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        Geosphere process report for the safety assessment
      - **Barrier process report**
        Engineered barrier process report for the safety assessment
      - **Biosphere synthesis report**
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- **Bilaga MKB PSU**
  Miljökonsekvensbeskrivning för utbyggnad och fortsatt drift av SFR
  - Samrådsredogörelse
  - ~~Konsekvensbedömning av vattenmiljöer vid utbyggnad av SFR~~
    Ersatt juli 2016 av bilaga SFR-U K:2
  - Naturmiljöutredning inför utbyggnad av SFR, Forsmark, Östhammar kommun.
- **Bilaga BAT**
  Utbyggnad av SFR ur ett BAT-perspektiv

Kompletteringar

(1) September 2015 – Svensk version av *Huvudrapport SR-PSU* i allmän del 2 samt ny version (3.0) av *Radionuclide inventory* i allmän del 1 kapitel 6
(2) Oktober 2015 – Fem uppdaterade rapporter i allmän del 2 samt ny version (4.0) av *Radionuclide inventory* i allmän del 1 kapitel 6
(3) Oktober 2017 – Uppdatering av *Huvudrapport SR-PSU* och *Input data report*

Technical Report

TR-14-08

Handling of future human actions in the safety assessment SR-PSU

Svensk Kärnbränslehantering AB

November 2014

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ISSN 1404-0344
SKB TR-14-08
ID 1433756
Updated 2015-10

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Svensk Kärnbränslehantering AB

November 2014

Update notice

The original report, dated November 2014, was found to contain both factual and editorial errors which have been corrected in this updated version. The corrected factual errors are presented below.

Updated 2015-10

Location	Original text	Corrected text
Page 18, Section 2.2, paragraph 4	...SSMFS 2008:21, where it is stated that that: *impact of future human activities, such as damage inflicted on the repository barriers, should be included in the category "less probable scenarios"* (SSM 2008a).	...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).
Page 19, paragraph 3	...SSMFS 2008:37 states that *"…the consequences of the disturbance of the repository's protective capability should be illustrated by calculations of the doses for individuals in the most exposed group, and reported separately apart from the risk analysis for the undisturbed repository…"*	...SSMFS 2008:37 states 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."*
Page 19, paragraph 3	...SSMFS 2008:21 it is stated *"…cases to illustrate damage to humans intruding into the repository…"* should be…	...SSMFS 2008:21 it is stated *"…cases to illustrate detriment to humans intruding into the repository…"* should be…
Page 41, paragraph 2 and 3	This is in line with the general guidelines to the regulations SSMFS 2008:37 (SSM 2008b), where it is stated that: *"A number of 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….", "….a set of stylised scenarios. i.e. it is impossible to foresee all future human actions."*	This is in line with international recommendations and the general guidelines to the regulations SSMFS 2008:37 (SSM 2008b). SSMFS 2008:37 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 1998) 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."*
Page 48, Table 5-7, Mo-93, all columns	9,48E+09 3,97E–01 7,89E+08 6,12E–02 4,24E+09 2,39E–01 3,80E+07 6,71E–03	1.96E+10 8.20E–01 1.46E+09 1.13E–01 4.52E+09 2.54E–01 1.01E+08 1.79E–02
Page 52, Table 5-8	Wrong data used in table	Table updated with correct data
Page 55, Table 5-9	Wrong data used in table	Table updated with correct data
Page 58, Table 5-10	Wrong data used in table	Table updated with correct data
Page 58, Figure 5-5	Wrong data used in figure	Figure updated with correct data
Page 59, Figure 5-6 a and d	Wrong data used in figure	Figure updated with correct data

Preface

This report compiles information on the handling of Future human actions that may influence the long-term radiation safety of the low- and intermediate level waste repository SFR in Forsmark. The report forms part of the SR-PSU safety assessment, which supports SKB's licence application to extend SFR.

The authors of the report are Eva Andersson (SKB), Graham Smith (GMS Abingdon Ltd), Sara Grolander (miljökonsult AB) and Thomas Hjerpe (Facilia AB).

The report has been reviewed by Lena Moren (SKB), Sven Keesmann (SKB) and Marie Wiborgh (Kemakta).

Stockholm, November 2014

Fredrik Vahlund
Project leader SR-PSU

Summary

Objectives and scope

This report documents the handling of future human actions (FHA) considered in the post-closure safety analysis of SFR (SR-PSU). The range of FHA considered includes actions that influence the post-closure safety of the repository in terms of potential harmful radiation effects on humans.

The report aims to provide a presentation of the following:

- General considerations concerning FHA, including: radioactive waste management principles and international recommendations and guidance, regulatory and assessment practice in other countries, and Swedish regulatory requirements and guidance.
- The FHA assessment methodology applied in SR-PSU.
- The features, events and processes (FEPs) related to FHA and their screening for further consideration within SR-PSU as part of the assessment of the post-closure safety.
- The selection and analysis of representative FHA scenarios according to which radiation exposure to humans might arise.
- Presentation of results of these representative scenarios, in terms of illustrative dose consequences for humans and other qualitative considerations.
- Discussion and conclusions regarding FHA and safety provided by the SFR.

No assignments of probabilities for particular FHA FEPs to occur, neither annual nor integrated over longer periods, are made in this report. This is because they are dependent on the probabilities of FHA and no clear scientific basis exists for their prediction. However, based on current experiences, it is possible to discuss how man might interfere with a repository in the future. Based on current knowledge and practice, probabilities for utilising wells intruding into the repository are assigned in the **Main report**. The utilisation of such a well is not included as a FHA scenario in this report but treated as a less probable scenario in the **Main report**. In this report, discussions are provided about the likelihood of different FHA scenarios to occur. This approach is supported by international recommendations and guidance, other national assessment practice and regulatory requirements, as well by the Swedish regulatory requirements and guidance.

Review of general issues associated with future human actions

FHA may impact the safety functions of the disposal systems. FHA might result in radioactive waste being brought back to the surface, e.g. through drilling activities. It is a consequence of the general strategy to concentrate and retain radioactive waste that leaves open various possibilities for future human contact with the radioactive waste. However, such possibilities are substantially reduced by isolating the waste from the surface environment in a geological disposal.

The review of international and national work carried out in this report has identified problematic issues associated with identification of FHA, notably the unpredictability of human behaviour. This work was supported and facilitated by the large amount of work, concerning both technical and social factors, carried out through the OECD Nuclear Energy Agency, documented in relatively recent guidance by both the International Atomic Energy Agency (IAEA) and International Commission on Radiological Protection (ICRP). National application of this international guidance outside Sweden has been considered, both as regards regulatory requirements and the assessments made with a view to demonstrating compliance with radiation protection objectives. No single universal approach has emerged, but much useful experience has been observed and considered from this work.

Previous work in Sweden has also been reviewed alongside Swedish regulatory requirements, which can be said to have been developed and applied in parallel to the international efforts.

Methodological approach: features, events and processes; future human actions scenarios; quantitative calculations, and qualitative analyses

A FEP analysis of FHA has been carried based on understanding of the system safety functions and system behaviour. FHA FEPs have been identified and described to allow for the screening out from further consideration within the remainder of the FHA assessment, or inclusion for further consideration in FHA scenarios. A significant FEP is intrusion by drilling. This FEP is not assumed likely until the site footprint has emerged from the sea about 3000 AD.

The FHA scenarios have been addressed by qualitative and quantitative analysis. Quantitative calculations regarding water fluxes after large scale water management in the area have been performed and used as a basis for qualitative discussion on the effect of such actions on SFR. Qualitative analysis of underground constructions has been performed. Quantitative dose calculations have been made of several FHA scenarios linked to drilling into the SFR and radioactive material being brought to the surface. The exposure of drill crew, or to those involved in construction work or those living at and consuming foods produced in areas left contaminated at the drill site are considered. All the calculations can only be regarded as illustrative. They include identified possible exposure modes, and further pessimistic assumptions have been made, consistent with international and national assessment practices.

Results and discussion

A range of arguments shows that, with exception of utilising a well into the repository (which is included in the Main report), the FHA scenarios identified in this report have little significance.

