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**TR-23-08**
March 2023

## Post-closure safety for SFR, the final repository for short-lived radioactive waste at Forsmark

# Handling of future human actions, PSAR version

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*Keywords:* Post-closure safety, SFR, Final repository, Low- and intermediate-level radioactive waste, Forsmark, Safety assessment, Future human actions, Human intrusion, Dose assessment, Features, events and processes (FEP).

# Summary

The final repository for short-lived radioactive waste (SFR) at Forsmark, Sweden is used for the final disposal of low- and intermediate-level operational waste from Swedish nuclear facilities. The PSAR assessment of post-closure safety is an important part of the construction license application for the extension of SFR. This report constitutes one of the main references supporting the **Post-closure safety report**.

## Purpose and objectives

Considering the time perspective of the post-closure safety assessment for the final repository for short-lived radioactive waste (SFR), it cannot entirely be ruled out that humans in the future, in some way, will conduct activities at, or near, the repository site that potentially may affect the conditions of the repository.

The purpose of this report is to document the handling of future human actions (FHAs) in the PSAR. Only inadvertent actions are addressed, potentially resulting in 1) changes to the barrier system affecting, directly or indirectly, the rate of the release of radionuclides from SFR, and 2) radioactive waste being brought to the surface giving rise to exposure of people at the surface. Inadvertent FHAs are defined as actions carried out without knowledge of the repository and/or its nature (the location of the repository, its purpose and the consequences of the actions). The main objective of this work is to facilitate the argument that the disposal concept for SFR is robust against a wide range of credible human activities.

## FHA FEP analysis

The FHA FEP analysis presented in this report is based on the safety functions defined in Chapter 5 of the **Post-closure safety report** and understanding of the behaviour of the repository system drawn from previous work and the rest of the PSAR. The list of identified FHA FEPs is the same as in SR-PSU (SKB TR-14-08) and consists of three societal FEPs and 14 technical FEPs.

The societal FEPs address potential developments of society and technology, and the issue of whether knowledge of the repository is retained by future generations. These aspects are handled by applying the commonly accepted approach that present-day social conditions and technical capabilities prevail throughout the assessment period. However, one exception is made from this. Assuming present-day conditions would imply that the knowledge of SFR also is preserved at the current level, and thus no inadvertent actions can occur. In the safety assessment, it is assumed that knowledge is lost, and thus FHA may occur, at the earliest 300 years after closure.

The technical FHA FEPs cover a wide range of credible human activities, such as drilling wells for water or geothermal energy, mining and other underground construction activities, and altering the land use. SKB considers drilling as a key FHA FEP. Although deemed unlikely to occur, geological drilling on the site is considered the most likely FHA to cause direct intrusion into the repository after knowledge of the site has been lost.

## FHA scenarios

Four stylised FHA scenarios have been identified and analysed in this report. This set of selected FHA scenarios is an illustrative set of credible future human actions, but should not be considered to be fully comprehensive or complete.

Two of the scenarios illustrate direct intrusion into the repository by drilling. The *drilling into the repository* scenario, which assumes that radioactive material being brought to the surface during the drilling event, giving rise to exposure of people, and the *intrusion well* scenario, in which drilling for a household water supply is addressed. The two other FHA scenarios illustrate future human actions not directly intruding into the repository, but which may have impacts on the repository due to potentially altered groundwater flows in the bedrock and through the waste vaults: the *water management* scenario and the *underground construction* scenario.

## Calculation cases and results

Three calculation cases are analysed in the *drilling into the repository* scenario, exposure of the drill crew during a drilling event, and exposure of people either performing construction or cultivating on land containing contaminated drilling detritus. For these cases, the effective dose maximum is 0.014 mSv, related to bringing a 1 m drill core from 2BMA to the surface resulting in exposure of the drill crew. The doses for the cases where people cultivate land containing contaminated drilling detritus are lower. Maximum effective dose to a construction worker, conducting work for one year on a landfill containing contaminated drilling detritus is 0.022 mSv, and maximum annual dose to a person cultivating vegetables and tubers on a similar landfill is about 0.0036 mSv.

One calculation case is analysed in the *intrusion well* scenario, the *intrusion well into the repository* calculation case. In this calculation case it is assumed that a water well is drilled, and that the borehole penetrates a waste vault. Consequently, the well water will contain radionuclides released from this vault. The well water is utilised as drinking water. The maximum annual dose for this case is 1.3 mSv, for a well drilled into one of the 2–5BLA waste vaults at 3000 AD. This is assumed to be the earliest possible time that a well can be drilled in to the repository, corresponding to when about 3/4 of the repository footprint to have become land due to shoreline regression.

One calculation case is analysed in the *water management* scenario, the *construction of a water impoundment* calculation case. In this calculation case it is assumed that a dam for a future water impoundment in the vicinity of SFR is constructed. The impoundment leads to increased groundwater flowrates in the bedrock surrounding the repository and through the waste vaults compared with the *base case* in the main scenario in the post-closure safety assessment. Postulating a four-fold increase in flowrate, the annual dose maximum is 0.012 mSv. This is about two times higher than the dose maximum in the *base case* (0.0056 mSv). Postulating a ten-fold higher flowrate, the annual dose maximum is 0.019 mSv, which is about 3.5 times higher than in the *base case*.

Two calculation cases are analysed in the *underground construction* scenario: the *mine in the vicinity of the Forsmark site* calculation case and the *rock cavern in the close vicinity of SFR* calculation case. In the case related to a mine, it is judged that the potential hydraulic impact on SFR from a hypothetical mine in the vicinity of the Forsmark site would be insignificant. In the case with the rock cavern, the same increases of the flowrates in the bedrock and through the waste vaults as in the *construction of a water impoundment* calculation case are assumed. Hence, the resulting doses in this calculation case are comparable to the doses in the *construction of a water impoundment* calculation case.

## Conclusions

The scenarios identified and analysed in this report are judged to provide a sufficiently broad perspective to facilitate the argument that SFR is robust against a wide range of credible future human activities.

A key outcome from the dose calculations is that most of the doses are below IAEA's criterion of 1 mSv (IAEA 2011), below which efforts to reduce the probability of intrusion or to limit its consequences are not warranted. Only in the calculation case with an intrusion well in a BLA vault, drilled at the earliest time possible, does the dose exceed 1 mSv. If annual doses in the range 1–20 mSv are indicated, reasonable efforts are warranted at the stage of development of the facility to reduce the probability of intrusion or to limit its consequences by means of optimization of the facility's design (IAEA 2011). For SFR this has been done by selecting geological disposal, which is widely deemed as the most effective measure to reduce the potential for human intrusion to occur.

The illustrative, and pessimistic, dose results in the present analysis do not give rise to concern relative to either of the IAEA ranges of doses warranting further reduction of the probability of intrusion or limiting its consequences by means of optimization of the facility's design, nor do they exceed the reference levels set by ICRP for existing or emergency situations (ICRP 2013). This is a clear indicator of the robustness of SFR to FHA. In conclusion, based on the analysis presented in this report, SFR is a robust disposal facility regarding a broad range of potential FHA.

# Sammanfattning

Slutförvaret för kortlivat radioaktivt avfall (SFR) i Forsmark, Sverige används för slutförvaring av låg- och medelaktivt driftavfall från svenska kärntekniska anläggningar. Analysen av säkerhet efter förslutning i PSAR är en viktig del av ansökan om medgivande för utbyggnaden av SFR. Denna rapport utgör en av huvudreferenserna till **Huvudrapporten säkerhet efter förslutning**.

## Syfte och mål

Med tanke på tidsperspektivet för analysen av säkerhet efter förslutning av Slutförvaret för kortlivat radioaktivt avfall (SFR) kan det inte helt uteslutas att människor i framtiden på något sätt kommer att genomföra handlingar på, eller nära, platsen för slutförvaret som potentiellt kan påverka förhållandena för förvaret.

Syftet med denna rapport är att dokumentera hanteringen av framtida mänskliga handlingar (future human actions, FHAs) i PSAR. Endast oavsiktliga handlingar behandlas, vilka potentiellt kan resultera i 1) påverkan på barriärsystemet som direkt eller indirekt inverkar på utsläppstakten av radionuklider från SFR, och 2) att radioaktivt avfall förs upp till ytan och ger upphov till exponering av människor på ytan. Oavsiktliga FHAs definieras som åtgärder som utförs utan kännedom om förvaret och/eller dess natur (förvarets plats, dess ändamål och konsekvenserna av handlingarna). Huvudsyftet med detta arbete är att understödja argumentet att slutförvaringskonceptet för SFR är robust mot ett brett spektrum av trovärdiga mänskliga handlingar.

## FHA-FEP-analys

FHA-FEP-analysen som presenteras i denna rapport utgår ifrån säkerhetsfunktionerna som definieras i kapitel 5 i **Huvudrapporten säkerhet efter förslutning**, och förståelse av hur slutförvarssystemet fungerar hämtad från tidigare arbete och övriga delar av PSAR. Listan med identifierade FHA-FEPs är densamma som i SR-PSU (SKB TR-14-08) och består av tre samhällsrelaterade FEPsoch 14 teknikrelaterade FEPs.

Samhällsrelaterade FEPs behandlar potentiell utveckling av samhället och teknik, och frågan om huruvida kunskapen om förvaret bibehålls av framtida generationer. Dessa aspekter hanteras genom att tillämpa det allmänt accepterade tillvägagångssättet att dagens sociala förhållanden och tekniska förmågor råder under hela analysperioden. Ett undantag görs dock från detta. Att anta nutida förhållanden skulle innebära att kunskapen om SFR också bevaras på nuvarande nivå, vilket gör att inga oavsiktliga handlingar kan förekomma. I analysen av säkerhet efter förslutning antas att kunskapen går förlorad, och FHA kan därmed inträffa, som tidigast 300 år efter förslutning.

Teknikrelaterade FEPs täcker ett brett spektrum av trovärdiga mänskliga handlingar, som att borra brunnar för vatten eller geotermisk energi, gruvdrift och andra underjordiska konstruktionsaktiviteter och förändrad markanvändning. SKB betraktar borrning som en central FEP för FHA. Även om det bedöms osannolikt att det kommer inträffa, anses bergborrning på platsen vara den mest sannolika mänskliga handlingen som kan orsaka direkt intrång i förvaret efter att kunskap om platsen har gått förlorad.

## FHA-scenarios

Fyra stiliserade FHA-scenarier har identifierats och analyserats i denna rapport. Uppsättningen av scenarier innehåller ett illustrativt set av trovärdiga framtida mänskliga handlingar, men ska inte betraktas vara komplett.

Två av scenarierna belyser direkt intrång i förvaret via borrning. Scenariot *borrning i förvaret*, som utgår ifrån att radioaktivt material förs upp till ytan under borrningen, vilket ger upphov till exponering av människor, och scenariot *intrångsbrunn*, där borrning för vattenförsörjning till ett hushåll behandlas. De två andra FHA-scenarierna belyser framtida mänskliga handlingar som inte resulterar i direkt

intrång i förvaret, men som kan ha påverkan på förvaret via potentiellt förändrade grundvattenflöden i berggrunden och genom förvarsdelarna: scenariot *vattenförvaltning* och scenariot *underjordisk anläggning*.

## Beräkningsfall och resultat

Tre beräkningsfall analyseras i scenariot *borrning i förvaret*, exponering av borrmanskapet under borrningen och exponering av personer som antingen utför byggarbete eller odlar på mark som innehåller kontaminerad borrkax. För dessa fall är den högsta effektiva dosen 0,014 mSv, associerad med att en 1 m borrkärna från 2BMA förs upp till ytan vilket resulterar i exponering av borrmanskapet. Doserna för fallen med odling på mark som innehåller kontaminerat borrkax är lägre. Högsta effektiva dosen till en byggarbetare som utför arbete under ett år på en deponi som innehåller kontaminerat borrkax är 0,022 mSv och den högsta årliga dosen till en person som odlar grönsaker och rotknölar på en liknande deponi är cirka 0,0036 mSv.

Ett beräkningsfall, *intrångsbrunn i förvaret*, analyseras i scenariot *intrångsbrunn*. Beräkningsfallet utgår ifrån att en brunn för vattenförsörjning borras och att borrhålet penetrerar en förvarsdel. Följaktligen kommer brunnsvattnet innehålla radionuklider som släppts ut från denna förvarsdel. Brunnsvattnet används som dricksvattenkälla. Den högsta årliga dosen för detta fall är 1,3 mSv, för en brunn borrad in i en av förvarsdelarna 2–5BLA vid 3000 e.Kr. Detta antas vara den tidigaste möjliga tidpunkten som en brunn kan borras in i förvaret, som motsvarar när strandlinjen har dragit sig tillbaka tillräckligt för att cirka 3/4 av förvarets fotavtryck har blivit land.

Ett beräkningsfall, *anläggning av en vattenreservoar*, analyseras i scenariot *vattenförvaltning*. Beräkningsfallet utgår ifrån att en damm för en framtida vattenreservoar anläggs i närheten av SFR. Vattenreservoaren leder till ökat grundvattenflöde i berggrunden som omger slutförvaret och genom förvarsdelarna jämfört med *basfallet* i huvudscenariot i analysen av säkerhet efter förslutning. Givet en fyrfaldig ökning av flödet är den högsta årliga dosen 0,012 mSv. Detta är ungefär två gånger högre än högsta dosen i *basfallet* (0,0056 mSv). Givet en tiofaldig ökning av flödet är den högsta årliga dosen 0,019 mSv, vilket är cirka 3,5 gånger högre än i *basfallet*.

Två beräkningsfall analyseras i scenariot *underjordisk anläggning*: *gruva i närheten av Forsmark* och *bergrum i närheten av förvaret*. I beräkningsfallet med en gruva bedöms den potentiella hydrauliska påverkan på SFR från en hypotetisk gruva i närheten av Forsmarksområdet vara obetydlig. I beräkningsfallet med bergrum antas samma ökningar av grundvattenflödet i berggrunden och genom förvarsdelarna som i beräkningsfallet *anläggning av en vattenreservoar*. Följaktligen är de resulterande doserna i detta fall jämförbara med doserna beräkningsfallet *anläggning av en vattenreservoar*.

## Slutsatser

Scenarierna som identifierats och analyserats i denna rapport bedöms ge ett tillräckligt brett perspektiv för att argumentera att SFR är robust mot ett brett spektrum av trovärdiga framtida mänskliga handlingar.

Ett viktigt resultat från dosberäkningarna är att de flesta doserna inte överstiger IAEA:s kriterium på 1 mSv (IAEA 2011), under vilket insatser för att minska sannolikheten för intrång eller att begränsa dess konsekvenser inte är motiverade. Endast i beräkningsfallet med en intrångsbrunn i en BLA-förvarsdel överstiger dosen 1 mSv, för en brunn som borras vid tidigast möjliga tidpunkt. Om årliga doser i intervallet 1–20 mSv indikeras är det berättigat att vidta rimliga åtgärder under anläggningens utvecklingsfas för att minska sannolikheten för intrång eller för att begränsa dess konsekvenser genom optimering av anläggningens design (IAEA 2011). För SFR har detta gjorts, då valet av geologisk slutförvaring anses allmänt vara den mest effektiva åtgärden för att minska potentialen för att mänskligt intrång sker.

De illustrativa och pessimistiska dosresultaten i denna analys ger inte upphov till farhågor i förhållande till IAEA:s dosintervall som föranleder ytterligare minskning av sannolikheten för intrång eller begränsa dess konsekvenser genom optimering av anläggningens design, och de överskrider inte heller de referensnivåer som fastställts av ICRP för befintlig exponering eller exponering i nödläge (ICRP 2013). Detta är en tydlig indikator på att SFR är robust mot FHA. Sammantaget, baserat på analysen som presenteras i denna rapport, är SFR ett robust slutförvar för ett brett spektrum av potentiella FHA.

# Contents

# 1 Introduction

This document is one of the main references to the **Post-closure safety report** that contributes to the preliminary safety analysis report (PSAR) for SFR, the repository for short-lived radioactive waste at Forsmark in Östhammar municipality, Sweden (Figure 1-1).

This chapter gives the background and a short overview of the PSAR post-closure safety assessment undertaken as part of the construction license application for the extension of SFR. Moreover, the purpose and content of this report are described.

## 1.1 Background

SFR is operated by the Swedish Nuclear Fuel and Waste Management Company, SKB, and is part of the Swedish system for management of waste from nuclear power plants, other nuclear activities, industry, research and medical care. In addition to SFR, the Swedish nuclear waste management system also includes the repository for spent nuclear fuel and the repository for long-lived radioactive waste (SFL) (Figure 1-2).

SFR consists of the existing part, SFR1 (Figure 1-2, grey part), and the extension, SFR3 (Figure 1-2, blue part). SFR1 is designed for disposal of short-lived low- and intermediate-level waste produced during operation of the Swedish nuclear power reactors, as well as waste generated during applications of radioisotopes in medicine, industry, and research. This part was taken into operation in 1988. SFR3 is designed primarily for disposal of short-lived low- and intermediate-level waste from decommissioning of nuclear facilities in Sweden. The extension is called SFR3 since the name SFR2 was used in a previous plan to build vaults adjacent to SFR1. The repository is currently estimated to be closed by year 2075.

The SFR waste vaults are located below the Baltic Sea and are connected to the ground surface via two access tunnels. SFR1 consists of one 70-metre-high waste vault (silo) and four 160-metre-long waste vaults (1BMA, 1–2BTF and 1BLA), covered by about 60 metres of bedrock. SFR3 consists of six waste vaults (2BMA, 1BRT and 2–5BLA), varying in length from 255 to 275 m, covered by about 120 metres of bedrock.

A prerequisite for the extension of SFR is the licensing of the extended facility. The licensing follows a stepwise procedure. In December 2014, SKB submitted two licence applications to extend and continue the operation of SFR, one to the Swedish Radiation Safety Authority (SSM) for permission under the Act on Nuclear Activities (SFS 1984:3) and one to the Land and Environment Court for permissibility under the Environmental Code (SFS 1998:808). In October 2019 SSM submitted their pronouncement to the Swedish Government and recommended approval of the permission sought by SKB. In November 2019 the Court submitted its statement to the Swedish Government and recommended approval of the licence application. The Swedish Government granted permit and permissibility in December 2021.

The current step in the licensing of the extended SFR is the processing of the construction license application, submitted by SKB to SSM for review under the Act on Nuclear Activities. The licence documentation consists of an application document and a set of supporting documents. A central supporting document is the preliminary safety analysis report (PSAR), with a general part consisting of ten chapters.[1] Chapter 9 of the general part of that report addresses post-closure safety. The **Post-closure safety report** is the main reference to Chapter 9, and this report is a main reference to the **Post-closure safety report**.

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[1] SKB, 2022. PSAR SFR – Allmän del kapitel 1 – Introduktion. SKBdoc 1702853 ver 3.0, Svensk Kärnbränslehantering AB. (In Swedish.) (Internal document)

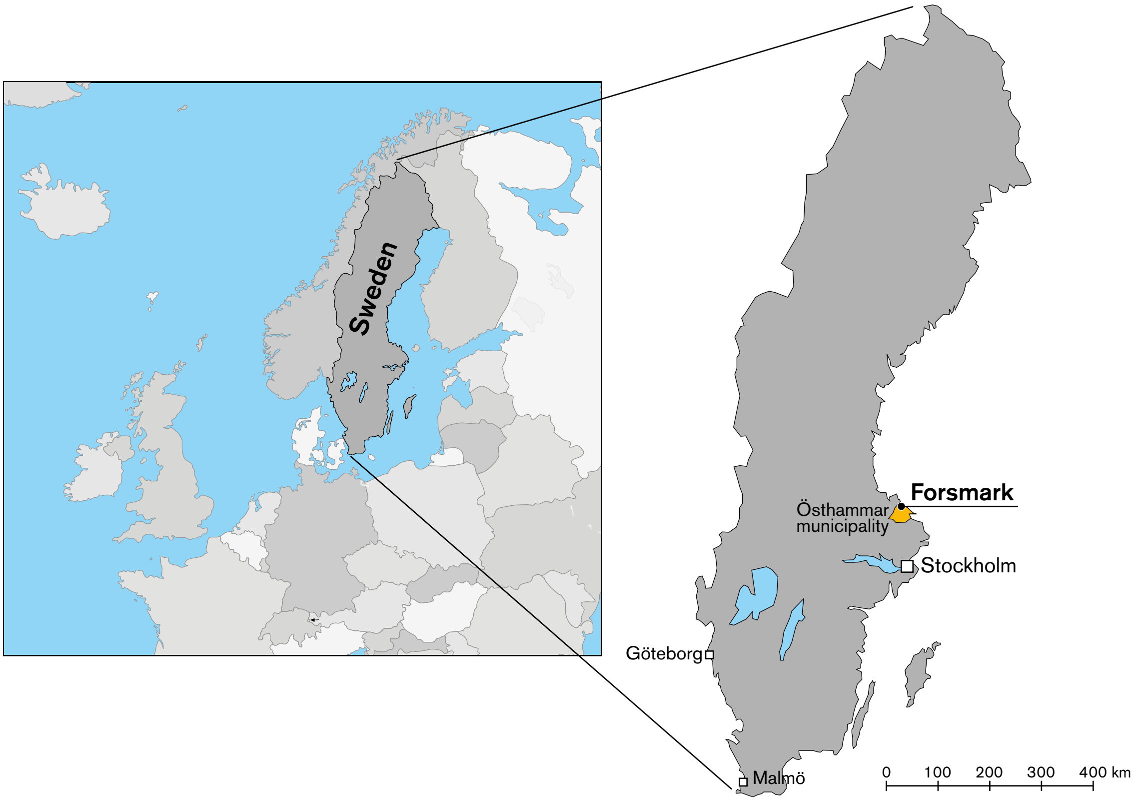

***Figure 1-1.*** *Location of the Forsmark site in Sweden (right) and in context with the countries in Europe (left). The site is situated in the Östhammar municipality, which belongs to the County of Uppsala.*

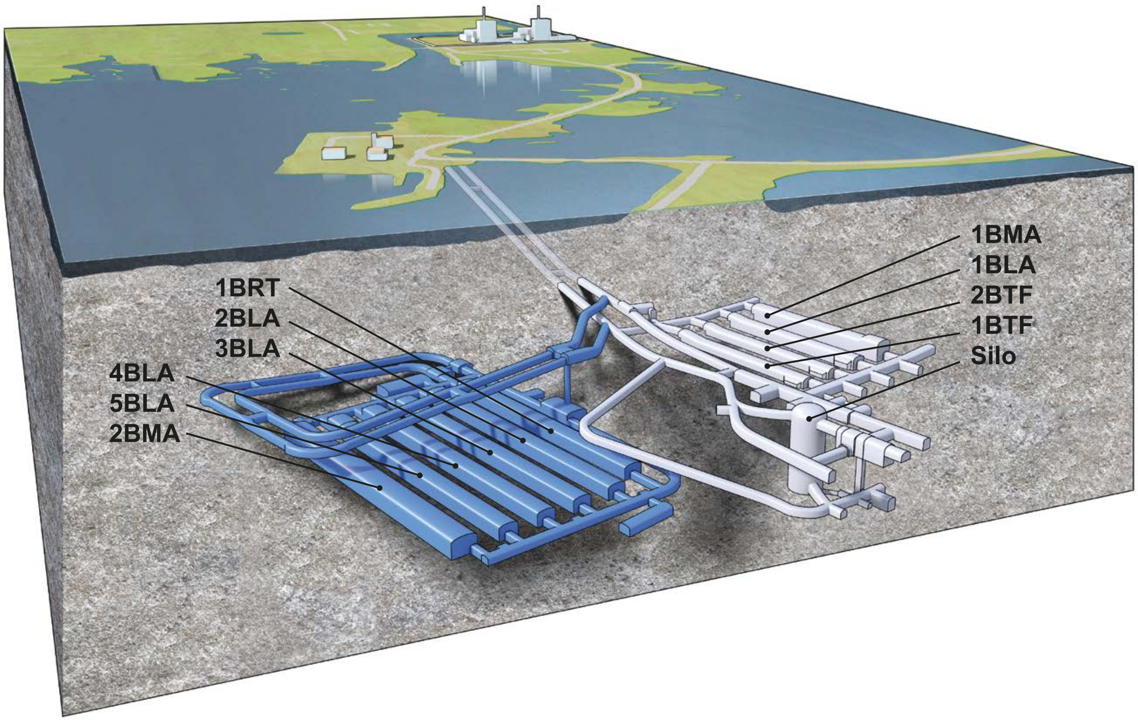

***Figure 1-2.*** *Schematic illustration of SFR. The grey part is the existing repository (SFR1) and the blue part is the extension (SFR3). The waste vaults in the figure are the silo for intermediate-level waste, 1–2BMA vaults for intermediate-level waste, 1BRT vault for reactor pressure vessels, 1–2BTF vaults for concrete tanks and 1–5BLA vaults for low-level waste.*

## 1.2 Post-closure safety assessment

### 1.2.1 Overview

The main role of the post-closure safety assessment is to demonstrate that SFR is radiologically safe for humans and the environment after closure. This is done by evaluating compliance with respect to the Swedish Radiation Safety Authority's regulations concerning post-closure safety and the protection of human health and the environment. Furthermore, the post-closure safety assessment is being successively developed in the stepwise licensing process for the extended SFR, and thus the results from the PSAR assessment[2] provide input to the forthcoming updated assessment to be carried out before trial operation of the facility.

The overall aim in developing a geological repository for nuclear waste is to ensure that the amounts of radionuclides reaching the accessible biosphere are such that possible radiological consequences are acceptably low at all times. Important aspects of the regulations are that post-closure safety shall be maintained through a system of passive barriers. The barrier system of SFR comprises engineered and natural barriers and the function of each barrier is to, in one or several ways, contribute to the containment and prevention or retention of dispersion of radioactive substances, either directly or indirectly by protecting other barriers in the barrier system. To achieve post-closure safety, two safety principles have been defined. *Limitation of the activity of long-lived radionuclides* is achieved by only accepting waste for disposal that conforms with the waste acceptance criteria for SFR. *Retention of radionuclides* is achieved by the function of the engineered and natural barriers. The two safety principles are interlinked and applied in parallel. The engineered barrier system is designed for an inventory that contains a limited amount of long-lived radionuclides, given the conditions at the selected site and the natural barriers.

The basis for evaluating compliance is a safety assessment methodology that conforms to the regulatory requirements regarding methodology, and that supports the demonstration of regulatory compliance regarding post-closure safety and the protection of human health and the environment. The overall safety assessment methodology applied is described in the **Post-closure safety report**, Chapter 2. The methodology was developed in SR-PSU (SKB TR-14-01[3]) based on SKB's previous safety assessment for SFR1 (SAR-08, SKB R-08-130). Further, it is consistent with the methodology used for the post-closure safety assessment for the final repository for spent nuclear fuel to the extent appropriate given the different nature of the two repositories.

### 1.2.2 Report hierarchy

The **Post-closure safety report** and main references for the post-closure safety assessment are listed and briefly described in Table 1-1, also including the abbreviated titles (in bold) by which they are identified in the text. Furthermore, there are numerous additional references that include documents compiled either by SKB or other organisations, or that are available in the scientific literature, as indicated in Figure 1-3.

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[2] For brevity, the PSAR post-closure safety assessment for SFR is also referred to as "the PSAR assessment" or "the PSAR" in the present report.

[3] For SKB reports without named authors, the report number is used instead of publication year when referring to them in the text.

**Table 1-1. Post-closure safety report and main references for the post-closure safety assessment. The reports are available at www.skb.se.**

| **Abbreviated title by which the reports are identified in this report and in the main references**<br>Report number | **Content** |
|---|---|
| **Post-closure safety report**<br>SKB TR-23-01 | The main report of the PSAR post-closure safety assessment for SFR. |
| **Initial state report**<br>SKB TR-23-02 | Description of the expected conditions (state) of the repository at closure. The initial state is based on verified and documented properties of the repository and an assessment of its evolution during the period up to closure. |
| **Waste process report**<br>SKB TR-23-03 | Description of the current scientific understanding of the processes in the waste form and in the packaging that have been identified in the FEP processing as potentially relevant for the post-closure safety of the repository. Reasons are given as to why each process is handled in a particular way in the safety assessment. |
| **Barrier process report**<br>SKB TR-23-04 | Description of the current scientific understanding of the processes in the engineered barriers that have been identified in the FEP processing as potentially relevant for the post-closure safety of the repository. Reasons are given as to why each process is handled in a particular way in the safety assessment. |
| **Geosphere process report**<br>SKB TR-14-05 | Description of the current scientific understanding of the processes in the geosphere that have been identified in the FEP processing as potentially relevant for the post-closure safety of the repository. Reasons are given as to why each process is handled in a particular way in the safety assessment. |
| **Climate report**<br>SKB TR-23-05 | Description of the current scientific understanding of climate and climate-related issues that have been identified in the FEP processing as potentially relevant for the post-closure safety of the repository. Description of the current scientific understanding of the future evolution of climate and climate-related issues. |
| **Biosphere synthesis report**<br>SKB TR-23-06 | Description of the present-day conditions of the surface systems at Forsmark, and natural and anthropogenic processes driving the future development of those systems. Description of the modelling performed for landscape development, radionuclide transport in the biosphere and potential exposure of humans and non-human biota. |
| **FEP report**<br>SKB TR-14-07 | Description of the establishment of a catalogue of features, events and processes (FEPs) that are potentially relevant for the post-closure safety of the repository. |
| **FHA report**<br>SKB TR-23-08<br>(this report) | Description of the handling of inadvertent future human actions (FHA) that are defined as actions potentially resulting in changes to the barrier system, affecting, directly or indirectly, the rate of release of radionuclides, and/or contributing to radioactive waste being brought to the surface. Description of radiological consequences of FHAs that are analysed separately from the main scenario. |
| **Radionuclide transport report**<br>SKB TR-23-09 | Description of the radionuclide transport and dose calculations carried out for the purpose of demonstrating compliance with the radiological risk criterion. |
| **Data report**<br>SKB TR-23-10 | Description of how essential data for the post-closure safety assessment are selected, justified and qualified through traceable standardised procedures. |
| **Model tools report**<br>SKB TR-23-11 | Description of the model tool codes used in the safety assessment. |

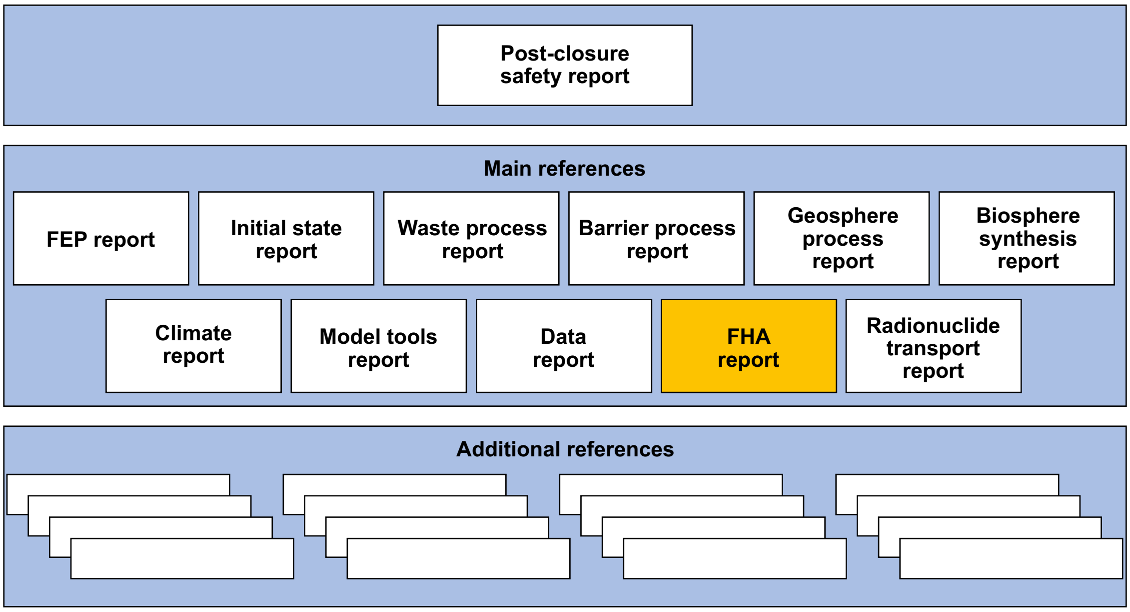

***Figure 1-3.** The hierarchy of the **Post-closure safety report**, main references and additional references in the post-closure safety. The present report is high-lighted in yellow.*

## 1.3 This report

This report documents the handling of future human actions (FHAs) in the PSAR. The report addresses inadvertent FHA potentially resulting in 1) changes to the barrier system affecting, directly or indirectly, the rate of the release of radionuclides from SFR, and 2) radioactive waste being brought to the surface giving rise to exposure of people at the surface. Inadvertent future human actions are defined as actions carried out without knowledge of the repository and/or its nature (the location of the repository, its purpose and the consequences of the actions).

