

Note that the fluxes are diffusive only at this boundary, because of the zero-concentration boundary condition.

Equation B1-5 can also be written:

\[
\left. \frac{dE(x)}{dx} \right|_{x=L} \leq 0 \quad (B1-7)
\]

where \( E(x) \) is defined as:

\[
E(x) \equiv \tilde{C}(x) - C(x) \quad (B1-8)
\]

To prove that B1-7 is indeed satisfied, we further define \( q_+(x) \) as:

\[
q_+(x) \equiv q_L - q(x) \quad (B1-9)
\]

Using these definitions, equation (B1-3) becomes:

\[
\frac{d}{dx} \left[ q(L) \cdot E(x) + \{q_+(x) + q(x)\} \cdot C(x) - D_e \left( \frac{dE(x) + C(x)}{dx} \right) \right] + \varepsilon \lambda \{E(x) + C(x)\} = 0 \quad (B1-10)
\]

Subtracting equation (B1-1) from (B1-10) gives:

\[
\frac{d}{dx} \left[ q(L) \cdot E(x) + q_+(x) \cdot C(x) - D_e \frac{dE(x)}{dx} \right] + \varepsilon \lambda E(x) = 0 \quad (B1-11)
\]

which can be rewritten as:

\[
\frac{d}{dx} \left[ q(L) \cdot E(x) - D_e \frac{dE(x)}{dx} \right] + \varepsilon \lambda E(x) = S(x) \quad (B1-12)
\]

where \( S(x) \) is defined as:

\[
S(x) \equiv - \frac{d[q_+(x)]}{dx} \cdot C(x) - \frac{dC(x)}{dx} \cdot [q_+(x)] \quad (B1-13)
\]
Equation B1-12 is an advection-diffusion-decay equation for \( E(x) \), where \( S(x) \) is a source term for the quantity of which \( E(x) \) is the concentration. From Equations B1-2, the solution to equation B1-12 is constrained by the boundary conditions:

\[
E(0) = 0 \quad \text{and} \quad E(L) = 0 \quad \text{(B1-14)}
\]

The solution to this advection-diffusion-decay equation will be a concentration \( E(x) \) that is a positive function of \( x \) throughout the interval \( 0 \leq x \leq L \) provided that the source term \( S(x) \) is also positive throughout the interval (\( E(x) \) will be zero throughout the interval if the source term is also zero).

If \( E(x) \) is a positive function of \( x \) (or zero throughout the interval), the boundary condition \( E(L) = 0 \) is only satisfied if:

\[
\left. \frac{dE(x)}{dx} \right|_{x=L} \leq 0 \quad \text{(B1-15)}
\]

which is the same as the condition B1-7 for the conservatism of the approach to assigning flow values to PICNIC-TD legs. Demonstrating the conservatism of the approach therefore amounts to demonstrating that the source term \( S(x) \) is positive (or zero) throughout the interval \( 0 \leq x \leq L \).

Since the Darcy velocity is assumed to be either constant or an increasing function of \( x \) (i.e. \( dq(x)/dx \geq 0 \)), from the definition given by Equation B1-9:

\[
\frac{dq_+(x)}{dx} \leq 0 \quad \text{(B1-16)}
\]

and

\[
q_+(x) \geq 0 \quad \text{(B1-17)}
\]

It is also known that:

\[
C(x) \geq 0 \quad \text{(B1-18)}
\]

and, given the boundary conditions given by equations B1-2,

\[
\frac{dC(x)}{dx} \leq 0 \quad \text{(B1-19)}
\]

---

33 Since \( E(x) \) is zero at each end, if \( E(x) \) is ever negative, it must have a minimum value at some \( x \) within \( 0 < x < L \). At that minimum point, \( E < 0, \frac{dE}{dx} = 0 \) and \( \frac{d^2E}{dx^2} > 0 \), which is inconsistent with \( S \geq 0 \). Hence, \( E(x) \) cannot be negative in \( 0 \leq x \leq L \).
From these equations, and from the definition of $S(x)$ in equation B-13:

$$S(x) \equiv - \frac{d[q_+(x)]}{dx} \cdot C(x) - \frac{dC(x)}{dx} \cdot [q_+(x)] \geq 0 \quad \text{(B1-20)}$$

It has thus been shown that the source term $S(x)$ is positive (or zero) throughout the interval $0 \leq x \leq L$, which confirms the conservatism of the approach to assigning flow values to PICNIC-TD legs when calculating transport of a single radionuclide.

**B.2 Transport model parameters applicable to all calculation cases**

Some of the transport parameter values applicable to all calculation cases have been presented in overview in Section 2.6. More comprehensive listings of transport parameter values are given in the following tables.

Material-specific parameter values, namely the dry bulk density of sorbing material (see Section 2.6), porosity, effective diffusion coefficients and sorption coefficients are presented in Tab. B2-1. Porosity, effective diffusion coefficient and sorption coefficient are in many instances considered to be element-specific (in the case of porosity to account e.g. for anion exclusion). In these instances, Tab. B2-1 refers to Tab. B2-2, which lists the parameter values for all calculated elements.

Radionuclide half-lives and biosphere dose conversion factors are given in Tab. B2-3. Tab. B2-4 gives waste-specific parameter values, including containment times, waste degradation rates (used to calculate radionuclide release rates on the basis of release being congruent with degradation) and the numbers of canisters containing specific types of SF and HLW. The total radionuclide inventories for each type of SF and their distributions between matrix, cladding and IRF are given in Tab. B2-5. Finally, the total nuclide inventories for each type of HLW, L/ILW and ILW are given in Tab. B2-6.

<table>
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<tr>
<th>Material</th>
<th>Bulk dry density of sorbing material $[\text{kg/m}^3]$</th>
<th>Porosity [-]</th>
<th>Effective diffusion coefficient $[\text{m}^2 \text{s}^{-1}]$</th>
<th>Sorption coefficient $[\text{m}^3/\text{kg}]$</th>
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<tr>
<td>Host rock</td>
<td>2'430</td>
<td>Element-dependent; see Tab. B2-2 (Opalinus Clay values)</td>
<td>Element-dependent; see Tab. B2-2 (Opalinus Clay values)</td>
<td>Element-dependent; see Tab. B2-2 (Opalinus Clay values)</td>
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<td>EDZ</td>
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<tr>
<td>SF / HLW mixing tanks (#1; see Tab. 2.6-1)</td>
<td>1'650</td>
<td>Element-dependent; see Tab. B2-2 (compacted bentonite values)</td>
<td>High to ensure complete mixing $(10^{-4})$</td>
<td>Element-dependent; see Tab. B2-2 (compacted bentonite values)</td>
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<tr>
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<tr>
<td>Mixing tank EDZs</td>
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<td>High to ensure complete mixing $(10^{-4})$</td>
<td>Element-dependent; see Tab. B2-2 (Opalinus Clay values)</td>
</tr>
<tr>
<td>V1 and V3 seals (#1 and #3; see Tab. 2.6-1)</td>
<td>1'650</td>
<td>Element-dependent; see Tab. B2-2 (compacted bentonite values)</td>
<td>Element-dependent; see Tab. B2-2 (compacted bentonite values)</td>
<td>Element-dependent; see Tab. B2-2 (compacted bentonite values)</td>
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<td>V2, V4 and V5 seals (#2; see Tab. 2.6-1)</td>
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<th>Sorption coefficient [m$^3$ kg$^{-1}$]</th>
<th>Porosity $^j$</th>
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$^j$ Porosity is element-specific to account, e.g. for anion exclusion.