The highest doses, results from the most pessimistic assumptions on a drilling technique, occur at the time when the repository foot print is expected to emerge above the shoreline at about 3000 AD. The doses are below 1 mSv and are considered to be very unlikely to occur. They are below the ICRP ranges of reference levels indicative of system robustness, i.e. for an existing exposure situation, a few mSv per y, and for an emergency exposure, 20–100 mSv.

It is always possible to envisage even more pessimistic assumptions for human behaviour and for parameters in models of dose assessment. However, it is considered that deep burial provides very much greater protection than leaving waste at the surface, and, in this respect, provides an optimised waste management solution in line with IAEA safety fundamentals.

Conclusion

The overall conclusion from this assessment is that results of FHA do not give rise to concern relative to reference levels set by ICRP. This is a clear indicator of the SFR's safety system robustness to FHA.

Sammanfattning

Mål och omfattning

Den här rapporten beskriver hur framtida mänskliga aktiviteter (FHA) har hanterats i säkerhetsanalysen för SFR (SR-PSU). FHA omfattar aktiviteter som kan påverka förvarets säkerhet efter förslutning och som potentiellt kan ge upphov till skadliga effekter på människor.

Rapporten syftar till att beskriva:

- Allmänna överväganden som har gjorts inför FHA-analysen, t.ex. avseende principer för hantering av radioaktivt avfall, internationella rekommendationer och riktlinjer, regelverk och praxis i andra länder, samt svenska myndigheters föreskrifter och riktlinjer.
- Metodik för FHA-analysen i SR-PSU.
- Egenskaper, händelser och processer (FEP) som är relaterade till FHA, samt en bedömning av hur dessa ska hanteras i SR-PSU.
- Val av ett antal representativa FHA-scenarier i vilka människor skulle kunna utsättas för exponering av radioaktivitet, och analys av dessa scenarier.
- Presentation av resultat från analyserna, både i form av doskonsekvenser för människor och som kvalitativa bedömningar.
- Diskussion och slutsatser om hur FHA kan komma att påverka säkerheten för SFR.

I den här rapporten görs ingen bedömning av den kvantitativa sannolikheten för att specifika FHA-händelser ska inträffa, varken på årsbasis eller över längre tidperioder. Detta på grund av att dessa händelser är kopplade till framtida mänskliga aktiviteter, och det saknas vetenskaplig grund för att bedöma den kvantitativa sannolikheten för att en specifik aktivitet ska inträffa. Det är emellertid möjligt att utifrån nuvarande erfarenhet diskutera hur människor kan komma att interagera med förvaret i framtiden. I huvudrapporten för SR-PSU uppskattas sannolikheten för att människor ska konstruera en brunn som tränger in i förvaret, baserat på hur människor konstruerar och använder brunnar idag. Användandet av en sådan brunn ingår inte i scenarioanalysen för FHA, utan hanteras som ett mindre sannolikt fall i huvudrapporten för SR-PSU. I den här rapporten diskuteras sannolikheten (utan att ansätta siffror) för att olika FHA-scenarier ska inträffa. Det här tillvägagångssättet stödjs av internationella rekommendationer och riktlinjer, av andra nationers praxis och riktlinjer, liksom av svenska myndigheters föreskrifter och riktlinjer.

Internationellt arbete kopplat till FHA

En konsekvens av att koncentrera och förvara radioaktivt avfall på en plats är att det öppnar möjligheten till framtida mänsklig kontakt med det radioaktiva avfallet. Sannolikheten för detta minskar betydligt genom att avfallet isoleras från ytekosystemen i ett geologiskt förvar. Framtida mänskliga aktiviteter kan dock resultera i att radioaktivt avfall transporteras tillbaka till ytan, till exempel genom borrning.

Den sammanställning av internationellt och nationellt arbete som gjorts i samband med den här rapporten belyser problematiken kring att identifiera relevanta framtida mänskliga aktiviteter som bör ingå i analysen, i synnerhet när det gäller det oförutsägbara mänskliga beteendet. Arbetet i denna rapport har underlättats genom det omfattande arbete som har genomförts av OECD Nuclear Energy Agency (OECD/NEA) när det gäller FHA (både tekniska och sociala aspekter), och som har dokumenterats genom riktlinjer utfärdade av IAEA och ICRP. Även andra länders tillämpningar av de internationella riktlinjerna har sammanställts. Ingen universalmetod för att identifiera relevanta FHA har framkommit i sammanställningen, men det finns mycket värdefulla erfarenheter som har tagits tillvara.

Metodik: FEP-analys, FHA-scenarier, kvantitativa beräkningar och kvalitativa analyser

En FEP-analys av framtida mänskliga aktiviteter genomfördes baserat på kunskapen om förvarssystemet och dess säkerhetsfunktioner. Relevanta FHA FEP:ar identifierades och beskrevs, och en bedömning gjordes av vilka av dessa FEP:ar som skulle inkluderas i scenarier i FHA-analysen. En FEP som bedömdes som signifikant är intrång i förvaret genom borrning. Detta antas inte kunna ske förrän förvarsplatsen ligger över strandlinjen, dvs ca 3000 AD.

FHA-scenarier har utvärderats genom både kvalitativ och kvantitativ analys. Kvantitativa dosberäkningarna har gjorts för FHA-scenariot 'borrning in i SFR' som kan leda till transport av radioaktivt material till ytan. Scenariot omfattar exponering av borrpersonal, exponering av byggarbetare som arbetar på mark där borrkax med radioaktivt material lämnats, liksom exponering av människor som bor på och konsumerar livsmedel som produceras på mark där borrkax med radioaktivt material lämnats. I överensstämmelse med internationell och nationell praxis inkluderas olika exponeringsvägar i bedömningen och analysen bygger på pessimistiska antaganden. De genomförda dosberäkningarna ska därför betraktas som illustrativa.

Resultat och diskussion

Analyserna visar att med undantag för att använda vatten från en brunn borrad in i SFR som dricksvatten och till bevattning (vilket inkluderas i ett mindre sannolikt scenario i huvudrapporten) har de FHA-scenarier som identifierats i denna studie liten betydelse för förvarets långsiktiga säkerhet. De högsta beräknade doserna i FHA scenarierna inträffar år 3000 AD när förvaret ligger över strandlinjen. De erhålls av borrpersonal genom pessimistiska antaganden om borrteknik och det kan anses vara mycket osannolikt att de inträffar. De högsta doserna är under 1 mSv och är därmed lägre än de referensnivåer för bedömning av förvarssystemets robusthet som ICRP angett, dvs några mSv per år för en befintlig exponeringssituation, och 20–100 mSv för exponering vid en nödsituation.

Det finns alltid möjlighet att göra ytterligare pessimistiska antaganden för mänskligt beteende och för parametrar i dosmodeller. Dock anses det att djup förvaring ger mycket större skydd än att lämna avfall på ytan, och att det, i detta avseende, ger en optimerad avfallshantering i linje med IAEA:s grundläggande säkerhetsprinciper. Den övergripande slutsatsen för den här analysen är att FHA inte ger upphov till doser som överskrider de referensnivåer som fastställts av ICRP, vilket är en tydlig indikation på SFR-förvarets långsiktiga säkerhet.

Contents

1 Introduction

1.1 Background

The final repository for short-lived radioactive waste (SFR) located in Forsmark, Sweden is currently being used for the final disposal of low- and intermediate-level operational waste from Swedish nuclear facilities. SKB plans to extend SFR to host waste from the decommissioning of the nuclear power plants and other nuclear facilities. Additional disposal capacity is needed also for operational waste from nuclear power units in operation since their operation life-times have been extended compared with what was originally planned.

The SFR repository includes waste vaults underground together with buildings above ground that include a number of technical installations. The underground part is located below the Baltic Sea. The existing facility (SFR 1) comprises five waste vaults with a disposal capacity of approximately 63,000 m^3. The extension (SFR 3[1]) will have a disposal capacity of 108,000 m^3 in five new waste vaults plus one new vault for nine boiling water reactor pressure vessels, see Figure 1-1.