### 1.3.1 Purpose

Considering the time perspective of the post-closure safety assessment of SFR, it cannot entirely be ruled out that humans in the future, in some way, will conduct activities at, or near, the Forsmark site that potentially may affect the conditions of the repository. The main purpose of this work is to facilitate the argument that the disposal concept for SFR is robust against a wide range of credible human activities. The report is an update of the FHA report for the safety assessment SR-PSU (SKB TR-14-08). The extent of the update is described in subsection 1.3.2.

### 1.3.2 Main developments since the SR-PSU

It was considered that the methodology applied for the handling of FHA in the SR-PSU was suitable for the scope of this report, and there was no need to make any major updates of it.

In the analysis of the drilling scenario in the SR-PSU, the highly stylised and simplified assumption was made that there were no releases of radionuclides from the waste vaults throughout the entire 100 000-year analysis period. Hence, radioactive decay was the only process accounted for when determining the amounts of radionuclides remaining in the waste vaults at the time of the drilling event. This led to misleadingly high doses the later in the analysis period the drilling event was assumed to occur, especially for waste vaults with a simpler design of the engineered barriers, such as BLA. An improvement in the PSAR is that, where applicable, the evolution of the radioactivity inventories in the waste vaults follow the results from analysing the *base case* in the main scenario (**Radionuclide transport report**, Chapter 5). This has not only the benefit that more processes are accounted for and the results will be less misleading, but also strengthens the integration of the handling of FHA with the overall PSAR.

A key update in the PSAR is that the *Intrusion well scenario* is identified as a residual scenario related to future human actions in the PSAR and is thus included in this report, whereas it was identified as a less probable scenario in SR-PSU (SKB TR-14-01). The reason for changing the classification of this scenario is that it is stated in the general advice on the application of the regulations (SSM 2008a) that residual scenarios should include cases to illustrate detriment to humans intruding into the repository.

Another change in the PSAR is the inclusion of a calculation case considering a water impoundment constructed in the vicinity of SFR, either for irrigation purposes or as a hydropower resource.

### 1.3.3 Contributing experts

Project leader for the PSAR safety assessment has been Jenny Brandefelt (SKB). The work related to handling of FHA in the PSAR is to a large degree based on the FHA report for the safety assessment SR-PSU (SKB TR-14-08), which was written by Eva Andersson (SKB), Graham Smith (GMS Abingdon Ltd), Thomas Hjerpe (Facilia AB, later Kemakta Konsult AB) and Sara Grolander (Sara Grolander Miljökonsult AB, later Kemakta Konsult AB). The updates of the handling of FHAs in the PSAR and the present report was performed by Thomas Hjerpe (Kemakta Konsult AB), Eva Andersson (SKB) and Per-Anders Ekström (Kvot AB). This report has been significantly improved by adjustments in accordance with comments provided in the factual review. Factual reviewers were Mike Thorne (Mike Thorne and Associates Ltd.) and Ari Ikonen (EnviroCase, Ltd.).

## 1.4 Structure of this report

This report comprises six chapters and one appendix. The following is a brief description of the contents:

**Chapter 1** – **Introduction.** This chapter describes the background and the role of the report. Furthermore, definitions are given and the abbreviations are explained.

**Chapter 2** – **Methodology for handling of FHA.** This chapter first discusses general considerations concerning aspects related to FHA as well as the Swedish national regulatory requirements and guidance. Then the methodology that SKB applies for handling of FHA in the PSAR is presented.

**Chapter 3** – **FHA FEP analysis.** The analysis of FHA FEPs is presented in this chapter, also including descriptions of the identified FHA FEPs.

**Chapter 4** – **FHA scenarios and calculation cases.** In this chapter, the FHA scenarios are identified, the qualitative and calculation cases used to analyse those scenarios are described, and results of the calculation cases are presented and discussed.

**Chapter 5** – **Summary and conclusions.** This chapter presents the summary of the FHA assessment in the PSAR and draws overall conclusions.

**Appendix A** – **Updated dose coefficients.** This appendix presents a comparison of the applied and updated dose coefficients used in the calculations, and an evaluation of the potential effect on the results if they were to be updated by using updated dose coefficients.

## 1.5 Terms and abbreviations

The present report contains terms and acronyms that either are rarely used outside SKB or can be regarded as specialised terminology within one or several of the scientific and modelling disciplines involved in the reported work. To facilitate the readability of the report, selected terms and acronyms are explained in Table 1-2.

**Table 1-2. Explanations of terms and abbreviations.**

| Name | Description |
|---|---|
| 1–2BMA | Vaults for intermediate-level waste in SFR. |
| 1–2BTF | Vaults for concrete tanks in SFR1. |
| 1–5BLA | Vaults for low-level waste in SFR. |
| 1BRT | Vault for reactor pressure vessels in SFR3. |
| AD | Anno Domini. |
| Annual dose | Assessment endpoint calculated as the annual effective dose to an adult, where the annual effective dose is defined as the effective dose from external exposure in a year, plus the committed effective dose from intakes of radionuclides in that year. |
| Barrier | In the safety assessment context, a barrier is a physical feature, engineered or natural, which in one or several ways contributes to the containment and retention or prevention of dispersion of radioactive substances, either directly or indirectly by protecting other barriers. |
| Bedrock | In the safety assessment context, the solid rock beneath the regolith also including the groundwater in the rock. |
| BIOPROTA | An international collaborative forum designed to support resolution of key issues in biosphere aspects of assessments of the long-term impact of contaminant releases associated with radioactive waste management (www.bioprota.org). |
| BioTEx | The Biosphere Transport and Exposure model. Used to calculate concentrations and subsequent transport of radionuclides in different environmental media in a biosphere object and potential doses to human and dose rates to non-human biota. |
| Calculation case | Used for the quantitative assessment of the scenarios selected in the safety assessment, typically by calculating doses. |
| Cautious | Indicates an expected overestimate of annual effective dose that follows from assumptions made, or models and parameter values selected, within the reasonably expected range of possibilities. |
| Effective dose | Effective dose is a measure of dose designed to reflect the amount of radiation detriment likely to result from the dose. It is defined as a weighted summation of the tissue or organ equivalent doses, that is the summation of the absorbed dose in each tissue or organ multiplied by appropriate radiation weighting factor, each multiplied by the appropriate tissue weighting factor. |
| Exposure | The act or condition of being subject to irradiation (not to be used as a synonym for dose, which is a measure of the effects of exposure). |
| FEP | Features, events and processes. |
| FHA | Future human actions. |
| Geosphere | The bedrock, including groundwater, surrounding the repository, bounded above by the surface system. |
| IAEA | International Atomic Energy Agency. |
| ICRP | International Commission on Radiological Protection. |
| Initial state | The expected state of the repository and its environs at closure of the repository. |
| Intermediate-level waste | Radioactive waste that requires final disposal in a geological repository and shielding during handling. Cooling of the waste is not required. |
| Long-lived radionuclide | In the safety assessment context, radionuclides with a half-life exceeding 31 years. |
| Low-level waste | Radioactive waste that requires final disposal in a geological repository. Shielding during handling and cooling are not required. |
| NEA | OECD Nuclear Energy Agency. |
| OECD | Organisation for Economic Co-operation and Development. |
| Optimisation | In radiological protection, optimisation means to strive to reduce the radiation doses as low as reasonably achievable while taking economic and societal factors into account. |

| Name | Description |
|---|---|
| Pessimistic | Indicates an expected overestimate of annual effective dose that follows from assumptions made, or models and parameter values selected, beyond the reasonably expected range of possibilities. |
| Protective capability | The capability to protect human health and the environment from the harmful effects of ionising radiation. |
| PSAR | Preliminary Safety Analysis Report. |
| PSU | Programme SFR extension. |
| Reference evolution | The probable post-closure evolution of the repository and its environs, including uncertainties in the evolution that may affect the protective capability of the repository. |
| Repository | The disposed waste packages, the engineered barriers and other repository structures. |
| Repository system | The repository, the bedrock and the biosphere surrounding the repository. Synonymous with repository and its environs. |
| Risk | Refers in the post-closure safety assessment to the radiological risk, defined as the product of the probability of receiving a radiation dose and the harmful effects of that radiation dose. |
| RK&M | Records, Knowledge and Memory, a NEA project. |
| SAFE | Post-closure safety assessment for SFR1 reported to the regulatory authorities in 2001. |
| Safety assessment | The safety assessment is the systematic process periodically carried out throughout the lifetime of the repository to ensure that all the relevant safety requirements are met and entails evaluating the performance of the repository system and quantifying its potential radiological impact on human health and the environment. The safety assessment corresponds to the term safety analysis in the Swedish Radiation Safety Authority's regulations. |
| Safety function | A role through which a repository component contributes to post-closure safety |
| Safety function indicator | A measurable or calculable property of a repository component that indicates the extent to which a safety function is upheld. |
| SAR-08 | Post-closure safety assessment for SFR1 reported to the regulatory authorities in 2008. |
| SFR | Final repository for short-lived radioactive waste at Forsmark. |
| SFR1 | The existing part of SFR. |
| SFR3 | The extension part of SFR. |
| Short-lived radionuclide | In the safety assessment context, radionuclides with a half-life shorter than 31 years. |
| Silo | Cylindrical vault for intermediate-level waste (part of SFR1). |
| SKB | Swedish Nuclear Fuel and Waste Management Company. |
| SR 97 | Safety Report 97. Preliminary post-closure safety assessment for the planned spent nuclear fuel repository, published in 1999. |
| SR-Can | Preliminary post-closure safety assessment for the planned spent nuclear fuel repository, published in 2006. |
| SR-PSU | Post-closure safety assessment that was a reference to the F-PSAR for the extended SFR, reported to the regulatory authority in 2014. |
| SR-Site | Post-closure safety assessment for a spent nuclear fuel repository in Forsmark, reported to the regulatory authority in 2011. |
| SSM | Swedish Radiation Safety Authority. |
| SSMFS | Regulations of the Swedish Radiation Safety Authority. |
| Surface system | In the safety assessment context, refers to the part of the repository system that is above the geosphere, with all its abiotic and biotic processes and features, as well as humans and human behaviour. Synonymous with Biosphere system. |
| Waste vault | Part of repository where waste is disposed. |

# 2 Methodology for handling of FHA

The methodology SKB applies to handle FHA in the post-closure safety assessment was initially developed for and implemented in the safety assessment SR 97 for the spent nuclear fuel repository (SKB TR-99-06) and reported in Morén et al. (1998). Since then, the methodology has been further developed and incorporated into the overall ten-step post-closure safety assessment methodology (**Post-closure safety report**, Section 2.6). The methodology used to address FHA in the PSAR is presented in Section 2.2, and it is to a large degree is the same as in SR-PSU (SKB TR-14-08, Chapter 3). But first, in Section 2.1, key aspects of how FHA are handled in this assessment are discussed.

## 2.1 Basis for handling of FHA

SKB's work with safety assessment considers Swedish regulations as well as international recommendations. Currently, there is international consensus that future human actions resulting in some disruption to the repository must be considered in the safety assessment as part of the safety case for a radioactive waste repository. See SKB TR-14-08, Section 2.1, for a valid description of waste management principles and international recommendations and guidance. In this section, the Swedish regulatory requirements relevant for the handling of FHA and how they are interpreted in the post-closure assessment are discussed. Furthermore, key aspects considered in the post-closure safety assessment are also addressed in this section.

### 2.1.1 Swedish regulatory requirements and interpretation in this report

The structure and content of safety assessment reports are regulated in regulations issued by the Swedish Radiation Safety Authority (SSM). There are two regulations specifically concerning post-closure safety of nuclear waste repositories: SSMFS 2008:21 (SSM 2008a) and SSMFS 2008:37 (SSM 2008b). Both include regulations and general advice concerning their application. The parts of the regulations and guidelines most relevant for the handling of FHA are discussed below with notes on how they have been interpreted and handled in the post-closure safety assessment.

SSMFS 2008:37, Section 8, states that "*the consequences of intrusion into a repository shall be reported…*". In the background and recommendations to the regulations, intrusion is defined as "*inadvertent human actions that impair the protective capability of the repository*". Intrusion is also mentioned in the general recommendations to SSMFS 2008:21, where it is stated that less probable scenarios should include: *"scenarios that take into account the impact of future human activities, such as damage inflicted on barriers"* (SSM 2008a).

In the post-closure safety assessment, it has been considered that the essential part of FHA is not the actions themselves resulting in the intrusion, but the impact on safety functions of the repository after the intrusion.

In the general guidelines to the regulations SSMFS 2008:37 it is stated that "*A number of future scenarios for inadvertent human impact on the repository should be presented. The scenarios should include a case of direct intrusion in connection with drilling in the repository and some examples of other activities that indirectly lead to a deterioration in the protective capability of the repository, for example by changing the hydrological conditions or groundwater chemistry in the repository or its surroundings. The selection of intrusion scenarios should be based on present living habits and technical prerequisites and take into consideration the repository's properties*"

Covering all possible future human actions in the assessment is undoable since foreseeing future human behaviour, techniques and objectives are inherently impossible; or in other words, the scenario uncertainties are unquantifiable. Instead, SKB includes a set of stylised scenarios addressing a range of credible future human actions based on present-day living habits and technical development.

In the general guidelines to Sections 2 and 3 in SSMFS 2008:21 it is stated that *"the repository site should be located at a secure distance from natural resources exploited today or which may be exploited in the future"*.

Natural resources were considered in siting. In the present report, potential effects of utilisation of credible natural resources situated the closest are considered.

Regarding reporting of consequences, the guidelines of SSMFS 2008:37 state that *"The consequences of the disturbance for the repository's protective capability should be illustrated by calculations of the doses for individuals in the most exposed group and be reported separately from the risk analysis for the undisturbed repository."* and *"An account need not be given of the direct consequences for the individuals intruding into the repository."* In the guidelines to SSMFS 2008:21 it is stated *"...cases to illustrate detriment to humans intruding into the repository..."* should be included in the residual scenarios. In their review of SR-Can (preliminary safety case for spent nuclear fuel repository) the authorities state that there should be *"...a stylised calculation of the injuries to human beings who intrude into the repository*" (Dverstorp and Strömberg 2008, Section 14.2, p 105) indicating that also the effects on drillers are to be evaluated in safety assessments.

In the PSAR, doses to the most exposed group following disturbance of the repository's protective capability are presented, including for example doses to a member of a drill crew.

### 2.1.2 Aspects of FHA considered in the post-closure safety assessment

SFR is situated at a depth of c. 60–120 m in an area without significant currently recognised mineral resources. Even so, the potential effects of actions aiming at utilisation of natural resources are considered.

FHA such as using the land for agricultural purposes are not included in the FHA analysis, since such FHA are considered not to have any potential to affect the safety functions of the barrier system. The region at the site is used by humans today and most likely will be so in the future. Descriptions of ongoing local human activities and land use are included in the biosphere part of the assessment and applied in the main calculation cases where a release of radionuclides to the biosphere is assumed (**Biosphere synthesis report)**. Future possible land use is considered in the biosphere assessment where development and utilisation of ecosystems are assessed, taking into account among other factors shoreline displacement, climate change, and different kinds of ecosystems and land use (see the **Biosphere synthesis report,** Werner et al. 2013, and the ecosystem reports: Andersson 2010, Aquilonius 2010 and Löfgren 2010).

There are also ongoing global human activities that may affect the repository, e.g. pollution of air and water and the emission of greenhouse gases. The climate evolution in the time perspective of the post-closure safety assessment is addressed in the **Climate report**. Climate-related changes are included as part of the reference evolution and the main scenario in the safety assessment (**Post-closure safety report**, Chapters 6 and 7). The emission of greenhouse gases may impact the climate and thus indirectly, the repository, and this matter is addressed in the main scenario. The emission of greenhouse gases is not included among FHA considered in this report, whereas pollution, e.g. acidification of air and water, which may have a direct impact on the repository, is considered.

The kind of FHAs that are the main issue in this report, and that were also the main concern in the report from the OECD/NEA working group (NEA 1995) and of the ICRP (ICRP 2000, 2013), are local post-closure actions with a potential impact on the repository. It is also this kind of actions that SSM mentions in its regulations and guidelines (SSM 2008b).

As discussed above, only inadvertent actions are considered, i.e. actions carried out without knowledge of the repository and/or its nature (the location of the repository, its purpose and the consequences of the actions). Based on this, actions that are inadvertent from the beginning may become advertent if continued once the hazard of the repository is recognised. For example, if as a result of drilling into a repository using present techniques, the repository and its radiological hazard is recognised. Any further drilling into the repository, or other actions taken which result in exposure, is to be judged as advertent and do not need to be considered in the FHA assessments. Accordingly, FHAs that are preceded by, for example, exploratory drilling that is capable of detecting the hazard are not likely to be continued without suitable safety precautions put in place. FHA which leads to exposure before the hazard is recognised are included in this report. Also, FHA that occur without any intent, such as accidents, e.g. plane crashes, or explosions are considered in the FHA assessment.

No values for the probabilities for specific FHAs to occur are assigned, either on an annual basis or integrated over longer periods. This is because there exists no scientific basis for their prediction. One cannot scientifically reliably predict how humans and society will develop and what uses, for instance, will be made of the Earth's subsurface thousands of years from now (see conclusions in NEA 1989). Accordingly, no estimates of the magnitude of radiological risks related to FHA are provided. On the other hand, based on past history and present-day conditions and practice, it is possible to discuss in a meaningful way how humans in the future might interfere with a repository. The results, alongside the related supporting information and discussion, may be used as indicators of system robustness to FHA by comparing them with appropriate reference dose levels. This approach is supported by international recommendations and guidance, other national assessment practice and regulatory requirements, and the regulatory requirements and guidance in place in Sweden.

## 2.2 Methodology

The overall assessment of post-closure safety for SFR is carried out in ten main steps. These steps are carried out partly concurrently and partly consecutively. The ten steps comprise (see the **Post-closure safety report**, Section 2.6, for more details):

1. FEPs
2. Description of initial state
3. Description of external conditions
4. Description of internal processes
5. Definition of safety functions
6. Compilation of input data
7. Reference evolution
8. Selection of scenarios
9. Analysis of selected scenarios
10. Conclusions

A key step of the methodology is the scenario selection (step 8). In many national radioactive waste programmes, one of two approaches is applied: 1) a bottom-up approach, where the scenarios are constructed from features, events and processes (FEPs), or 2) a top-down approach, where safety functions are first defined, and then used to identify FEPs that may affect the safety functions (NEA 2012). These two approaches have been brought forward in IAEA Safety Standards (IAEA 2012).

The SKB methodology for selecting the main scenario and less probable scenarios applies a bottom-up approach. Thus, the first step in the list above includes obtaining a FEP catalogue in the sense that it covers all factors potentially relevant to post-closure safety and hence that need to be addressed in the assessment. However, the assessment of FHA does not strive to be fully comprehensive, but more to identify a set of scenarios representing an illustrative set of credible future human actions. To that end, it is more suitable that the selection of FHA scenarios applies a top-down approach, using the safety functions defined in step 5 as a key starting-point for identifying FHA FEPs.

For clarity, and traceability to earlier FHA assessments performed by SKB, the methodology for handling of FHA in the post-closure safety assessment can be characterised in terms of three main tasks: 1) FEP analysis, 2) Scenarios and calculation cases, and 3) Evaluation of, and conclusions from, the results. These three tasks, and selected sub-tasks, are illustrated in Figure 2-1, and further elaborated in Sections 2.2.1 to 2.2.3.

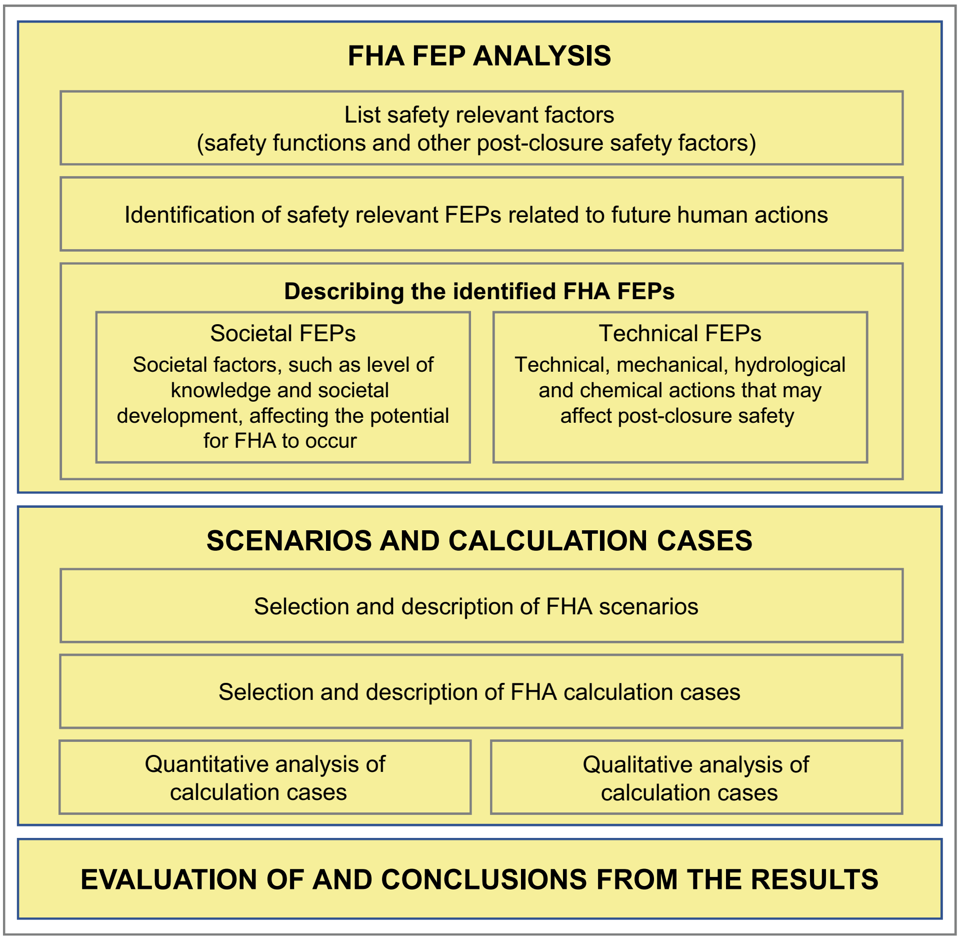

***Figure 2-1.*** *Overview of the main tasks and sub-tasks in the methodology for handling of FHA in the post-closure safety assessment.*

### 2.2.1 FHA FEP analysis

The first task towards selecting FHA scenarios is to conduct the FHA FEP analysis. The first step here is to compile a list of factors relevant for post-closure safety, consisting of the safety functions defined in Chapter 5 in the **Post-closure safety report** and other factors important for overall post-closure safety. The analysis includes identification, and descriptions, of FEPs related to human actions that potentially may affect the safety relevant factors. For clarity, and traceability back to previous assessments, the FHA FEPs are categorised as either societal FEPs or technical FEPs. The way of describing societal and technical FEPs is summarised as follows:

- **Societal FEPs**. The description of societal FEPs comprises the identification of framework scenarios that describe feasible societal contexts for FHA that could affect the radiological safety of a geological repository. The framework scenarios are intended to be seen as credible narratives, i.e. they should serve as credible societal contexts for a limited set of possible human actions with safety-related and/or radiological impacts.
- **Technical FEPs**. The description of the technical FHA FEPs comprises an account of the actions in technical terms, from a technology point-of-view, and commenting on their potential impact on repository performance. For convenience, aspects of technical FEPs are divided into thermal, hydrological, mechanical and/or chemical impacts on post-closure safety.

The set of identified FHA FEPs comprises the FEP list carried forward in the safety assessment (see Section 2.2.2). Note that no values for the probabilities for specific FHA FEPs to occur are assigned, either in annual terms or integrated over longer periods. This is because the FEPs are dependent on the probabilities of the FHAs to occur, and no scientific basis exists for their prediction (Section 2.1.2).

### 2.2.2 FHA scenarios and calculation cases

The next task is evaluating the results of the FHA analysis and selecting and describing a set of stylised scenarios addressing future human actions, within specific FHA scenarios. The selected scenarios are intended to comprise an illustrative set of credible future human actions but should not be considered fully comprehensive or complete. FHA scenarios are, in the overall safety assessment, classified as residual scenarios, which means they do not aim to provide input to the compliance against the regulatory risk criteria (see the **Post-closure safety report**, Chapter 2, for more details on the role of scenarios in the PSAR).

The selected FHA scenarios are analysed either by performing calculations to derive a value for a quantitative assessment end-point or by means of qualitative discussions. For assessing a FHA scenario, one of the following two options is chosen:

- **Quantitatively**. One or more calculation cases are identified for quantitative analyses of a FHA scenario. The assessment endpoint is determined, and suitable models and data are selected within the boundaries of the specific scenario to which the calculation cases apply.
- **Qualitatively**. The potential impact of the FHA scenario is assessed by reasoning and argument. The discussion may include comparisons with results and conclusions from analyses not directly aiming at assessing FHA scenarios but that are of a relevant nature.

### 2.2.3 Evaluation of results and conclusions

The quantitative and qualitative results are then evaluated primarily with regard to Swedish regulations, but also in relation to recommendations and guidance provided by international organizations. The set of results is intended to be broad enough to provide a robust demonstration of post-closure safety in relation to the possible consequences of FHA. The clear documentation of arguments at each step in the process is intended to support independent review and to facilitate further iteration, as necessary. It should be stressed that quantitative assessment of potential radiological impacts related to FHA, especially inadvertent intrusion, is to be considered in the context of optimisation rather than being compared with regulatory risk and dose constraints.

# 3 FHA FEP analysis

The FHA FEP analysis is as discussed above based on a top-down approach. Thus, factors relevant for the post-closure safety of SFR are addressed first in this chapter (Section 3.1). This is followed by the identification of FEPs related to FHA that potentially may affect these factors (Section 3.2). Finally, in Section 3.3, the identified FHA FEPs are described in more detail.

## 3.1 Safety relevant factors

The list of safety relevant factors primarily consists of the safety functions for post-closure safety of SFR defined in the **Post-closure safety report**, Chapter 5 (summarised in Section 3.1.1). In addition to these, a few other factors are identified as relevant from the FHA perspective (Section 3.1.2).

### 3.1.1 Safety functions in the PSAR

Defining the safety functions for post-closure safety of SFR is step 5 in the overall post-closure safety methodology (**Post-closure safety report**, Section 2.6). The result from this work is presented in the **Post-closure safety report**, Chapter 5. Below is a summary of the safety functions.

The post-closure safety of SFR is achieved by limiting the activity of long-lived radionuclides disposed in the repository and ensuring that the transport of radionuclides from the waste, through the engineered barriers and through the geosphere and biosphere is sufficiently retarded. The overall post-closure safety principles for SFR are therefore formulated as *limitation of the activity of long-lived radionuclides* and *retention of radionuclides*. A detailed and quantitative understanding and evaluation of repository safety requires a description of how the overall safety principles relate to the components of the repository. Based on the understanding of the properties of the components and the long-term evolution of the system, several *safety functions* connected to the safety principles can be identified. In this context, a safety function is defined as how a repository component contributes to post-closure safety. Each safety function is associated with one or several *safety function indicators*, defined as a measurable or calculable property of a repository component that is used to evaluate the extent to which the safety function is upheld over time.

Table 3-1 presents the set of safety functions and safety function indicators defined for the PSAR (reproduced from the **Post-closure safety report**, Table 5-1). As seen in the table, the biosphere has a safety function defined regarding the avoidance of boreholes in the vicinity of the repository. An important safety aspect of SFR is its current location beneath the Baltic Sea, where it is expected to remain for at least 1 000 years after closure (**Post-closure safety report**, Section 6.2). In addition to the beneficial hydraulic features, the sub-sea location of the repository also prevents humans locating boreholes above or downstream of the repository for the purpose of water extraction. However, it cannot be completely ruled out that drilling under water may be conducted for purposes other than water extraction. The location of the repository in relation to the shoreline is considered of crucial importance for the possibility of boreholes in the repository area or immediately downstream of the repository. The safety function *avoid boreholes in the direct vicinity of the repository* is defined with the two safety function indicators: (few/absent) *intrusion boreholes*, and (few) *boreholes downstream of the repository*.

**Table 3-1. Safety functions and safety function indicators defined in the PSAR (reproduced from Table 5-1 in the Post-closure safety report). See the Initial state report for the descriptions of the components of the repository system.**

| Safety function | Safety function indicator | Repository system (sub-)component |
|---|---|---|
| **Waste form and waste packaging** | | |
| Limit quantity of activity | Activity of each radionuclide in each waste vault: limited | Waste form in silo, 1–2BMA, 1BRT, 1–2BTF, 1–5BLA |
| Limit gas formation | Amount of gas-forming materials: low | Waste form and waste packaging in silo, 1–2BMA, 1BRT and 1–2BTF |
| Limit advective transport | Hydraulic conductivity: low | Waste packaging (concrete tanks) in 1–2BTF |
| Limit corrosion | pH in porewater: high<br>Redox potential $E_h$: low | Waste form with induced activity in 1BRT |
| Sorb radionuclides | Amount of cementitious material: high<br>pH in porewater: high<br>Redox potential: low (reducing)<br>Concentration of complexing agents: low | Waste form and waste packaging in silo, 1–2BMA, 1BRT and 1–2BTF |
| **Engineered barriers** | | |
| Limit advective transport | Hydraulic conductivity in concrete and bentonite: low | Bentonite in silo and plugs<br>Outer concrete structures in 1–2BMA |
| | Hydraulic conductivity in backfill (including crushed rock foundation): high | Backfill (including crushed rock foundation) in 1–2BMA and 1–2BTF |
| Allow gas passage | Permeability: sufficient to allow gas passage | Gas evacuation system in silo and 2BMA<br>Cementitious materials in 1BMA and 1–2BTF |
| Sorb radionuclides | Amount of cementitious material: high<br>pH in porewater: high<br>Redox potential: low (reducing)<br>Concentration of complexing agents: low | Cementitious materials in silo, 1–2BMA, 1BRT, and 1–2BTF |
| **Repository environs** | | |
| Provide favourable hydraulic conditions | Hydraulic conductivity: low<br>Hydraulic gradient: low | Geosphere |
| Provide chemically favourable conditions | Redox potential: low (reducing) | Geosphere |
| Avoid boreholes in the direct vicinity of the repository | Intrusion boreholes: few/absent<br>Boreholes downstream of the repository: few | Biosphere, geosphere |

### 3.1.2 Other factors for post-closure safety in an FHA perspective

Isolation of the radioactive waste from the biosphere, which prevents exposure to humans and the environment, is predominantly ensured by the geosphere and the repository depth. Initially, the design of the repository provides a higher degree of retention than for later times when structures, such as the engineered barriers, in the repository may degrade. FHA may have a local effect on barrier functions. For example, a borehole may locally affect the barrier but should not have a large effect on the transport of radionuclides from the repository which is dependent on the low groundwater flow through the waste vaults and retardation in material in the repository as well as in the geosphere. Therefore, the focus of the FHA analysis in this report is to identify FHA that may give rise to direct contact with radionuclides by humans and on FHA that may affect the water flow or retardation in the repository.

Locating the repository at depth beneath the present-day sea floor contributes to keeping the waste isolated from man for a long time to come, much longer, for example than in land-based repositories

(EC 1993). FHA that might cause substantial disruptions to the protective capability of the repository have been considered already in the siting of SFR and in the repository design. The disposal site was selected in an area with no known natural resources and the efforts/resources required for an intrusion of the repository were considered when selecting the depth of the repository.