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<td>Panel 1: 47.8 % Panel 2: 52.2 %</td>
<td>Containment time: 10'000 years IRF: instant release fraction (see Tab. B2-5) Release rate (matrix): $10^{-7}$ 1/a Release rate (cladding): $3 \times 10^{-5}$ 1/a</td>
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<td>BE-D-3, 408 disposal canisters (see Tab. B2-5)</td>
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<td>Containment time: 10'000 years glass matrix dissolution rate $1.5 \times 10^{-7}$ g/cm²/day</td>
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<td>ILW1</td>
<td>Containment time: 100 years, Instant release after containment of all radionuclides, except $^{14}$Corg,cong.rel, which is released with a constant rate within 10'000 years after containment</td>
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<td>L/ILW AG-1 (see Tab. B2-6)</td>
<td>Panel 1: 37.5 % Panel 2: 62.5 %</td>
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Tab. B2-5: Total radionuclide inventories [Bq] in SF canisters and their distributions [%].

| Radionuclide | BE-S-1 | | BE-D-2 | | BE-D-3 | |
|--------------|--------|--------|--------|--------|--------|
|              | matrix | clad. | IRF    | matrix | clad. | IRF    | matrix | clad. | IRF    |
| $^{10}$Be    | $1.5 \times 10^{10}$ | 0.0 | 10.0   | $1.1 \times 10^{10}$ | 0.0 | 10.0   | $6.9 \times 10^{9}$ | 0.0 | 10.0   |
| $^{14}$C$_\text{inorg}$ | $5.6 \times 10^{13}$ | 0.0 | 10.0   | $3.6 \times 10^{13}$ | 0.0 | 10.0   | $2.5 \times 10^{12}$ | 0.0 | 10.0   |
| $^{14}$C$_\text{org}$ | $4.9 \times 10^{13}$ | 0.0 | 10.0   | $2.0 \times 10^{13}$ | 0.0 | 10.0   | $1.5 \times 10^{13}$ | 0.0 | 10.0   |
| $^{36}$Cl    | $1.9 \times 10^{12}$ | 0.0 | 10.0   | $8.9 \times 10^{11}$ | 0.0 | 10.0   | $6.7 \times 10^{11}$ | 0.0 | 10.0   |
| $^{41}$Ca    | $2.4 \times 10^{11}$ | 0.0 | 10.0   | $1.4 \times 10^{11}$ | 0.0 | 10.0   | $1.1 \times 10^{11}$ | 0.0 | 10.0   |
| $^{59}$Ni    | $1.1 \times 10^{14}$ | 0.0 | 10.0   | $7.9 \times 10^{13}$ | 0.0 | 10.0   | $4.9 \times 10^{13}$ | 0.0 | 10.0   |
| $^{63}$Ni    | $1.2 \times 10^{16}$ | 0.0 | 10.0   | $7.7 \times 10^{15}$ | 0.0 | 10.0   | $5.7 \times 10^{15}$ | 0.0 | 10.0   |
| $^{79}$Se    | $1.3 \times 10^{12}$ | 0.0 | 10.0   | $9.6 \times 10^{11}$ | 0.0 | 10.0   | $6.5 \times 10^{11}$ | 0.0 | 10.0   |
| $^{90}$Sr    | $2.2 \times 10^{18}$ | 0.0 | 10.0   | $1.0 \times 10^{18}$ | 0.0 | 10.0   | $1.2 \times 10^{18}$ | 0.0 | 10.0   |
| $^{93}$Zr    | $1.4 \times 10^{14}$ | 0.0 | 10.0   | $9.4 \times 10^{13}$ | 0.0 | 10.0   | $6.5 \times 10^{13}$ | 0.0 | 10.0   |
| $^{93m}$Nb   | $1.0 \times 10^{14}$ | 0.0 | 10.0   | $7.9 \times 10^{13}$ | 0.0 | 10.0   | $4.4 \times 10^{13}$ | 0.0 | 10.0   |
| $^{94}$Nb    | $1.1 \times 10^{13}$ | 0.0 | 10.0   | $2.4 \times 10^{13}$ | 0.0 | 10.0   | $1.5 \times 10^{13}$ | 0.0 | 10.0   |
| $^{93}$Mo    | $3.4 \times 10^{12}$ | 0.0 | 10.0   | $5.2 \times 10^{11}$ | 0.0 | 10.0   | $3.3 \times 10^{11}$ | 0.0 | 10.0   |
| $^{96}$Tc    | $9.3 \times 10^{14}$ | 0.0 | 10.0   | $7.0 \times 10^{14}$ | 0.0 | 10.0   | $4.5 \times 10^{14}$ | 0.0 | 10.0   |
| $^{107}$Pd   | $8.4 \times 10^{12}$ | 0.0 | 10.0   | $8.7 \times 10^{12}$ | 0.0 | 10.0   | $3.9 \times 10^{12}$ | 0.0 | 10.0   |
| $^{108}$mAg  | $1.2 \times 10^{12}$ | 0.0 | 10.0   | $8.1 \times 10^{11}$ | 0.0 | 10.0   | $5.7 \times 10^{11}$ | 0.0 | 10.0   |
| $^{126}$Sn   | $2.5 \times 10^{12}$ | 0.0 | 10.0   | $2.4 \times 10^{12}$ | 0.0 | 10.0   | $1.2 \times 10^{12}$ | 0.0 | 10.0   |
| $^{129}$I    | $2.3 \times 10^{12}$ | 0.0 | 10.0   | $1.8 \times 10^{12}$ | 0.0 | 10.0   | $1.1 \times 10^{12}$ | 0.0 | 10.0   |
Tab. B2-5: (continued)

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C  Understanding the Results

C.1  Flow modelling

C.1.1  Typical hydraulic heads and Darcy velocities

To better understand the flow modelling results, it is instructive to examine the hydraulic heads that drive the flows and also the flows themselves at various points within the repository. Hydraulic head values at the flow network junctions for the base case and for the calculation cases of the overriding system analyses SA1, SA4 and SA6 for the HLW repository are shown as colour-coded spots in Figs. C1-1 and C1-2.