The waste vaults of SFR1 are situated in rock beneath the sea floor, and are covered by about 60 metres of granitoid rock, c 3–7 metres of regolith and c 3–4 metres of seawater (Sohlenius et al. 2013). The different waste vaults contain different types and radioactivities of waste (see further the **Initial state report)**. The underground part of the facility is reached via two tunnels (Figure 1-2). The planned extension SFR 3 will function in the same way as the existing repository, but the rock vaults will be situated at c 120 m depth. In addition to similar wastes as those deposited SFR 1, reactor vessels from Swedish boiling water reactors are also planned to be stored at SFR. Forsmark is situated in an area with post-glacial uplift and shoreline displacement and with time SFR will be located below land instead of sea.

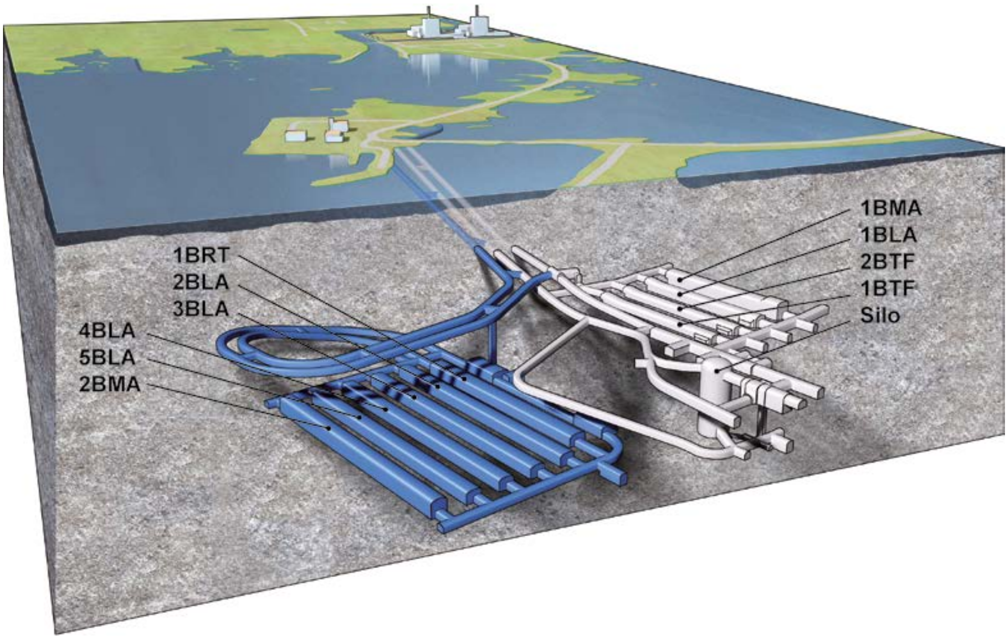

Figure 1-1. *Schematic illustration of SFR. The grey part is the existing repository (SFR 1) and the blue part is the planned extension (SFR 3). The waste vaults in the figure are the silo for intermediate-level waste, 1–2BMA vaults for intermediate-level waste, 1–2BTF vaults for concrete tanks, 1–5BLA vaults for low-level waste and the BRT vault for reactor pressure vessels.*

[1] The extension is called SFR 3 since the name SFR 2 was used in a previous plan to build vaults adjacent to SFR 1 for disposal of reactor core components and internal parts. The current plan is to dispose of this waste in a separate repository.

The long-term post closure safety of the whole SFR has been assessed and documented in the **SR-PSU Main report** with supporting documents, see Section 1.2. The Main report is part of SKB's licence application to extend and continue to operate SFR. The present report is a supporting document and describes the handling of Future Human Actions that may influence the long term safety of SFR.

1.2 Report hierarchy in the SR-PSU safety assessment

The applied methodology for the long-term safety comprises ten steps and is described in Chapter 2 of the Main report of SR-PSU. Several of the steps carried out in the safety assessment are described in more detail in supporting documents, so called Main references that are of central importance for the conclusions and analyses in the Main report. The full titles of these reports together with the abbreviations by which they are identified in the following text **(abbreviated names in bold font)** together with short comments on the report contents are given in Table 1-1.

There are also a large number of additional references. The additional references include documents compiled within SR-PSU, but also documents compiled outside of the project, either by SKB or equivalent organisations as well as in the scientific literature. Additional publications and other documents are referenced in the usual manner.

A schematic illustration of the safety assessment documents is shown in Figure 1-2.

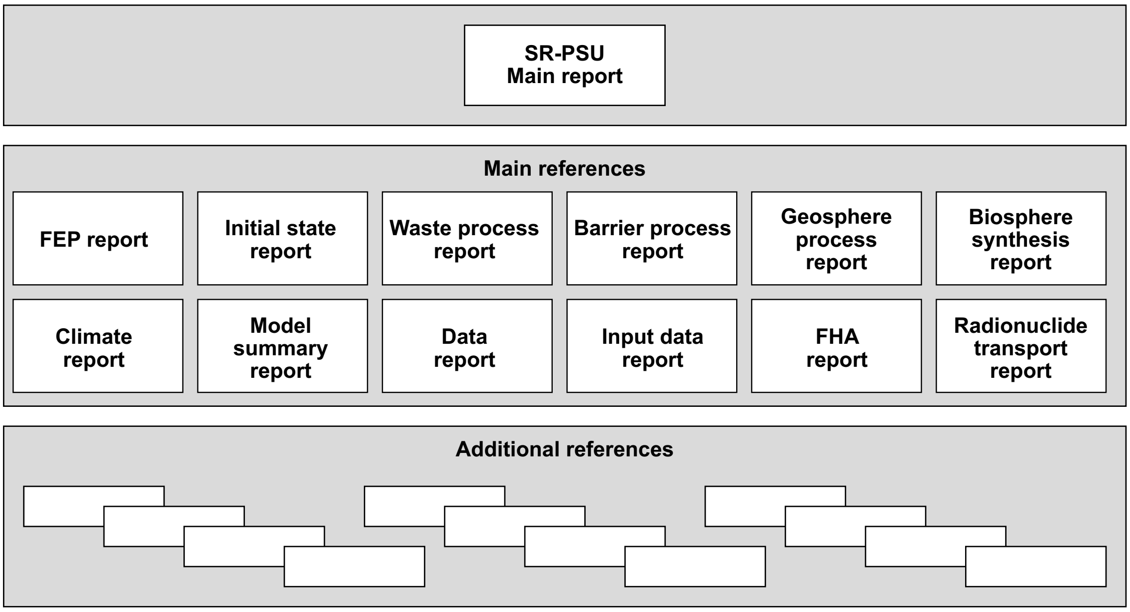

***Figure 1-2.** The hierarchy of the Main report, Main references and additional references in the SR-PSU long-term safety assessment. The additional references either support the Main report or any of the Main references.*

Table 1-1. Main report and Main references in the SR-PSU long term safety assessment. All reports are available at www.skb.se.