Table 3-2 summarises how the different components of SFR contribute to retain and retard the dispersion of radionuclides and to isolate the radioactive waste from the surface environment. The list is limited to the context of FHA as addressed in the present report. The indicators in Table 3-2 are selected on the basis that a change in them may either have a direct impact on a safety function in SFR or affect the motivation for the FHA to occur, thus affecting the likelihood.

The indicators should be interpreted in the context of the state of the component when a human action is assumed to occur. The indicators should then be evaluated in terms of whether or not they would affect a FHA scenario. For example, an intact engineered barrier may be more likely to be recognised during future human actions such as drilling, i.e. humans would potentially realise the abnormalities and cease the action before coming in contact with the waste.

**Table 3-2. Repository components and indicators identified as relevant in the context of assessing FHA for SFR.**

| Component | Indicator |
|---|---|
| Waste form and packaging | Integrity of waste packages |
| Engineered barriers | Integrity of engineered barriers |
| Geosphere | Depth<br>Natural resources |
| Surface system | Location of the repository in relation to the shoreline |

## 3.2 FEPs potentially affecting the safety relevant factors

In previous safety assessments for a repository for spent nuclear fuel, thorough societal and technical analyses have been performed (SKB TR-10-53). The societal analysis showed that it is possible to construct internally consistent and feasible social scenarios in which unintentional human actions that could have an impact on the proposed spent nuclear fuel repository may occur. For a repository closer to the surface, like SFR, this conclusion is particularly relevant.

In the PSAR, the list of identified FEPs related to FHA is the same as in the previous assessment (SKB TR-14-07, SKB TR-14-08). Three societal FEPs of special interest and 14 technical FEPs are presented in the **FEP report**. The basis for this selection is provided in the following text.

To identify FEPs related to FHA with potential detrimental impacts on repository safety, the safety functions (Table 3-1) and other concerns relevant for post-closure safety (Table 3-2) have been considered. The FHA FEPs identified that may have a potential impact on the repository are given in Table 3-3. To facilitate scenario selection, and to make a clear link to the previous work (SKB TR-10-53, SKB TR-14-08), the FEPs are also categorised according to whether they are related to societal or technical aspects. The technical aspects are divided into thermal, hydrological, mechanical and/or chemical impacts on post-closure safety to visualise what types of actions are performed. The societal FEPs mainly affect the potential[4] for the future human action to occur and do not directly have an impact on the safety functions or functions of the barrier system. An assessment of the technical FEPs shows that FHA cannot significantly affect the amounts of waste already stored in the repository but may affect all other safety functions of the repository. In Table 3-4 the identified technical FHA FEPs are related to the safety functions (Table 3-1) that the FEP potentially may affect. This is further discussed in Section 3.3, where descriptions of the FEPs are given with an account of how the FHA for each FEP can affect the safety of the repository.

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[4] the term 'potential for' is in this work used as a general statement related to any feature that may affect the likelihood for a FHA to occur and the timing when it may occur.

**Table 3-3. FEPs related to future human actions with potential impact on post-closure safety.**

| FEP number | Name | Brief description | Related to | | | | |
|---|---|---|---|---|---|---|---|
| | | | Societal aspects | Thermal impact | Hydrological impact | Mechanical impact | Chemical impact |
| FHA01 | State of knowledge | Knowledge of the repository | X | | | | |
| FHA02 | Societal development | Development of society | X | | | | |
| FHA03 | Technological development | Technological development of society | X | | | | |
| FHA04 | Heat storage | Build heat storage system | | X | X | X | |
| FHA05 | Heat pump system | Build heat pump system | | X | X | X | |
| FHA06 | Geothermal energy | Extract geothermal energy | | X | X | X | |
| FHA07 | Heating/cooling plant | Build plant that generates heating/cooling on the surface above the repository | | X | | | |
| FHA08 | Drilled well | Construct water well | | | X | X | |
| FHA09 | Water management | Surface and groundwater water management including building dams, build hydropower plants, irrigation systems, drainage system, etc. | | | X | X | |
| FHA10 | Altered land use | Change conditions for groundwater recharge by changes in land use | | | X | | |
| FHA11 | Drilling | Drilling in the rock | | | X | X | |
| FHA12 | Underground constructions | Build rock cavern, tunnel, shaft, etc. | | | X | X | |
| FHA13 | Quarry | Excavate open-cast mine or quarry | | | X | X | |
| FHA14 | Landfill | Construct dump or landfill | | | | | X |
| FHA15 | Bombing, blasting, explosions and crashes | Deliberate or accidental explosions and crashes in the vicinity of the repository | | | X | X | |
| FHA16 | Hazardous waste facility | Store/dispose hazardous waste in the rock | | | X | X | X |
| FHA17 | Contamination with chemical substances or chemical conditions | Acidify air, water, soil and bedrock, sterilise regolith, cause accident liming, pest controls, etc. | | | | | X |

**Table 3-4. The technical FEPs related to future human actions mapped to the safety functions of the repository that the FEP may affect. The societal FEPs FHA01 to FHA03 are of overarching nature and do not affect the safety function directly; instead, they affect the likelihood for the unintentional human intrusion to occur.**

| | Safety function | FHA04 | FHA05 | FHA06 | FHA07 | FHA08 | FHA09 | FHA10 | FHA11 | FHA12 | FHA13 | FHA14 | FHA15 | FHA16 | FHA17 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Waste form and waste packaging** | Limit quantity of activity | | | | | | | | | | | | | | |
| | Limit gas formation | | | | | | | | | | | | | | |
| | Limit advective transport | X | X | | X | X | X | | X | X | | | | X | |
| | Limit corrosion | | | | | | | | | | | | | | |
| | Sorb radionuclides | X | | | | X | X | | X | X | | X | | X | X |
| **Engineered barriers** | Limit advective transport | X | X | | X | X | X | | X | X | | | | X | |
| | Sorb radionuclides | X | | | | X | X | | X | X | | X | | X | X |
| | Allow gas passage [a)] | X | X | | | X | | | X | X | | | | X | |
| **Repository environs** | Provide favourable hydraulic conditions | X | | | X | | X | X | X | X | X | | X | X | |
| | Provide chemically favourable conditions | | | | | | | | | | | X | | X | X |
| | Avoid boreholes in the direct vicinity of the repository | X | X | X | | | | | X | | | | | | |

[a)] This safety function is related to that gas should be allowed to escape from the waste vaults. Drilling into a vault will have an impact by forming a new pathway for the gas to escape. Since gas should be allowed to escape, this new pathway has no negative effect on this safety function.

### 3.2.1 SKB's FEP database

An important and formal tool for ensuring that all relevant factors have been taken into account in the post-closure safety assessment is a database of FEPs that are of potential importance for post-closure safety for a radioactive waste repository. SKB's FEP database comprises FEP catalogues for all three of SKB's final repositories (SFR, SFL and the repository for spent nuclear fuel). The FEP database is based on the results of work with earlier safety assessments for the repository for spent nuclear fuel, see the FEP report for SR-Site (SKB TR-10-45), and earlier safety assessments for SFR, that is SAFE, SAR-08 and SR-PSU (SKB R-01-13, SKB R-08-12, SKB TR-14-07). The PSAR uses the SFR FEP catalogue (PSAR version), **Post-closure safety report**, Section 3.6. The 17 FHA FEPs included in the SFR FEP catalogue (PSAR version) are the same as in the SR-PSU version (SKB TR-14-07).

## 3.3 Description of FHA FEPs

The basic premises for inclusion or exclusion of the societal and technical FEPs identified in Section 3.2 in the scenario formulation and calculation cases for FHA are presented in this section. Consideration is taken of earlier FHA assessments at SKB, discussion material in this document, as well as new justifying references.

### 3.3.1 State of knowledge (FHA01)

***Premises***

ICRP (2013) notes that application of the protection system is influenced by the level of oversight or 'watchful care' of the repository. Three main time frames have to be considered: time of direct oversight, when the disposal facility is being operated and is under active supervision; time of indirect oversight, when the disposal facility is partly or fully sealed during which indirect regulatory, administrative or societal oversight might continue; and time of no oversight, when the memory of the repository has been lost. Excluding any intentional acts, FHA that affects the safety functions of a repository are assumed to be possible only when the knowledge about the repository, particularly about its purpose, has been lost.

The importance of knowledge preservation in this context is recognised internationally though the on-going work in an NEA project on Preservation of Records, Knowledge and Memory (RK&M) across generations. In a consensus document (NEA 2014), it is stated that while the intention is not to abandon repositories for geological disposal of radioactive waste, either before or after closure, as with many long-term projects, it is a question of minimising the risks of losing records, knowledge and memory (RK&M). The recognized goal is to preserve information for future generations while maintaining technical and societal oversight of the repository for as long as practicable. Three guiding principles for RK&M preservation in NEA (2014) are:

- Maintaining RK&M for a radioactive waste repository after its closure will allow future members of society to take informed decisions regarding the repository and its contents and to prevent inadvertent human intrusion.
- Preparing for future RK&M preservation is best addressed while waste management plans are being designed and implemented, and funding is available for this important component of long-term planning.
- During the operational phase, institutional stakeholders must prepare for the post-closure phase, when their own roles will be reduced and increasing roles will be played by other stakeholders with new responsibilities, especially in the area of RK&M preservation.

The key issue in the current context is how long institutional measures can be relied upon to remove any chance of FHA affecting repository safety functions. In the latest assessment for a repository for spent nuclear fuel performed, the knowledge was assumed to be preserved for at least 300 years (SKB TR-10-53). Jensen (1993) concluded that today's archive methods may achieve the conservation of written information for up to 1 000 years, but that markers at the site may pose interpretation problems. Beuth and Navarro (2010) noted that the experience in Germany shows that information about geological work could be preserved for some hundreds of years. This experience was derived from German mining archives that are still in use and preserved to this day. They recommended that inadvertent human intrusion should only be assumed to take place after at least 500 years. The French regulatory guide on geological disposal (ASN 2008) at §A2 2.2.1 notes that it is necessary to fix a time before which no involuntary human intrusion can occur due to the continuing memory of the existence of the repository. This memory depends on the sustainability of measures that can be implemented during the archiving of institutional documents in accordance with the rules in place at the time. Under these conditions, loss of memory of the existence of the repository can be placed reasonably beyond 500 years. This value of 500 years is retained in ASN (2008) as the minimum date of occurrence of human intrusion. Defining the characteristics of situations of inadvertent human intrusion is selected based on following cautious assumptions: the existence and location of, and/or the nature of, the repository is forgotten, and the technological capabilities of the intruders are the same as today.

#### *Inclusion/exclusion in scenario development*

The state of knowledge of the repository is an important FEP to include in the scenario selection since only inadvertent actions are to be included in FHA analysis. For this assessment, it is assumed that knowledge is lost, and thus FHA may occur, at the earliest 300 years after closure. It is noted that 300 years is a shorter time span than until the entire repository is situated directly below land and not submerged under the sea. In reality, although drilling is technically possible below sea, the lack of natural resources in the area leads to the consideration that the FHA are far less likely, but cannot be ruled out totally, as long as the repository is situated beneath the sea floor.

### 3.3.2 Societal development (FHA02)

#### *Premises*

Societal development determines the knowledge level of the society and its ability to retain that knowledge. The level of societal development and implications for safety of geological disposal were considered in SKI/SSI/SKB (1989). There it was noted that many alternative technical advances and other developments are possible that might mitigate any safety issues, but that these should not be relied upon in making a safety case. That society may regress in terms of technological development was also noted. In this case, technologically relevant knowledge of the repository would be lost, but so also would likely the technical means for a directly disruptive FHA, such as deep drilling. By the same token, it can be acknowledged that those with the capability to deep-drill would likely also be capable of recognizing radioactive properties of drilled material, as part of routine geological investigation procedures (see discussion in Smith et al. 2013). However, that discovery might not occur until some degree of radiation exposure has occurred.

Societal development also includes the legitimacy of government and relative governability of society. Legitimacy describes to what extent the population gives approval and support to those in power. IAEA (2003) noted that a commonly accepted approach to societal assumptions is to use current conditions, both as regards human behaviour affecting exposure but also as regards how behaviour is part of technological development. If changes at a site must be taken into account, for example, as a result of climate change, current data from other sites which presently reflect the assumed changed conditions can be used. This is on the basis that the variability in present conditions at different locations is one way of representing the spectrum of the future variability at any specific site. Thus, the current range of technical development seen in other places now reflects what could be possible at the site in future, assuming that no further technical developments are made.

#### *Inclusion/exclusion in scenario development*

Societal development is included based on continued present-day social conditions and technical capabilities. However, one exception is made from this. Assuming present-day conditions would imply that the state of knowledge is also preserved; for the scenario selection, it is assumed that the societal development allows for loss of memory of the repository after, at earliest, 300 years (cf. Section 3.3.1).

### 3.3.3 Technological development (FHA03)

#### *Premises*

Considerations here are readily included in the discussion of societal development (FHA02, Section 3.3.2).

#### *Inclusion/exclusion in scenario development*

Technical development is included based on continued present-day social conditions and technical capabilities. This has significant implications for the consideration of technical FEPs, as discussed below.

### 3.3.4 Heat storage (FHA04)

#### *Premises*

Thanks to its heat capacity and uniform temperature, rock can be used to store thermal energy. The uniform temperature conditions can also be utilised for the location of facilities that require a low or stable temperature. The heat in a heat storage facility is typically supplied and stored in hot water. The water may have been heated by the sun or be waste heat from some industrial enterprise. Large storages, with large volume in relation to area at great depths, have the greatest potential. Such an installation requires extensive excavation.

#### *Technology*

Hot water can be stored in rock caverns, which may be filled with boulders, or in boreholes. A borehole storage system consists of many boreholes into which the hot water is pumped. The rock around the borehole may be fractured by blasting. The technology exists today, and pilot systems have been built.

Rock caverns for heat storage are built relatively near the surface, at a depth of a few tens of metres. The temperature increase with increasing depth is not crucial for the system's efficiency. However, the temperature gradient is lower at greater depths, resulting in lower losses, so the choice of depth of the store is an optimization question. The number and depth of the boreholes in a borehole storage system depend on how much heat is to be stored. A large number of boreholes drilled to a depth of several hundred metres may be required for large communities.

#### *Potential impact on the repository and its functions*

A heat storage facility would affect thermal, hydrological and mechanical state variables and processes in the geosphere. The extent and nature of the changes depends on how the storage is designed and constructed. The construction of a heat storage facility may lead to drilling and intrusion into the repository. A heat storage facility in the vicinity may also affect the capability of the geosphere to provide favourable hydraulic and transport conditions.

#### *Inclusion/exclusion in scenario development*

Since development of a heat storage plant would require extensive drilling investigation for application at a specific site, there is potential for intrusion into the repository and the FEP is considered in the scenario selection. It is assumed that such drilling and other investigations would result in identification of any significant radioactive contamination in the drilling detritus and/or of the anomaly presented by the repository. This may give rise to exposure to radioactive material brought to the surface and can be handled within a scenario addressing a drilling event. Development of a heat storage itself is not considered further as this would involve intentional intrusion.

### 3.3.5 Heat pump system (FHA05)

#### *Premises*

Ground-source heat pump systems are addressed here, which is one solution for utilising geothermal energy. The energy can be extracted either by circulating water or another heat transfer fluid through boreholes in the rock (closed-loop system), or by pumping up the groundwater (open-loop system). In the former case, a temperature gradient develops towards the borehole. This gradient varies between the winter and summer seasons. If groundwater is utilised directly as the heat source, the groundwater flow rate must be great enough to cover the need. Today the most common solution is closed systems, and open systems utilising groundwater are only used where there are large aquifers like eskers or in areas with limestone. Thus, in Forsmark an open system can only be expected in Börstilsåsen whereas the rest of the area is made up of granite and is only suitable for closed heat pump systems.

#### *Technology*

The technology is available today and many systems are in operation. Systems for small buildings are common, with boreholes in which a heat transfer fluid, usually a mixture of water and small amounts of antifreeze, circulates in a closed loop. One 100–200 metres deep borehole can supply a single-family home with its energy needs. In densely built-up areas, systems with several deeper holes supporting several households are possible, although this is not very common today. The depth of the boreholes is related to the energy need and the capacity of the drilling equipment.

#### *Potential impact on the repository and its functions*

A ground-source heat pump system affects thermal, and to some extent, hydrological processes and state variables in the geosphere. If water is pumped up, hydrological processes will be directly affected. The hydrological impact of small systems of the type described above is limited. However, since heat pump systems include drilling to depths of 100–200 metres they may include drilling into the repository and thereby affect the barriers of the repository.

#### *Inclusion/exclusion in scenario development*

Since a heat pump system, regardless of whether it is a closed-loop or open-loop system, would include drilling there is potential for intrusion into the repository and the FEP should be considered in scenario selection. It is assumed that such drilling may give rise to exposure to radioactive material brought to the surface and can be handled within a scenario addressing a drilling event. Development of a heat pump system itself is not considered further in the FHA assessment since only closed-loop heat pump systems are suitable for the Forsmark area and thus radionuclides would not be brought to the surface via the heat pump system.

### 3.3.6 Geothermal energy (FHA06)

#### *Premises*

By *geothermal energy* is here meant energy that can be used directly, without storage or concentration in a heat pump. Sites with potential for extraction of geothermal energy have been avoided in the siting process. With current technology, the most common systems (dry steam and flash steam systems) require temperatures of at least 150–200 °C. At Forsmark, the temperature is about 18 °C and the thermal gradient is about 13 °C/km at 1 km depth (SKB TR-08-05, Section 6.2.9). Thus, such high temperatures are expected only at depths of at least 10 km. A newer less commonly used technique is the binary cycle power plant, which works with temperatures down to about 60 °C. At Forsmark, such a temperature is expected at a depth of at least 4 km. The heat can either be extracted by pumping up hot groundwater or by pumping water from the surface through natural and/or blast-induced fractures in the hot rock. Since the groundwater flow at great depth in crystalline rock is limited, the latter option is more likely.

### *Technology*

The technology exists today, but existing geothermal energy plants at the great depths as would be required at Forsmark are scarce. In a system for extraction of geothermal heat, at least two boreholes are drilled and connected via a fracture system. Water is pumped down on one side of the fracture system and up on the other side. The water is heated as it passes through the fracture system. Systems of this type exist today in areas where the temperature increases rapidly with depth.

### *Potential impact on the repository and its functions*

If a system of the type described above should nevertheless be built, it would probably not have any significant impact on the repository, since the operational zone would be located far below the repository. Nearby boreholes would locally affect fracture frequency and transmissivity, but the impact on the capability of the geosphere to provide favourable hydrologic and transport conditions is considered to be low. However, a borehole directly into the repository would affect the repository safety functions.

### *Inclusion/exclusion in scenario development*

Avoiding a site with a favourable thermal gradient was considered already in the site selection for SFR; the geological setting in Forsmark is of no particular interest regarding utilisation of geothermal energy. The construction of a geothermal energy plant at the site is considered very unlikely. Nevertheless, if it was to be constructed it would involve drilling and this FHA FEP is included as part of a scenario addressing a drilling event.

## 3.3.7 Heating/cooling plant (FHA07)

### *Premises*

Temperature gradients are a driving force for groundwater flow, although usually less important than pressure gradients. If the temperature change itself is to affect the safety of the repository, temperatures below freezing or above boiling at repository depth are required. It is difficult to imagine a surface plant that would generate heating/cooling that could affect the repository, and there are no examples of such plants today.

### *Technology*

The technology that would generate heating or cooling to the repository depths are not part of present technology.

### *Inclusion/exclusion in scenario development*

Since this FEP would require technology not currently available, it is not considered in the scenario selection.

## 3.3.8 Drilled well (FHA08)

### *Premises*

Geological wells where the water is abstracted for drinking water or for irrigation are drilled through water-conducting zones. Their depths in Northern Uppland, where Forsmark is located, are generally no greater than 50 to 100 m (Werner et al. 2013, Figure 6-2), with only 1 % reaching down to 120 metres (Odén et al. 2016, Table 4-1). Wells into the repository are not considered likely, based on current placement of wells in the terrestrial landscape. The repository footprint is currently submerged under the sea. Even after land-rise results in the area becoming land (after about 1 000 years, at the earliest, **Post-closure safety report**) the area will not be a favourable location for wells within the future landscape (see further discussion in Werner et al. 2013). However, it cannot be ruled out entirely.

### *Technology*

The technology exists, and there are drilled wells in Sweden and in the county of Uppland where Forsmark is situated (Werner et al. 2013).

### *Potential impact on the repository and its functions*

A drilled well intruding the repository would affect the safety functions of the repository and could lead to repository-derived radionuclides becoming mixed with the well water. Exposure of humans could then occur when the well water is utilised, for example if used as a drinking water supply.

### *Inclusion/exclusion in scenario development*

Evaluating the consequences of abstracting water from a well intruding into the repository is included in the scenario selection.

## 3.3.9 Water management (FHA09)

Water management is taken to include several actions affecting hydrology, for example building dams, changing the course or extent of surface water bodies, building hydropower plants, or building drainage/infiltration systems.

### *Premises*

Dams are built to create a water reservoir, provided that the topography and other ground conditions are suitable. A reservoir impoundment may be used for fish farming, drinking water, irrigation, hydropower, etc. Dams may also be built for recreational or aesthetic purposes, and may be linked to land use (FHA10, Section 3.3.10). Surface water bodies can be altered by changes in land use associated with for example agriculture or forestry or any kind of construction. The direction and flow of streams can be altered; canals can be dug to link streams, lakes and the sea. Sea bays can be diked; wetlands can be drained, etc. To build a hydropower plant, flowing water with an elevation difference (head) is needed. A hydropower plant includes a dam and often also tunnels and rock caverns. The hydrology at the site can also be affected by construction in the rock since this requires drainage, so that the rock cavern will not be water filled. Near surface layers may be drained to make the area suitable for some special purpose. Drainage changes the ground conditions.

An irrigation system requires a source of water. The source may be a well, a reservoir or a surface water body. Surface water can be utilised directly or by construction of canals or ditches. Irrigation affects the conditions for groundwater infiltration.

### *Technology*

The art of building dams and altering surface water bodies is old and the technology well known. The technique for building hydropower plants and irrigation/drainage systems are well known, and requires the same technology. In addition, technology for underground construction may also be needed (FHA12, Section 3.3.12).

### *Potential impact on the repository and its functions*

Water management activities may locally affect hydraulic gradients and impact the flow through the waste vaults, thereby affect the safety function that the geosphere should provide favourable hydraulic conditions. Also, areas that have previously been groundwater recharge areas may become discharge areas, and vice versa. The conditions for groundwater infiltration may be affected.

### *Inclusion/exclusion in scenario development*

Water management activities are considered in the scenario selection.

### 3.3.10 Altered land use (FHA10)

#### *Premises*

Land use refers to the different ways humans utilise the environment, such as practising forestry or agriculture. Changes in land use may affect the conditions for groundwater recharge. The magnitude of the impact depends on how land use is changed. For example, if wetlands are drained and used for agriculture the groundwater level will be altered, or if terrestrial areas are built on and/or covered with some relatively impermeable coating, groundwater recharge will be affected. Such land use changes are on-going today, although not presently in the Forsmark area.

#### *Technology*

Humans have affected their environment for very long time by changing land use and the necessary technologies are available.

#### *Potential impact on the repository and its functions*

Changes of land use may affect the transport and accumulation of radionuclides in the biosphere. However, since altered land use is expected to occur near the surface and not have any significant impact on deeper conditions, they should have insignificant effect on the safety functions of the repository system due to the depth of SFR.

#### *Inclusion/exclusion in scenario development*

Altered land use is not further considered in the selection of FHA scenarios since there are no expected effects on the safety functions of the repository. However, land use is addressed in the PSAR; it is part of the biosphere description and future changes in land use are considered in the landscape development modelling (**Biosphere synthesis report**).

### 3.3.11 Drilling (FHA11)

#### *Premises*

SKB considers drilling as a key FEP when addressing the potential impact on the repository of FHA. Although deemed unlikely to occur, geological drilling on the site after the closure and after knowledge of the repository has been lost, this is the FHA considered the most likely cause of direct intrusion into the repository. This view is shared by several radioactive waste management organizations. In a project designed within the BIOPROTA[5] Forum, it was concluded that the most likely cause of human intrusion is various forms of geological or other investigation by borehole drilling (Smith et al. 2013).

If future humans decide to drill at the Forsmark site, it is not possible to reliably predict for what reason they would drill. Table 3-5 lists a range of present-day human actions involving geological drilling. In summary, they are related to drilling water wells (FHA08), interest in mining (FHA12, FHA13), geothermal energy (FHA06), oil and gas exploration and exploitation, and geological investigations for scientific research and special constructions such as future waste disposal (FHA16).

For Forsmark specifically, the evaluation of the potential for ore and industrial minerals shows that the area contains several minor mineralizations that might be explored in the future (Lindroos et al. 2004). These locations are situated several kilometres away from the repository footprint. In addition, the repository itself comprises a heterogeneity in the rock and, if mineral explorations are commenced in the area, may be detected during investigations. This could attract the interest of the people performing the mineral exploration, and non-intrusive investigations may be followed by exploratory drilling.

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[5] BIOPRTOA is an international collaboration forum which seeks to address key uncertainties in the assessment of radiation doses in the long-term arising from releases of radionuclides as a result of radioactive waste management practices – www.bioprota.org.

Although it has been argued that such scenarios are very unlikely due to the application of siting criteria for repositories, it has been acknowledged (Charles and McEwen 1991) that it is difficult to predict what resources could be considered economically exploitable in the future, or of research interest. For example, it may be noted that investigations by deep drilling into apparently uninteresting rocks have nevertheless taken place to investigate the viability of radioactive waste disposal.

**Table 3-5. Credible reasons for future humans to conduct geological drilling, with comments on drilling depths and geological formations (modified from Smith et al. 2013, Table 1).**

| Human actions | Depth | Formations to drill |
|---|---|---|
| Mining exploration/exploitation | Shallow and deep | Crystalline rocks or sedimentary environments |
| Water supply | Normally only up to about 100 m | Fractured rocks or porous rocks/formations |
| Geothermal energy exploration/exploitation | Deep | Sedimentary and crystalline rocks (fractured or not) |
| Hydrocarbon exploration | Deep | Fractured or porous rock formations with lower permeability formations (reservoirs) |
| Future waste disposal location (toxics and/or radioactive) | Shallow and deep | Crystalline rocks with limited fracturing, and sedimentary formations with low permeability |
| Oil/gas exploration and exploitation | Shallow and deep | Various rock formations |
| Oil/gas underground storage | Shallow and deep | Sedimentary formations (mainly old caverns in evaporates) and crystalline rocks |
| $CO_2$ storage | Deep | Sedimentary formations |
| Scientific research | Shallow and deep | General |
| Building and construction | Generally, less than 50 m, apart from very exceptional examples, such as deep tunnels and secure facilities | General |
| Brine injection wells (mining industry) | Shallow to intermediate. Generally, less than 100 m | Fractured Rocks or porous rocks/formations. |

### *Technology*

Drilling deep holes in rock has been done for thousands of years. Drilling methods commonly used nowadays are presented in Table 3-6. Although present technologies can reach to substantial depths, a typical depth in rock for a water-supply well is estimated to be 60 m in the Forsmark area (Werner et al. 2013).

*Cable tool drilling* is a traditional way of drilling water wells. Many large diameter water supply wells, especially deep wells in bedrock aquifers, have been drilled using this method. Cable tool drilling was probably the earliest method used and has been in continuous use for some 4000 years. Cable tool rigs operate by repeatedly raising and dropping the drill string of a heavy drilling bit. The drill bit breaks or crushes consolidated rock into small fragments. During the drilling process, the drill string is periodically removed from the borehole and a bailer is lowered into it to collect the drill cuttings (rock fragments, soil, etc). If the borehole is dry, water is added so that the drill cuttings will flow into the bailer. Cable tool rigs are simple and cheap, but loud and very slow to operate. Being slow, cable tool rigs are nearly obsolete in many industrialised countries (due to the cost of wages for drillers) and the technique has largely been replaced by faster drilling techniques.

**Table 3-6. Characteristics of present-day drilling techniques (modified from Table 2 in Smith et al. 2013).**

| Method | Depth | Materials applied to: |
|---|---|---|
| Cable tool | < 600 m | Unconsolidated formations: mud, sand, gravel. Semi-consolidated soft and a few fractured or karstic compact materials: clay, loam, limestone, etc. |
| Rotary drilling | < 12 000 m | Semi-consolidated and consolidated formations, from soft to hard and abrasive. |
| Reverse circulation | < 500 m | Semi-consolidated and consolidated formations, from soft to hard and abrasive. |
| Percussion rotary | < 1 500 m | Hard rocks, compact and abrasive. |
| Diamond core | < 1 800 m | All kinds of formations. |

*Rotary drilling* uses a sharp, rotating drill bit to dig down through the rock. Although the idea of rotary drilling is old, it did not rise in use or popularity until the early 1900s. The concept of rotary drilling is quite simple, but the actual mechanics of modern rigs are quite complicated. The basic rotary drilling system consists of four groups of components: 1) the *prime mover*, providing the power to the entire rig, 2) *hoisting equipment*, tools used to raise and lower other equipment that go into or come out of the borehole, 3) *rotating equipment,* components that serve to rotate the drill bit, which in turn digs the hole deeper and deeper into the ground, and 4) *circulating system* that consists of drilling fluid, which is circulated down through the borehole throughout the drilling process. Features of the circulating system include cooling and lubricating the drill bit and removing debris and cuttings. Using sizable machinery, depths of several kilometres may be reached with the rotary drilling technique.

*Reverse circulation drilling* is a relatively new method, developed for sampling in the early 1970s. Reverse circulation uses dual wall drill rods that comprise an outer drill rod, with inner tubes located inside it. These inner tubes provide a continuous sealed pathway for the drill cuttings to be transported from the drill bit face to the surface. The circulating medium, in most cases high-pressure air, enters the annulus between the rod and tube via the air swivel, which is normally part of the drill string, or sometimes mounted on top of the rotation head. The air travels down the annulus to the drilling tool, which is usually a reverse circulation hammer. The cuttings are returned to the surface through the inner tubes in the drill string and rotation head. Reverse circulation drilling typically utilises large rigs and machinery and depths of up to 500 metres are routinely achieved.

*Percussion rotary (or down-the hole) drilling* is basically a mini jack hammer that screws on the bottom of a drill rod. The fast hammer action breaks hard rock into small flakes and dust and is blown clear by the air exhaust from the hammer. The drill uses a pneumatic reciprocating piston-driven ‘hammer’ to energetically drive a heavy drill bit into the rock. The drill bit is hollow, usually constructed from alloy steel with heavy tungsten-carbide inserts that provide the cutting face of the bit. The cuttings are blown up the outside of the drill rod and collected at the surface.

Percussion rotary drilling has been in use since the 1950s and is one of the fastest ways to drill hard rock. It is used primarily for mineral exploration, water bore drilling and blast-hole drilling in mines, as well as for other applications such as engineering.

*Diamond core drilling (or diamond exploration drilling)* differs from other geological drilling in that a solid core is extracted from depth, for examination on the surface. The key technology of the diamond drill is the actual diamond drill bit itself. It is composed of industrial diamonds set into a soft metallic matrix. The bit is mounted onto a drill stem, which is connected to a rotary drill. Water is injected into the drill pipe to wash out the rock cuttings produced by the bit. Advancing the drill by rotary action (and washing) causes a core to be extracted inside the barrel. Methods have been developed to pull up the core inside the barrel. If the rock were to be continuous solid granite, and the core broke at the drill bit, then it would be a simple matter to stop the drilling and lower a simple grabbing device by a wire and pull up the core. However, many applications require an undisturbed core in fractured rock, in such situations elaborate wire-line devices are used for core extraction.