Fig. C1-1:  Resistor network flow models for the HLW repository base case (upper figure) and case SA1 (lower figure), with hydraulic heads at junctions indicated by colour-coded spots.
Fig. C1-2: Resistor network flow models for HLW repository case SA4 (upper figure) and case SA6 (lower figure), with hydraulic heads at junctions indicated by colour-coded spots.
For the cases with lower hydraulic conductivity along the tunnel system (BC and SA1), with the exception of the junctions marked "HU", which correspond to the upper ends of the ramp and shaft seals, all the junctions are similarly coloured dark blue and thus have similar heads, close to the ambient head of 55 m at repository depth. Thus, the head drops over the ramp and shaft seals are much greater than the head drop over any other tunnel section (or seal). By contrast, for the cases with higher hydraulic conductivity along the tunnel system (SA4 and SA6), with the exception of the junctions at the dead-ends of the emplacement rooms, which remain dark blue, all the junctions are similarly coloured light blue and thus have similar heads, this time close to zero (which is the reference head imposed at the upper boundary of the host rock).

Typical flow fields around an emplacement room or other tunnel types with a given hydraulic head can be inferred from Fig. 3.2-1 of Chapter 3. In that figure, head values in the room or tunnel are assumed to be 45 m (Test 1), 30 m (Test 2), 15 m (Test 3) and 0 m (Test 0). Thus, referring to Fig. C.1-1, the open end of an emplacement room in case SA1 will have a flow around it similar to that in Test 1. In this case, no stagnation point occurs above the tunnel, and advective release to the host rock above the tunnel is possible. By contrast, referring to Fig. C1-2, the open end of an emplacement room in case SA6 will have a flow around it similar to that in Test 0. Therefore, there is a stagnation point, flow around the perimeter of the tunnel is always inwardly directed and no advective release of radionuclides to the host rock can occur. SA4 lies somewhere between Tests 2 and 3, both of which also show stagnation points, suggesting that advective release from the emplacement rooms to the host rock will again be inhibited.

The calculated flow values along the tunnel system in these same calculation cases are shown in Figs C1-3 and C1-4 as colour coded bars between junctions (the pointed end(s) of each bar indicate the direction of flow). The figures do not only show how flows along the ramp and shafts increase as higher the hydraulic conductivities are assigned to the tunnels and their EDZs, but also how higher flows are confined to areas near the ramp and shafts in the base case and in SA1, while extending deeper into the repository tunnel system in SA4 and SA6. This is consistent with the head results, which show that high head gradients are confined to the ramp and shafts in the base case and in SA1, but not in SA4 and SA6.

The flow velocities in the SF / HLW emplacement rooms are very low in all cases. Even in case SA6, they are only in the order of 0.03 m$^3$ per year. They are still lower in the ILW emplacement room, being in the order of 0.005 m$^3$ per year. The cross-section areas of the SF / HLW emplacement rooms are around 5 m$^2$, those for the ILW emplacement rooms are around 100 m$^2$ (including EDZ). Thus, the Darcy velocities in the emplacement rooms are in the order of millimetres per year or lower. In the repository tunnel system, higher Darcy velocities are encountered, though they are still very small, with Darcy velocities never exceeding a few centimetres per year along the ramp and shafts, even in the highest hydraulic conductivity cases.

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32 A zero head value in the tunnel system is also assumed in the calculations of asymptotic values for the total flow from the repository, see Section C.1.2.
Fig. C1-3: Resistor network flow models for the HLW repository base case (upper figure) and case SAI (lower figure), with flow values along legs indicated by colour-coding.
Fig. C1-4: Resistor network flow models for HLW repository case SA4 (upper figure) and case SA6 (lower figure), with flow values along legs indicated by colour-coding.
C.1.2 Asymptotic behaviour for very high hydraulic conductivities

As described in Chapter 5, globally increasing the hydraulic conductivity in the tunnel system (i.e. going from $BC \rightarrow SA1 \rightarrow SA2 \rightarrow \ldots \rightarrow SA6$) increases all the calculated flows, but the increase is seen to level off with increasing hydraulic conductivity, since the inflow to the repository is ultimately limited by the low hydraulic conductivity of the rock. To further illustrate this "levelling-off" effect, the total flow from the repository (i.e. the sum of flows along the ramp and shafts) and from the individual repository emplacement rooms or panels can be calculated in the case of a very high hydraulic conductivity in the tunnel system based on a relatively simple analysis, and the results compared with the asymptotic values derived from more detailed flow modelling.

In the simple analysis it is assumed that:

- the high hydraulic conductivity in the tunnel system results in the head in the tunnel system being equal to that at the upper boundary of the host rock (this is not the case for more realistic hydraulic conductivities; see Figs. C1-1 and C1-2, above); and

- repository tunnels (or areas of the repository consisting of many tunnels) can be approximated as planar elements into which water flows vertically from the rock below.

Based on these assumptions, the hydraulic gradient between the lower boundary of the host rock and the planar areas representing the repository tunnel system is then approximately twice the ambient hydraulic gradient. If this gradient is denoted by $i_{\text{lim}}$, then the flow $Q$ [m$^3$ s$^{-1}$] into one such area $A$ [m$^2$] is given by:

$$Q = A \cdot i_{\text{lim}} \cdot K_{GE0} \quad \text{(C1-1)}$$

where $K_{GE0}$ [m/s] is the hydraulic conductivity of the host rock.

The areas used to calculate the asymptotic flows are presented, with explanations, in Tab. C1-1.

Note that one of the tunnels in the HLW repository (part of the observation tunnel in Fig. A2-3) is not included in the estimate of the total repository area, since its effective leg width is assumed not to be limited by the presence of any nearby tunnels.\footnote{33 The equivalent leg width, as defined in Appendix A.2, could, in principle, have been used, but this has not been done since only this single tunnel is not expected to contribute significantly to the overall inflow to the repository tunnel system.} For the same reason, the ramp is not included in the case of the L/ILW repository. Thus, the asymptotes calculated from these areas are slight underestimates.\footnote{34 Note that the total flow calculated for the whole L/ILW repository in case $SA6$ is slightly higher than the asymptote (see Fig. C1-5).}
Tab. C1-1: Areas used to calculate asymptotic flows.