Abbreviation used when referenced in this report	Text in reference list	Comment on content
Main report	**Main report, 2014**. Safety analysis for SFR. Long-term safety. Main report for the safety assessment SR-PSU. SKB TR-14-01, Svensk Kärnbränslehantering AB.	This document is the main report of the SR-PSU long-term post-closure safety assessment for SFR. The report is part of SKB´s licence application to extend and continue to operate SFR.
Barriers process report	**Engineered barriers process report**, **2014**. Engineered barrier process report for the safety assessment SR-PSU. SKB TR-14-04, Svensk Kärnbränslehantering AB.	Describes the current scientific understanding of the processes in the engineered barriers that have been identified in the FEP processing as potentially relevant for the long-term safety of the repository. Reasons are given in the process report as to why each process is handled a particular way in the safety assessment.
Biosphere synthesis report	**Biosphere synthesis report**, **2014**. Biosphere synthesis report for the safety assessment SR-PSU. SKB TR-14-06, Svensk Kärnbränslehantering AB.	Describes the handling of the biosphere in the safety assessment. The report summarises site description and landscape development, FEP handling, exposure pathway analysis, the radionuclide model for the biosphere, included parameters, biosphere calculation cases and simulation results.
Climate report	**Climate report**, **2014**. Climate and climate-related issues for the safety assessment SR-PSU. SKB TR-13-05, Svensk Kärnbränslehantering AB.	Describes the current scientific understanding of climate and climate-related processes that have been identified in the FEP processing as potentially relevant for the long-term safety of the repository. The report also describes the climate cases that are analysed in the safety assessment.
Data report	**Data report, 2014.** Data report for the safety assessment SR-PSU. SKB TR-14-10, Svensk Kärnbränslehantering AB.	Qualifies data and describes how data, including uncertainties, that are used in the safety assessment are quality assured.
FEP report	**FEP report, 2014.** FEP report for the safety assessment SR-PSU. SKB TR-14-07, Svensk Kärnbränslehantering AB.	Describes the establishment of a catalogue of features, events and processes (FEPs) that are of potential importance in assessing the long-term functioning of the repository.
FHA report	**FHA report**, **2014**. Handling of future human actions in the safety assessment SR-PSU. SKB TR-14-08, Svensk Kärnbränslehantering AB.	The present report describes radiological consequences of future human actions (FHA) that are analysed separately from the main scenario, which is based on the reference evolution and less probable evolutions.
Geosphere process report	**Geosphere process report**, **2014**. Geosphere process report for the safety assessment SR-PSU. SKB TR-14-05, Svensk Kärnbränslehantering AB.	Describes the current scientific understanding of the processes in the geosphere that have been identified in the FEP processing as potentially relevant for the long-term safety of the repository. Reasons are given in the process report as to why each process is handled a particular way in the safety assessment.
Initial state report	**Initial state report**, **2014**. Initial state report for the safety assessment SR-PSU. SKB TR-14-02, Svensk Kärnbränslehantering AB.	Describes the conditions (state) prevailing in SFR after closure. The initial state is based on verified and documented properties of the repository and an assessment of the evolution during the period up to closure.
Input data report	**Input data report**, **2014**. Input data report for the safety assessment SR-PSU. SKB TR-14-12, Svensk Kärnbränslehantering AB.	Describes the activities performed within the SR-PSU safety assessment and the input data used to perform these activities.
Model summary report	**Model summary report**, **2014**. Model summary report for the safety assessment SR-PSU. SKB TR-14-11, Svensk Kärnbränslehantering AB.	Describes the calculation codes used in the assessment.
Radionuclide transport report	**Radionuclide transport report**, **2014**. Radionuclide transport and dose calculations for the safety assessment SR-PSU. SKB TR-14-09, Svensk Kärnbränslehantering AB.	Describes the radionuclide transport calculations carried out for the purpose of demonstrating fulfilment of the criterion regarding radiological risk.
Waste process report	**Waste process report, 2014.** Waste form and packaging process report for the safety assessment SR-PSU. SKB TR-14-03, Svensk Kärnbränslehantering AB.	Describes the current scientific understanding of the processes in the waste and its packaging that have been identified in the FEP processing as potentially relevant for the long-term safety of the repository. Reasons are given in the process report as to why each process is handled in a particular way in the safety assessment.

1.3 Aim and scope of this report

This report documents the handling of FHA considered in SR-PSU. The range of FHA considered includes actions that influence the post-closure safety of the repository in terms of harmful effects of radiation.

The report aims to present the following:

- General considerations concerning FHA, including: radioactive waste management principles and international recommendations and guidance, regulatory and assessment practice in other countries, and Swedish regulatory requirements and guidance.
- The FHA assessment methodology applied in SR-PSU.
- The features, events and processes (FEPs) related to FHA and their screening for further consideration within SR-PSU as part of the assessment of impact on post-closure safety.
- The selection and analysis of representative FHA scenarios according to which radiation exposure to humans might arise.
- Presentation of results of these representative scenarios, in terms of illustrative dose consequences for humans and other qualitative considerations.
- Discussion and conclusions regarding FHA and safety provided by the SFR.

This report considers the direct consequences FHA in so far as they result in: changes to the barrier system giving rise to higher release of radionuclides from the SFR than assessed in the main calculation case of the assessment, and/or radioactive waste or contaminated solid subsurface material being brought to the surface giving rise to exposure to people at the surface. The consequences of utilising water from a drilled well in the area are considered separately, in the main calculation cases for SR-PSU **(Main report, Radionuclide transport report)**.

1.4 Structure of this report

Chapter 1 gives an introduction and presents the aim and scope of the report. **Chapter 2** describes general considerations concerning FHA, including: radioactive waste management principles, international recommendations and guidance, regulatory and assessment practice in other countries, and Swedish national regulatory requirements and guidance. Information is also provided on previous FHA work in Sweden. This provides the assessment context for the analysis of FHA within SR-PSU, providing background to and justifying the methodology applied, set out in **Chapter 3**. **Chapter 4** provides the analysis of FHA FEPs, including their screening for further consideration within SR-PSU as part of the assessment of impact on post-closure radiation safety. **Chapter 5** identifies the FHA scenarios, describes the qualitative and calculation cases used to analyse those scenarios, and presents and discusses the results of the calculation cases and considers the implications for safety. **Chapter 6** provides overall conclusions. A list of abbreviations used is given in **Appendix A**. **Appendix B** provides examples of handling of FHA in other countries and finally, **Appendix C** gives information on equations for one of the calculation cases.

2 General considerations

2.1 Waste management principles and international recommendations and guidance

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. There are examples of international projects where experience from work with human intrusion is shared, e.g. PAMINA and BIOPROTA (Galson et al. 2009, Bailey et al. 2011, Smith et al. 2013). However, there is no agreed international position on how to incorporate future human actions into safety assessment. SKB takes part in the ongoing IAEA project HIDRA. The HIDRA project objectives are to describe considerations for addressing future human actions in post-closure safety assessment based on the common safety principles, requirements and recommendations from the IAEA, ICRP and OECD/NEA and experiences in different countries and to identify and share information related to application of those requirements. However, already at present, there are a number of identified international documents and principles that serves as a basis for the FHA assessment in SR-PSU. These are discussed below.

The International Atomic Energy Agency's (IAEA) Fundamental Safety Principles (IAEA 2006) include within their scope radioactive waste management. The fundamental safety objective is to protect people and the environment from harmful effects of ionising radiation. Other principles taken from the same reference that are particularly relevant in the current context include:

Principle 5: Protection must be optimised to provide the highest level of safety that can reasonably be achieved.

Principle 6: Measures for controlling radiation risks must ensure that no individual bears an unacceptable risk of harm.

Principle 7: People and the environment, present and future, must be protected against radiation risks.

These safety principles might be complied with in a number of ways as regards disposal of waste. Disposal strategies for hazardous waste generally can be divided into two conceptual approaches (EC 1993, IAEA 2011a):

- Dilute and disperse.
- Concentrate and contain.

The strategy commonly adopted in the disposal of solid radioactive waste is to contain[2] the waste and to retain it so that it is kept away from the accessible biosphere[3] by means of geological disposal. The intent is to isolate the waste from man and the biosphere for as long a time as possible. The potential exposure to radiotoxic material is an inescapable consequence of the concentration and deposition of the radioactive waste in a repository. Consequently, both natural processes potentially prejudicing isolation and human intrusion have to be considered in the development and safety assessment of such a disposal system.

[2] Containment is defined in IAEA (2007) as "methods or physical structures designed to prevent or control the release and the dispersion of radioactive substances", and in ICRP (2013) as confining the radionuclides within the manmade barriers that either constitute the waste form or that separate the waste form from the host geological formation.

[3] The biosphere is that part of the environment that is normally inhabited by living organisms, and the 'accessible biosphere' is taken generally to include those elements of the environment, including groundwater, surface water and marine resources, that are used by people or accessible to people (IAEA 2011a, §2.2).