#### *Potential impact on the repository and its functions*

In the case that holes are drilled in the future in the Forsmark region, it cannot be entirely ruled out that a borehole is sunk within the repository footprint and to at least repository depth. If a waste package is penetrated, radioactive materials may be brought to the surface leading to exposure of the persons working at the drill site, and potentially also the public later in the future. The borehole will, both in the cases when a waste package is penetrated or the drill hole penetrates a waste vault but does not hit a waste package, also form a potential transport pathway for radionuclides, hence impairing the function of the engineered barriers and the geosphere to provide favourable hydrological and transport conditions. If water is pumped out of the borehole, the transport conditions are further affected.

Even if a borehole does not directly hit the repository, there may be an impact on the repository performance. This will depend on how deep the borehole is and what it is used for. A borehole that is sunk close to the repository with a purpose that affects thermal or hydrological variables or processes can affect the capability of the geosphere to provide favourable hydrological and transport conditions, at least if the borehole intersects water-conducting fractures that are in contact with the repository.

#### *Inclusion/exclusion in scenario development*

Drilling into the repository is considered in the selection of FHA scenarios.

### 3.3.12 Underground constructions (FHA12)

#### *Premises*

One reason for building tunnels and shafts in the rock is for mining purposes, that is to extract minerals in the rock. Rock caverns may also be built for the purpose of storing or disposing something. The rock is chosen as a storage medium because it is suitable due to prevailing conditions (temperature, pressure, chemical environment, etc). The purpose is to protect the stored material from outside influences, or the surrounding environment from the stored material. The reason for locating a facility sub-surface can also be that there is not enough room on the surface, or the land is considered very valuable for some reason. In densely built-up areas, tunnels are built for vehicle traffic, power and telephone lines and sewers. The rock can also be utilised for various fortifications and shelters. Rock caverns can also be used for weapons testing or storage of hazardous waste.

Since building in rock is expensive, today at least, rock caverns are generally located as near the surface as possible, consistent with their purpose. In many cases, a rock cover of a few tens of metres is enough. In some cases, conditions are better at greater depth. An example is a repository for hazardous waste, which takes advantage of the hydrological, mechanical and chemical conditions deep down in the bedrock. Another example involves taking advantage of the increased temperature at greater depth (see FHA06). A rock cavern can also be built for the purpose of obtaining a water head to generate electricity. For such a plant to be profitable, periodically fluctuating electricity prices are required. The plant generates electricity when prices are high, and during low-price periods the water is pumped up again.

#### *Technology*

The technology is known. Examples of rock caverns at great depths are found in the mining industry. Blasting is normally used for rock excavation. In some cases, drilling is used.

#### *Potential impact on the repository and its functions*

A rock cavern near the repository would potentially affect the capability of the geosphere to provide favourable hydrological and transport conditions. If the rock cavern is kept dry, groundwater flow and conditions for transport of substances with the groundwater will be affected.

Rock caverns, tunnels, shafts and boreholes are potential transport pathways for undesirable substances to and from the repository. Transient effects on rock saturation during construction and after abandonment may also affect groundwater flows at the repository. A rock cavern may also affect the capability of the geosphere to provide chemically favourable conditions for the repository. For example, during operation of a sub-surface facility close to the repository, salinity can increase at repository depth.

#### *Inclusion/exclusion in scenario development*

Rock caverns in the vicinity of the repository and potential exploratory drilling during their development are considered in the selection of FHA scenarios.

### 3.3.13 Quarry (FHA13)

#### *Premises*

The bedrock at the Forsmark sites consists of commonly occurring crystalline rocks. If someone wanted to mine the rock as a resource, a quarry is the most likely alternative. Since stone is heavy, good conditions for transport between the quarry and the place of use is an important siting factor. Drainage needs can also be a factor in selection of a quarry site; for example, the quarry can be constructed on a height. Since it is easier, and most likely economically favourable, to mine near the surface and crystalline rock is plentiful, it is unlikely that the depth of the quarry would exceed a few tens of metres.

A formation where the rock has unusually high quality – for example high strength, beautiful colour and texture, or is easy to split – gives the raw material a higher value. In such cases, it is likely that a quarry may be dug deeper, perhaps down to one hundred metres. Such areas have been avoided in the repository siting process.

#### *Technology*

The technology exists; blasting with charges adjusted to the desired size of the rock blocks would most likely be utilised.

#### *Potential impact on the repository and its functions*

The capability of the geosphere to provide favourable hydrological and transport conditions may be affected in the same manner as for underground constructions (FHA12). Since rock surfaces would become exposed, conditions for groundwater infiltration would be altered.

The groundwater composition, at least near the surface, would also be altered. If the chemical environment were altered this would mainly be a secondary effect of the altered hydrological and transport conditions. As stated above, most quarries reach only to tens of metres and would have minor effect on repository safety functions.

#### *Inclusion/exclusion in scenario development*

Sites with unusually high-quality rock (for example high strength, beautiful colour and texture, or is easy to split) where quarries may be dug deeper have been avoided in the repository siting process, and SFR is situated deeper than quarries normally reach. This FEP is not included in selection of FHA scenarios per se but can be expected to have similar impacts as a rock cavern (included in the FHA scenario selection for FHA12).

### 3.3.14 Landfill (FHA14)

#### *Premises*

Undesirable waste products are often deposited on confined sites (landfills). Stone and soil material can also be dumped in landfills. Landfills are often located on land judged to be of less value, but favourably situated for transport purposes.

#### *Technology*

The waste product can be deposited directly on the site. In some cases, the land is prepared by e.g. drainage or creation of an impermeable layer.

#### *Potential impact on the repository*

The landfill comprises a mechanical load. The load is judged to be negligible in relation to natural variations in the stresses in the rock. A landfill affects the conditions for groundwater infiltration. Groundwater composition is affected, at least locally and near the surface. It is, however, uncertain if the chemically favourable environment at repository depth would be altered. This depends on the composition of the dumped material and engineering measures adopted in the form of for example drainage and sealing layers. However, a release of substances from a landfill would have to be very large to affect the chemical conditions in the repository (covered by FHA17, Section 3.3.17).

#### *Inclusion/exclusion in scenario development*

It is very unlikely that a landfill would affect the mechanical load on the repository due to the depth of SFR. It is also very unlikely that the landfill would affect the chemical composition of the groundwater to such a degree that changed chemical conditions at repository depth would affect the safety functions. Hence, this FEP is not further considered in the scenario selection.

### 3.3.15 Bombing, blasting, explosions and crashes above the repository (FHA15)

#### *Premises*

Blasting on the surface is often done in conjunction with various kinds of construction. It may be a question of blasting away a bit of rock that is in the way or excavating basements or road cuts. Measures of this kind are considered not to affect the safety of the repository. Bombs may detonate on the surface of a repository, either due to malicious acts or if the site is used for weapons testing. A bomb that detonates near the ground surface could create a crater resulting in local fracturing of the rock.

#### *Technology*

Besides controlled blasting this FEP is primarily related to accidents. That is there is rather a failure in technique for a crash to occur at the site. Accidents like airplane crashes and larger industrial explosions occur at present, though major disruptive accidents are rare, and the frequency of such accidents would occur at a specific area such as in the vicinity of the SFR repository site is very low.

#### *Potential impact on the repository*

It is assumed that the safety of the repository would normally not be affected by most events, deliberate or accidental, that could occur within this FEP, as the effects would only penetrate to a few metres or, at most, tens of metres. A bomb that could threaten the safety of the repository would have to have a very powerful pressure wave. Testing of such large bombs in the vicinity of Forsmark in peacetime is unthinkable in the present societal context. Maliciously detonated large bombs affecting the repository are judged very unlikely.

#### *Inclusion/exclusion in scenario development*

Due to the significant depths of SFR, explosions and crashes are considered very unlikely to have any effect on the repository and are not included in the FHA scenario selection.

### 3.3.16 Hazardous waste facility (FHA16)

#### *Premises*

If the site is selected for disposal of some type of hazardous waste, the choice will have been carefully considered, consistent with a desire to dispose of the waste safely that warrants the effort. Siting, design, construction and operation of repositories for radioactive waste have contributed to the development of this method for disposing of hazardous waste. Both technology and methods for evaluating the safety of waste repositories have been developed.

### *Technology*

The waste can be placed in rock caverns or injected into the bedrock. If the waste is placed in rock caverns, these can be provided with various kinds of barriers. The waste would probably be in such form that it is judged to be stable in the environment offered by the rock. If the waste is injected, it must be in liquid form. If drilling technology becomes much cheaper and more accessible than today, it is conceivable that waste will be disposed in this manner. Facilities for geological disposal of radioactive waste are in operation or in the planning/construction stage in several countries. There are also plans to dispose of mercury in rock caverns. Technologies to inject radioactive waste exist and have been employed in the USA and in the former Soviet Union. Boreholes are drilled to a suitable depth. The waste is injected directly into permeable layers in the bedrock. It is also possible to increase the rock permeability by blasting or hydrofracturing.

### *Potential impact on the repository and its functions*

If boreholes are drilled for injection of waste, the capability of the geosphere to provide chemically favourable conditions for a radioactive waste repository may be affected, depending on the properties of the injected substance and the placement and properties of the borehole. The capability of the rock to provide favourable hydrological and transport conditions may also be affected, especially during construction and operation of a waste repository. Injected substances or substances that escape from a closed waste repository could also affect the rock's capacity to retain radionuclides.

### *Inclusion/exclusion in scenario development*

Since site investigation for a waste repository would include drilling, there is potential for intrusion into the repository and the FEP should be considered in scenario selection. It is assumed that such drilling would result in identification of any significant radioactive contamination in drilled material and/or of the anomaly presented by the repository. This may give rise to exposure to material brought to the surface (part of a drilling scenario), but development of a repository itself is not considered further as this would involve intentional intrusion (see Section 2.1.2).

## 3.3.17 Contamination with chemical substances or altering chemical conditions (FHA17)

### *Premises*

This FEP can include a number of activities potentially affecting the chemical conditions at the site, e.g. construction of a sanitary landfill (see also FHA14, Section 3.3.14), acidified air, water, soil and bedrock, an accident resulting in chemical contamination or intentional change in chemical conditions, e.g. liming, or pest controls. Contamination with chemical substances from the surface must be very substantial to affect the safety of the repository.

### *Potential impact on the repository and its functions*

If chemicals are released in such quantities that sorption in the near-field is affected, retardation of radionuclides from the repository could be decreased. However, as stated above, the release of chemical substances would have to be very large to affect the chemical conditions in the repository.

### *Inclusion/exclusion in scenario development*

It is very unlikely that chemicals would be released in such quantities that the chemical conditions at repository depth would be altered to such a degree that the safety functions would be affected. Hence, this FEP is not further considered in the scenario selection.

# 4 FHA scenarios and calculation cases

The selection of scenarios is part of the overall safety assessment methodology for the PSAR (**Post-closure safety report**, Section 2.6). The set of scenarios aims to illustrate the most important courses of development of the repository system. Three types of scenarios are considered in the PSAR:

- The main scenario takes into account the most probable changes within the repository system based on the initial state, the reference external conditions, and the reference evolution. It is used as the starting point for the analysis of the impact of uncertainties, especially a *base case* is used as a starting point for this analysis. The main scenario contributes to the calculation of radiological risk.
- Less probable scenarios evaluate scenario uncertainties and other uncertainties that are not addressed within the framework of the main scenario. These scenarios contribute to the calculation of radiological risk, albeit with a lower probability than the main scenario.
- Residual scenarios are selected to illustrate the significance of individual barriers and barrier functions, detriment to humans intruding into the repository, and the consequences of an unsealed repository that is not monitored. Residual scenarios are selected and studied independently of probabilities of their occurrence and are therefore not included in the calculation of radiological risk.

The FHA scenarios in this chapter are thus classified as residual scenarios in the overall the PSAR, and the results from their calculation cases are not propagated to the assessment of radiological risk.

## 4.1 Basis for FHA scenario selection

In the FEP analysis (Chapter 3), a set of FHAs was identified that have a potential impact on post-closure safety of the repository and that should be considered when selecting FHA scenarios to analyse. This chapter uses the results of Chapter 3 to identify FHA scenarios, and either defines the endpoints, assumptions and parameters to be used in calculation cases, or provides the qualitative arguments by which the scenarios can be addressed. The aim is to select a set of illustrative scenarios that covers the actions with potential to impair the repository performance and/or lead to radiological consequences to humans. This is in line with international recommendations and the general guidelines to the regulations SSMFS 2008:37 (SSM 2008b), which states that:

*"A number of future scenarios for inadvertent human impact on the repository should be presented. The scenarios should include a case of direct intrusion in connection with drilling in the repository…."*

IAEA, ICRP and NEA have all recommended that one or more stylised scenarios be developed to demonstrate the robustness of the disposal system rather than speculating about all types of inadvertent intrusion that could possibly occur and e.g. ICRP Publication 81 (ICRP 2000) states:

*"Because the occurrence of human intrusion cannot be totally ruled out, the consequences of one or more typical plausible stylised intrusion scenarios should be considered by the decision-maker to evaluate the resilience of the repository to potential intrusion."*

The scenario selection is not intended to focus on the reason for the FHA but rather to identify the potential consequences. The resulting FHA FEPs from Chapter 3 are summarised in Table 4-1 with a link to selected FHA scenarios. The scenarios related to drilling into the repository, water management and underground constructions were also selected in the SR-PSU. The intrusion well scenario was also identified in the SR-PSU, but as a less probable scenario and not as a FHA scenario. In Table 4-2, the scenarios are summarised with a link to identified calculation cases and qualitative analyses to be made for the identified FHA scenarios. It may here be noted that there are some differences compared with the SR-PSU. The calculation case addressing the removal of the SFR pier (SKB TR-14-08, Section 5.3.2) has been replaced with a more general calculation case related to a water impoundment, and the qualitative considerations of a traffic tunnel (SKB TR-14-08, Section 5.4.2) have been replaced with a more quantitative calculation case related to underground constructions. The scenario descriptions, calculations and results are further expanded in Sections 4.2 to 4.5.

**Table 4-1. FHA FEPs linked to selected FHA scenarios.**

| FEP | Name | FHA scenario | Comment |
|---|---|---|---|
| **FHA01** | State of knowledge | All scenarios | It is assumed that the memory of the repository is lost at the earliest after 300 years. |
| **FHA02** | Societal development | All scenarios | Strongly linked to state of knowledge. In principle, no development is assumed; that is, present-day social and institutional conditions in Sweden apply in all scenarios. With one exception, it is assumed that the societal development allows for loss of memory of the repository after, at earliest, 300 years. |
| **FHA03** | Technological development | All scenarios | Strongly linked to societal development. It is assumed that the present-day level of technology applies in all scenarios. |
| **FHA04** | Heat storage | Drilling into the repository | If a heat storage system were to be constructed it would, given present-day praxis, be preceded by a geological investigation, potentially including drilling. Given present-day technology this would result in discovery of SFR and the nature of the waste. Thereafter any intrusion would be intentional and the intruders are responsible for their own actions. Hence, the aspect related to drilling in this FEP is considered in the scenario selection. |
| **FHA05** | Heat pump system | Drilling into the repository | With current technology water is not brought to the surface by the closed-loop heat pump system, which is the only appropriate system to construct within the footprint of SFR. However, the construction of a heat pump system requires drilling. Hence, the aspect related to drilling in this FEP is considered in the scenario selection. |
| **FHA06** | Geothermal energy | Drilling into the repository | With present-day technology this is unlikely to occur, but if it would occur it involves drilling. Hence, the aspect related to drilling in this FEP is considered in the scenario selection. |
| **FHA07** | Heating/cooling plant | No scenario selected | Would require technological development and is not further considered in the scenario selection. |
| **FHA08** | Drilled well | Intrusion well | Utilising the water from a well drilled into the repository as drinking water is considered in the scenario selection. |
| **FHA09** | Water management | Water management | Water management activities are considered in the scenario selection. |
| **FHA10** | Altered land use | No scenario selected | This FEP is not considered in the selection of FHA scenarios. However, various types of land use, such as agriculture, are considered in the biosphere assessment (**Biosphere synthesis report**). |
| **FHA11** | Drilling | Drilling into the repository | Drilling is identified as a key FEP in the selection of FHA scenarios. |
| **FHA12** | Underground constructions | Drilling into the repository Underground construction | Exploratory drilling direct into the repository and potential effects on safety functions of a rock cavern in the vicinity of the repository are considered. |
| **FHA13** | Quarry | No scenario selected | Quarries to a few tens of metres would have a minor impact on the repository. In addition, the quality of the bedrock was considered in siting to avoid the use of a site suitable for quarries. Thus, this FEP is not considered in the scenario selection, but its potential impacts are expected similar as for a rock cavern (FHA12). |
| **FHA14** | Landfill | No scenario selected | It is considered unlikely that releases at a landfill would have an impact at the repository depth, hence, this FEP is not considered in the scenario selection. |
| **FHA15** | Bombing, blasting, explosions and crashes above the repository | No scenario selected | Due to the depth of SFR, explosions and crashes are considered very unlikely to have any effect on the repository, hence, this FEP is not considered in the scenario selection |
| **FHA16** | Hazardous waste facility | Drilling into the repository | Following the same argumentation as above for heat storage (FHA04), only the aspect of drilling is considered in the scenario selection for this FEP. |
| **FHA17** | Contamination with chemical substances or altering chemical conditions | No scenario selected | It is considered unlikely that releases of chemicals would have an impact at the repository depth, hence, this FEP is not considered in the scenario selection. |

**Table 4-2. FHA-scenarios in the PSAR with identified FHA calculation cases.**

| Scenario | Calculation cases | Comment |
|---|---|---|
| **Drilling into the repository** | FHA_D_DE<br>Drilling event | This calculation case assumes that a waste package is hit during the drilling event and waste is brought to the surface in the drilling detritus. Potential consequences are evaluated by calculating doses to the drill crew directly exposed during drilling. |
| | FHA_D_Con<br>Construction on drilling detritus landfill | This calculation case assumes that a waste package is hit when drilling and waste is brought to the surface in the drilling detritus and left on a landfill. It is assumed that humans, after the borehole is abandoned, utilise the landfill for construction. Potential consequences are evaluated by calculating the doses to workers during construction on the landfill. |
| | FHA_D_Cul<br>Cultivation on drilling detritus landfill | This calculation case assumes that a waste package is hit when drilling and waste is brought to the surface in the drilling detritus and left on a landfill. It is assumed that humans, after the borehole is abandoned, utilise the landfill to cultivate crops. Potential consequences are evaluated by calculating doses to farmers working on, and eating the crops grown on the landfill. |
| **Intrusion well** | FHA_IW<br>Intrusion well | These calculation cases assume that future generations will use a geological well where the borehole has hit directly into a waste vault. Potential consequences are evaluated by calculating doses from using the abstracted water. Two cases are identified for this scenario, coupled with the near-field releases for two cases under the *global warming variant of the main scenario* |
| **Water management** | FHA_WM<br>Construction of a dam | Modelling to evaluate the dose consequences of an increased flow through the repository. |
| **Underground construction** | FHA_UC_RC<br>A rock cavern in the close vicinity of the repository | Modelling to evaluate the dose consequences of an increased flow through the repository. |
| | FHA_UC_M<br>A mine in the vicinity of the Forsmark site | Qualitative assessment of potential hydrological impacts on the repository by constructing a mine at the nearest credible location for mineral resources. |

## 4.2 Drilling into the repository scenario

Drilling (FHA11) is considered a credible action that may lead to direct intrusion into the repository. It is judged that drilling can be inadvertent and at the same time technically possible and practically feasible, plausible, and conceivable in the societal context. The reasons for drilling may vary; as shown in Table 4-1. Therefore, this scenario in addition to directly addressing FHA11, also includes part of FHA04, FHA05, FHA06, FHA12 and FHA16.

### 4.2.1 Scenario description

The precise reason for future humans to drill at the Forsmark site is not an important driver for the scenario description; as the comments in Table 4-1 show, it can be expected that drilling is an action included in rather many FEPs related to FHA. The drilling scenario aims to comprise several credible future human actions that may impair repository performance and regardless of the reason for drilling, the effect on the repository performance will be similar.

The premises for this scenario are that the technology and motivation to drill to repository depth exists (as detailed in Section 3.3.11), that the knowledge of the location and/or purpose of the repository is lost, and that the intruders do not initially recognise the radioactive nature of drilling material which they may come into contact with. As described in Section 3.1.1 the main safety principles of SFR are *limitation of the activity of long-lived radionuclides* and *retention of radionuclides*. A single borehole into the repository is assumed to have an insignificant effect on these safety principles; instead, this scenario focuses on how future humans could be exposed to radioactive materials brought up to the surface.

The main assumption in the drilling scenario is that the borehole directly intersects a waste vault and brings radioactive material up to the surface. To be cautious regarding potential dose consequences to humans, it is assumed that the borehole penetrates a waste package. For any drilling method, it is likely that drilling detritus presented by the waste package, or other components of the repository, will be seen as an anomaly and the drilling will be stopped for further investigations, which may lead to recognition of the purpose of SFR. Material brought to the surface may give rise to exposure of drilling crew workers who might examine the drilled material, before its hazardous nature is recognised, and proper safety measures are put into place. In addition, the contaminated drilling detritus is assumed to be disposed in a near-by landfill.

For the initial period after closure, the SFR will still be situated below the sea, and the shoreline displacement is not expected to raise SFR above the shoreline until about year 3000 AD (**Post-closure safety report**, **Biosphere synthesis report)**. Although exploratory drilling can be performed below sea, the lack of natural resources in the area leads to the view that intrusion by drilling before the repository is situated above the shoreline is deemed very unlikely and therefore this scenario is not evaluated before year 3000 AD.

#### *Calculation cases identified to analyse the drilling scenario*

Two radiation exposure situations related to drilling into the repository are considered when identifying calculation cases for analysing the drilling scenario: exposure of people involved during the drilling event, and exposure of people utilising land containing contaminated drilling detritus from the drilling event. Three calculation cases have been identified to analyse these two exposure situations:

- *Drilling event* (FHA_D_DE)
- *Construction on drilling detritus landfill* (FHA_D_Con)
- *Cultivation on drilling detritus landfill* (FHA_D_Cul)

These three calculation cases are addressed in the sections below.

### 4.2.2 Drilling event (FHA_D_DE)

In this calculation case, it is assumed that a borehole is drilled and that the drill penetrates a waste package in the repository. Consequently, radioactive material is brought to the surface in the drill detritus, which causes exposure of the drill crew. Exposure pathways considered are external irradiation, inhalation of dusts which might be generated from the same material and inadvertent ingestion of the same material. This set is consistent with the assessments described in Smith et al. (2013).

In this calculation case, it is assumed that the technique used is either diamond core drilling using water, which is a commonly used technique for deep exploratory drilling in crystalline rock, or rotary drilling using air, which is a commonly used technique when detailed information about the rock is not needed. The actual conditioned waste comprises a wide range of materials with varying properties, such as steel drums, ISO containers, concrete blocks, etc (further described in the **Initial state report**). It is not likely that the drilling, especially diamond core drilling, would proceed without problems in all parts of the repository and bring back cores to the surface that would not alert the drill crew that they have hit something unusual. When analysing this calculation case, it is assumed that drilling proceeds as would be expected if the drilling was done in a typical rock formation; hence, it is assumed that the repository has no effect on the drilling procedure and that some waste is brought to the surface before the discovery of the hazard. This is a cautious assumption that may be particularly unlikely if the drill hits a piece of stainless steel.

Furthermore, there will be a pronounced heterogeneity in the spatial distribution of radionuclides and their activities within the repository. When analysing this calculation case, the simplification is made that the radionuclide inventory in a waste vault is uniformly distributed.

The exposure of the drill crew, quantified in terms of effective doses received during the drilling event, is modelled with the same model and input parameter as in Smith et al. (2013) (described in the section 'Models and data applied'). The only assessment-specific data for the PSAR are the waste inventory of the repository.

### *Models and data applied*

This calculation case estimates effective doses to drillers using either the diamond core drilling technique or the rotary drilling technique. These are included in the 58 cases for which normalised dose results are presented in Smith et al. (2013). These normalised results relate to the dose due to unit activity inventory concentrations (1 Bq $g^{-1}$) and comprise a range of relevant radionuclides assumed to be present in 1 m long cores of brought to the surface and contacted and examined by the drillers for one hour. These normalised results can be used as dose conversion factors (DCFs) and used together with assessment-specific activity concentrations in the waste. The activity in the waste vaults used in this calculation case are same as in the *base case* (described in the **Radionuclide transport report**, Chapter 5). Hence, not only radioactive decay is accounted for but also radionuclide releases from the repository.

The normalised doses to drillers, assuming diamond core drilling with water and that the material excavated consist of concrete is denoted DCW_CO_D (Diamond Core, Water, Concrete, Driller) in Smith et al. (2013), and the normalised doses to drillers assuming rotary drilling with air is denoted RA_CO_D (Rotary, Air, Concrete, Driller).

Table 4-3 to Table 4-5 provide the models and parameter data used by Smith et al. (2013), applied to estimate the pathways-specific effective dose from the three exposure pathways considered: external radiation ($D_{ext}$), inhalation ($D_{inh}$) and inadvertent ingestion ($D_{ing}$). The total effective dose ($D_{tot}$) is then calculated by summing the three pathway-specific dose contributions, according to:

$$D_{tot} = D_{ext} + D_{inh} + D_{ing} \text{ [Sv]}$$

where the effective doses from external irradiation, inhalation and inadvertent ingestion are derived as follows:

$$D_{ext} = 1.4 \cdot 10^{-13} \cdot f_1 \cdot f_2 \cdot \frac{1}{x^2} \cdot \rho \cdot V \cdot t_{exp} \cdot \sum_i (E_i \cdot S_i)$$

$$D_{inh} = R \cdot d \cdot t_{exp} \cdot \sum_i (I_{inh,i} \cdot S_i)$$

$$D_{ing} = m \cdot t_{exp} \cdot \sum_i (I_{ing,i} \cdot S_i)$$

Parameters are explained in Table 4-3 to Table 4-5. It is acknowledged that the normalised dose results in Smith et al. (2013) were calculated using dose coefficients for occupational intake from ICRP Publication 68 (ICRP 1994), $I_{inh,i}$ in the equation above, and these have been superseded by the values recommended in ICRP Publications 134 (ICRP 2016) and 137 (ICRP 2017). A comparison of the applied and updated dose coefficients is presented in Appendix A.

It is noted that if a whole solid core is brought to the surface, this increases the potential dose from external irradiation, since there is a greater opportunity to be close to all the material brought to the surface. For internal irradiation, the opposite is true, i.e. smaller particles associated with contaminated drill cuttings are more easily inhaled giving rise to internal dose. The data are selected to maximise the dose from all three modes of exposure, but it is acknowledged that alternative assumptions could be made. These alternatives are discussed in Chapter 6 in Smith et al. (2013).

A 1 m length of core material is assumed to be taken to the surface for the normalised DCFs. This is also applied here in the calculations. However, the implications of longer cores are considered in Section 'Results' below, alongside other discussion of the results. The input data from Smith et al. (2013) are judged appropriate also for the PSAR and the doses to the drill crew in FHA_D_DE are calculated by:

$$D_{RA,i} = DCF_{RA\_CO\_D} \cdot S_i$$

$$D_{DCW,i} = DCF_{DCW\_CO\_D} \cdot S_i$$

Where:

$D_{RA,I}$ is the dose from radionuclide *I* to a member of the drill crew using the drilling technique rotary drilling with air, Sv

$D_{DCW,I}$ is the dose from radionuclide *I* to a member of the drill crew using the drilling technique diamond core drilling with water, Sv.

$DCF_{RA\_CO\_D}$ and $DCF_{DCW\_CO\_D}$ are dose conversions factors derived from Smith et al. (2013) for a unit release using the drilling techniques rotary drilling with air, and diamond core drilling with water, respectively and assuming that the material in the repository is concrete. Equations, assumptions and parameter values to derive these dose conversion factors are described above and in Table 4-3 to Table 4-5. The DCFs applied are presented in Table 4-6.

$S_i$ is the average activity concentration of a radionuclide in the sample.

**Table 4-3. Data for calculation of the effective dose from external irradiation ($D_{ext}$) (cf. Smith et al. 2013, Section 4.2). RA_CO_D is rotary drilling with air, DCW_CO_D is diamond core drilling with water.**

| Parameter or constant | | Value | Unit |
|---|---|---|---|
| $1.4 \times 10^{-13}$ | Constant value relating exposure rate to source size and distance. Here, R refers to the exposure, in roentgens. | $1.4 \times 10^{-13}$ | (100R m$^2$)/ (MeV h Bq) |
| $f_1$ | Conversion factor from exposure to effective dose | 0.7 | Sv·100R$^{-1}$ |
| $f_2$ | Self-shielding factor | 1 | – |
| x | Distance from the source | 1 | m |
| $E_i$ | Mean gamma energy per disintegration for radionuclide *i* | Radionuclide dependent [a)] | MeV |
| $S_i$ | Average activity concentration of a radionuclide *I* in the sample | 1 [b)] | Bq g$^{-1}$ |
| ρ | Density of sample (value for concrete used for all materials in this analysis) | $2.4 \times 10^6$ | g m$^{-3}$ |
| V | Volume of sample (m$^3$), where<br>$V = \pi \times r^2 \times h$ | 0.34 (RA_CO_D)<br>0.02 (DCW_CO_D) | m$^3$ |
| | $r$ Borehole radius | 0.33 (RA_CO_D)<br>0.07 (DCW_CO_D) | m |
| | $h$ Core length | 1 | m |
| $t_{exp}$ | Exposure time | 1 | h |

[a)] The mean gamma energy per disintegration for each parent radionuclide considered, including the contributions from short-lived decay products which are assumed to be in equilibrium with the parent radionuclide, are given in Table 12 in Smith et al. (2013).

[b)] For the normalised DCF derived in Smith et al. (2013), a value of 1 Bq g$^{-1}$ waste was applied.

**Table 4-4. Parameter data for calculation of the effective dose from inhalation ($D_{inh}$) (cf. Section 3.1 in Smith et al. 2013). RA_CO_D is rotary drilling with air, DCW_CO_D is diamond core drilling with water.**

| Parameter | | Value | Unit |
|---|---|---|---|
| $t_{exp}$ | Exposure time | 1 | h |
| R | Respiration rate | 3 | m$^3$ h$^{-1}$ |
| d | Air dust concentration, where dust is derived from drilling material | $1 \times 10^{-2}$ (RA_CO_D)<br>$2.0 \times 10^{-3}$ (DCW_CO_D) | g m$^{-3}$ |
| $I_{inh,i}$ | Dose per unit intake by inhalation of radionuclide *i* | Radionuclide dependent [a)] | Sv Bq$^{-1}$ |
| $S_i$ | Average activity concentration of radionuclide *I* in the sample | 1 [b)] | Bq g$^{-1}$ |

[a)] The doses per unit intake by inhalation are given in Table 11 in Smith et al. (2013), which are based on the values for committed effective doses per unit inhalation for workers in ICRP (1994). The assigned inhalation class for the aerosols relates to whether absorption is considered to be fast, medium or slow (F, M or S) from respiratory tissues into body fluids. The 'default' class indicates the relevant absorption rate for dose calculations provisionally assumed to be relevant to human intrusion calculations.

[b)] For the normalised DCF derived in Smith et al. (2013), a value of 1 Bq g$^{-1}$ waste was applied.

**Table 4-5. Data for calculation of the effective dose from inadvertent ingestion ($D_{ing}$), (cf. Section 3.1 in Smith et al. 2013). RA_CO_D is rotary drilling with air, DCW_CO_D is diamond core drilling with water.**

| Parameter | | Value | Unit |
|---|---|---|---|
| $t_{exp}$ | Exposure time | 1 | h |
| m | Intake by ingestion | $8 \times 10^{-4}$ (RA_CO_D)<br>$1.7 \times 10^{-2}$ (DCW_CO_D) | g $h^{-1}$ |
| $I_{ing,i}$ | Dose per unit intake by ingestion of radionuclide *i* | Radionuclide dependent a) | Sv $Bq^{-1}$ |
| $S_i$ | Average activity concentration of radionuclide *I* in the sample | 1 b) | Bq $g^{-1}$ |

a) The dose per unit intake by (inadvertent) ingestion are given in Table 10 in Smith et al. (2013), which are the default values for committed effective doses per unit ingestion for workers in ICRP (1994).

b) For the normalised DCF derived in Smith et al. (2013), a value of 1 Bq $g^{-1}$ waste was applied.