<table>
<thead>
<tr>
<th>HLW repository</th>
<th>Area [m²]</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panel 1</td>
<td>308'000</td>
<td>HLW Panel 1 consists of 11 emplacement rooms that, according to Tab. A1-1, are 700 m long (not including the V1 seal) and have an effective leg width (tunnel separation) of 40 m.</td>
</tr>
<tr>
<td>Panel 2</td>
<td>336'000</td>
<td>HLW Panel 2 consists of 12 emplacement rooms, which have the same physical dimensions as those of Panel 1.</td>
</tr>
<tr>
<td>ILW-1</td>
<td>5'520</td>
<td>ILW-1 consists of a single room that is 80 m long (not including the V5 seal) and has an effective leg width of 69 m.</td>
</tr>
<tr>
<td>ILW-2</td>
<td>2'415</td>
<td>ILW-2 consists of a single room that is 35 m long (not including the V5 seal) and has the same effective leg width as ILW-1.</td>
</tr>
<tr>
<td>Total repository</td>
<td>1'006'200</td>
<td>Obtained by summing the blue area (126'000 m²) and the green area (220'000 m²) in Fig. A2-3, the areas of Panels 1 and 2 (ILW-1 and ILW-2 are included in the green area) and the effective area of the modelled part of the ramp (200 m long and with an effective leg width of 35 m).</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>L/ILW repository</th>
<th>Area [m²]</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panel 1</td>
<td>51'000</td>
<td>L/ILW Panel 1 consists of 3 emplacement rooms that, according to Tab. A1-2, are 200 m long (not including the V5 seal) and have an effective leg width (tunnel separation) of 85 m.</td>
</tr>
<tr>
<td>Panel 2</td>
<td>85'000</td>
<td>L/ILW Panel 2 consists of 5 emplacement rooms, which have the same physical dimensions as those of Panel 1.</td>
</tr>
<tr>
<td>Total repository</td>
<td>313'700</td>
<td>Obtained by summing the blue area (42'500 m²) and the green area (108'000 m²) in Fig. A2-4 and the areas of Panels 1 and 2.</td>
</tr>
</tbody>
</table>

The asymptotic flows for the HLW repository are obtained by multiplying the planar areas by the product of the hydraulic conductivity of the rock (2 × 10⁻¹⁴ m s⁻¹), the hydraulic gradient between the between the lower boundary of the host rock and the planar areas (110 m / 55 m = 2.0) and the number of seconds in a year (3.156 × 10⁷ s a⁻¹). In the case of the L/ILW repository, the flows are obtained in a similar way, but with a higher hydraulic conductivity of the rock (10⁻¹³ m s⁻¹) and a slightly higher hydraulic gradient (105 m / 50 m = 2.1).

The total flow from the HLW and L/ILW ramp and shafts; and the flows from the repository emplacement rooms or panels into the repository tunnel system calculated in this way are shown in Fig. C1-5, together with the respective results of the base cases and overriding system analyses (SA). The results can be seen to approach the predicted asymptotic values as the hydraulic conductivity of the tunnel system increases and are virtually identical to the predicted asymptotic values in case SA6.

As discussed in Section A.3.2, inflow to the shafts, which is omitted in the calculations plotted in Fig. C1-5 (Resistor Network Code calculations and asymptotes) is not expected to be significant for the higher hydraulic conductivity cases.
Fig. C1-5: Summary of key flows calculated for the HLW repository and the L/ILW repository in the overriding system analyses (SA) and in the base case (BC). Asymptotic values, calculated as described in the main text, are shown as dashed lines.
C.2 Transport modelling

C.2.1 Relative contributions from different waste forms in the HLW repository

The relative contributions of SF, HLW, ILW-1 and ILW-2 to the calculated dose rate in the base case for a HLW repository (HLW_BC) are illustrated in Fig. C2-1. For all waste forms, the dose rate is dominated by the host rock transport pathway. The maximum dose rate due to SF is about one order of magnitude higher than that due to HLW, which is in turn more than two orders of magnitude higher than the maxima due to ILW-1 and ILW-2. Both SF and ILW display a double peak in their dose curves, which is associated with the contribution of radionuclides with shorter and longer half-lives (see next section). The relative contributions from the different waste forms are similar in other calculations, with the SF maximum being always the highest, followed by HLW, with ILW-1 and ILW-2 the lowest. However, the relative importance of the host rock transport path relative to transport through the repository tunnel system decreases as the assumed hydraulic conductivities of the tunnels and seals are increased.

Fig. C2-2 shows the example of case HLW_SA4. In this case, for all waste forms, the dose rate is dominated by transport via the repository tunnel system. The maximum dose rate due to SF is between one and two orders of magnitude higher than that due to HLW, which in turn is more than one order of magnitude higher than the maxima due to ILW-1 and ILW-2.
Fig. C2-1: Evolution of dose rate in calculation case *HLW_BC*, showing contributions of SF (top graph), HLW (middle graph), ILW-1 and ILW-2 (bottom graph).
Fig. C2-2: Evolution of dose rate in calculation case HLW_SA4, showing contributions of SF (top graph), HLW (middle graph), ILW-1 and ILW-2 (bottom graph).
C.2.2 Relative contributions of different radionuclides

The relative contributions of different radionuclides to dose rate due to the dominant host rock path in the HLW and L/ILW bases cases (HLW_BC and L/ILW_BC) are shown in Fig. C2-3.

For both repositories, there is a first peak at around 40'000 to 50'000 years that is dominated by organic carbon. In the case of the HLW repository, this first peak is associated with ILW and, to some extent, with the SF instant release fraction (IRF) (see Figs. C2-1 and C2-2). There is a second much broader peak that, for the HLW repository, reaches its highest value at around one million years and is dominated by I-129, with Se-79 and Cl-36 making smaller contributions. This second peak is associated with SF and HLW. In the case of the L/ILW repository, the second peak is less broad than for the HLW repository and occurs earlier, at around 300'000 years. This peak is dominated by Cl-36 and Se-79, with I-129 making a much smaller contribution.

Fig. C2-4 shows similar plots for the cases HLW_SA4 and LILW_SA4, this time for dose rates due to releases via the dominant ramp/shaft pathways. Releases from the host rock in the SA4 cases are similar to those in the corresponding base cases in Fig. C2-3, as are the contributions of the different radionuclides (not shown).

The HLW repository dose rate peaks at a few tens of thousands of years and is dominated by I-129, with Se-79, Cl-36, and organic C-14 contributing progressively less (the contribution of organic C-14 being some three orders of magnitude below that of Cl-36). This peak is followed by a lower, plateau extending to 10^7 years (the calculation end time) that is dominated by I-129, other radionuclides having decayed substantially by this time. The early I-129 peak is associated mainly with the SF IRF, while the plateau is associated with the longer-term release from the SF waste form. Note that the first peak is only evident in cases HLW_SA2 to HLW_SA6. In case HLW_SA1, it is not distinguishable above the plateau.

In the case of the L/ILW waste repository, releases via the access structures also peaks at a few tens of thousands of years and are dominated by Cl-36, with lesser contributions from Se-79, organic C-14 and I-129.

The radionuclides dominating the releases via the repository access structures are the same in other calculation cases, I-129 and Se-79 in the case of the HLW repository and Cl-36 and Se-79 in the case of the L/ILW repository.