There is a long-standing international consensus (e.g. IAEA 1995, 1997, NEA 1995a), that the society that receive the benefits, or more specifically the nuclear power producers that receive the profits, of the electric power production and generate the radioactive waste should bear the responsibility for developing a safe disposal system. In doing so, the freedom of action and safety of future generations have to be considered, as far as reasonably possible, i.e. in line with the principles mentioned above. However, current society cannot be required to protect future societies from their own intentional and planned activities, if they are aware of their consequences. This is valid irrespective of the intent of the planned actions, i.e. whether they are carried out for benevolent or malicious reasons. Based on this consideration, it is concluded that only inadvertent human actions, i.e. those taken without knowledge of the repository, need to be considered in the design and safety assessments of repositories for radioactive waste. Earlier advice from the NEA defines inadvertent actions as (NEA 1995b):

"Those in which either the repository or its barrier system are accidentally penetrated or their performance impaired, because the repository location is unknown, its purpose is forgotten or the consequences of the actions are unknown."

Human intrusion (HI) has been considered an issue in post-closure safety of solid radioactive disposal for many years (NEA 1989). The difficulty of including HI scenarios in safety assessments for radioactive waste consists in justifying assumptions about human behaviour over relevant periods of time. Risk assessment typically includes consideration of the likelihood of radiation exposure as well as the probability of harm arising as a result of that exposure. The risk associated with an exposure is a function of the size of the dose[4] and the likelihood of harm arising from that level of dose (NRPB 1983). Site selection away from natural resources may reduce the probability of human intrusion, but it is not obvious what will be considered as a resource in the future. Thus, it has been concluded that the likelihood that HI occurs should not be ignored in reaching an informed decision on radioactive waste management, but it is necessary to recognise the illustrative nature of long-term probability estimates (Smith et al. 1999).

Accordingly, over the last decade or so, the development of protection objectives with respect to FHA and HI has focussed upon the level of radiation exposure rather than an attempt at estimating the risks. ICRP Publication 81 recommendations on long-lived radioactive waste disposal (ICRP 2000) note the difficulties of estimating probabilities of HI, but that its occurrence cannot be entirely ruled out. ICRP therefore recommends (§ 62) that "one or more typical plausible stylised scenarios" should be considered by the decision-maker to evaluate the resilience of a repository to postulated events or scenarios.

Similar guidance is given in the ICRP's most recent guidance on geological disposal of long-lived radioactive waste, (ICRP 2013); viz:

At § 62:
"Waste is disposed of in a geological disposal facility for the purposes of containment and isolation (one aspect of which is avoidance of human intrusion). It is necessary to distinguish between deliberate and inadvertent human intrusion into the facility. The former is not discussed further in this report as it is considered outwith the scope of the responsibility of the current generation to protect a deliberate intruder (i.e. a person who is aware of the nature of the facility). The design and siting of the facility have to include features to reduce the possibility of inadvertent human intrusion."

At § 63:
"A release resulting from inadvertent human intrusion, such as drilling into the facility, could migrate through the geosphere and biosphere, resulting in exposures that are indirectly related or incidental to the intrusion event. It is also possible that inadvertent human intrusion could bring waste material to the surface, and hence lead to direct exposure of the intruder and nearby populations. This introduces the possibility of elevated exposures and significant doses, which is an inescapable consequence of the decision to isolate and concentrate the waste rather than diluting or dispersing it."
At § 64:

[4] Dose is taken in this report to mean effective dose, and for the purpose of comparison with annual dose limits, is the sum of external effective dose received in a year and the committed effective dose from intakes in that year, as defined in ICRP (2007).

" While the actual probability of inadvertent human intrusion at a specific site is largely unknowable as it is based on future human actions, it is assumed that the probability of inadvertent intrusion during the direct and indirect oversight periods is extremely low, and that if it occurred, appropriate countermeasures could be taken to avoid significant impact."

At § 65:

"In the distant future, if indirect oversight has ceased, the occurrence of human intrusion cannot be excluded. Therefore, the consequences of one or more plausible stylised intrusion scenarios should be considered by decision makers to evaluate the resilience of the disposal system to potential inadvertent intrusion. Any estimates of the magnitude of intrusion risks are, by necessity, dependent on assumptions that are made about future human behaviour. As no scientific basis exists for predicting the nature or probability of future human actions, the Commission continues to consider it inappropriate to include the probabilities of such events in a quantitative performance assessment that is to be compared with dose or risk constraints. At the planning stage, the results of the stylised or simplified calculations can, if required, be used as indicators of system robustness by comparing them with numerical values of dose. If this approach is taken, the application of the reference levels defined for emergency and/or existing exposure situations is recommended."

ICRP recommend that the reference level for an existing exposure situation should be a few mSv per year, and for an emergency exposure, in the range of 20–100 mSv for the first year (ICRP 2013). However, they also note that a fully optimised system may result in a distribution of doses which include some doses that are above the reference level.

The IAEA requirements on disposal of radioactive waste given in SSR-5 (IAEA 2011a) set out different international guidance on criteria relating to HI. The key text is as follows:

- The dose limit for members of the public for doses from all planned exposure situations is an effective dose of 1 mSv in a year. This and its risk equivalent are considered criteria that are not to be exceeded in the future.
- To comply with this dose limit, a disposal facility (considered as a single source) is so designed that the calculated dose or risk to the representative person who might be exposed in the future as a result of possible natural processes affecting the disposal facility does not exceed a dose constraint of 0.3 mSv in a year or a risk constraint of the order of 10^{-5} per year.
- In relation to the effects of inadvertent human intrusion after closure, if such intrusion is expected to lead to an annual dose of less than 1 mSv to those living around the site, then efforts to reduce the probability of intrusion or to limit its consequences are not warranted.
- If human intrusion were expected to lead to a possible annual dose of more than 20 mSv per year, to those living around the site, then alternative options for waste disposal are to be considered; for example, disposal of the waste below the surface, or separation of the radionuclide content giving rise to the higher dose.
- If annual doses in the range 1–20 mSv are indicated, then reasonable efforts are warranted at the stage of development of the facility to reduce the probability of intrusion or to limit its consequences by means of optimisation of the facility's design.

These IAEA criteria allow a higher dose for inadvertent HI than the dose (or its risk equivalent) for scenarios due to natural processes. According to the IAEA, these dose criteria for HI apply only to "those living around the site". They do not apply, for example, to geological investigators who may be exposed through their work. In the absence of any explanation, the exclusion of this exposure situation may be hard to understand given the significance of this scenario in the history of HI studies, e.g. NEA (1989, 1995b). In addition, regarding exposure situations, ICRP (2013) says at § 63 that inadvertent human intrusion could bring waste material to the surface and hence lead to direct exposure of the intruder and nearby populations. This implies a wider consideration of exposures within the stylised scenarios than required by IAEA in IAEA (2011a). To be inclusive, in this study, the ICRP approach to scenarios is adopted and direct exposure to the drilling crew and workers on the site are included.

The above guidance on intentional intrusion is that it shall be excluded from consideration of safety and safety assessment as it is considered out of scope of the current generation to protect a deliberate intruder. However, placement in a geological repository is regarded as providing long term passive nuclear security (IAEA 2011a). Clearly, waste placed at depth is less subject also to malicious activity than material left at the surface and the disposal concept is consistent with IAEA Principle 5 (in IAEA 2006) mentioned above.

Another relevant publication is the IAEA safety guide on Geological Disposal Facilities for Radioactive Waste (IAEA 2011b). It does not discuss safety assessment in great detail but the following quotation is relevant to human intrusion assessment:

"Active institutional controls such as monitoring may also be applied for a period after closure of a geological disposal facility, for example, to address public concerns and licensing requirements or as protection against human intrusion."

"The safety assessment should include some stylised calculations of the consequences of inadvertent human intrusion into the closed disposal facility."

Thus, this text lends further support to ICRP (2013) discussed above.

2.2 Swedish regulatory requirements and interpretation in this report

The structure and content of safety assessment reports are regulated in on regulations issued by the Swedish Radiation Safety Authority (SSM). The regulations are based on pertinent components of framework legislation, the most important being the Act on Nuclear Activities (1984:3) and the Radiation Protection Act (1988:220). In addition, guidance on radiation protection matters is provided by a number of international bodies, and national legislation is often, as in the case of Sweden, influenced by international recommendations.