**Table 4-6. Dose conversion factors (DCF) for rotary drilling with air (RA_CO_D) and diamond core drilling with water (DCW_CO_D) used in the drilling event calculation case.**

| Radionuclide a) | $DCF_{DCW\_CO\_D}$ [Sv/(Bq/g)] | $DCF_{RA\_CO\_D}$ [Sv/(Bq/g)] | Radionuclide | $DCF_{DCW\_CO\_D}$ [Sv/(Bq/g)] | $DCF_{RA\_CO\_D}$ [Sv/(Bq/g)] |
|---|---|---|---|---|---|
| H-3 | 5.8E–13 | 1.4E–12 | Po-210 | 4.0E–08 | 1.0E–07 |
| C-14-org | 2.2E–11 | 6.1E–11 | Ra-226 | 3.2E–08 | 2.4E–07 |
| C-14-inorg | 2.2E–11 | 6.1E–11 | Ra-228 | 3.1E–08 | 1.5E–07 |
| C-14-ind | 2.2E–11 | 6.1E–11 | Ac-227 | 3.4E–06 | 1.7E–05 |
| Cl-36 | 6.0E–11 | 2.3E–10 | Pa-231 | 8.5E–07 | 4.2E–06 |
| Ca-41 | 3.8E–12 | 3.9E–12 | Th-228 | 2.7E–07 | 1.4E–06 |
| Co-60 | 9.2E–09 | 2.0E–07 | Th-229 | 5.3E–07 | 2.6E–06 |
| Ni-59 | 2.9E–12 | 2.8E–11 | Th-230 | 8.8E–08 | 4.2E–07 |
| Ni-63 | 5.4E–12 | 1.5E–11 | Th-232 | 1.5E–07 | 7.5E–07 |
| Se-79 | 5.6E–11 | 3.5E–11 | U-232 | 5.2E–08 | 2.3E–07 |
| Sr-90 | 7.6E–10 | 1.3E–09 | U-233 | 2.2E–08 | 1.1E–07 |
| Zr-93 | 7.9E–11 | 3.0E–10 | U-234 | 2.2E–08 | 1.1E–07 |
| Nb-93m | 5.1E–12 | 1.5E–11 | U-235 | 2.0E–08 | 1.1E–07 |
| Nb-94 | 5.8E–09 | 1.3E–07 | U-236 | 2.0E–08 | 9.6E–08 |
| Mo-93 | 5.6E–11 | 2.1E–11 | U-238 | 1.8E–08 | 8.9E–08 |
| Tc-99 | 3.5E–11 | 1.2E–10 | Np-237 | 1.4E–07 | 7.1E–07 |
| Pd-107 | 1.1E–12 | 2.6E–12 | Pu-238 | 2.8E–07 | 1.4E–06 |
| Ag-108m | 5.9E–09 | 1.3E–07 | Pu-239 | 3.0E–07 | 1.5E–06 |
| Sn-126 | 7.1E–09 | 1.5E–07 | Pu-240 | 3.0E–07 | 1.5E–06 |
| I-129 | 2.1E–09 | 1.2E–09 | Pu-241 | 5.5E–09 | 2.7E–08 |
| Ba-133 | 4.4E–11 | 9.4E–11 | Pu-242 | 2.9E–07 | 1.4E–06 |
| Cs-135 | 3.8E–11 | 2.3E–11 | Am-241 | 2.6E–07 | 1.3E–06 |
| Cs-137 | 2.3E–09 | 4.5E–08 | Am-242m | 2.3E–07 | 1.1E–06 |
| Sm-151 | 2.6E–11 | 1.2E–10 | Am-243 | 2.5E–07 | 1.2E–06 |
| Eu-152 | 4.3E–09 | 9.1E–08 | Cm-244 | 1.6E–07 | 8.1E–07 |
| Pb-210 | 1.9E–08 | 3.7E–08 | Cm-245 | 2.3E–07 | 1.1E–06 |
| | | | Cm-246 | 2.3E–07 | 1.1E–06 |

a) DCFs for four radionuclides included in the *base case* are not available (Cd-113m, Ho-166m, Cm-242 and Cm-243). It is judged that excluding them from the analysis have insignificant impact on the results. Ho-166m has low initial activity inventory, and the three others has short half-lives and will decay during the period when the memory of the repository is assumed to be kept.

In all waste vaults, it is assumed that the inventory of each radionuclide is uniformly distributed within the materials in the waste and matrix. The following data have been used in this calculation case, masses are taken from the inventory report (SKB R-18-07) and heights from the **Initial state report**:

- In the silo, the total weight of the waste and matrix is $1.9 \times 10^7$ kg, dominated by cement, concrete, ion-exchange resin and bitumen, and the height is about 50 m,
- In the 1BMA vault, the total weight of the waste and matrix is $9.7 \times 10^6$ kg, dominated by cement, concrete, ion-exchange resin and bitumen, and the height is 7.3 m,
- In the 2BMA vault, the total weight of the waste and matrix is it is $2.5 \times 10^7$ kg, dominated by concrete and iron/steel, and the height is 7.4 m,
- In the 1BTF vault, the total weight of these materials is $3.7 \times 10^6$ kg, dominated by concrete, ion-exchange resin and ash, and the height is 4.9 m,
- In the 2BTF vault, the total weight of these materials is $3.4 \times 10^6$ kg, dominated by ion-exchange resin, concrete and filter aids, and the height is 4.9 m,
- In the 1BRT vault, the total weight of these materials is $1.3 \times 10^7$ kg, dominated by concrete and iron/steel, and the height is 5.1 m,
- In the 1BLA vault, the total weight of these materials is $4.9 \times 10^6$ kg, dominated by iron/steel, other inorganic materials and plastic/rubber, and the height is 7.8 m,
- In the 2–5BLA vaults, the total weight of these materials is $5.4 \times 10^7$ kg, dominated by iron/steel, concrete, sand/soil and other inorganic materials, and the height is 8.1 m.

#### *Results*

Doses to a member of the drill crew are derived for two drilling techniques (rotary drilling and diamond core drilling) and for drilling into each waste vault, with vaults 2–5BLA treated identical, i.e. results are obtained for 16 variants of drilling techniques and waste vaults. The total doses for intrusion at any time during the entire assessment period, considering a one-metre intrusion into a waste vault, are presented in Figure 4-1. Figure 4-2 shows the same results, but focuses on the first three millennia after closure, and contains also hypothetical doses if no credit is taken for the 300-year period during which it is assumed that the memory of SFR will be kept. All dose maxima, and key contributing radionuclides, are presented in Table 4-7.

The highest dose maximum is 0.014 mSv, and is obtained for rotary drilling into 2BMA directly after the memory of SFR is assumed to be lost, that is at 2375 AD. The second highest dose maximum is 0.010 mSv, and is obtained for rotary drilling into the silo, also at 2375 AD. Note that the shoreline at this time has not reached the area above SFR (**Biosphere synthesis report**, Table 9-1). This implies that the dose maximum relates to either offshore drilling, or sinking a highly deviating drillhole from onshore. The dose maxima occur in the beginning of the assessment period for all waste vaults.

The total and radionuclide-specific doses for radionuclides most contributing to the dose maxima are plotted in Figure 4-3 for rotary drilling into 2BMA and the silo (the two waste vaults with highest dose maxima). At the time of dose maxima, Am-241 is the main contributor to the dose, followed by Pu-239 (Table 4-7). With time, as Am-241 decays, Pu-239 dominates the dose to a member of the drill crew, followed by the contributions from Nb-94 and Pu-240 (Figure 4-3).

These results are based on dose coefficients for occupational intake that have been updated. An evaluation of the potential effect on the results in this calculation case is presented in Appendix A, if the results applied from Smith et al. (2013) where to be updated by applying the updated dose coefficients. It is concluded that, since Am-241 and Pu-239 are dominating the dose maxima, the resulting total doses would in this calculation case likely decrease if applying the updated dose coefficients. However, the decrease would likely be less than a factor of two.

The doses discussed above have the underpinning stylised assumption that a 1 m length of core material is brought to the surface and causes exposure to the drill crew. If the assumption is made that the full heights of waste in the vaults are brought to the surface during the drilling event, then the doses related to 1 m core material can illustratively be scaled with the height of the waste. Then, the highest dose maxima would be about 0.5 mSv, originating from rotary drilling into the silo at 2375 AD. The second highest dose maxima would then be about 0.1 mSv, for rotary drilling into 2BMA at 2375 AD.

Regarding the two drilling techniques, the doses to a member of the drill crew is consistently about five times lower for diamond core drilling than for rotary drilling (Table 4-7 and Figure 4-1). The reason for this is that the diamond core drilling technique brings less detritus, thus less activity, to the surface. As said above, Figure 4-2 and Figure 4-3 also include calculated hypothetical doses for the period when it is assumed that the memory of SFR will be kept, i.e. at least 300 years after closure. The reason for this is to highlight the potential importance of this period from a dose consequence perspective. If no credit would be taken for a period of kept memory of SFR, the potential doses to a member of the drill crew would be in the range from 3 to about 60 times higher, depending on which waste vault is considered, than assuming intrusion at the earliest 300 years after closure. The main reason for this is that the activities of short-lived radionuclides, such as Co-60, Cs-137 and Pu-241, and also Pu-238, significantly decrease due to decay during the period when it is assumed that intrusion will not occur.

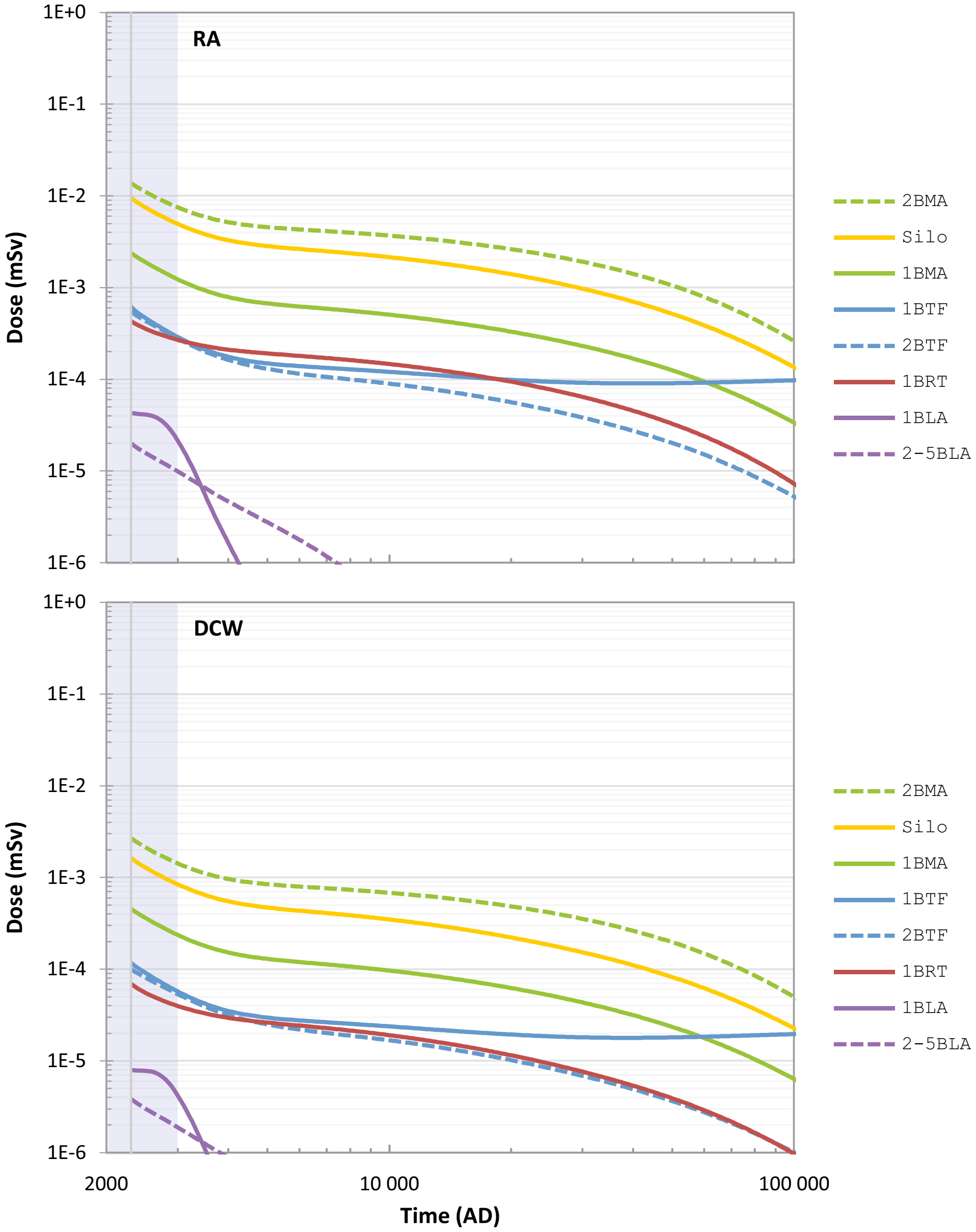

***Figure 4-1.*** *Dose to a member of the drill crew during drilling into the different waste vaults, top: using rotary drilling with air (RA); bottom: diamond core drilling (DCW). The submerged period is indicated by the blue shaded area and the earliest time when it is assumed that memory of SFR may be lost is marked with a grey vertical line.*

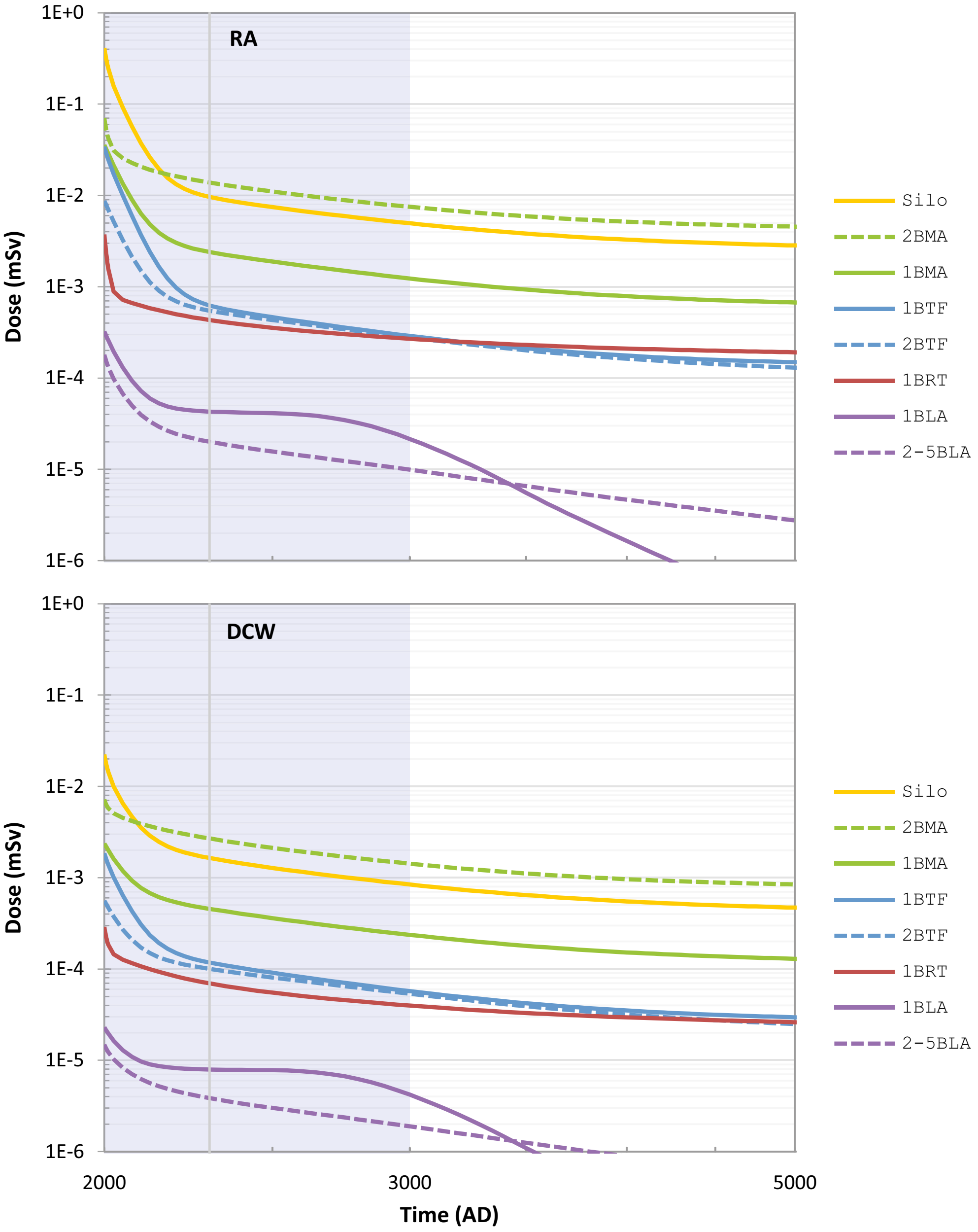

***Figure 4-2.*** *Dose during the first three millennia after closure to a member of the drill crew during drilling into the different waste vaults. Top: using rotary drilling with air (RA); bottom: diamond core drilling (DCW). Hypothetical doses during the first 300 years when it is assumed that the memory of SFR will be kept (marked with a grey vertical line) are included. The submerged period is indicated by the blue shaded area.*

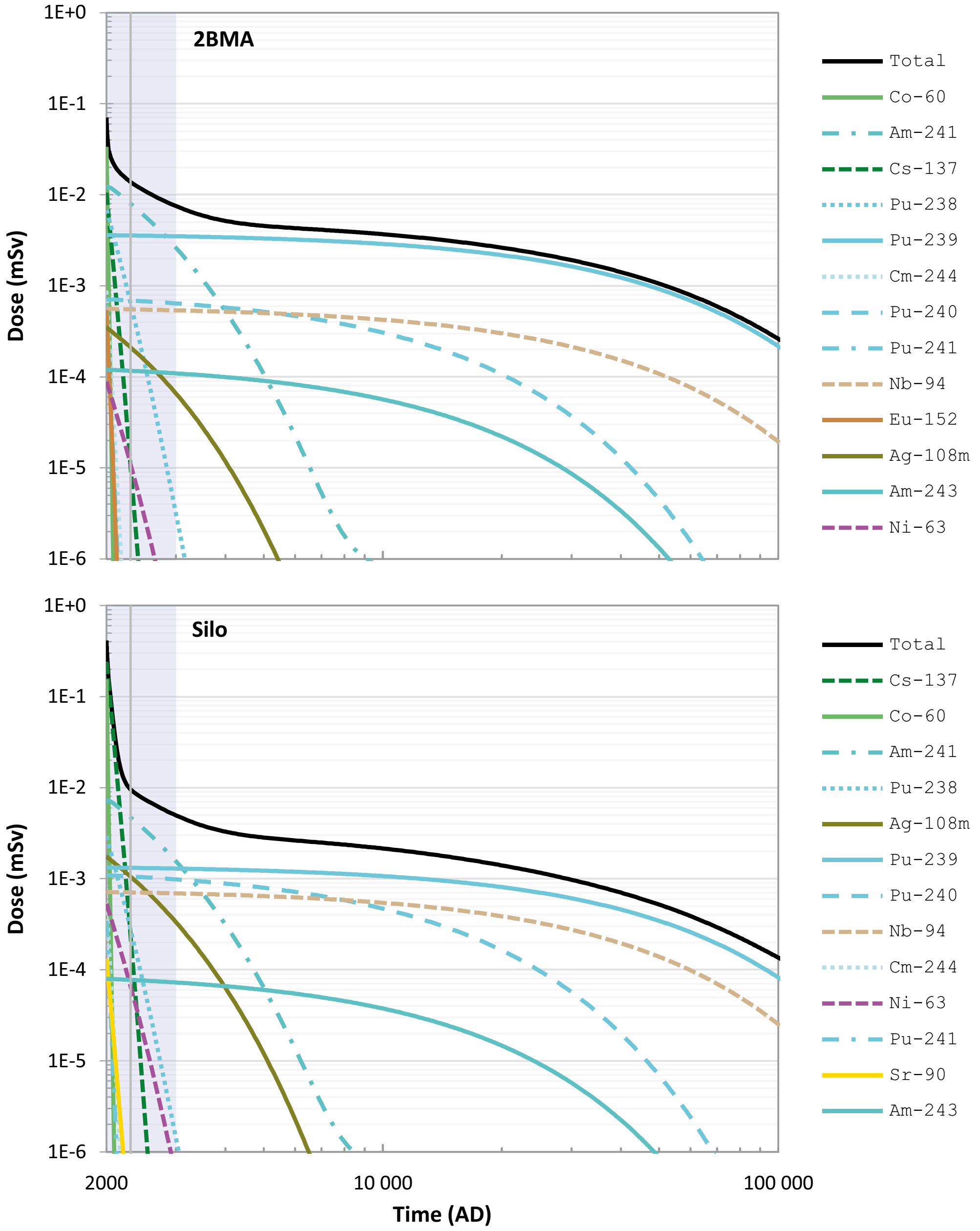

*Figure 4-3.* *Doses, total and from radionuclides most contributing to the dose maxima, to a member of the drill crew during rotary drilling into 2BMA (top) and the silo (bottom). Hypothetical doses during the first 300 years when it is assumed that the memory of SFR will be kept (marked with a grey vertical line) are included. The submerged period is indicated by the blue shaded area.*

**Table 4-7. Dose maxima for calculation case FHA_D_DE with contributions to the dose from the most contributing radionuclides at the time of dose maxima (300 years after closure).**

| **Waste vault**<br>**Drilling technique**<br>**Dose max [mSv]**<br>**Dose contribution [%]** | **Silo**<br>RA<br>9.6E−03 | **Silo**<br>DCW<br>1.6E−03 | **1BMA**<br>RA<br>2.4E−03 | **1BMA**<br>DCW<br>4.6E−04 | **2BMA**<br>RA<br>1.4E−02 | **2BMA**<br>DCW<br>2.7E−03 |
|---|---|---|---|---|---|---|
| Am-241 | 49 % | 59 % | 59 % | 63 % | 58 % | 60 % |
| Pu-239 | 14 % | 16 % | 17 % | 18 % | 26 % | 27 % |
| Pu-240 | 11 % | 13 % | 11 % | 11 % | 5 % | 5 % |
| Ag-108m | 11 % | | 6 % | | | |
| Nb-94 | 7 % | | | | | |
| Pu-238 | | | | | 5 % | 5 % |

| **Waste vault**<br>**Drilling technique**<br>**Dose max [mSv]**<br>**Dose contribution [%]** | **1BRT**<br>RA<br>4.3E−04 | **1BRT**<br>DCW<br>6.9E−05 | **1BTF**<br>RA<br>6.2E−04 | **1BTF**<br>DCW<br>1.2E−04 | **2BTF**<br>RA<br>5.5E−04 | **2BTF**<br>DCW<br>1.0E−04 |
|---|---|---|---|---|---|---|
| Am-241 | 35 % | 44 % | 62 % | 67 % | 53 % | 58 % |
| Pu-239 | 12 % | 16 % | 13 % | 14 % | 16 % | 18 % |
| Pu-240 | 17 % | 21 % | 10 % | 11 % | 13 % | 14 % |
| Ag-108m | 7 % | | | | 10 % | |
| Nb-94 | 20 % | 6 % | | | | |
| Pu-238 | 7 % | 8 % | | | | |
| Cs-137 | | | 5 % | | | |

| **Waste vault**<br>**Drilling technique**<br>**Dose max [mSv]**<br>**Dose contribution [%]** | **1BLA**<br>RA<br>4.3E−05 | **1BLA**<br>DCW<br>7.9E−06 | **2–5BLA**<br>RA<br>2.0E−05 | **2–5BLA**<br>DCW<br>3.9E−06 |
|---|---|---|---|---|
| U-238 | 30 % | 34 % | | |
| Am-241 | 24 % | 26 % | 56 % | 59 % |
| U-235 | 11 % | | | |
| Ac-227 | 10 % | 11 % | | |
| Ag-108m | 9 % | | | |
| Pu-238 | | | 6 % | 7 % |
| Pu-239 | 5 % | | 13 % | |
| Pu-240 | | | 13 % | |

### 4.2.3 Construction on drilling detritus landfill (FHA_D_Con)

In this calculation case, it is assumed that a borehole is drilled that penetrates a waste package in the repository (as in FHA_D_DE). Thereafter, radioactive material is assumed to be brought to the surface as drill core detritus and disposed in a shallow uncovered landfill at the drill site. Potential consequences, in terms of effective doses, are evaluated for a worker during construction on a site including the contaminated landfill. This construction worker scenario is based on the ‘Construction scenario’ in Oatway and Mobbs (2003), sub-scenario, ‘exposed uniform contamination distribution’.

Consideration is given to external irradiation from the ground, inhalation of dust, external exposure from soil on the skin and inadvertent ingestion.

The same activity concentrations in the drilling detritus as in FHA_D_DE are used in this calculation case, except that the calculations here are limited to include only the rotary drilling with air. The relative importance of the different exposure pathways considered here is not affected by the drilling technique. Hence, the key factor is the volume of contaminated materials brought to the surface that is mixed with soil in a landfill. It is thus sufficient to only include the rotary drilling technique since the volume of drilling detritus per drilled metre is about 20 times larger compared with the diamond core drilling technique. As for FHA_D_D E, it is assumed in the simulations that the drilling brings radioactive material to the surface due to drilling 1 m into the waste in each waste vault, and the potential impacts of drilling further into more waste are addressed in the discussion.

### *Models and data applied*

Cautiously, it is assumed that there is no loss of activity from the landfill area in the time between when the landfilling takes place and use of the land for construction commence. The activity concentrations in the waste vaults used in this calculation case are same as in the *base case* (described in the **Radionuclide transport report**, Chapter 5). Hence, not only is radioactive decay accounted for but also radionuclide releases from the repository.

As stated above, this construction worker calculation case is based on the 'Construction scenario' in Oatway and Mobbs (2003). Basically, the same assumptions as in Oatway and Mobbs (2003) are adopted for the construction worker scenario and therefore normalised dose conversion factors from Oatway and Mobbs (2003) can be used to calculate the dose to a construction worker. It is acknowledged that the normalised dose conversion factors were calculated using dose rate coefficients from U.S. Environmental Protection Agency for external exposure to radionuclides in soil from Eckerman and Ryman (1993), and these have been superseded by the values recommended in Bellamy et al. (2019). A comparison of the applied and updated dose coefficients is presented in Appendix A.

The assessment-specific assumptions needed in this calculation case are the volume of the landfill, the activity concentrations of radionuclides in the excavated material, and the exposure time in a year of work. Although construction sites can be assumed to be large, it is selected that the contaminated drilling detritus is uniformly mixed in a small shallow landfill with the area of 272 $m^2$ and to a depth of 1 m, hence the land has a volume of 272 $m^3$ (the relatively small construction area is selected to be the same size as the agricultural land in FHA_D_Cul). This landfill is then assumed to be redeveloped for either residential or commercial use, alongside other surrounding land. Because of the small area of the landfill containing the contaminated drilling detritus, it is assumed that a worker stays in this area no longer than 200 hours in a year.

The model applied in this case to calculate the dose to a construction worker in a year of work on the site, $D_{con}$, can be expressed as follows:

$$D_{con} = DCF_{con} \cdot Expfrac \cdot S_{i,core} \cdot \frac{V_{excavated}}{V_{mixed}}$$

Where:

$DCF_{con}$ is the dose conversion factor, Sv/a per Bq/g. The DCF values are taken from Table 25 in Oatway and Mobbs (2003). For the radionuclides lacking a value in Oatway and Mobbs (2003), the reasoning in Section 4.4.2 of Smith et al. (2013) was used to select an analogue value from Oatway and Mobbs (2003). This is based on comparisons with levels set for exemption and clearance of individual radionuclides in IAEA (2005). The resulting DCFs are presented in Table 4-8.

*Expfrac* is the time a construction worker is assumed to be exposed at the site divided by the time assumed in Oatways and Mobbs (2003), i.e. in this case 200 h divided by 2000 h (*Expfrac* = 0.1).

$S_{i,core}$ is the radionuclide concentration in the drilling detritus (i.e. the drill core).

$V_{excavated}$ is the volume of the contaminated drilling detritus (0.34 $m^3$, cf. Table 4-3).

$V_{mixed}$ is the volume of the landfill the detritus is mixed in (272 $m^3$).

**Table 4-8. Dose conversion factors used in calculation case construction on drilling detritus landfill (FHA_D_Con).**

| Radionuclide [a] | $DCF_{CON}$ [Sv/(Bq/g)] | Radionuclide | $DCF_{CON}$ [Sv/(Bq/g)] |
|---|---|---|---|
| H-3 | 2.4E–12 | Po-210 | 1.4E–05 |
| C-14-org | 3.1E–06 | Ra-226 | 7.6E–04 |
| C-14-inorg | 3.1E–06 | Ra-228 | 4.1E–04 |
| C-14-ind | 3.1E–06 | Ac-227 | 1.4E–03 |
| Cl-36 | 3.1E–06 | Pa-231 | 3.4E–04 |
| Ca-41 | 2.3E–09 | Th-228 | 7.8E–04 |
| Co-60 | 1.1E–03 | Th-229 | 2.8E–04 |
| Ni-59 | 2.3E–09 | Th-230 | 3.4E–05 |
| Ni-63 | 2.3E–09 | Th-232 | 5.9E–05 |
| Se-79 | 6.1E–08 | U-232 | 1.2E–04 |
| Sr-90 | 3.1E–06 | U-233 | 8.7E–06 |
| Zr-93 | 6.1E–08 | U-234 | 8.4E–06 |
| Nb-93m | 6.1E–08 | U-235 | 5.3E–05 |
| Nb-94 | 1.1E–03 | U-236 | 7.6E–06 |
| Mo-93 | 2.3E–09 | U-238 | 1.8E–05 |
| Tc-99 | 6.1E–08 | Np-237 | 1.2E–04 |
| Pd-107 | 2.3E–09 | Pu-238 | 1.1E–04 |
| Ag-108m | 1.1E–03 | Pu-239 | 1.2E–04 |
| Sn-126 | 1.1E–03 | Pu-240 | 1.2E–04 |
| I-129 | 3.1E–06 | Pu-241 | 2.1E–06 |
| Ba-133 | 3.1E–06 | Pu-242 | 1.2E–04 |
| Cs-135 | 3.1E–06 | Am-241 | 1.0E–04 |
| Cs-137 | 2.4E–04 | Am-242m | 1.0E–04 |
| Sm-151 | 1.1E–08 | Am-243 | 1.0E–04 |
| Eu-152 | 1.1E–03 | Cm-244 | 3.1E–06 |
| Pb-210 | 6.5E–06 | Cm-245 | 1.2E–04 |
| | | Cm-246 | 1.2E–04 |

[a] DCFs for four radionuclides included in the *base case* are not available (Cd-113m, Ho-166m, Cm-242 and Cm-243). It is judged that excluding them from the analysis have insignificant impact on the results. Ho-166m has low initial activity inventory, and the three others has short half-lives and will decay during the period when the memory of the repository is assumed to be kept.

### *Results*

Effective doses are derived for a construction worker conducting work for one year on a landfill containing drilling detritus from rotary drilling into each waste vault, with vaults 2–5BLA treated identical, i.e. results are obtained for eight variants.

The total doses during the entire assessment period, considering a one-metre intrusion into a waste vault, are presented in Figure 4-4. Figure 4-5 shows the same results, but focuses on the first three millennia after closure, and contains also hypothetical doses if no credit is taken for the 300-year period during it is assumed that the memory of SFR will be kept. All dose maxima, and key contributing radionuclides, are presented in Table 4-9.

The highest dose maximum is 0.022 mSv and arises for a landfill related to drilling into the silo at 2375 AD, that is directly after the memory of SFR is assumed to be lost. The second highest dose maximum is 0.0099 mSv, and arises for a landfill related to drilling into 2BMA, also at 2375 AD. Note that the shoreline at this time has not reached the area above SFR (**Biosphere synthesis report**, Table 9-1). This implies that the dose maximum relates to either offshore drilling, or sinking a highly deviating drillhole from onshore. The dose maxima occur in the beginning of the assessment period for all waste vaults.