In all cases, the same radionuclides dominate the calculated dose rates. These are organic C-14, Cl-36, I-129 and Se-79. Referring to Appendix B, Tab. B2-2, these are all radionuclides that are assumed to be non-sorbing in both the near field and geosphere. Other radionuclides are retarded by sorption, allowing more time for the attenuation of their release rates by radioactive decay.

\[^{35}\text{Ag-108m is also attributed a zero-sorption value, although its half-life is too short to appear as a significant contributor to dose rate.}\]
Fig. C2-3: Evolution of dose rate due to the host rock path in calculation cases $HLW\_BC$ (top graph) and $L/LILW\_BC$ (bottom graph), showing the contributions of each calculated radionuclide.

Ch-14 denotes C-14 in organic form. Ch-14C denotes the fraction of organic C-14 released congruently with metal corrosion in the L/ILW repository and in the ILW part of the HLW repository.
Fig. C2-4: Evolution of dose rate due to the ramp/shaft pathways in calculation cases HLW SA4 (top graph) and L/ILW SA4 (bottom graph), showing the contributions of each calculated radionuclide.

Ch-14 denotes C-14 in organic form. Ch-14C denotes the fraction of organic C-14 released congruently with metal corrosion in the L/ILW repository and in the ILW part of the HLW repository.
C.2.3 Relative contributions of transport paths via the repository tunnel system and via the host rock

As noted in Chapter 5, the dose rate maxima due to shaft and ramp releases follow the same general trend as the flows along these paths: generally increasing with growing hydraulic conductivity values in the tunnel system, but levelling off at very high hydraulic conductivity values. Conversely, the dose rate maxima for release from the host rock decrease with higher hydraulic conductivity values in the tunnel system. This is because the more the flow in the host rock is diverted into the tunnel system, the less radionuclide release there is to the host rock.

Fig. C2-5 shows the maximum dose rates due to releases via the HLW repository tunnel system and the access structures as a function of the total flow from the SF / HLW emplacement rooms to the tunnel system (as noted in the previous sections, doses due to releases from the ILW rooms are relatively small).

The slope of this log-log graph is approximately unity, as shown by the red dashed line, indicating that maximum dose rates are roughly proportional to the flow from the emplacement rooms. As noted in the previous section, the maximum dose rates for transport via the repository tunnel system and the access structures are dominated by the long-lived I-129 IRF in SF. This IRF is released to the mixing tanks that represent the SF / HLW emplacement rooms, giving a certain dissolved concentration, $C$, in the pore fluid of the mixing tank. The maximum release rate from the mixing tank to the repository tunnel system is then expected to be equal to the flow from the emplacement room panels to the tunnel system, $Q_p$, multiplied by $C$. The maximum dose rate is expected to be approximately equal to this release rate multiplied by the biosphere dose conversion factor for I-129, which explains why the maximum dose rates are roughly proportional to the flow from the emplacement rooms. The transport time through the tunnel system is not a significant parameter here, given the relatively long half-life of I-129 ($1.6 \times 10^7$ a).

To test this explanation, the maximum dissolved concentration of I-129 in the mixing tank due to the IRF can be evaluated as follows:

- The total inventory of I-129 in SF in the repository is $5.18 \times 10^{12}$ Bq, of which 7.62 % is IRF, giving an IRF inventory of $3.95 \times 10^{11}$ Bq (values derived from Tab. B2-5).
- The pore volume of the mixing tank is equal to the product of the number of SF / HLW emplacement rooms (23), the room length (700 m), the assumed mixing tank porosity (0.05 for anions in the tunnel and 0.14 for EDZ) and the assumed mixing tank cross-sectional area per room. ($\pi \times 1.25 \text{ m} \times 1.25 \text{ m}$ for the tunnel and $\pi \times (1.95 \text{ m} + 1.25 \text{ m}) \times 0.7 \text{ m}$ for the EDZ), giving a volume of $2.0 \times 10^4$ m$^3$.
- The biosphere dose conversion factor for I-129 is $2 \times 10^{-10}$ mSv/Bq (Tab. B2-3).
- Thus, in terms of the dose to which it gives rise, the maximum dissolved concentration of I-129 in the mixing tank due to the IRF is $C = 0.0040$ mSv/m$^3$, i.e. the product of the IRF inventory and the biosphere dose conversion factor, divided by the pore volume of the mixing tank.

The red dashed line in Fig. C2-5 corresponds to max dose rate = $0.0040$ mSv/m$^3 \times Q_p$. The fact that the calculated points lie generally below the dashed line may be attributed to (i) spreading of the I-129 release during transport through the repository tunnel system and access structures and (ii) radioactive decay. Note also that diffusive release from the emplacement rooms may be important especially in the base case, given the very low flow rates from the emplacement rooms in this case. This may be why the corresponding point in Fig. C2-5 lies slightly above the
dashed line, while other points lie below it. Note also that the IRF concentrations of other radio-
nuclides in the mixing tank, in terms of dose, are significantly lower, e.g. \(6.04 \times 10^{-5}\) mSv/m\(^3\) for Cl-36 and \(7.07 \times 10^{-4}\) mSv/m\(^3\) for Se-79, explaining the dominance of I-129 in e.g. Fig. C2-4 (although the cladding release should in principle also to be taken into account in the case of Cl-36, as does the release from the HLW matrix in the case of Se-79).

![Graph showing maximum dose rates and flow from emplacement rooms](image)

Fig. C2-5: Maximum dose rates due to releases via the HLW repository tunnel system and access structures as a function of the total flow from the SF / HLW emplacement rooms (black symbols) and maximum dose rates due to releases via the host rock as a function of total flow from the SF / HLW emplacement rooms (blue symbols).

The position of the points relative to the red dashed line shows the approximate proportionality between maximum dose rate and these flows. Its slope (0.0040 mSv/m\(^3\)) corresponds to the maximum dissolved concentration of I-129 in the mixing tanks due to the IRF. The blue dashed line corresponds to the total amount of I-129 released from the SF matrix.