It is stated in Swedish law (Act on Nuclear Activities SFS 1984:3) that the society that receives the benefits, or more specifically the nuclear power producers that receive the profits, of the electric power production and generate the radioactive waste should bear the responsibility for developing a safe disposal system.

There are two regulations specifically concerning post-closure safety of nuclear waste repositories:

- "The Swedish Radiation Safety Authority's regulations and general advice concerning safety in connection with the disposal of nuclear material and nuclear waste", SSMFS 2008:21 (SSM 2008a).
- "The Swedish Radiation Safety Authority's regulations and general advice concerning the protection of human health and the environment in connection with the final management of spent nuclear fuel and nuclear waste" 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 SR-PSU:

- SSMFS 2008:37, Section 9 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 SR-PSU it has been considered that the essential part of FHA is not the actions 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*"

To cover all possible future human actions is undoable due to impossibility to foresee future human behavior, techniques and objectives. Instead, SKB includes a set of stylised scenarios to describe a range of possible future humans actions based on present living habitats and technical development. Direct intrusion to the repository is one of the included scenarios and possible effects of altered hydrological water fluxes and chemical depositions are also discussed in this report.

- 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 and in the present report potential effects of utilisation of the closest situated natural resources are investigated.

- Regarding reporting of consequences the guidelines of SSMFS 2008:37 states 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 SR-PSU doses to the most exposed group following disturbance of the repository's protective capability are presented, including doses to drill crew.

2.3 Previous work in Sweden

A study of human intrusion by borehole drilling directly into a repository for spent fuel and and its dose consequences was carried out by Charles and McEwen (1991) for the SSI, which considered borehole drilling directly into waste canisters for spent fuel, and into potentially contaminated backfill and surrounding rock. Only the doses to the drilling workers and geologists were considered. It was noted that the annual probability of any of these events was extremely low; the doses in the case of non-canister penetration were much lower, but also more likely to occur.

In their review of SKB's programme for research, development and demonstration from 1995 (SKB 1995), the Swedish Nuclear Power Inspectorate (SKI) pointed out (SKI 1996, p 87) that SKB: *"... must develop their own strategy for how issues relating to human intrusion should be handled in future safety assessments."* SKI further stated that the work performed within OECD/NEA (NEA 1995a) was an adequate basis for the development of a strategy to handle FHA.

FHA that can affect the safety of a repository involve questions concerning the evolution of society and human behaviour. These are questions that cannot be answered by conventional scientific methods. For example, it is not possible to predict knowledge that does not exist today, and knowledge is judged to be a key factor in this context. By necessity, the strategy must be based on present-day knowledge obtained from people alive and active today. To get a broad view of the multifaceted question of FHA, the ambition was, in line with the NEA working group recommendations, to involve people active within a broad spectrum of relevant fields in the development of a strategy (NEA 1995a). For this purpose, the development was based on the results of workshops to which people with varying knowledge and backgrounds were invited. In total three workshops were held.

1. Skebo December 1997; with the purpose of supporting the choice of scenarios involving FHA to be included in safety assessments and providing a basis for the development of a strategy to handle FHA.
2. IVA March 1998; to make a list of human actions that can affect the safety of the final repository, based on current technical knowledge and a description of that repository, and describe and justify the actions in technical terms.
3. Frösunda May 1998; to construct framework scenarios (framework conditions) that describe feasible societal contexts for FHA that can affect the radiological safety of a deep geological repository.

The results from the workshop at Skebo, together with the recommendations of the NEA working group (NEA 1995a), formed the basis for the development of the strategy presented in SR 97 (SKB 1999a). At the two latter workshops, the strategy was further developed and partly carried out. The results from the workshops were reported (Morén et al. 1998). In the safety assessment SR 97 (SKB 1999b), the developed strategy and the results from the technical and societal analysis carried out at the workshop at IVA and Frösunda were used to select FHA scenarios for which consequences were analysed.

The FHA-study from 1998, used for the safety assessment SR 97, was later translated from Swedish to English and updated prior to the next safety assessment of spent fuel disposal SR-Can (SKB 2006a, b). The review of SR-97, by the authorities and their international group of experts (SKI 2000, SKI/SSI 2001), was referred to and considered in the updated FHA-report issued in 2006 (SKB 2006b). Among other things, the strategy to handle FHA was modified as a result of the reviewers' comments. The safety assessment SR-Can illustrated human intrusion by presenting and evaluating three different illustrative cases. This was commented by the authorities in their review of SR-Can (Dverstorp and Strömberg 2008). Further modifications of this approach were thus made for SR-Site, as a result of the review comments. The illustrative cases themselves were modified and, for example, the dose to drilling personnel was added and the effect of an unsealed repository was added to the analysis (SKB 2010b).

In the previous safety assessment for SFR, a quantitative analysis was made of utilising water from a well drilled directly into the repository (SKB 2008a).

2.4 Regulatory and assessment practice in other countries

In Appendix B, examples of regulatory approaches to and assessments of FHA scenarios from various countries are presented. The examples show that, while the range of requirments discussed in Section 2.1 is broadly recognised, there is not an overall consistent regulatory or assessment approach. It is recognised that HI has to be assessed (showing compliance with the regulatory requirements given), but that results need to be considered alongside other safety considerations. International guidance on how to carry out such assessments has been lacking. This situation has given rise to international cooperative work on human intruder dose assessment for deep geological disposal, as reported in Smith et al. (2013) and to further work within IAEA's on-going HIDRA project.

3 Methodology

The methodology SKB applies to address FHA in post-closure safety assessment was initially developed for and implemented in the safety assessment SR 97 (SKB 1999b) and reported in Morén et al. (1998). Since then, the methodology has been further developed and implemented in the safety assessments SR-Can (SKB 2006a, b) and SR-Site (SKB 2011, 2010b) and is further developed in this safety assessment. In SAR-08, a simpler methodology was used resulting in one FHA scenario being analysed, i.e. utilising water from a well drilled into the repository. A similar scenario is assessed in SR-PSU but in addition, a comprehensive FEP analysis has been performed resulting in further scenarios being considered. This chapter presents the methodology used to address FHA in SR-PSU.

The core of the methodology is scenario development. In many national radioactive waste programmes, one of the two approaches is applied: 1) a bottom-up approach, where the scenarios are constructed from FEPs, or 2) a top-down approach, where safety functions are first identified and then focus on those FEPs, acting single or in combinations, that can affect those safety functions (NEA 2012). These two approaches have also been brought forward in the relatively recent IAEA Safety Standard Series No. SSG-23 (IAEA 2012). The SKB methodology for FHA scenario development applies a top-down approach.

The stepwise methodology, based on the top-down approach for development of FHA scenarios that are applied in SR-PSU is illustrated in Figure 3-1.