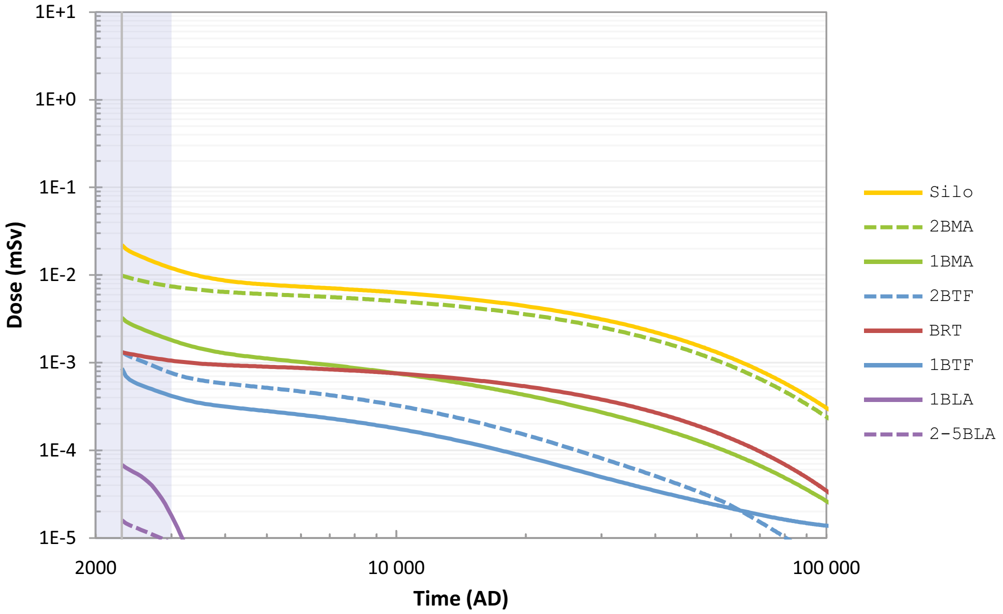

*Figure 4-4.* *Doses in a year for a construction worker conducting work on a landfill containing rotary drilling detritus from the different waste vaults. The submerged period is indicated by the blue shaded area and the earliest time when it is assumed that memory of SFR may be lost is marked with a grey vertical line.*

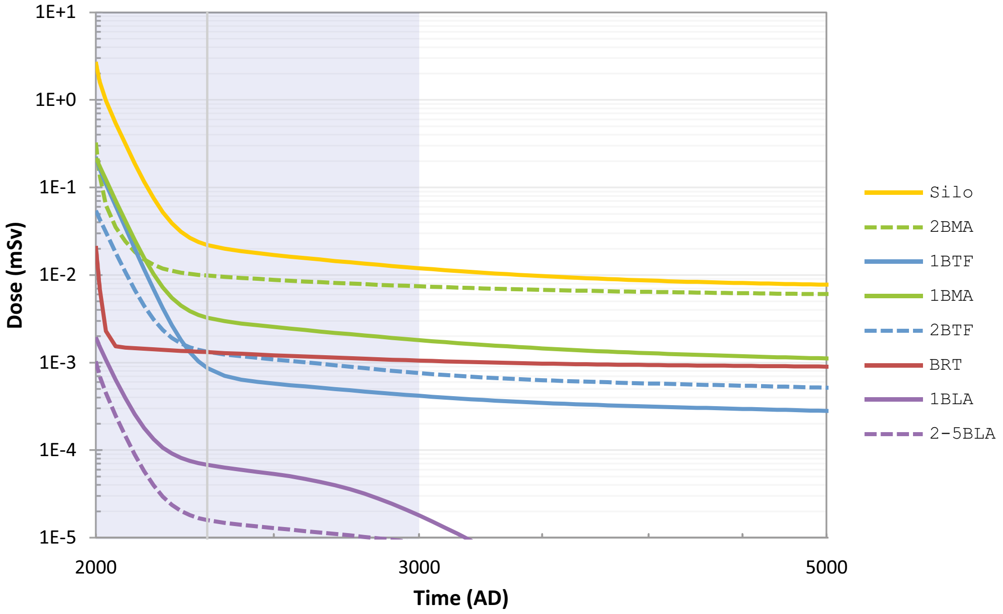

*Figure 4-5.* *Dose during the first three millennia after closure to a construction worker conducting work on a landfill containing rotary drilling detritus from the different waste vaults. Hypothetical doses during the first 300 years when it is assumed that the memory of SFR will be kept (marked with a grey vertical line) are included. The submerged period is indicated by the blue shaded area.*

**Table 4-9. Dose maxima for calculation case FHA_D_Con with contributions to the dose from the most contributing radionuclides at the time of dose maxima (300 years after closure).**

| **Waste vault**<br>**Dose max [mSv]**<br>**Dose contribution** | **Silo**<br>2.2E−02 | **1BMA**<br>3.3E−03 | **2BMA**<br>9.9E−03 | **1BRT**<br>1.3E−03 | **1BTF**<br>8.6E−04 | **2BTF**<br>1.3E−03 | **1BLA**<br>6.8E−05 | **2–5BLA**<br>1.6E−05 |
|---|---|---|---|---|---|---|---|---|
| Ag-108m | 52 % | 24 % | 9 % | 23 % | 29 % | 42 % | 59 % | 38 % |
| Nb-94 | 35 % | 31 % | 80 % | 74 % | 9 % | 13 % | 15 % | 44 % |
| Cs-137 | 7 % | | | | 23 % | | | |
| Am-241 | | | | | 5 % | | | 7 % |
| C-14-inorg | | 34 % | | | 31 % | 37 % | 11 % | |
| Pu-239 | | | 5 % | | | | | |
| U-238 | | | | | | | 5 % | |

The total and radionuclide-specific doses for radionuclides most contributing to the dose maxima are plotted in Figure 4-6 for landfills related to drilling into the silo and 2BMA (highest dose maxima). At the time of dose maxima for a landfill related to drilling into the silo or 2BMA, at 2375 AD, Ag-108m and Nb-94 are the dominating contributors to the total dose (Table 4-9). After a few thousands of years, as Ag-108m decays, Nb-94 will dominate the dose to the construction worker (see Figure 4-6).

These results are based on dose rate coefficients for external exposure that have been updated. An evaluation of the potential effect on the results in this calculation case is presented in Appendix A, if the results applied from Oatway and Mobbs (2003) where to be updated by applying the updated dose coefficients. It is concluded that, despite the large increase in doses rate coefficient for some radionuclides in Bellamy et al. (2019) compared with Eckerman and Ryman (1993), it is deemed that it is only doses due to Cs-137 that would have a significant impact on the results in this calculation case, if the calculations were re-done using updated values. However, since Cs-137 is an important radionuclide for dose related to the silo, the highest dose maximum in this calculation case could increase up to about 0.1 mSv (factor of five).

Figure 4-5 and Figure 4-6 also include calculated hypothetical doses for the period over which it is assumed that the memory of SFR will be kept, that is to at least 300 years after closure. This highlights the potential importance of this period from a dose consequence perspective. If no credit were to be taken for a period of retained memory of SFR, the potential doses to a construction worker would be in the range from about 20 to 250 times higher, depending on which waste vault is considered, than assuming intrusion at the earliest 300 years after closure. The main reason for this is that the activities of short-lived radionuclides, especially Co-60, Cs-137 and Eu-152, significantly decrease due to decay during the period where it is assumed that intrusion will not occur.

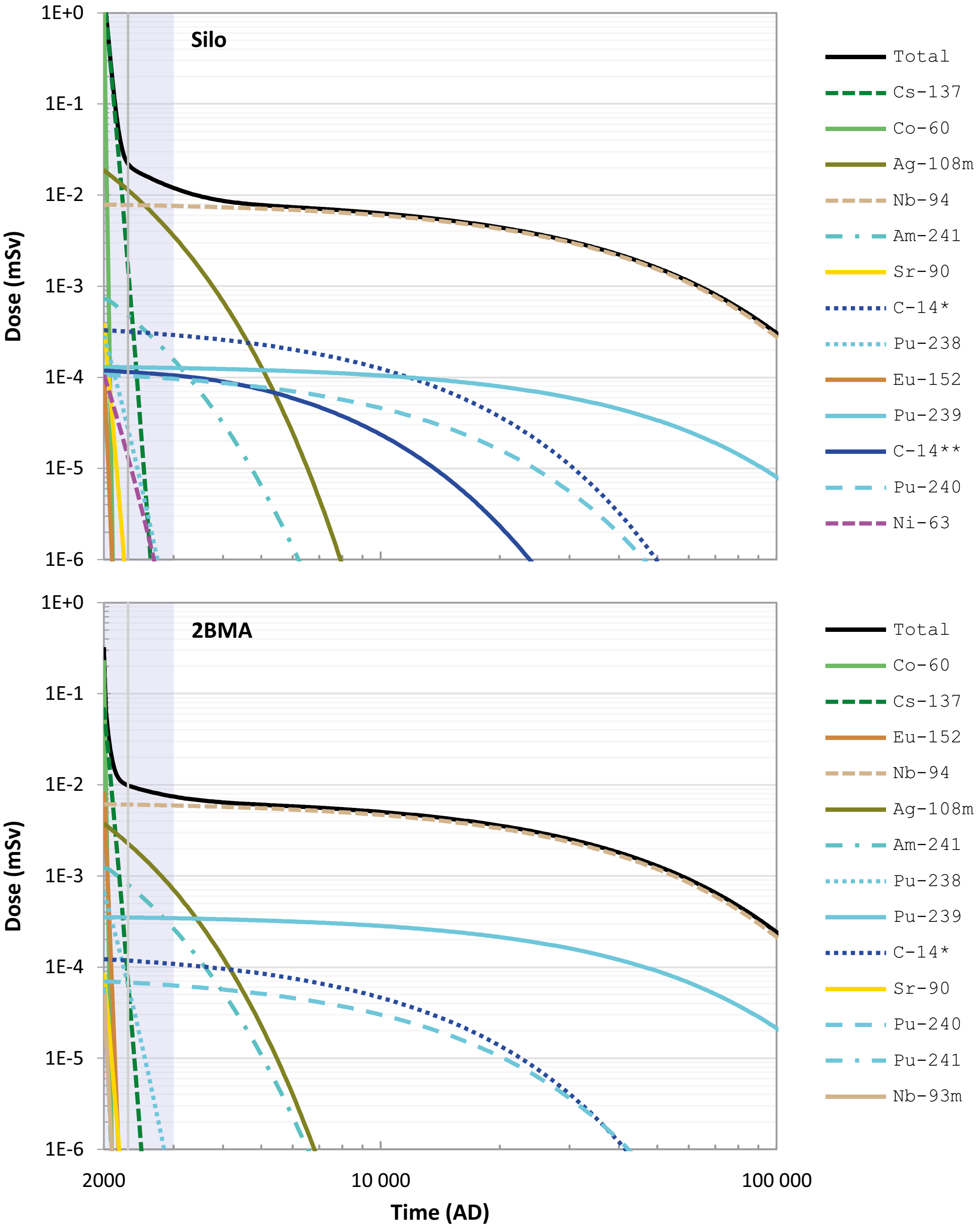

***Figure 4-6.*** *Doses, total and from radionuclides most contributing to the dose maxima, to a construction worker conducting work on a landfill containing rotary drilling detritus from the silo (top) and 2BMA (bottom). C-14* and C-14** relates to doses from inorganic and organic fractions, respectively.*

### 4.2.4 Cultivation on drilling detritus landfill (FHA_D_Cul)

This calculation case considers a shallow uncovered landfill with the same characteristics as in FHA_D_Con, thus including the same radionuclide concentrations. Potential consequences, in terms of annual doses[6], are calculated for a member of a family that is self-sustained with respect to vegetables and root crops produced through small-scale horticulture. i.e. cultivating a garden plot with a location coincident with the landfill. As for the case FHA_D_Con, this calculation case only includes the rotary drilling technique.

#### *Models and data applied*

Cautiously, it is assumed that there is no loss of activity from the landfill in the time between when the landfilling takes place and the use of the land for a garden plot. The activity concentrations in the waste vaults used in this calculation case are same as in the *base case* (described in the **Radionuclide transport report**, Chapter 5). Hence, not only is radioactive decay accounted for but also radionuclide releases from the repository.

The BioTEx model (**Biosphere synthesis report**, Chapter 7) is used in this calculation case, limited to evaluating doses to only the potentially exposed group Garden-plot household, GP (**Biosphere synthesis report**, Section 6.2). The model and input parameters are further described in Saetre et al. (2013) and Grolander (2013). The key difference in this calculation case, compared with how the BioTEx model is used in the *base case* and other cases evaluating doses from geosphere releases, is that the soil contains radionuclides only originating from the drilling event. That is, no radionuclides originating from the repository due to releases are introduced by fertilisation or irrigation water.

#### *Results*

Annual doses are derived for a family member cultivating vegetables and tubers on a landfill containing waste originating from rotary drilling into each waste vault, with 2–5BLA treated as identical waste vaults, i.e. results are obtained for eight variants.

The total doses during the entire assessment period, considering a one-metre intrusion into a waste vault, are presented in Figure 4-7. Figure 4-8 shows the same results, but focuses on the first three millennia after closure, and addresses also what the hypothetical doses would be if no credit is taken to the 300-year period during which it is assumed that the memory of SFR will be kept. All dose maxima, and key contributing radionuclides, are presented in Table 4-10.

All dose maxima occur at 2375 AD, i.e. directly after the memory of SFR is assumed to be lost. The highest dose maximum is 0.0036 mSv and is obtained for cultivation on a landfill related to drilling into the silo. The second highest dose maximum is 0.0007 mSv and is obtained for a landfill related to drilling into 1BMA or 2BMA.

The total and radionuclide-specific doses for radionuclides most contributing to the dose maxima are plotted in Figure 4-9 for the cultivation on landfills related to drilling into the silo and 1BMA, the vaults resulting in the highest dose maxima. At the dose maximum for drilling into the silo, Ni-63 dominates the dose. Ni-63 is also the main contributor to the dose maximum for 1BMA (see also Table 4-10). With time, as Ni-63 decays, Ni-59 will become the dominant radionuclide in respect of the dose to the family member that cultivates the garden plot (Figure 4-9).

Figure 4-8 and Figure 4-9 also include calculated hypothetical doses for the period for which it is assumed that the memory of SFR will be kept, that is for at least 300 years after closure, to highlight the potential importance of this period from a dose consequence perspective. If no credit were to be taken for a period of the memory of SFR kept, the potential dose to a family member that cultivates the garden plot would be in the range from about 20 to 500 times higher, depending on which waste vault is considered, than assuming intrusion at the earliest 300 years after closure.

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[6] Calculated as the annual effective dose to an adult, where the annual effective dose is defined as the effective dose from external exposure in a year, plus the committed effective dose from intakes of radionuclides in that year.

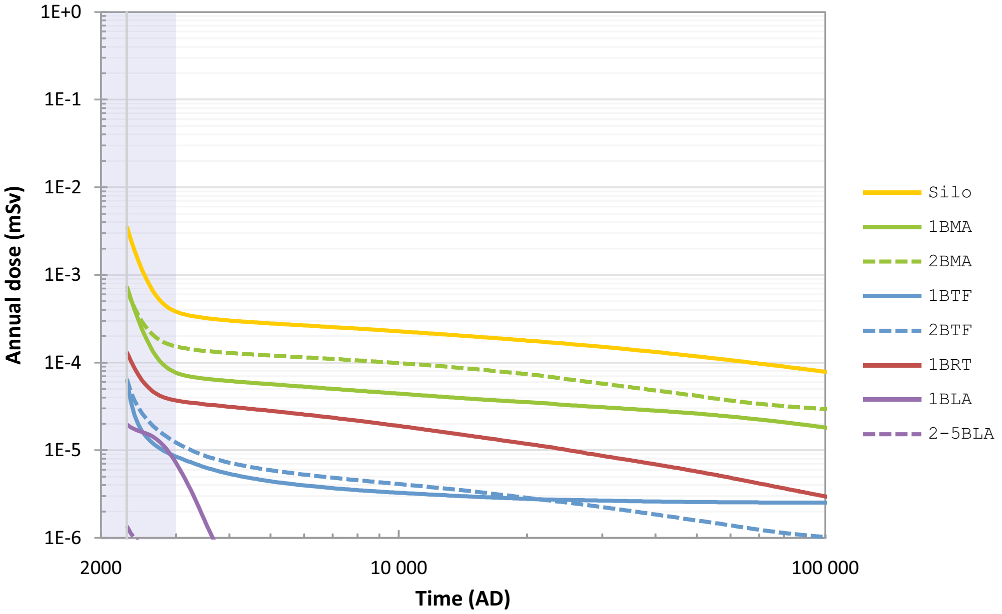

*Figure 4-7. Annual dose to a family member cultivating a landfill containing rotary drilling detritus from the different waste vaults. The submerged period is indicated by the blue shaded area and the earliest time when it is assumed that memory of SFR may be lost is marked with a grey vertical line.*

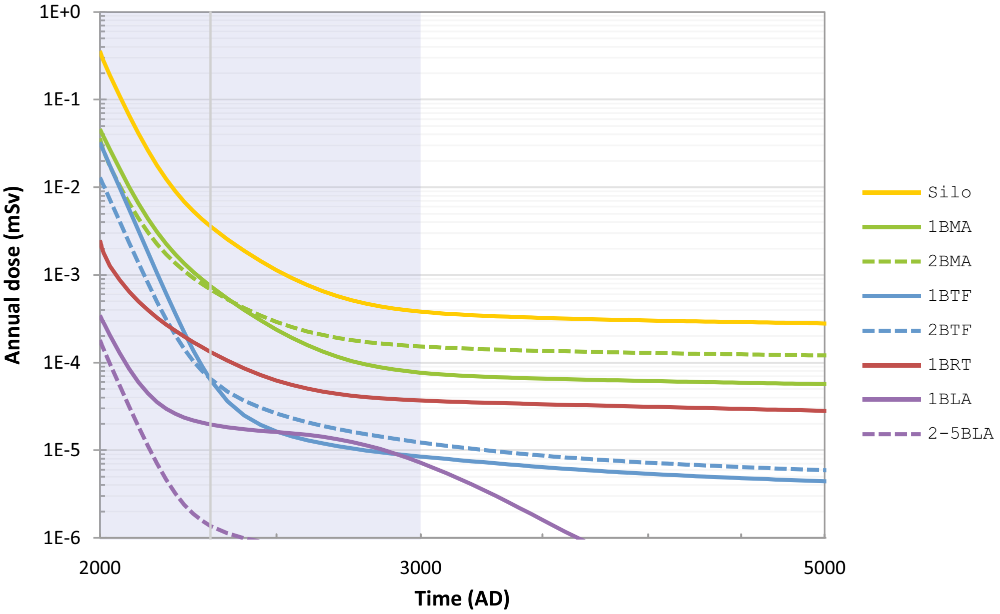

*Figure 4-8. Annual dose during the first three millennia after closure to a family member cultivating a landfill containing rotary drilling detritus from the different waste vaults. Hypothetical doses during the first 300 years when it is assumed that the memory of SFR will be kept (marked with a grey vertical line) are included. The submerged period is indicated by the blue shaded area.*

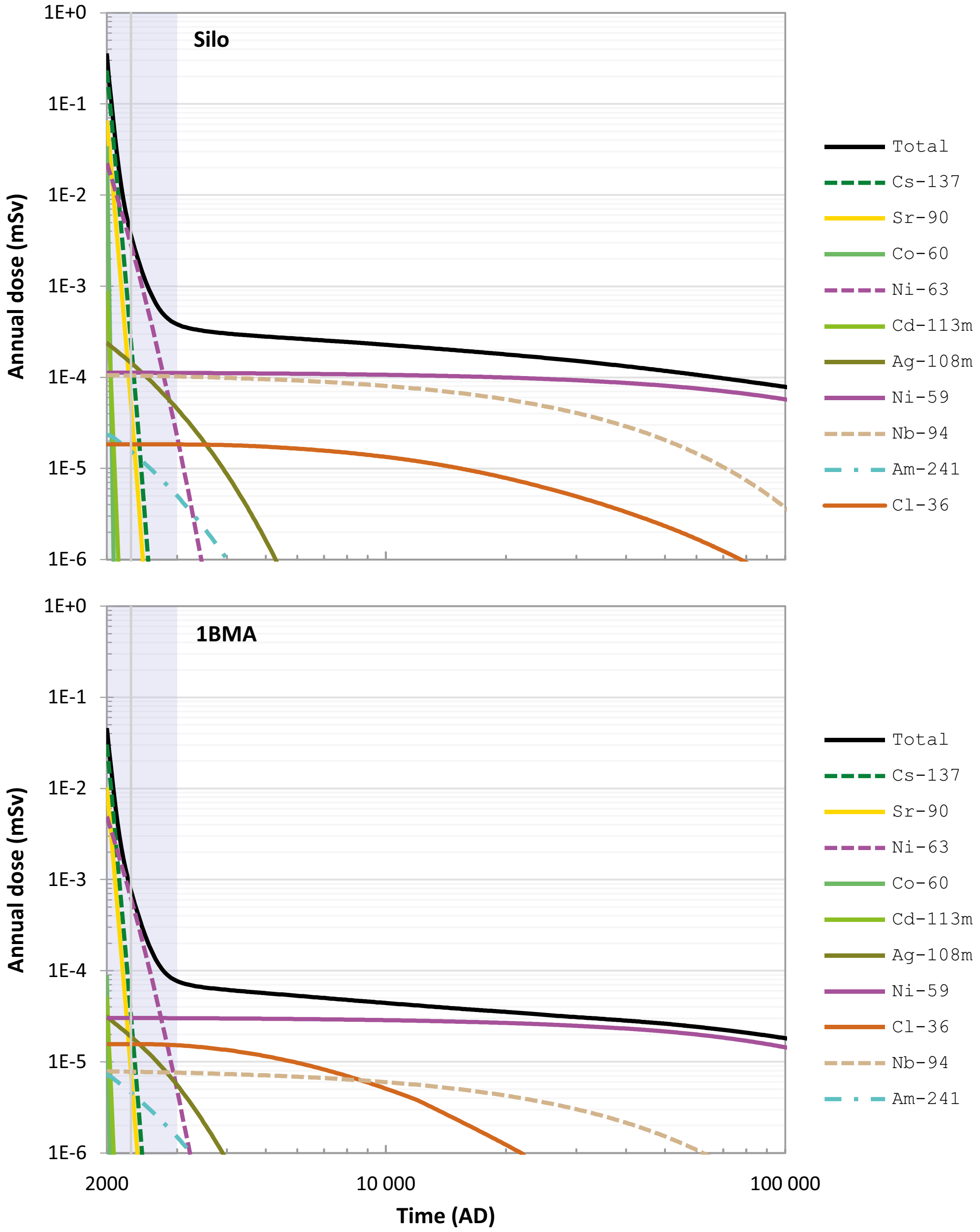

***Figure 4-9.** Doses, total and from radionuclides most contributing to the dose maxima, to a family member cultivating a garden plot on a landfill containing rotary drilling detritus from the silo (top) and 1BMA (bottom).*

**Table 4-10. Annual dose maxima for calculation case FHA_D_Cul and radionuclide-specific contributions to the dose maxima (occurs 300 years after closure for all waste vaults).**

| **Waste vault** | **Silo** | **1BMA** | **2BMA** | **1BRT** | **1BTF** | **2BTF** | **1BLA** | **2–5BLA** |
|---|---|---|---|---|---|---|---|---|
| **Dose [mSv]** | 3.6E−03 | 7.5E−04 | 6.8E−04 | 1.3E−04 | 6.4E−05 | 6.5E−05 | 2.0E−05 | 1.4E−06 |
| **Contribution** | | | | | | | | |
| Ni-63 | 78 % | 83 % | 69 % | 67 % | 32 % | 51 % | 19 % | 31 % |
| Cs-137 | 7 % | 4 % | 2 % | | 44 % | 12 % | 1 % | 7 % |
| Ag-108m | 4 % | 3 % | 4 % | 3 % | 5 % | 11 % | 3 % | 6 % |
| Am-241 | | | 4 % | | 2 % | | | 3 % |
| Ni-59 | 3 % | 4 % | 2 % | 3 % | 2 % | 3 % | | 1 % |
| Sr-90 | 1 % | 1 % | 2 % | | 4 % | 6 % | | 4 % |
| Nb-94 | 3 % | 1 % | 12 % | 10 % | 2 % | 3 % | | 7 % |
| Mo-93 | 2 % | | 3 % | 15 % | 3 % | 5 % | | 4 % |
| Cl-36 | | 2 % | 1 % | | 3 % | 3 % | 13 % | 11 % |
| C-14 | | | | | | 2 % | | |
| Ca-41 | | | | | | | | 5 % |
| Tc-99 | | | | | | | | 2 % |
| U-238 | | | | | | | 47 % | 3 % |
| U-235 | | | | | | | 14 % | 13 % |

## 4.3 Intrusion well scenario

Drilling a well for water supply (FHA08) is considered a credible action that may lead to direct intrusion into the repository. It is judged that drilling a well can be inadvertent and at the same time technically possible and practically feasible, plausible, and conceivable in the societal context.

### 4.3.1 Scenario description

Drilling a well for water supply is a common practice today, especially in rural areas, and is deemed a credible human action also in the future. Based on well depth statistics, a well for household water is typically around 60 m deep in the Forsmark area (Werner et al. 2013), but a deeper well cannot be excluded.

The premises for this scenario are that the technology and motivation to drill a water well to repository depth exist, that the knowledge of the location and/or purpose of the repository is lost, and that the intruders do not recognise that the drawn water contains repository-derived radionuclides. As described in Section 3.1.1, the overall safety principles of SFR are *limitation of the activity of long-lived radionuclides* and *retention of radionuclides*. A single borehole into the repository is assumed to have an insignificant effect on these safety principles; instead, this scenario focuses on how future humans could be exposed due to utilising the well water.

The main assumption in the intrusion well scenario is that the borehole for the well directly intersects a repository waste vault and the water drawn contains radionuclides from the repository. Currently, and also directly after the closure of SFR, the repository footprint on the surface is submerged under the sea. Wells for drinking water drilled into the repository are assumed possible, at the earliest, when the repository footprint will have become land due to shoreline regression, and high enough above sea level (about 1 m) to avoid sea water intruding into the well. This is assumed to occur at earliest about year 3000 AD in the *present-day climate variant* of the reference evolution (**Biosphere synthesis report**, Chapter 9). This time is cautiously selected as the earliest a household water well may be drilled. It can be noted that this means that the assumed 300-year period of institutional control is not a measure that has any impact on the consequences of the future human action assessed in this scenario, if it was to occur.

#### ***Calculation cases identified to analyse the intrusion well scenario***

One calculation case is identified for the intrusion well scenario, coupled to the releases from the repository in the *base case* under the main scenario:

- *Intrusion well into the repository* (FHA_IW)

The calculation case is presented below.

### 4.3.2 Intrusion well into the repository (FHA_IW)

In this calculation case, it is assumed that a water well is drilled and that the borehole penetrates into a waste vault of the repository. Consequently, radionuclides released from this vault are mixed with the well water. The only exposure pathway considered is utilising the well water as the source of drinking water. This simple single-pathway approach is selected since it is expected that exposure due to drinking water will dominate. Using the well water also for irrigating a garden plot would result in higher doses, although likely not more than a few tenths of percent higher. Table C-1 in the **Biosphere synthesis report** indicates that doses from ingestion of water from a drilled well are about 5 times higher for many radionuclides than doses from ingestion of food from a garden plot irrigated with the same water. The results from the radionuclide transport model for the repository in the *base case* are applied (**Radionuclide transport report**, Chapter 5), in which radionuclide releases from the repository commence shortly after the closure of SFR.

#### ***Models and data applied***

The concentrations of radionuclides in the intrusion well are very cautiously assumed to be equal to the pore water concentrations in the backfill. In waste vaults lacking backfill (BLA), the concentrations are assumed to be equal to the concentrations in free water in the vault. The radionuclide concentrations used in this FHA calculation case are taken from the *base case* (**Radionuclide transport report**, Chapter 5). The annual dose is calculated using a daily intake of drinking water of 2 litres (Grolander 2013, Section 10.3).

Currently, the footprint of SFR is submerged under the sea. Wells for drinking water can be drilled into the repository at the earliest when the shoreline has passed the repository and the land is at least 1 m above sea level to avoid the saline water intruding into the well (Werner et al. 2013, Section 6.4). The location of the shoreline in the *base case* is summarised at important time points in the **Biosphere synthesis report**, Table 9-1. At 2500 AD, the shoreline is located directly above the repository and at 3000 AD about 75 % of the surface above the repository has become land. It will likely take a few hundreds of years more until the entire surface above the repository has become land at least 1 m above sea level. However, in this calculation case it is cautiously selected that a well can be drilled into the repository at 3000 AD at the earliest.

#### ***Results***

Annual doses are derived for a person utilising the water from a well drilled into one waste vault. The four waste vaults 2–5BLA result in almost identical doses and are represented below by the average doses over these vaults, denoted 2–5BLA. The total doses, summed over all radionuclides, are presented in Figure 4-10 for the entire assessment period. The dose maxima over all waste vaults span from about 0.04 mSv (1BTF) to 1.3 mSv (2–5BLA). The dose maxima for most waste vaults occur at 3000 AD, i.e. directly after it is assumed a well may be drilled. Only the silo and 2BMA have dose maxima at later times, at 4050 AD and at the end of the assessment period, respectively. Figure 4-11 shows the same doses, limited to the first 10 000 years, also including hypothetical doses assuming no credit for either the 1000-year period during which no intrusion well may be drilled or the 300-year period for which it assumed that memory of SFR will be kept.