The figure also shows maximum dose rates due to releases via the host rock as a function of total flow from the SF / HLW emplacement rooms. The results for the base case and for SA1, SA2 and SA3 are very similar to each other, and are only affected in case SA3, where relatively large amounts of water are diverted from the rock to the repository tunnel system (as the hydraulic conductivity of the repository tunnel system and access structures increases, more flow is diverted to these structures from the host rock). Their maximum dose rate is of the same order of magnitude as, but still significantly lower than, total release rate of I-129 from the SF matrix: the assumed dissolution rate of the SF matrix is \(10^{-7}\) a\(^{-1}\); multiplying this by the product of the SF matrix inventory (total inventory of \(5.18 \times 10^{12}\) Bq, of which 92.36 % is in the matrix, giving a matrix inventory of \(4.78 \times 10^{12}\) Bq) and the biosphere dose conversion factor for I-129
of $2 \times 10^{10}$ mSv/Bq gives a release rate of $9.58 \times 10^5$ mSv/a. This is plotted as a blue dashed line in Fig. C2-5. Thus, while some of the SF matrix release of I-129 reaches the biosphere via advective / dispersive transport in the host rock in these cases (exiting through its upper boundary), the remainder can be assumed to either migrate through the repository tunnel system or to diffusive to the lower boundary of the host rock. The maximum dose rates due to releases via the host rock for $SA4$ to $SA6$ are not shown in the figure. This is because the amount of water diverted to the repository tunnel system in these cases is such that there are no releases to the host rock by advection in these cases, although diffusive release continues (see the discussion of the mixing tank approach in Section 3.4.2).

In order to understand the partitioning of the maximum release rates and corresponding maximum dose rates between the different access structures, we make the assumption that the overall release rate via these structures is distributed according to the relative flow rates along these structures. Under this assumption, the maximum dose rate due to releases along the shaft would be equal to the maximum dose rate due to release along all types of access structure, multiplied by the ratio of the flow along the shaft to the total flow along all types of access structure. Equivalently, we can define a normalised maximum dose rate (in units of m$^3$ a$^{-1}$) due to releases along the shaft as the maximum dose rate for this path multiplied by the total flow along all types of access structure and divided by the maximum dose rate due to release along all types of access structure.

Fig. C2-6 shows the normalised maximum dose rates due to releases via each of the HLW repository access structures as a function of the total flow along the structure. The two quantities can be seen to be quite similar in many of the calculation cases considered (i.e. they follow the red dashed line), especially in the cases of the ramp and the construction shaft, showing that the assumption that the overall release rate via these structures is approximately distributed according to the relative flow rates along these structures is reasonable. This observation suggests that the concentration of the radionuclide that dominates maximum dose rates (I-129 for the HLW repository) is rather uniform, i.e. well mixed, within the repository tunnel system between the emplacement rooms and the ramp and construction shaft, at least for the layout assumed in the present study. The ventilation shaft, being less directly connected to the SF / HLW emplacement rooms, gives somewhat lower does rates, implying more significant dilution of I-129 concentration before the ventilation shaft is reached.
Fig. C2-6: Normalised maximum dose rates due to releases via the HLW repository tunnel system and to the ventilation shaft (VS), the construction shaft (CS) and the ramp as a function of the flow rates along these access structures.

The "normalised max. dose" \( [\text{m}^3/\text{a}] \) from a given access structure (VS, CS, ramp) is obtained by multiplying the max. dose rate \([\text{mSv}/\text{a}]\) due to that structure by the sum of the flows from all access structures \([\text{m}^3/\text{a}]\), divided by the maximum of the summed dose from all access structures \([\text{mSv}/\text{a}]\) (see main text).

The position of the points relative to the red dashed line indicates that the maximum normalised dose rates are approximately equal to the corresponding flow rates.

Corresponding graphs for the L/ILW are shown in Figs. C2-7 and C2-8. The dominant radionuclides for the L/ILW repository are Cl-36 and Se-79 (see Section C.2.2 of this appendix), the full inventories of which are released instantly at 100 years to the mixing tanks representing the emplacement room panels. The maximum dissolved concentrations of these radionuclides in the mixing tank can be evaluated as follows:

- The total inventories of Cl-36 and Se-79 in the L/ILW repository are \(4.91 \times 10^{12} \text{ Bq}\) and \(2.00 \times 10^{11} \text{ Bq}\), respectively;
- The pore volume of the mixing tank is equal to the product of the number of L/ILW emplacement rooms (8), the room length (200 m), the assumed mixing tank porosity (0.2 for tunnel and 0.14 for EDZ) and the assumed mixing tank cross-sectional area per room \((\pi \times 6.27 \text{ m} \times 6.27 \text{ m}\) for the tunnel and \(\pi \times (6.97 \text{ m} + 6.27 \text{ m}) \times 0.7 \text{ m}\) for the EDZ), giving a volume of \(4.6 \times 10^4 \text{ m}^3\).
- The biosphere dose conversion factors for Cl-36 and Se-79 are \(7 \times 10^{-12} \text{ mSv/Bq}\) and \(6.6 \times 10^{-11} \text{ mSv/Bq}\), respectively.
Thus, in terms of the dose to which it gives rise, the maximum dissolved concentrations of Cl-36 and Se-79 in the mixing tank are \( C = 7.47 \times 10^{-4} \text{ mSv/m}^3 \) and \( 2.87 \times 10^{-4} \text{ mSv/m}^3 \), i.e. the product of the IRF inventory and the biosphere dose conversion factor, divided by the pore volume of the mixing tanks, giving a total concentration of \( 1.03 \times 10^{-3} \text{ mSv/m}^3 \).

![Diagram showing dose rates vs flow rates](image)

**Fig. C2-7:** Maximum dose rates due to releases via the L/ILW repository tunnel system and access structures as a function of the total flow from the emplacement rooms (black symbols) and maximum dose rates due to releases via the host rock as a function of total flow from the emplacement rooms (blue symbols).

The position of the points relative to the red dashed line shows the approximate proportionality between maximum dose rate and these flows. Its slope \((1.03 \times 10^{-3} \text{ mSv/m}^3)\) corresponds to the maximum dissolved concentration of Cl-36 and Se-79 in the mixing tanks.

The red dashed line in Fig. C2-7 corresponds to max dose rate \( = 9.73 \times 10^{-4} \text{ mSv/m}^3 \times Q_p \). The fact that the calculated points lie generally below the dashed line may again be attributed to (i) spreading of the Cl-36 and Se-79 release during transport through the repository tunnel system and access structures and (ii) radioactive decay. Diffusive release from the emplacement rooms may again be important especially in the base case, given the very low flow rates from the emplacement rooms in this case, which may be why the corresponding point, as well as that for \( SA1 \), in Fig. C2-7 lie above the dashed line, while other points lie below it.

As in the case of the HLW repository, maximum dose rates due to releases via the host rock base case and for \( SA1, SA2 \) and \( SA3 \) are very similar to each other, and almost independent of flow from the emplacement rooms. The maximum dose rates due to releases via the host rock for \( SA4 \) to \( SA6 \) are not shown in the figure, because the amount of water diverted to the repository tunnel system in these cases is such that there are no releases to the host rock by advection in these cases.
Fig C2-8 shows that the overall release rate via the access structures, i.e. the two shafts and the ramp, is distributed roughly according to the relative flow rates along the structures. This observation suggests that the concentrations of the radionuclides dominating maximum dose rates (Cl-36 and Se-79 for the L/ILW repository) are rather uniform, i.e. well mixed, within the repository tunnel system for the currently assumed layout.