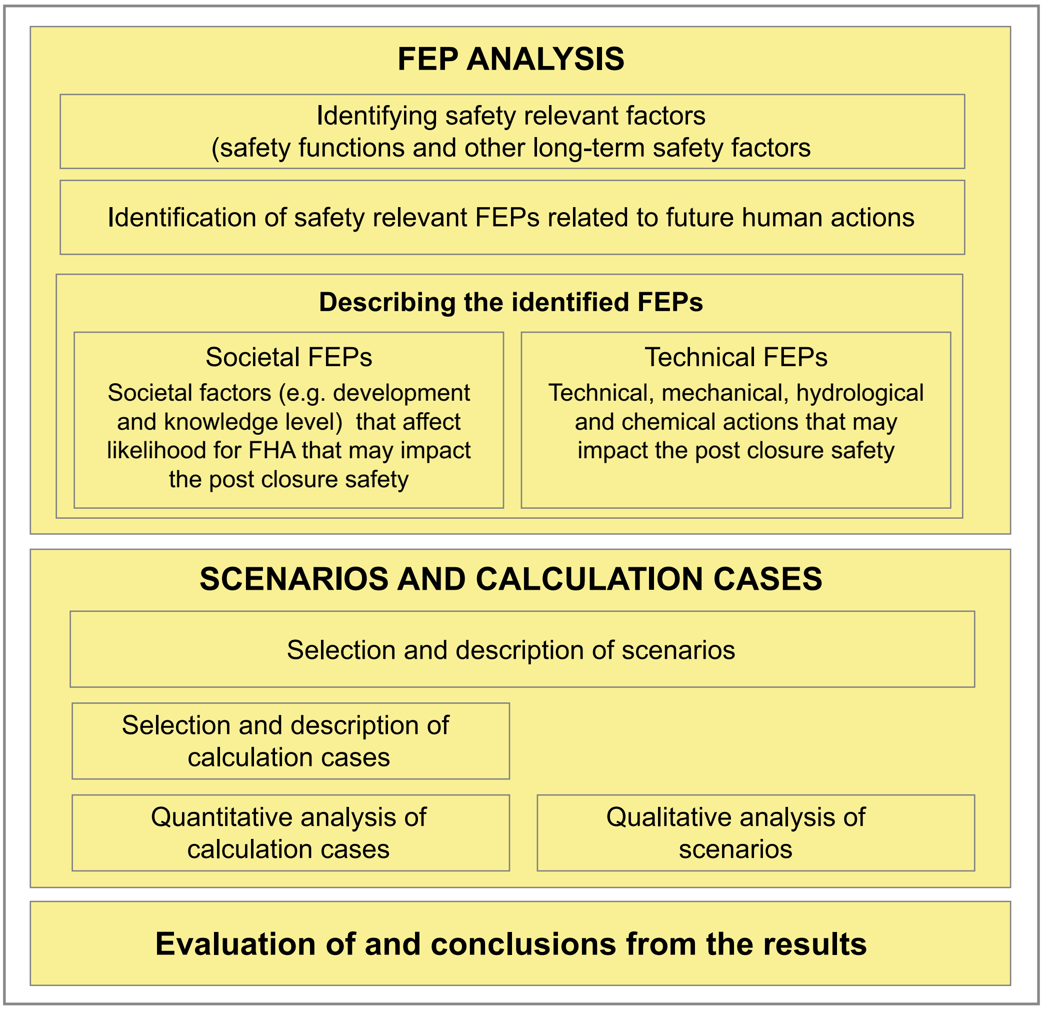

Figure 3-1. *Overview of the steps in the method for handling FHA in the present safety assessment.*

3.1 Analysis of safety functions and FHA FEP

The top-down approach for scenario development starts with identification of safety functions of the SFR repository and other factors important for the overall post-closure safety. Then, FEPs related to FHA that potentially affect them are identified. Finally, the identified FEPs are described in more detail. 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 can be 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 FEPs related to FHA comprises the actions in technical terms, from a technology point-of-view, and commenting on the potential impact on the repository performance.

The set of identified FHA FEPs comprises the FEP list carried forward in the safety assessment (see Section 3.2). This top-down approach differ from the approach applied in other parts of the safety assessment SR-PSU, where the initial step is to identify all the FEPs that are important for the evolution and function of the repository and it's environs and a subsequent step involves identifying and describing the safety functions (**Main report)**.

3.2 Selection of FHA scenarios and identification of calculation cases for further consideration

The results of the analysis of technical and societal FEPs are combined and a set of stylised scenarios addressing future human actions, below denoted FHA scenarios, is selected and described. The selected set of scenarios is intended to comprise a representative set of credible future human actions.

The selected FHA scenarios are analysed either by performing calculations to derive a value for a proper 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 end-point 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. The discussion may include comparisons with results and conclusions from analyses not directly aiming at assessing FHA scenarios, but are of a relevant nature.

3.3 Evaluation of results and conclusions

The quantitative and qualitative results are then evaluated with regard to Swedish regulations and 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.

4 Analysis of safety functions and FEPs

As discussed in Chapter 3, the type of FEP analysis used to address FHA is a top-down approach. In this chapter, first, some general considerations and assumptions for the FHA are given in Section 4.1. Thereafter, the FEP analysis starts with identifying safety functions of the SFR repository, and other factors important for the overall post-closure safety (Section 4.2), and then the FEPs related to FHA that potentially affect post closure safety are identified (Section 4.3). The obtained FEP list is also cross-checked against other relevant FEP lists, to ensure that no relevant FEPs have been overlooked. The final step in the FEP analysis is to describe the identified FEPs in more detail (Section 4.4).

4.1 General considerations of future human actions considered in the SR-PSU post-closure safety assessment

This report considers the individual dose consequences of FHA in so far as they result in: changes to the barrier system giving rise to higher release of radionuclides from the SFR than assumed in the main calculation case of the assessment, and/or radioactive waste being brought to the surface giving rise to exposure to people at the surface. The consequences of utilising water abstracted from a drilled well in the area are considered in the main calculation cases for SR-PSU (**Main report**, **Radionuclide transport report**). The radiological consequences (dose) from intrusion, e.g. the drilling activity itself as opposed to those from abstraction of well water, are considered in the current report. Below follows a description of FHA aspects considered in this 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. 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 others shore line development, climate change, and different kinds of ecosystems and land use (see the **Biosphere synthesis report,** Werner et al. 2014, 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. Major climate changes are expected in the time perspective of the post-closure safety assessment. Changes related to the climate, e.g. shoreline displacement, and the development of permafrost and ice sheets, are the most important naturally occurring external factors affecting the repository in a time perspective from several hundreds to hundreds of thousands of years. Climate-related changes are included as part of the reference evolution and the main scenario in the safety assessment. The emission of greenhouse gases may impact the climate and thus indirectly, the repository, and this matter is considered as a variant of the main scenario. Therefore, 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 FHA 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 1995a) and of the ICRP (ICRP 2000, 2013) are local, post-closure actions with potential impact on the final repository. It is also this kind of actions that SSM mentions in its regulations and guidelines (SSM 2008b).

As discussed in Section 2.1 only inadvertent actions, i.e. actions carried out without knowledge of the repository's location, its purpose or the consequences of the actions, are considered. 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 the repository using present techniques, the repository is recognised, then any further drilling into the repository or other actions taken which result in exposure, by those with knowledge of the hazard are to be judged as advertent and do not need to be considered in the FHA assessments. Accordingly, FHAs that are preceded by exploratory drilling that is capable of detecting of the hazard are not likely to be continued without suitable safety precautions in place. Any FHA which lead to exposure before the hazard is recognised are included. Also, FHA that occur without any intent, such as accidents by plane crashes or explosions are considered in the FHA assessment.

No assignments of probabilities for particular FHA FEPs to occur, neither annual nor integrated over longer periods, are made except for the utilisation of well water for drinking (handled in the **Main report**).This is because the FEPs are dependent on the probabilities of FHA and no scientific basis exists for their prediction. One cannot scientifically predict how humans and society will develop and what uses, for instance, there will be of the earth's subsurface thousands of years from now (see conclusions in NEA 1989). Accordingly, no estimates of the magnitude of FHA risks are provided for comparison with risk constraints. 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 might interfere in the future with a repository. For utilising of well water, there is data in well archives that can be used to calculate probabilities for this scenario and thereby this scenario can be included in risk summations. For other FHA scenarios, qualitative discussion is provided of the likelihood of the different scenarios occurring. 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.

4.2 Safety functions and other post-closure safety related factors

4.2.1 Safety functions

The terms *safety functions* and *safety performance indicators*[5] were introduced in the safety assessment of the KBS-3 repository for spent nuclear fuel, SR-Can (SKB 2006a). Safety functions pertain to the period after the repository has been closed (the post-closure period). Similar terms and methods have been applied to assessment of SFR 1 (SKB 2008b) and are applied in the present safety assessment (see the **Main report)**. In contrast to a KBS-3 repository, where safety is largely based on containment of the spent nuclear fuel and isolation of it from the living environment, safety in the SFR repository are based principally on limitation of the activity of long-lived radionuclides and retention of radionuclides. This retention is achieved by means of limited water flows and sorption of radionuclides in different media of the near-field and the geosphere.