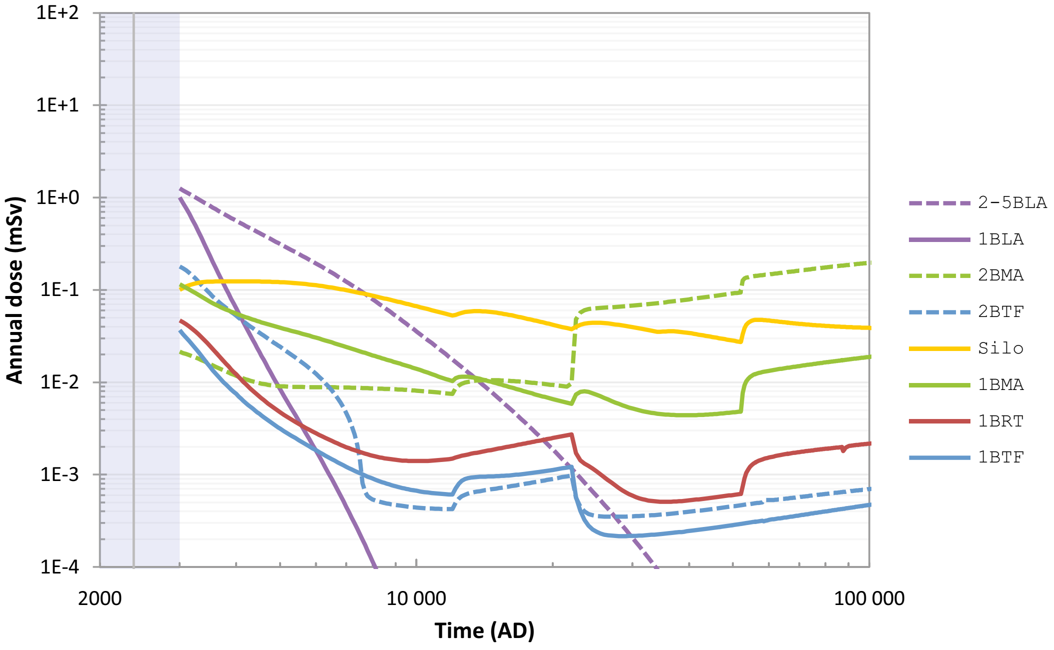

***Figure 4-10.*** *Annual doses for a well drilled into the different waste vaults in the calculation case FHA_IW. The submerged period is indicated by the blue shaded area and the earliest time when it is assumed that memory of SFR may be lost is marked with a grey vertical line.*

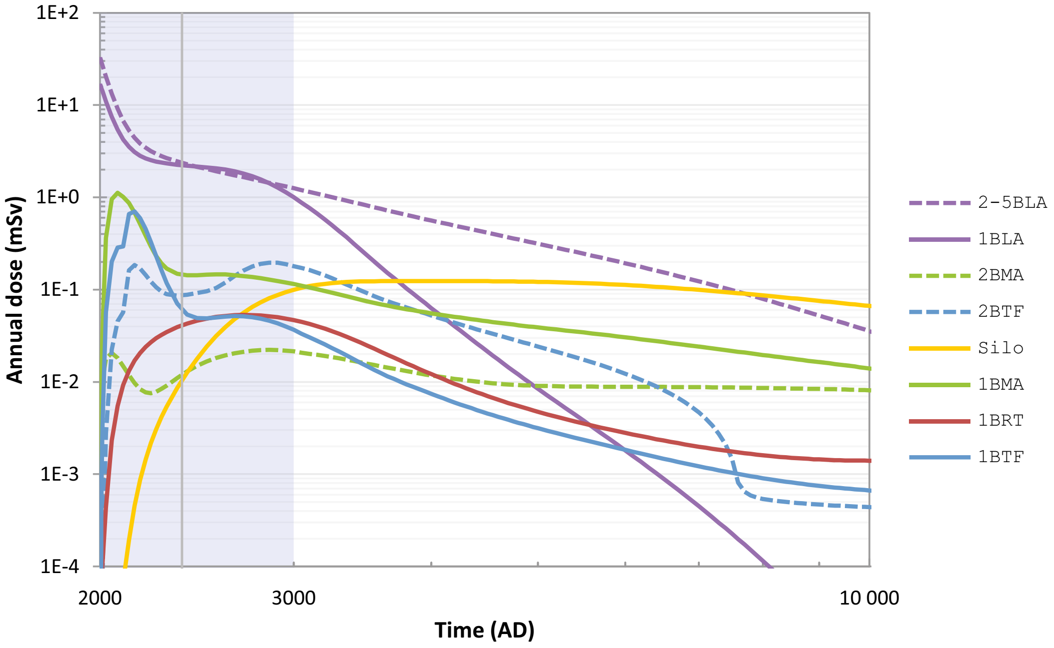

***Figure 4-11.*** *Annual doses for the first ten millennia for a well drilled into the different waste vaults in the calculation case FHA_IW, including hypothetical doses if no credit is taken either for the 1000-year period during which it is assumed that no intrusion well may be drilled (blue shaded area) or the earliest time when it is assumed that memory of SFR may be lost (marked with a grey vertical line).*

The total and radionuclide-specific doses for radionuclides contributing most to the dose maxima are plotted in Figure 4-12 to Figure 4-14 for 2–5BLA, silo and 2BMA. These are the three waste vaults resulting in the highest doses over time. All dose maxima and key contributing radionuclides are presented in Table 4-11. Note that Figure 4-11 to Figure 4-14 also include calculated hypothetical doses for the initial 1 000-year period when no intrusion well may be drilled since the site is submerged. This is further discussed below.

At the time of dose maximum for 2–5BLA, i.e. at 3000 AD, the radionuclides most contributing to the total dose are Am-241 (33 %), Pu-239 (24 %) and Pu-240 (23 %). Initially, Cs-137 would hypothetically have dominated the total dose, if a well could have been drilled, but since its half-life is about 30.2 years it decays significantly and makes an insignificant contribution after the submerged period (Figure 4-12). Co-60, Sr-90 Ni-63 and Pu-238 would also, hypothetically, have contributed during the early phase after closure, but these also have sufficiently short half-lives to not give any significant contributions to the total dose after the submerged period (Figure 4-12).

Compared with the BLA waste vaults, the silo has a barrier system with considerably higher protective capability. This leads to a rather slow initial increase in the radionuclide concentrations in the water in the vault, and hence in the well water. Consequently, doses are initially low for the silo and reach their maximum at 4050 AD (Figure 4-13). The radionuclides most contributing to the total dose at the time of dose maximum are the organic fraction of C-14, I-129, Se-79 and Mo-93 (Table 4-11).

As for the silo, 2BMA also has barriers with high protective capability and hypothetical doses, if a well could have been drilled, during the first submerged 1000 years would not be significantly higher than the doses calculated after the area above SFR becomes land. In fact, 2BMA has the dose maximum at the end of the assessment period and the radionuclide dominating the total dose at that time is Po-210, with a minor contribution from Ra-226 (Table 4-11). These radionuclides are decay products of U-234.

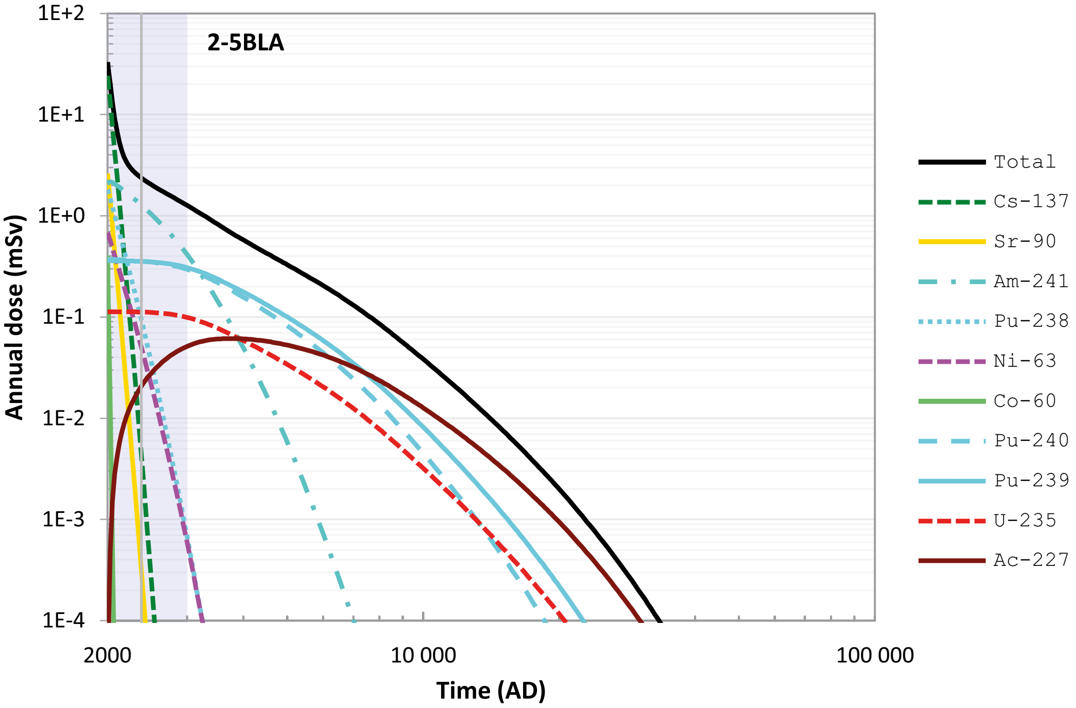

***Figure 4-12.*** *Annual doses, total and from radionuclides most contributing to the dose maximum and hypothetically directly after closure, for an individual utilising the water from a well drilled into 2–5BLA in FHA_IW. Hypothetical doses if no credit is taken either for the 1000-year period during which it is assumed that no intrusion well may be drilled (blue shaded area) or the earliest time when it is assumed that memory of SFR may be lost (marked with a grey vertical line).*

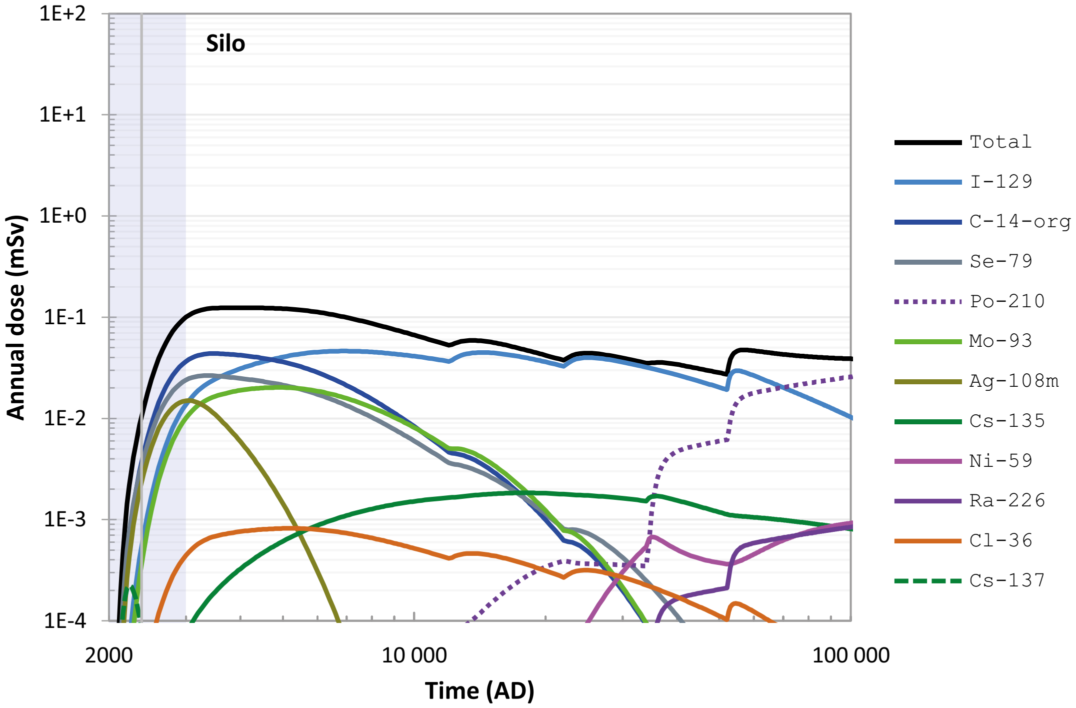

*Figure 4-13. Annual doses, total and from radionuclides most contributing to the dose maximum and hypothetically directly after closure, for an individual utilising the water from a well drilled into the silo in FHA_IW. Hypothetical doses if no credit is taken either for the 1000-year period during it is assumed that no intrusion well may be drilled (blue shaded area) or the earliest time when it is assumed that memory of SFR may be lost (marked with a grey vertical line).*

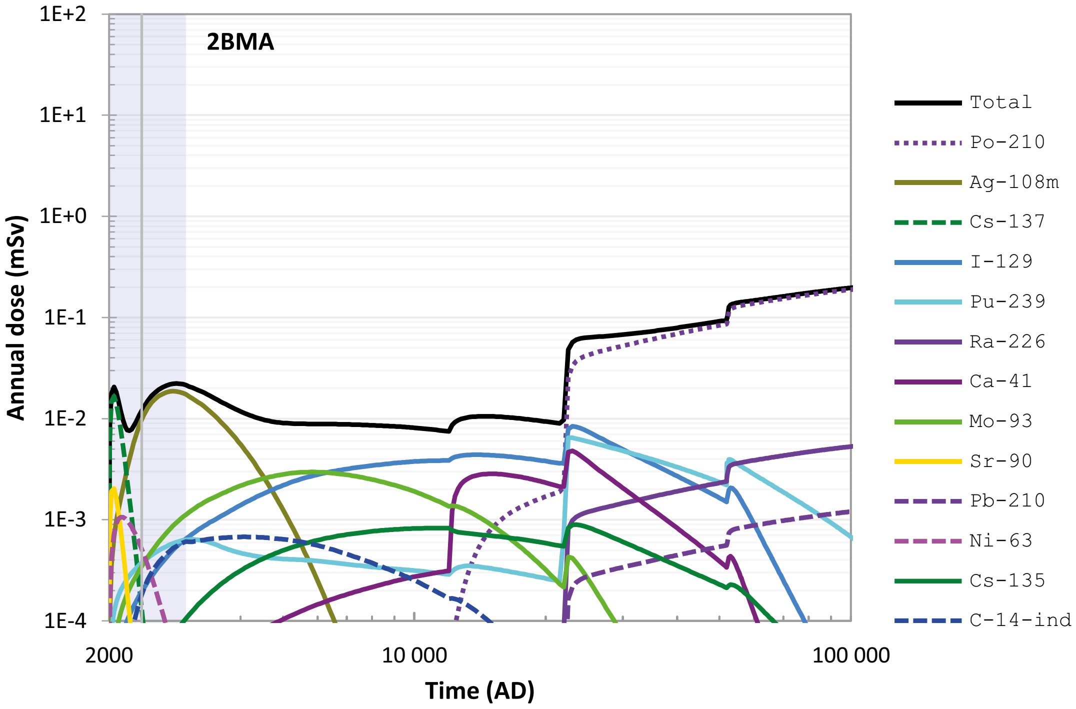

*Figure 4-14. Annual doses, total and from radionuclides most contributing to the dose maximum and hypothetically directly after closure, for an individual utilising the water from a well drilled into 2BMA in FHA_IW. Hypothetical doses if no credit is taken either for the 1000-year period during it is assumed that no intrusion well may be drilled (blue shaded area) or the earliest time when it is assumed that memory of SFR may be lost (marked with a grey vertical line).*

**Table 4-11. Annual dose maxima for calculation case FHA_IW with contributions to the dose from key radionuclides at the time of dose maxima.**

| **Waste vault** | **Silo** | **1BMA** | **2BMA** | **1BRT** | **1BTF** | **2BTF** | **1BLA** | **2–5BLA** |
|---|---|---|---|---|---|---|---|---|
| **Dose [mSv]** | 0.12 | 0.11 | 0.20 | 0.047 | 0.037 | 0.18 | 1.0 | 1.3 |
| **Time [AD]** | 4050 | 3000 | 102 000 | 3000 | 3000 | 3000 | 3000 | 3000 |
| **Dose contribution** | | | | | | | | |
| C-14-org | 34 % | 34 % | | | 20 % | | | |
| Se-79 | 20 % | 5 % | | | 6 % | | | |
| Mo-93 | 15 % | | | 13 % | 8 % | | | |
| Ag-108m | | 43 % | | 86 % | 32 % | 9 % | | |
| I-129 | 25 % | 11 % | | | 32 % | | | |
| Po-210 | | | 96 % | | | | | |
| Ac-227 | | | | | | | 9 % | |
| Pa-231 | | | | | | | 5 % | |
| U-235 | | | | | | | 17 % | 8 % |
| U-238 | | | | | | | 58 % | |
| Pu-239 | | | | | | 46 % | | 24 % |
| Pu-240 | | | | | | 35 % | | 23 % |
| Am-241 | | | | | | | | 33 % |

Figure 4-11 to Figure 4-14 include calculated hypothetical doses for the initial 1 000-year period when no intrusion well may be drilled since the site is submerged. The reason for this is to highlight the potential importance of this period from a dose perspective. In contrast to the *drilling into the repository scenario* (Section 4.2) where the doses are calculated from the inventory in the waste packages, the doses are here derived from the radionuclide releases from the waste packages in the *base case* (**Radionuclide transport report**, Chapter 5). In this calculation case, this leads to the hypothetical doses prior to 3000 AD for the silo, 2BMA, 2BTF and 1BRT being similar to, or lower than, the dose maxima in the period beyond 3000 AD (Figure 4-11). For the BLA waste vaults, 1BMA and 1BTF, the dose maxima for the hypothetical doses during the submerged period are about 10–30 times higher than their corresponding dose maxima beyond 3000 AD (Figure 4-11). This does not mean that the measure of locating SFR under the sea is not effective from a human intrusion perspective – even though the results indicate that the doses are lower for only some of the waste vaults, its currently submerged location greatly lowers the potential for the intrusion well to be drilled in the first place.

## 4.4 Water management scenario

Water management (FHA09) is considered to embrace several credible actions that potentially may lead to altered groundwater flows at repository depth.

### 4.4.1 Scenario description

The premises for this scenario are that the technology and motivation to conduct a sufficiently major activity, related to water management, exists and that the knowledge of the location and/or purpose of the repository is lost. This scenario assumes that a water impoundment is constructed in the vicinity of SFR using parts of existing causeways, for example as a hydropower resource or for irrigation purposes. It is assumed that the potential impact at repository depth by this action is representative of, or has a greater impact than, many types of water management actions.

#### *Calculation cases identified to analyse the water management scenario*

One calculation case has been identified to be representative of a major water management activity:

- *Construction of a water impoundment* (FHA_WM)

This calculation case is presented below.

### 4.4.2 Construction of a water impoundment (FHA_WM)

To analyse the scenario with a water impoundment in the vicinity of SFR, it is assumed that the SFR pier and/or other artificial causeways in the area are utilized and modified as part of a dam for a future water impoundment. The effect of such an impoundment would be increased groundwater heads in a wide area upstream of the repository. As an illustrative example of the effects of an impoundment, this calculation case uses the work published by the Swedish authorities (SSM 2019), where a future water impoundment on the west edge of the hydrogeological domain for the SFR modelling is assumed (SSM 2019, Figure 9), and the increase in flowrate through the vaults due this impoundment is estimated.

It should be noted that to build the suggested impoundment, at least 1 km of extra embankments would have to be constructed. The high permeability of the existing causeways also means that extensive engineering work would be needed to make the impoundment dams tight enough. Furthermore, at nearby Kallrigafjärden, located to the southeast of the SFR, a much larger impoundment could be constructed with less effort.

To estimate if altered hydrological conditions in the repository due to the impoundment would have any impact on radiological consequences, annual doses are also calculated. For simplicity, it is assumed in the radionuclide transport calculations that the impoundment will be built 300 years after closure of the repository and will exist throughout the 100 000 year assessment period.

#### *Models and data applied*

The hydrogeological analysis in SSM (2019) is based on the simplified model presented in SSM (2017). In this simplified model, flow paths through the repository are assumed to pass from the surface, through a brittle deformation zone, through the sparsely fracture host rock and the repository to a second brittle deformation zone and further back up to the surface. In the analysis, a 5 m head difference between inflow and outflow points is assumed to exist approximately 1 000 years in the future. Furthermore, a 15 m deep impoundment is assumed on top of the upstream brittle deformation zone, which is assumed to not cause any significant changes in the flow paths. In the calculations performed for SSM, the 15 m deep impoundment resulted in a factor of four increase of the flowrates through the repository (SSM 2019). The simplified model applied by SSM is based on a linear system. Due to the dominance of the effect of the deformation zones, the flow paths passing through the repository are not assumed to change significantly in SKB's full 3D hydrogeological model either, when the impoundment is considered, and therefore the approach suggested by SSM is valid.

The radionuclide transport and dose calculations are based on the *base case* (described in detail in the **Radionuclide transport report**, Chapter 5). The *base case* constitutes the basis for the analysis of the main scenario and, thus, for the radionuclide transport and dose calculations in the PSAR. External conditions follow from the *present-day climate variant* of the reference evolution (**Post-closure safety report**, Chapter 6). It assumes that present-day climate conditions prevail for the entire assessment period and that the initial rate of shoreline regression is dominated by the post-glacial isostatic uplift, resulting in 1 000 years of submerged conditions above the repository. After terrestrial conditions have been fully established in the area, the conditions in the geosphere and the biosphere are assumed to remain constant for the rest of the assessment period, and all the geosphere release is cautiously assumed to be discharged to biosphere object 157_2 just north of the repository. During this period, temporal changes in the transport conditions for the radionuclides are confined to the repository, primarily as a result of physical and chemical degradation of the concrete barriers in the waste vaults.

The data applied in the radionuclide transport calculations are the same as in the *base case*, except for the groundwater flowrates in the bedrock and through the waste vaults. Considering that the calculations performed for SSM (SSM 2019) resulted in a factor of four increase of the flowrates through the repository, it has here been selected to analyse the postulated condition of a four-fold increase of the flowrates in the bedrock and through the waste vaults compared with the *base case*. In addition, to investigate the potential impact of even more altered hydrological conditions, a ten-fold increase of flowrates is also analysed.

The potentially exposed groups included in the dose calculations are garden-plot households (GP) and drained mire farmers (DM) (**Biosphere synthesis report**, Section 6.2). The historical land use variants related to hunter-gatherers and infield-outland farmers are not included. This to be consistent with the assumption of present-day level of technology in all FHA scenarios (Table 4-1).

### *Results*

The annual doses to the most exposed groups in the *base case* and for the postulated higher flow rates in the bedrock and through the waste vaults are shown in Figure 4-15. For the four-fold increase in flow rate, corresponding to the results from the calculations performed for SSM (SSM 2019), the dose maximum increases from 0.0056 mSv to 0.012 mSv. For the ten-fold higher postulated increase in flowrate the dose maximum is 0.019 mSv.

The annual doses from individual radionuclides contributing most to the total dose are shown in Figure 4-16 and Figure 4-17, including the relative increase in the individual dose maxima compared with the *base case*. As may be expected, it is radionuclides of elements that are non-sorbing in the repository and in the geosphere, such as C, Mo and I, for which doses increase most when the flowrates are increased. The doses for C-14, Mo-93 and I-129 increase about 2.5–3 times when the flowrate is increased 4 times and increased about 5 times when the flowrate is increased 10 times. Mo-93 is the radionuclide contributing most to the dose maximum in the *base case*, and also in this calculation case.

The results obtained from analysing this illustrative example indicates that a large-scale water management action, as assumed in this calculation case, may lead to altered hydrological conditions in the geosphere and the repository, and may potentially lead to increased doses. However, the doses increase rather moderately compared with the *base case*, even for postulated ten-fold higher flow rates.

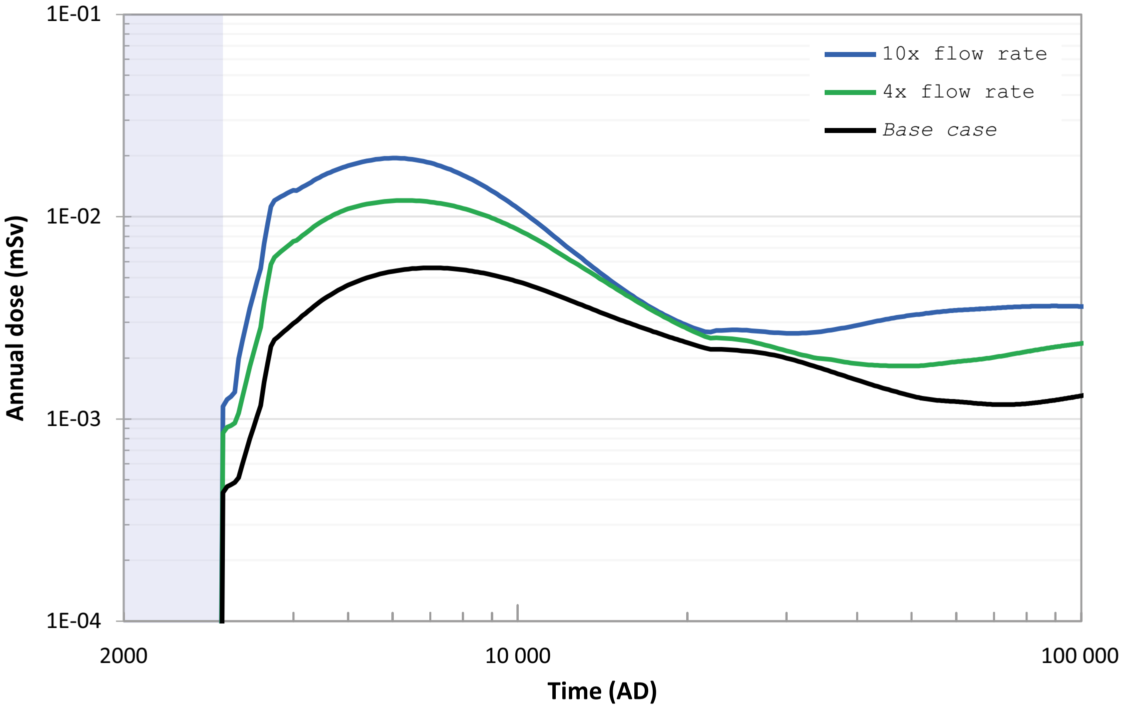

***Figure 4-15.*** *Annual doses to the most exposed group in the construction of a water impoundment calculation case, applying four- and ten-fold higher flow rates in the bedrock and through the waste vaults. The black line shows the annual dose in the base case for comparison. The submerged period is indicated by the blue shaded area.*

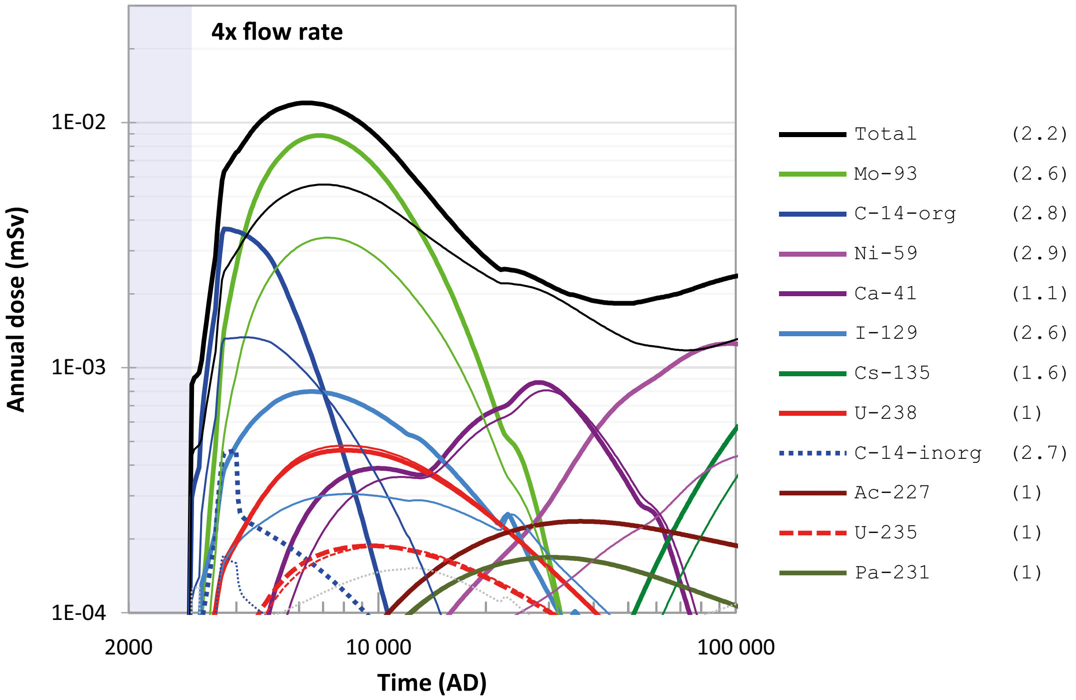

*Figure 4-16. Annual doses, total doses and for the radionuclides contributing most to the total dose, to the most exposed group in the construction of a water impoundment calculation case, for four-fold higher flow rates in the bedrock and through the waste vaults. The thin lines show the corresponding doses in the base case for comparison. The numbers in the round brackets represent the ratio of the dose maxima in this calculation case and the base case.*

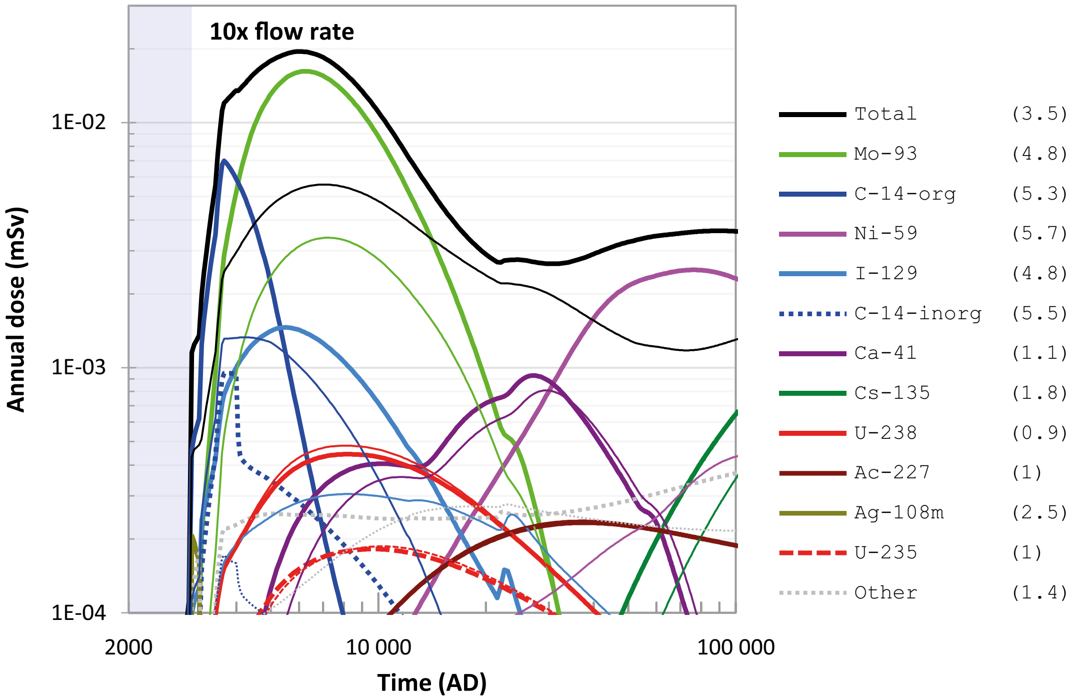

*Figure 4-17. Annual doses, total doses and for the radionuclides contributing most to the total dose, to the most exposed group in the construction of a water impoundment calculation case, for ten-fold higher flow rates in the bedrock and through the waste vaults. The thin lines show the corresponding doses in the base case for comparison. The numbers in the round brackets represent the ratio of the dose maxima in this calculation case and the base case.*

## 4.5 Underground construction scenario

That humans in the future may develop underground constructions (FHA12) in the vicinity of SFR is considered a credible action. Potential exploratory drilling in the case that the construction is to be developed within the SFR footprint is addressed in the drilling scenario (Section 4.2). This scenario addresses impacts on the repository from potentially altered groundwater flows due to an underground construction near SFR.

### 4.5.1 Scenario description

The premises for this scenario are that the technology and motivation to construct large underground excavations exist and that the knowledge of the location and/or purpose of the repository is lost. The main assumption is that a major underground construction is built near the SFR.

#### *Calculation cases identified to analyse the underground construction scenario*

Two types of underground constructions in the vicinity of the repository are considered, leading to the selection of the following two calculation cases:

- *Rock cavern in the close vicinity of SFR (FHA_UC_RC).*
- *Mine in the vicinity of the Forsmark site (FHA_UC_M).*

### 4.5.2 Rock cavern in the close vicinity of SFR (FHA_UC_RC)

The impacts of a rock cavern on the capacity of the rock to provide favourable hydrological and transport conditions for SFR will depend on the location, depth and size of the rock cavern. The purpose for which the rock cavern is constructed is of lesser importance.

A cavern west of the Singö deformation zone (cf. Figure 4-18) would not influence the SFR repository negatively as the hydraulic gradient is from west to east and a regional deformation zone is in between. A nearby cavern north, south or east of the repository could result in somewhat larger hydraulic gradients and hence larger flow through the waste vaults. Depending on where the cavern is constructed, and on its size, not only the gradient but also the location and length of a flow path may be affected.

As an illustrative example of a rock cavern, this calculation case uses the work published by the Swedish authorities (SSM 2019), where a rock cavern located within 0.5 km northeast of SFR was assumed and the increase in flowrate through the waste vaults was estimated. To estimate if altered hydrological conditions in the repository due to the rock cavern have any impact on radiological consequences, annual doses are also calculated.

#### *Models and data applied*

The hydrogeological analysis used in this calculation case is based on the simplified model presented in SSM (2017). In this model, flow paths through the repository are assumed to pass from the surface, through a brittle deformation zone, through the sparsely fracture host rock and the repository to a second brittle deformation zone back up to the surface. To scope the potential effect of a rock cavern on flows through the SFR, a simple calculation was performed with a cavern located within 0.5 km northeast of SFR, with its floor approximately 35 m below the ground level, so that the net difference in hydraulic head was 40 m (SSM 2019). In the calculations performed for SSM, the assumed rock cavern could lead to an increase in median flow rates through the waste vaults by roughly a factor 4 to 5 (SSM 2019).