![Graph](image)

**Fig. C2-8:** Normalised maximum dose rates due to releases via the L/ILW repository tunnel system and to the ventilation shaft (VS), the operations shaft (CS) and the ramp as a function of the flow rates along these access structures.

The "normalised max. dose" [m$^3$/a] from a given access structure (VS, CS, ramp) is obtained by multiplying the max. dose rate [mSv/a] due to that structure by the sum of the flows from all access structures [m$^3$/a], divided by the maximum of the summed dose from all access structures [mSv/a] (see main text).

The position of the points relative to the red dashed line indicates that the maximum normalised dose rates are approximately equal to the corresponding flow rates.

### C.3 Summary of main observations

For the HLW repository, SF always makes the largest contribution to the dose rate maximum, followed by HLW and finally ILW. The dose rates due to releases via the repository access structures (ramp and shafts) peak at a few tens of thousands of years and are dominated by I-129, followed by Se-79 and Cl-36. C-14 always decays substantially before reaching the biosphere, either via the repository tunnel system and access structures or via the host rock. The peak dose rate is followed by a period of lower, but roughly constant dose rate extending to 10$^7$ years (the calculation end time) that is again dominated by I-129. The earlier I-129 peak is associated mainly with the SF IRF, while the plateau is associated with the longer-term release from the SF waste matrix.
In the case of the L/ILW waste repository, the calculated dose rates due to releases via the repository access structures also peak at a few tens of thousands of years and are dominated by Cl-36, with lesser contributions from Se-79, organic C-14 and I-129. Releases via the host rock are dominated by Cl-36 and Se-79 and peak at a few hundred thousand years.

For the HLW repository, the maximum dose rate due to releases via the repository access structures is reasonably well approximated (though somewhat overestimated) in most cases by the product of the concentration due to the I-129 IRF from SF and the flow rate from the emplacement rooms to the repository tunnel system. For the L/ILW repository (especially for higher tunnel flow rates), the maximum dose rate due to releases via these routes is reasonably well approximated by the total concentrations of Cl-36 and Se-79 (in units of dose) and the flow rate from the emplacement rooms to the repository tunnel system. In case SA1, however, due to the assumed effectiveness of the repository sealing and the consequent very low flow rates from the emplacement rooms, diffusive release from the emplacement rooms to the repository tunnel system is important. For both repositories, the distribution of the dose rate between the access structures is proportional to relative flows along the access structures in all cases.

Dose rates due to releases via the host rock dominate over those due to releases via the access structures in those cases where the repository sealing is assumed to be most effective, i.e. in the base cases and in cases SA1, SA2 and SA3; the dose rate maxima for this path are similar in all these cases.

Thus, releases via the repository tunnel system and access structures are significant only in cases where the repository sealing is markedly less effective (esp. SA4, SA5 and SA6; hydraulic conductivities of backfilled tunnels $10^{-9}$ m s$^{-1}$ or higher, of EDZs $10^{-8}$ m s$^{-1}$ or higher). The key factor affecting peak dose rates (summed over all access structures) in these cases is the flow rate from the emplacement rooms to the repository tunnel system. Note that, even in the highest hydraulic conductivity case (SA6), Darcy velocities leaving the emplacement rooms never exceed a few millimetres per year. In cases SA4, SA5 and SA6, as the assumed hydraulic conductivities in the tunnels and access structures increase, the heads at repository depth become closer to zero (i.e. which is the reference value imposed at the upper boundary of the host rock), and the flow rates from the emplacement rooms approach asymptotic values that are determined by the hydraulically effective areas of these rooms and by the hydraulic conductivity of the host rock.

In the tunnel systems, higher Darcy velocities are encountered, though they are still very small, with Darcy velocities never exceeding a few centimetres per year along the ramp and shafts, even in the highest hydraulic conductivity cases.
# List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Explanation and Remarks</th>
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<tbody>
<tr>
<td>2D</td>
<td>two-dimensional</td>
</tr>
<tr>
<td>BC</td>
<td>base case</td>
</tr>
<tr>
<td>BE</td>
<td>spent fuel [German: abgebrannte Brennelement]</td>
</tr>
<tr>
<td>BE-D-n</td>
<td>spent fuel type</td>
</tr>
<tr>
<td>BE-S-n</td>
<td>spent fuel type</td>
</tr>
<tr>
<td>BFE</td>
<td>Swiss Federal Office of Energy [German: Bundesamt für Energie]</td>
</tr>
<tr>
<td>CS</td>
<td>operations / construction shaft</td>
</tr>
<tr>
<td>CSA</td>
<td>leg cross-sectional area</td>
</tr>
<tr>
<td>EDZ</td>
<td>excavation damage zone</td>
</tr>
<tr>
<td>ENSI</td>
<td>Swiss Federal Nuclear Safety Inspectorate</td>
</tr>
<tr>
<td>ENSI-G03/e</td>
<td>ENSI's specific design principles for deep geological repositories and requirements for the safety case</td>
</tr>
<tr>
<td>GAST</td>
<td>Gas-Permeable Seal Test at the Grimsel Test Site</td>
</tr>
<tr>
<td>HLW</td>
<td>(vitrified) high-level waste</td>
</tr>
<tr>
<td>HLW-F-1</td>
<td>high-level waste type</td>
</tr>
<tr>
<td>HLW-U-1</td>
<td>high-level waste type</td>
</tr>
<tr>
<td>HR</td>
<td>host rock</td>
</tr>
<tr>
<td>IAEA</td>
<td>International Atomic Energy Agency</td>
</tr>
<tr>
<td>ILW</td>
<td>intermediate-level waste</td>
</tr>
<tr>
<td>ILW-1</td>
<td>intermediate-level waste – group 1</td>
</tr>
<tr>
<td>ILW-2</td>
<td>intermediate-level waste – group 2</td>
</tr>
<tr>
<td>IRF</td>
<td>instant release fraction</td>
</tr>
<tr>
<td>KEG</td>
<td>Nuclear Energy Law (German: Kernenergiegesetz)</td>
</tr>
<tr>
<td>KNE</td>
<td>Commission for Nuclear Waste Disposal [German: Kommission Nukleare Entsorgung]</td>
</tr>
<tr>
<td>KNS</td>
<td>Federal Commission for Nuclear Safety [German: Eidgenössischen Kommission für nukleare Sicherheit]</td>
</tr>
<tr>
<td>L/ILW</td>
<td>low- and intermediate-level waste</td>
</tr>
<tr>
<td>LLW</td>
<td>low-level waste</td>
</tr>
<tr>
<td>MOX</td>
<td>mixed oxide fuel</td>
</tr>
<tr>
<td>Nagra</td>
<td>National Cooperative for the Disposal of Radioactive Waste [German: Nationale Genossenschaft für die Lagerung radioaktiver Abfälle]</td>
</tr>
<tr>
<td>NPP</td>
<td>nuclear power plant</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Explanation and Remarks</td>
</tr>
<tr>
<td>--------------</td>
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</tr>
<tr>
<td>PICNIC-TD</td>
<td>code for modelling radionuclide transport along discrete legs</td>
</tr>
<tr>
<td>RNC</td>
<td>resistor network code (code used for flow modelling)</td>
</tr>
<tr>
<td>SF</td>
<td>spent fuel</td>
</tr>
<tr>
<td>SGT</td>
<td>Sectoral Plan for Deep Geological Repositories [German: Sachplan geologische Tiefenlager]</td>
</tr>
<tr>
<td>STMAN</td>
<td>family of computer codes used for near-field radionuclide release and transport modelling</td>
</tr>
<tr>
<td>URL</td>
<td>underground rock laboratory (test area)</td>
</tr>
<tr>
<td>VPAC</td>
<td>Versatile Performance Assessment Code</td>
</tr>
<tr>
<td>VS</td>
<td>ventilation shaft</td>
</tr>
</tbody>
</table>
## List of Principal Mathematical Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Explanation and Remarks</th>
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<tr>
<td>( a )</td>
<td>radius of an emplacement room, tunnel or shaft (including EDZ) [m]</td>
</tr>
<tr>
<td>( b )</td>
<td>half width of inner domain of host rock leg [m]</td>
</tr>
<tr>
<td>( c )</td>
<td>major axis of elliptical room or tunnel [m]</td>
</tr>
<tr>
<td>( d )</td>
<td>spacing between emplacement rooms and width of outer domain of host rock leg; or minor axis of elliptical room or tunnel [m]</td>
</tr>
<tr>
<td>( f )</td>
<td>complex potential [m²/s]</td>
</tr>
<tr>
<td>( h, h', \bar{h} )</td>
<td>hydraulic head [m]</td>
</tr>
<tr>
<td>( l, l_{im} )</td>
<td>hydraulic gradients, ( i ) can also denote ( \sqrt{-1} )</td>
</tr>
<tr>
<td>( n )</td>
<td>porosity [-]</td>
</tr>
<tr>
<td>( n^E )</td>
<td>element-specific porosity [-]</td>
</tr>
<tr>
<td>( q )</td>
<td>Darcy velocity [m/s]</td>
</tr>
<tr>
<td>( r )</td>
<td>radial direction [m]</td>
</tr>
<tr>
<td>( u )</td>
<td>Cartesian coordinate in transformed complex plane [m]</td>
</tr>
<tr>
<td>( v )</td>
<td>Cartesian coordinate in transformed complex plane [m]</td>
</tr>
<tr>
<td>( w )</td>
<td>the diameter of a room or tunnel including the EDZ [m]</td>
</tr>
<tr>
<td>( w_c )</td>
<td>the flow capture width of a circular emplacement room or tunnel including the EDZ [m]</td>
</tr>
<tr>
<td>( w_e )</td>
<td>the flow capture width of an elliptical emplacement room or tunnel including the EDZ [m]</td>
</tr>
<tr>
<td>( x )</td>
<td>Cartesian coordinate [m]</td>
</tr>
<tr>
<td>( y )</td>
<td>Cartesian coordinate [m]</td>
</tr>
<tr>
<td>( A )</td>
<td>area of (part of) the repository [m²]</td>
</tr>
<tr>
<td>( B )</td>
<td>half width of outer domain of host rock leg [m]</td>
</tr>
<tr>
<td>( C )</td>
<td>radionuclide concentration [mol/m³]</td>
</tr>
<tr>
<td>( D )</td>
<td>spacing of parallel underground structures [m]</td>
</tr>
<tr>
<td>( D_e )</td>
<td>effective diffusion coefficient [m²/s]</td>
</tr>
<tr>
<td>( E )</td>
<td>element</td>
</tr>
<tr>
<td>( F_L, F_L )</td>
<td>(radio)nuclide fluxes [mol/m²/s]</td>
</tr>
<tr>
<td>( H_A )</td>
<td>ambient head at repository depth [m]</td>
</tr>
<tr>
<td>( H_u, H_l )</td>
<td>head imposed at the upper and lower boundaries of the host rock [m]</td>
</tr>
<tr>
<td>( K )</td>
<td>hydraulic conductivity [m/s]</td>
</tr>
<tr>
<td>( K_d^E )</td>
<td>sorption coefficient of element ( E ) [m³/kg]</td>
</tr>
<tr>
<td>( K_{GEO, K_u, K_v} )</td>
<td>hydraulic conductivity of the host rock [m/s]</td>
</tr>
<tr>
<td>Symbol</td>
<td>Explanation and Remarks</td>
</tr>
<tr>
<td>--------</td>
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</tr>
<tr>
<td>$L$</td>
<td>transport path length; or length of an emplacement room [m]</td>
</tr>
<tr>
<td>$L_{tot}$</td>
<td>total length of all tunnels considered [m]</td>
</tr>
<tr>
<td>$L_{uu}, L_{li}$</td>
<td>vertical distances from the tunnel axis to the upper and lower boundaries of the host rock [m]</td>
</tr>
<tr>
<td>$N$</td>
<td>number of emplacement rooms in a panel [-]</td>
</tr>
<tr>
<td>$Pe$</td>
<td>Peclet number [-]</td>
</tr>
<tr>
<td>$Q, Q_{b}, Q_{i}, Q_{m}, Q_{p}$, $Q_{s}, Q_{uu}, Q_{tot}, Q_{lot}$</td>
<td>water flow rates [m$^3$/s]</td>
</tr>
<tr>
<td>$R^E$</td>
<td>retardation coefficient of element $E$ [-]</td>
</tr>
<tr>
<td>$V_{uu}, V_{v}, V_{x}, V_{y}, V_{\infty}$</td>
<td>Darcy velocities [m/s]</td>
</tr>
<tr>
<td>$W$</td>
<td>effective leg width [m]</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>longitudinal dispersion coefficient [m]</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>anisotropy factor / ratio of EDZ radius to tunnel radius [-]</td>
</tr>
<tr>
<td>$\rho_s$</td>
<td>dry bulk density of sorbing material [kg/m$^3$]</td>
</tr>
<tr>
<td>$\rho$</td>
<td>dry bulk density of sand / bentonite mixture [kg/m$^3$]</td>
</tr>
<tr>
<td>$\phi$</td>
<td>velocity potential [m$^2$/s]</td>
</tr>
<tr>
<td>$\psi$</td>
<td>stream function [m$^2$/s]</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>radionuclide decay rate [s$^{-1}$]</td>
</tr>
</tbody>
</table>