This increase in the flow rate is abouts the same as that applied in the *construction of a water impoundment* calculation case, where a 15 m deep impoundment resulted in a factor of four increase of the flow rates through the repository (Section 4.4.2). Hence, the radionuclide transport and dose calculations for the *construction of a water impoundment* calculation case are applicable also for this calculation case, in which annual doses due to four-fold and ten-fold increases in the bedrock and through the waste vaults compared with the *base case* are estimated.

### *Results*

The resulting annual doses for the *construction of a water impoundment* calculation case, presented in Section 4.4.2 are applicable for this calculation case related to a rock cavern. Hence, the results indicate that the construction of a rock cavern in the vicinity of SFR may lead to altered hydrological conditions in the geosphere and the repository and may potentially lead to increased doses. However, the doses increase rather moderately compared with the *base case*, even for postulated ten-fold higher flow rates.

### 4.5.3 Mine in the vicinity of the Forsmark site (FHA_UC_M)

The ore potential at Forsmark has been analysed within the site investigations for a repository for spent nuclear fuel. There is today no interest in mining iron ore of the type that occurs in the municipality of Östhammar and the Forsmark area. Even viewed in a long-term perspective, it is very unlikely that there will be any new prospecting for iron ores of the type found there (Lindroos et al. 2004).

However, in an area southwest of the Forsmark site´, a felsitic to metavolcanic rock, judged to have a small potential for iron oxide mineralisation, has been identified (Lindroos et al. 2004) (Figure 4-18). The mineral deposits have been assessed to be of no economic value. Nevertheless, as this judgement may be revised in the future due to economic reasons, the potential exploitation of this mineralisation is addressed.

Since the mineralisation at the present is judged to be of no value, it is impossible to describe the design of a mine exploiting the mineralisation based on current mining standards. It could be a quarry or a mine and the depth could be from tens to hundreds of metres or for mines a thousand metres or even deeper.

### *Results*

If a mine were to be constructed in the vicinity of the Forsmark site, it may be assumed that the largest influence on the repository would occur if the construction took place near the repository (cf. Section 4.5.2). The argument for SFR is based on the assessment of the potential hydraulic impact from a mine on the planned spent nuclear fuel repository (SKB TR-10-53).

The spent nuclear fuel repository is located so that the closest distance between the repository and a hypothetical mine in the potential area for mineralisation would be around 1 to 1.5 km (Figure 4-18). In order to assess the potential influence on the repository, results from analyses of the hydraulic impact of an open repository were used, which showed that at a distance of about 1 km from the repository, the drawdown at 450 m depth was negligibly small. The reason for this small radius of influence is the low hydraulic conductivity of the rock mass volumes at repository depth. These results are valid at the depth of the spent nuclear fuel repository. But since SFR is located about 2 km even further away from the potential area for mineralisation than the spent nuclear fuel repository, it is judged the potential hydraulic impact on SFR from a hypothetical mine would be insignificant.

In addition, the influence on SFR from the planned spent nuclear fuel repository has been assessed and the results indicate a negligible influence for present climate conditions (Hellman et al. 2014). This also is assumed to be the case for future temperate climate conditions as the change in boundary conditions only will result in a more locally, topography driven, flow field in the SFR area.

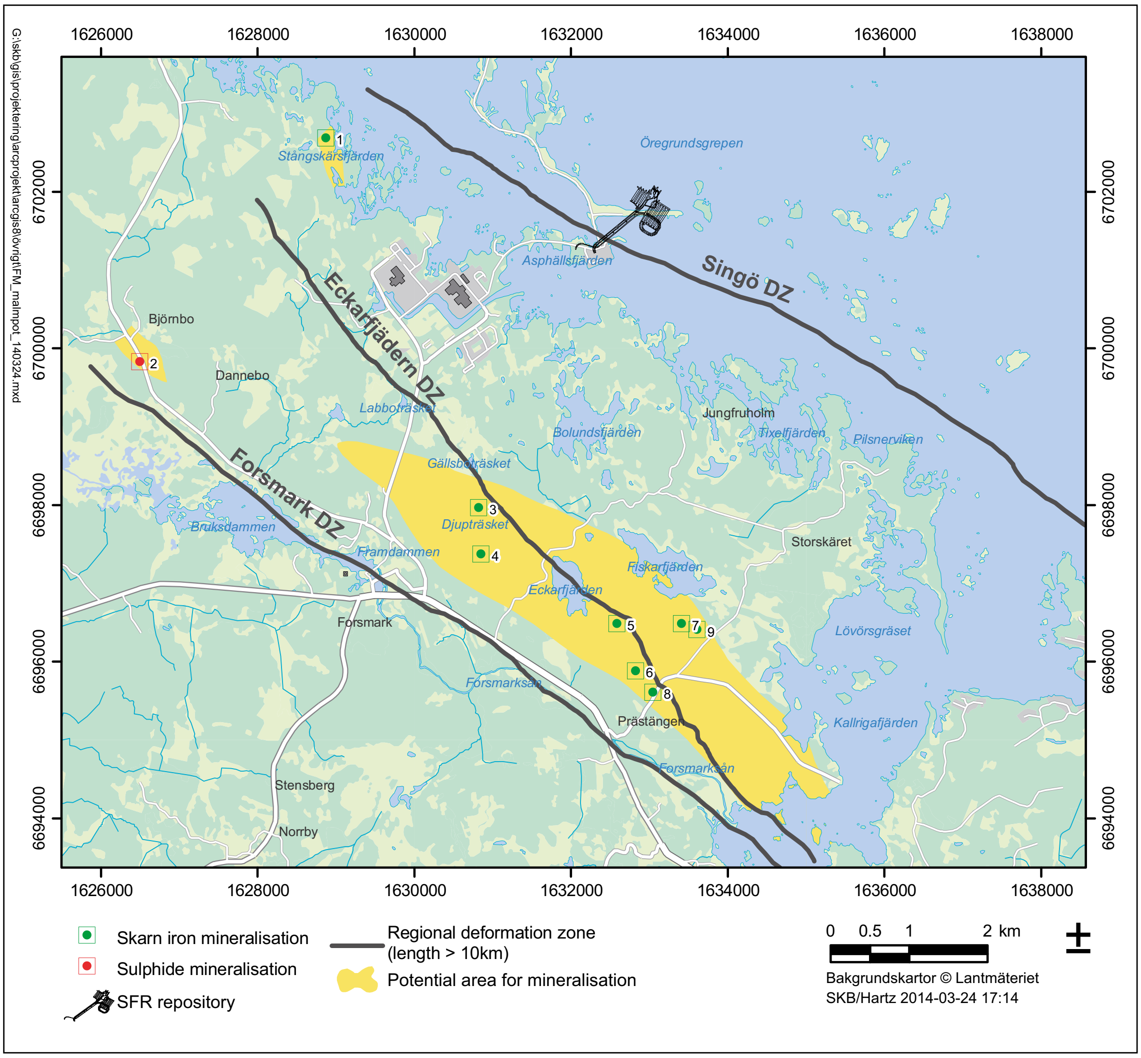

***Figure 4-18.*** *Map showing the areas on the surface that are judged to have some exploration potential for mineral deposits (modified after Figure 6-5 in SKB TR-10-53).*

# 5 Summary and conclusions

This report presents the handling of future human actions (FHA) considered in the PSAR. Those are actions potentially resulting in 1) changes to the barrier system affecting, directly or indirectly, the rate of the release of radionuclides from SFR, and/or 2) radioactive waste being brought to the surface giving rise to exposure of people at the surface. In the assessment, FHAs are limited to inadvertent actions, which are defined as actions carried out without knowledge of the repository and/or its nature (the location of the repository, its purpose and the consequences of the actions). This chapter briefly summarises the methodological approach to handle FHAs (Section 5.1) and the FHA scenarios and the results from analysing them (Section 5.2) and presents the overall conclusions on FHA in the context of the PSAR (Section 5.3).

## 5.1 Methodological approach to handle FHAs

A FHA FEP analysis was carried out, based on the safety functions defined in Chapter 5 of the **Post-closure safety report**, and the understanding of the behaviour of the repository system drawn from previous work and the rest of the PSAR. FHA FEPs were identified and described, and their potential impact on the repository safety is discussed, to allow for the selection of a set of stylised FHA scenarios. The selected scenarios are intended to comprise an illustrative set of credible future human actions but should not be considered fully comprehensive or complete. The FHA scenarios are then described, and analysed either qualitatively, by reasoning or arguing that they have similar impacts to those determined in calculations performed for other purposes in the PSAR, or quantitatively in terms of deriving doses to humans. All the results should be regarded as illustrative and are not to be used to evaluate regulatory compliance with risk or dose constraints.

## 5.2 FHA scenarios and calculation cases

Four stylised FHA scenarios have been identified and analysed in this report. Two of them illustrate direct intrusion into the repository by drilling. These two are the *drilling into the repository* scenario, which focuses on radioactive material being brought to the surface during the drilling event, giving rise to exposure of people, and the *intrusion well* scenario, in which drilling for a household water supply is addressed.

Three calculation cases are analysed in the *drilling into the repository* scenario; exposure of the drill crew during a drilling event, and exposure of people either cultivating or performing construction on land containing contaminated drilling detritus from a drilling event. For these three cases, the calculated effective dose maximum is 0.014 mSv, related to bringing a 1 m drill core from 2BMA to the surface, which results in exposure of the drill crew. If the more pessimistic assumption is made that the full heights of waste in the vaults are brought to the surface during the drilling event, then the highest dose maxima would be about 0.5 mSv, origin from rotary drilling into the silo. For this to occur, 50 m of material from the borehole needs to be handled without realising its radiological hazard. The doses for the two cases where people utilise the land containing contaminated drilling detritus from the drilling event are lower. Maximum effective dose to a construction worker, conducting work for one year on a landfill containing contaminated drilling detritus, is 0.0022 mSv, and maximum annual dose to a person cultivating vegetables and tubers on a similar landfill is about 0.0036 mSv.

For the *intrusion well* scenario, the calculated annual dose maximum is 1.3 mSv for a well drilled into one of the 2–5BLA waste vaults at 3000 AD. This is assumed to be the earliest possible time a well can be drilled into the repository, corresponding to when about 3/4 of the repository footprint to have become land due to shoreline regression.

The two other FHA scenarios illustrate future human actions not directly intruding into the repository, but which may have impacts on the repository due to potentially altered groundwater flow in the bedrock and through the waste vaults: the *water management* scenario and the *underground construction* scenario.

One calculation case is analysed in the *water management* scenario, namely the *construction of a water impoundment* calculation case. It is assumed in this case that the SFR pier and/or other artificial causeways in the area are utilized and modified as part of a dam for a future water impoundment in the vicinity of SFR. Annual doses are calculated, postulating that the impoundment results either in a four-fold or a ten-fold increase of the groundwater flowrates in the bedrock and through the waste vaults compared with the *base case* in the main scenario in the post-closure safety assessment. These hydrological impacts are selected based on calculations performed for SSM, where a 15 m deep impoundment resulted in a factor of four increase of the groundwater flow rates through the repository (SSM 2019). For the postulated four-fold increase in flow rate, the annual dose maximum is 0.012 mSv. This is about two times higher than the dose maximum in the *base case* (0.0056 mSv). For the postulated ten-fold higher flowrate, the annual dose maximum is 0.019 mSv, which is about 3.5 times higher than in the *base case*.

Two calculation cases are analysed in the *underground construction* scenario: the *mine in the vicinity of the Forsmark site* calculation case and the *rock cavern in the close vicinity of SFR* calculation case. In the case involving a mine, it is judged that the potential hydraulic impact on SFR from a hypothetical mine in the vicinity of the Forsmark site would be insignificant. The argument made for SFR is based on the assessment of the potential hydraulic impact from a mine on the planned spent nuclear fuel repository (SKB TR-10-53). In the case with the rock cavern, the same increases of the flowrates in the bedrock and through the waste vaults as in the *construction of a water impoundment* calculation case are assumed. These hydrological impacts are selected based on calculations performed for SSM, where a rock cavern located within 0.5 km northeast of SFR was assumed and the increase in flow rate through the repository was estimated to be a factor of four to five (SSM 2019). Hence, the resulting annual doses in this calculation case are comparable to the doses in the *construction of a water impoundment* calculation case.

## 5.3 Conclusions

The scenarios identified and analysed in this report are judged to provide a sufficiently broad perspective to facilitate the argument that SFR is robust against a wide range of credible future human activities.

A key outcome from the dose calculations is that most of the doses are below 1 mSv, which is the criterion set out by the IAEA (2011) below which efforts to reduce the probability of intrusion or to limit its consequences are not warranted. Only in the calculation with an intrusion well in the BLA vaults does the dose exceeds 1 mSv for a well drilled at the earliest time possible (3000 AD) or within a few hundreds of years after that. After about 3300 AD, all doses are below 1 mSv. If, according to the IAEA, annual doses in the range 1–20 mSv are indicated, then reasonable efforts are warranted at the stage of development of the facility to reduce the probability of intrusion or to limit its consequences by means of optimisation of the facility's design (IAEA 2011). For SFR this has been done by selecting geological disposal, which is widely deemed as the most effective measure to reduce the potential[7] for human intrusion to occur. Furthermore, compartmentalising the radioactive waste into several waste vaults is a measure related to limiting the consequences if intrusion was to occur.

The results from analysing the scenarios without a direct intrusion into SFR, i.e. water management and underground constructions in the vicinity of the repository, show that safety functions of the geosphere to provide favourable hydrological conditions and the engineered barriers to limit advective transport are influenced in these scenarios. However, the resulting annual doses are considerably below 1 mSv, and are within a factor of five larger than those in the *base case* (**Post-closure report**, Chapter 7). This clearly indicates that SFR is robust against these types of FHAs.

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[7] The term 'reduce the potential for' is a general statement reflecting the desire to identify features that will help to delay or reduce the likelihood of human intrusion, or any other future human action.

The scenarios involving direct intrusion into SFR, i.e. drilling into the repository and intrusion wells, have a larger influence on the safety functions of the geosphere to provide favourable hydrological conditions and the engineered barriers to limit advective transport. Considering a single bore hole, the impairment is local, and it is considered that the performance of the repository as whole is not significantly weakened.

The illustrative, and pessimistic, dose results in the present analysis do not give rise to concern relative to either the IAEA ranges of doses warranting further reduction of the probability of intrusion or to limit its consequences by means of optimisation of the facility, or relative to the reference levels set by ICRP in either existing situations or emergency situations (ICRP 2013). This is a clear indicator of the robustness of SFR to FHAs.

In conclusion, based on the analysis presented in this report, SFR is a robust disposal facility regarding a broad range of potential FHA.

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# Appendix A

## Updated dose coefficients

When analysing the *drilling into the repository scenario*, results taken from Smith et al. (2013) and Oatway and Mobbs (2003) are applied. In these two publications, the results were derived using dose coefficients where, partly, there is now updated values available.

This appendix presents a comparison of the applied and updated dose coefficients from the ICRP and U.S. Environmental Protection Agency (EPA) used in the calculations. Furthermore, an evaluation of the potential effect on the results in the *drilling into the repository scenario* is made, if the results from Smith et al. (2013) and Oatway and Mobbs (2003) were to be updated with updated dose coefficients.

### Comparison of dose coefficients

Dose coefficients for occupational intakes of radionuclides in ICRP Publication 68 (ICRP 1994), later compiled in ICRP Publication 119 (ICRP 2012) have been superseded by the values recommended in ICRP Publications 130 (ICRP 2015), 134 (ICRP 2016) and 137 (ICRP 2017). Tables A1 and A2 presents the new and old dose coefficients for occupational intake by inhalation and ingestion, limited to radionuclides available in the ICRP reports and relevant in the *drilling into the repository scenario*.

Dose rate coefficients from EPA for external exposure to radionuclides in soil in Eckerman and Ryman (1993) have been superseded by the values recommended in Bellamy et al. (2019). Table A3 presents new and old dose rate coefficients for radionuclides uniformly distributed in soil to infinite depth.

**Table A1. Committed effective dose coefficients (Sv Bq$^{-1}$) for occupational intake by inhalation, and the ratios between the new and old values. Data from ICRP 1994 (ICRP 68) are selected as the highest values, and data from ICRP (2016, 2017) (ICRP 134, 137) are selected to match reasonably well regarding particulate materials and size.**

| Radionuclide | ICRP 134, 137 | ICRP 68 | Ratio | Radionuclide | ICRP 134, 137 | ICRP 68 | Ratio |
|---|---|---|---|---|---|---|---|
| Th-229 | 1.2E−04 | 6.9E−05 | 1.74 | U-233 | 3.1E−06 | 6.9E−06 | 0.45 |
| Nb-94 | 3.8E−08 | 2.5E−08 | 1.52 | Cm-245 | 1.2E−05 | 2.7E−05 | 0.44 |
| Cs-137 | 9.3E−09 | 6.7E−09 | 1.39 | Cm-246 | 1.2E−05 | 2.7E−05 | 0.44 |
| Th-232 | 4.0E−05 | 2.9E−05 | 1.38 | U-236 | 2.8E−06 | 6.3E−06 | 0.44 |
| Th-230 | 3.4E−05 | 2.8E−05 | 1.21 | U-234 | 3.0E−06 | 6.8E−06 | 0.44 |
| Pa-231 | 1.0E−04 | 8.9E−05 | 1.12 | Sr-90 | 3.2E−08 | 7.7E−08 | 0.42 |
| Eu-152 | 2.4E−08 | 2.7E−08 | 0.89 | Cm-244 | 7.0E−06 | 1.7E−05 | 0.41 |
| Cs-135 | 8.8E−10 | 9.9E−10 | 0.89 | Am-241 | 1.1E−05 | 2.7E−05 | 0.41 |
| Np-237 | 1.3E−05 | 1.5E−05 | 0.87 | Am-243 | 1.1E−05 | 2.7E−05 | 0.41 |
| H-3 | 3.5E−11 | 4.1E−11 | 0.85 | Pu-241 | 2.2E−07 | 5.8E−07 | 0.38 |
| Ba-133 | 1.3E−09 | 1.8E−09 | 0.72 | Th-228 | 9.0E−06 | 2.5E−05 | 0.36 |
| I-129 | 6.6E−08 | 9.6E−08 | 0.69 | U-232 | 7.4E−06 | 2.6E−05 | 0.28 |
| Sm-151 | 1.7E−09 | 2.6E−09 | 0.65 | Co-60 | 4.2E−09 | 1.7E−08 | 0.25 |
| Pb-210 | 7.0E−07 | 1.1E−06 | 0.64 | Ra-228 | 4.1E−07 | 1.7E−06 | 0.24 |
| Nb-93m | 5.4E−10 | 8.6E−10 | 0.63 | Zr-93 | 5.5E−09 | 2.9E−08 | 0.19 |
| Pu-242 | 1.9E−05 | 3.1E−05 | 0.61 | Po-210 | 2.8E−07 | 2.2E−06 | 0.13 |
| Pu-238 | 1.8E−05 | 3.0E−05 | 0.60 | Mo-93 | 1.4E−10 | 1.4E−09 | 0.10 |
| Pu-239 | 1.9E−05 | 3.2E−05 | 0.59 | Ra-226 | 1.6E−07 | 2.2E−06 | 0.07 |
| Pu-240 | 1.9E−05 | 3.2E−05 | 0.59 | Tc-99 | 2.0E−10 | 3.2E−09 | 0.06 |
| U-235 | 2.8E−06 | 6.1E−06 | 0.46 | Ac-227 | 3.2E−05 | 6.3E−04 | 0.05 |
| Am-242m | 1.1E−05 | 2.4E−05 | 0.46 | Ca-41 | 6.7E−12 | 1.9E−10 | 0.04 |
| U-238 | 2.6E−06 | 5.7E−06 | 0.46 | C-14 | 1.3E−11 | 5.8E−10 | 0.02 |

**Table A2. Committed effective dose coefficients (Sv Bq$^{-1}$) for occupational intake by ingestions, and the ratios between the new and old values. Data from ICRP (1994) (ICRP 68) are selected as the highest value, and data from ICRP (2016, 2017) (ICRP 134, 137) are selected to match reasonably well (regarding particulate materials and size).**

| Radionuclide | ICRP 134, 137 | ICRP 68 | Ratio | Radionuclide | ICRP 134, 137 | ICRP 68 | Ratio |
|---|---|---|---|---|---|---|---|
| Nb-94 | 2.3E−09 | 1.7E−09 | 1.35 | Ra-226 | 1.3E−07 | 2.8E−07 | 0.46 |
| H-3 | 5.1E−11 | 4.2E−11 | 1.21 | Th-229 | 2.1E−07 | 4.8E−07 | 0.44 |
| Cs-137 | 1.4E−08 | 1.3E−08 | 1.08 | Th-228 | 3.1E−08 | 7.2E−08 | 0.43 |
| Ba-133 | 1.0E−09 | 1.0E−09 | 1.00 | Tc-99 | 2.7E−10 | 7.8E−10 | 0.35 |
| Co-60 | 3.2E−09 | 3.4E−09 | 0.94 | Cm-244 | 3.9E−08 | 1.2E−07 | 0.33 |
| Sr-90 | 2.4E−08 | 2.8E−08 | 0.86 | Th-232 | 7.0E−08 | 2.2E−07 | 0.32 |
| I-129 | 9.4E−08 | 1.1E−07 | 0.85 | Am-242m | 6.0E−08 | 1.9E−07 | 0.32 |
| Po-210 | 1.8E−07 | 2.4E−07 | 0.75 | Am-241 | 5.9E−08 | 2.0E−07 | 0.30 |
| U-234 | 3.5E−08 | 4.9E−08 | 0.71 | Am-243 | 5.8E−08 | 2.0E−07 | 0.29 |
| U-238 | 3.1E−08 | 4.4E−08 | 0.70 | Cm-245 | 6.0E−08 | 2.1E−07 | 0.29 |
| U-233 | 3.5E−08 | 5.0E−08 | 0.70 | Cm-246 | 6.0E−08 | 2.1E−07 | 0.29 |
| U-235 | 3.2E−08 | 4.6E−08 | 0.70 | Th-230 | 6.0E−08 | 2.1E−07 | 0.29 |
| U-236 | 3.2E−08 | 4.6E−08 | 0.70 | C-14 | 1.6E−10 | 5.8E−10 | 0.28 |
| Cs-135 | 1.3E−09 | 2.0E−09 | 0.65 | Np-237 | 3.0E−08 | 1.1E−07 | 0.27 |
| U-232 | 1.8E−07 | 3.3E−07 | 0.55 | Pa-231 | 1.8E−07 | 7.1E−07 | 0.25 |
| Ra-228 | 3.4E−07 | 6.7E−07 | 0.51 | Pu-241 | 1.1E−09 | 4.7E−09 | 0.23 |
| Pu-242 | 1.2E−07 | 2.4E−07 | 0.50 | Nb-93m | 2.7E−11 | 1.2E−10 | 0.23 |
| Pu-239 | 1.2E−07 | 2.5E−07 | 0.48 | Zr-93 | 5.0E−11 | 2.8E−10 | 0.18 |
| Pu-240 | 1.2E−07 | 2.5E−07 | 0.48 | Ac-227 | 1.7E−07 | 1.1E−06 | 0.15 |
| Pu-238 | 1.1E−07 | 2.3E−07 | 0.48 | Sm-151 | 1.2E−11 | 9.8E−11 | 0.12 |
| Pb-210 | 3.2E−07 | 6.8E−07 | 0.47 | Mo-93 | 2.0E−10 | 2.6E−09 | 0.08 |
| Eu-152 | 6.5E−10 | 1.4E−09 | 0.46 | Ca-41 | 5.7E−12 | 2.9E−10 | 0.02 |

**Table A3. Effective dose rates coefficients (Sv Bq$^{-1}$ s$^{-1}$ m$^{3}$) for external exposure to radionuclides uniformly distributed in soil of infinite depth, and the ratios between the new and old values. Data from Bellamy et al. (2019) (FGR 15) and Eckerman and Ryman (1993) (FGR 12).**

| Radionuclide | FGR 15 | FGR 12 | Ratio | Radionuclide | FGR 15 | FGR 12 | Ratio |
|---|---|---|---|---|---|---|---|
| H-3 | 3.4E−23 | 0 | - | Th-232 | 2.7E−21 | 2.4E−21 | 1.12 |
| Ni-59 | 4.5E−22 | 0 | - | Am-241 | 2.2E−19 | 2.0E−19 | 1.11 |
| Ni-63 | 4.1E−21 | 0 | - | Ra-226 | 1.7E−19 | 1.6E−19 | 1.10 |
| Zr-93 | 4.8E−21 | 0 | - | Th-230 | 6.2E−21 | 5.7E−21 | 1.08 |
| Pd-107 | 6.8E−22 | 0 | - | U-235 | 3.8E−18 | 3.5E−18 | 1.07 |
| Ra-228 | 7.4E−22 | 0 | - | Pu-239 | 1.5E−21 | 1.4E−21 | 1.04 |
| Sm-151 | 5.5E−21 | 3.6E−24 | 1 528 | Th-228 | 4.0E−20 | 3.8E−20 | 1.04 |
| C-14 | 3.1E−20 | 5.9E−23 | 534 | Th-229 | 1.6E−18 | 1.6E−18 | 1.03 |
| Cs-135 | 8.4E−20 | 1.7E−22 | 489 | U-234 | 1.9E−21 | 1.8E−21 | 1.02 |
| Se-79 | 3.5E−20 | 8.2E−23 | 426 | Eu-152 | 3.6E−17 | 3.5E−17 | 1.02 |
| Cm-246 | 1.3E−19 | 4.4E−22 | 282 | Np-237 | 3.7E−19 | 3.7E−19 | 1.00 |
| Tc-99 | 1.0E−19 | 5.8E−22 | 174 | Co-60 | 8.3E−17 | 8.3E−17 | 1.00 |
| Sr-90 | 2.6E−19 | 3.5E−21 | 76.3 | Nb-94 | 4.8E−17 | 4.9E−17 | 0.99 |
| Cs-137 | 2.6E−19 | 4.5E−21 | 57.5 | Ba-133 | 9.6E−18 | 9.8E−18 | 0.99 |
| Cl-36 | 4.2E−19 | 1.3E−20 | 31.7 | Ag-108m | 4.8E−17 | 4.8E−17 | 0.99 |
| Pu-242 | 3.1E−21 | 5.3E−22 | 5.80 | U-236 | 9.3E−22 | 9.5E−22 | 0.98 |
| Pu-241 | 7.5E−23 | 2.8E−23 | 2.64 | Ac-227 | 2.3E−21 | 2.4E−21 | 0.97 |
| U-238 | 9.2E−22 | 4.3E−22 | 2.16 | U-232 | 4.0E−21 | 4.2E−21 | 0.93 |
| Cm-244 | 1.0E−21 | 4.8E−22 | 2.09 | Pu-240 | 5.5E−22 | 6.0E−22 | 0.91 |
| I-129 | 7.9E−20 | 5.1E−20 | 1.54 | Pa-231 | 8.5E−19 | 9.4E−19 | 0.90 |
| Pb-210 | 1.3E−20 | 1.1E−20 | 1.19 | Pu-238 | 5.3E−22 | 6.2E−22 | 0.85 |
| Cm-245 | 1.9E−18 | 1.6E−18 | 1.18 | Nb-93m | 3.0E−22 | 3.9E−22 | 0.77 |
| Sn-126 | 8.1E−19 | 7.0E−19 | 1.17 | Mo-93 | 1.7E−21 | 2.2E−21 | 0.76 |
| Po-210 | 3.0E−22 | 2.6E−22 | 1.14 | U-233 | 4.9E−21 | 6.8E−21 | 0.73 |
| Am-243 | 7.5E−19 | 6.7E−19 | 1.12 | Am-242m | 5.5E−21 | 7.7E−21 | 0.72 |

## Evaluation of impact on the results

### Drilling event calculation case

In this calculation case (see Section 4.4.2), normalised doses from Smith et al. (2013) are used, which has been derived using dose coefficients for occupational intakes of radionuclides from ICRP (1994), which have been superseded by the values recommended in ICRP (2015, 2016, 2017). Dose coefficients from these publications, for relevant radionuclides, are presented in Tables A1 and A2.

At the time of dose maxima, Am-241 is the main contributor to the dose, followed by Pu-239 (Table 4-7). With time, as Am-241 decays, Pu-239 will dominates the dose to a member of the drill crew, followed by the contributions from Nb-94 and Pu-240.

The updated dose coefficients for Am-241, Pu-239 and Pu-240 are lower than the values in ICRP 68; about 60–70 % lower for Am-241 and 40–50 % lower for Pu-239 and Pu-240 (Tables A1 and A2).

The updated dose coefficients for Nb-94 are about 35–50 % higher than the values in ICRP 68.

From this it can be concluded that, since Am-241 and Pu-239 are dominating the dose maxima, the resulting total doses presented in Section 4.2.2 would likely decrease if the calculations were re-done using updated dose coefficients. However, the decrease would likely be less than a factor of two.

### Construction on drilling detritus landfill calculation case

In this calculation case (see Section 4.4.3), normalised dose conversion factors from Oatway and Mobbs (2003) are used, which has been derived using dose rate coefficients from EPA for external exposure from radionuclides in soil from Eckerman and Ryman (1993), which have been superseded by the values recommended in Bellamy et al. (2019). Dose rate coefficients from these publications, for relevant radionuclides, are presented in Table A3.

At the time of dose maxima for a landfill related to drilling into the silo or 2BMA, at 2375 AD, Ag-108m and Nb-94 are the dominating contributors to the total dose, with significant contributions from Cs-137 for a few waste vaults (Table 4-9). The dose rate coefficients for Ag-108m and Nb-94 have not change much between FGR 15 and FGR 12 (only ~1 % difference). Thus, the results would not change significantly if the updated values were to be used in the calculations.

Cs-137 in the other hand, has increased a factor of 57.5 (Table A3) and may very well become the most contributing radionuclide to the dose maxima for especially the silo and 1BTF. Assuming the dose from Cs-137 is only due to external exposure in the soil (as indicated in Oatway and Mobbs 2003, Table 25), the dose from Cs-137 at time of dose maximum may for the silo increase from 0.0017 mSv to 0.095 mSv, thus increasing the total dose maximum about a factor of five to 0.12 mSv. For 1BTF, the increase in the total dose maximum would be about a factor of 14, resulting in 0.012 mSv

Also doses from Am-241, C-14, Pu-239 and U-238 have significant contributions to the total dose for some waste vaults. Am-241 and Pu-239 have small increases in doses rate coefficients in FGR 15 compared with FGR 12, and for U-238 the value is doubled (Table A3). These differences would not affect the results significantly.

C-14 is not included in Oatway & Mobbs, hence there is no information on which exposure pathways dominates the normalised dose conversion factor applied in the calculations in this report. However, since C-14 is a low-energy beta emitter, the contribution to the total dose from C-14 due to external exposure from C-14 in soil is likely much lower compared with the dose from the other considered pathways (exposure from soil on the skin, inhalation of dust, and inadvertent ingestion of contaminated materials). Thus, it is considered unlikely that results would change significantly if the updated value for C-14 was to be used in the calculations.

Other radionuclides where the doses rate coefficients have increased significantly in FGR 15 compared with FGR 12 (such as Sm-151, Cs-135, Se-79, Cm-246, Tc-99 and Sr-90) all have low contributions to the total dose at dose maximum (at 2375 AD) and onwards throughout the assessment period. Thus, even the dose rate coefficients have increased up to three orders of magnitudes, it is deemed that the results would likely not change significantly if the updated values were to be used in the calculations.

To conclude, despite the large increase in doses rate coefficient for some radionuclides in FGR 15 compared with FGR 12, it is deemed that it is only doses due to Cs-137 that would have a significant impact on the results in the *construction on drilling detritus landfill calculation case* if the calculations were re-done using updated values. However, since Cs-137 is an important radionuclide for dose related to the silo, the highest dose maximum in this calculation case could increase up to a factor of five.

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