A complete description of how the safety principles limitation and retention are achieved by various components in the repository system is required for a detailed and quantitative understanding and evaluation of repository safety. Based on an understanding of the properties of the components and the long-term evolution of the system, safety functions that are subordinate to activity limitation and retention are identified. In this respect, a safety function is defined as the role of a repository component in contributing to safety. In order to be able to evaluate safety, it is desirable to be able to express or relate the safety functions to measurable or calculable quantities. A safety function indicator is thus a measurable or calculable quantity by means of which a safety function can be evaluated.

Employing safety functions has proved to be a good tool for deriving a comprehensive set of (safety challenging) scenarios for the sound analysis of the performance of a repository. Table 4-1 presents the set of safety functions and safety performance indicators identified for SFR in the **Main report.** The different components have different safety functions but the low flow in the geosphere and the repository's location relative to the shoreline are the same for all parts.

[5] Denoted *safety function indicators* in the safety assessment SR-Can.

As seen in Table 4-1, the biosphere, which is not a component of the repository system per se, has been assigned a safety function in the FHA analysis made regarding delay of any possibility for intrusion by drilling for wells. This aspect of the biosphere is positive in a radiological risk and potential radiation dose perspective, but is not commonly regarded as a safety function. In the planning of SFR, however, a location beneath the Baltic Sea was considered to be favourable in the sense that no water abstraction wells are likely to be drilled down to the repository before the process of land uplift had reached the point where the repository is no longer submerged. The initial location of the shoreline relative to the SFR footprint is therefore treated here as a safety function. The safety function is the location of the repository footprint at the surface in relation to the shoreline.

4.2.2 Main functions of the barrier system in a relation to FHA

Isolation of the radioactive inventory from man and the environment is predominantly ensured by the rock and the repository depth and, after closure, also by the backfill and plugs. Initially, the design of the repository provides a higher degree of retention than for later times when structures in the repository may degrade. FHA may have a local effect on the 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 water fluxes through the repository and retention in material in the repository as well as retention 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 for humans and on FHA that may affect the water flow or retention 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 which might cause substantial disruptions to the protective capability of the repository have been considered already in the siting of the disposal facility and in the design of the repository. 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 4-1. Components, safety functions and safety performance indicators for the SFR repository. BTF, BMA and silo are different parts of the repository (see figure 1-2 and the Initial state report)

Safety function	Safety performance indicator	Component
Safety principle: Limitation of radioactive inventory		
Limited quantity of activity	Activity of each radionuclide in each waste vault	Waste in 1BMA, 2BMA, 1BTF, 2BTF, Silo, 1BLA, 2-5BLA and BRT
Safety principle: Retardation of radionuclide transport		
Low flow in repository	Hydraulic contrast	1-2BMA, 1-2BTF
	Hydraulic conductivity	Bentonite in Silo and plugs
	Gas pressure	Silo
Low flow in bedrock	Hydraulic gradient	Geosphere
	Hydraulic conductivity	Geosphere
Good retention	pH	Cementitious materials in waste packages Concrete barriers in 1-2BMA, 1-2BTF, silo and BRT
	Redox potential	Cementitious materials in waste packages Concrete barriers in 1-2BMA, 1-2BTF, silo and BRT Geosphere
	Concentration of complexing	Cementitious materials in waste packages Concrete barriers in 1-2BMA, 1-2BTF, silo and BRT
	Available sorption surface area	Cementitious materials in waste packages Concrete barriers in 1-2BMA, 1-2BTF, silo and BRT
	Corrosion rate	Reactor pressure vessels BRT
Avoid inadvertent intrusion	Intrusion well Well in discharge area.	Biosphere[1]

[1] The biosphere and timing aspects of its safety function are discussed further in the main text and in Table 4-2.

Table 4-2 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 and should not be interpreted in the context of the main scenario. The indicators in Table 4-2 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 of the FHA to occur, affecting the likelihood.

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

4.3 FEPs potentially impairing post-closure safety

In previous safety assessments for a spent fuel repository, thorough societal and technical analyses have been performed (SKB 2010b). 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 fuel repository may occur. For a respository closer to the surface, like SFR, this conclusion is particularly relevant.

In SR-PSU, three societal FEPs of special interest are identified and described below (FHA 01, 02 and 03). The list of technical activities which could have an effect on the spent fuel repository performance has been revisited in order to evaluate if they are valid also for SFR. In total 14 technical FEPs is 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 4-1) and other concerns relevant for post-closure safety (Table 4-2) have been considered. The FHA FEPs identified that may have a potential impact on the repository are given in Table 4-3. To facilitate scenario selection and development, and to make a clear link to the previous work (SKB 2010b), 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 the post-closure safety in order to visualise what type of actions are performed. The societal FEPs mainly affect the likelihood for the unintentional human intrusion 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 affect the amounts of waste already stored in the repository but may affect all other safety functions of the repository. In Table 4-4 the identified technical FHA FEPs are related to the safety functions (Table 4-1) that the FEP may affect. In Section 4.4 a thorough description of each FEP is given with description of how the FHA for each FEP can affect the safety of the repository.

Table 4-2. Repository components and indicators identified relevant in the context of assessing FHA for the SFR repository.

Component	Indicator
Waste	Integrity of waste packages
Engineered barriers	Integrity of engineered barriers
Geosphere	Depth
	Natural resources
	Host rock suitability
Biosphere	Location in relation to shoreline, at time of closure and thereafter for a significant time

Table 4-3. FEPs related to future human actions with potential impact on post-closure safety of SFR.

FEP number	Name	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 the society	X				
FHA03	Technological development	Technological development of the society	X				
FHA04	Heat storage	Build heat store		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 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	
FHA16	Hazardous waste facility	Store/dispose hazardous waste in the rock			X	X	X
FHA17	Contamination with chemical substances or chemical conditions	Construct sanitary landfill (refuse tip), acidify air, water, soil and bedrock, sterilise regolith, cause accident liming, or pest controls, etc					X

Table 4-4. 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	FHA18
Limited quantity of activity															
Low flow in repository	X	X		X	X	X		X	X	X		X	X		
Low flow in bedrock	X	X		X	X	X	X	X	X						
Good retention	X				X	X		X	X		X		X	X	X
Avoid inadvertent intrusion	X	X	X	X	X		X	X			X	X			X

4.3.1 Use of SKB's FEP database to ensure completeness of the SR-PSU FHA FEP lists

An important and formal tool for ensuring that all relevant factors have been taken into account in the safety assessment is databases of FEPs that are of importance for post-closure safety in a nuclear waste repository. SKB's FEP database covers both the Spent Fuel Repository and SFR. The FEP database is based on the results of work with earlier safety assessments for the Spent Fuel Repository – SR-Site, SR-Can and SR 97 – which is described in the FEP reports for SR-Site (SKB 2010a) and SR-Can (SKB 2006c), in the Process report for SR 97 (SKB 1999a) and in the supporting documentation for the interaction matrices that have been constructed for a final repository according to the KBS-3 method (Pers et al. 1999).

The database has been further developed in the SR-PSU assessment so that it also covers SFR. Handling of FEPs has been documented in database format in previous studies for SFR as well. The work and the database then followed the methodology with interaction matrices and are documented for the two most recent safety assessments, SAFE (SKB 2001) and SAR-08 (SKB 2008b). The work of updating SKB's FEP database, is described in the **FEP report**. The work has resulted in a version of SKB's FEP database that contains FEP catalogues for SR 97, SR-Can, SR-Site and SR-PSU. The database also contains all project FEPs in the NEA's international FEP database, versions 1.2 (NEA 1999) and 2.1 (NEA 2006), including the classification and properties of these FEPs.

The FHA FEPs are included in the SKB FEP database and were also checked against earlier FHA FEPs and the NEA FEP database. This also ensures that the set of FEPs is consistent with former analyses at SKB or by NEA as a measure of quality assurance.

4.4 Description of FEPs

This section provides the basic premises for inclusion or exclusion of the societal and technical FEPs identified in Section 4.3 in scenario formulation and calculation cases for FHA. Consideration is taken to earlier FHA assessments at SKB (see Section 2.3), discussion material in this document, as well as new justifying references.

4.4.1 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 disrupt the safety functions of a repository are assumed to be possible only when the knowledge about the repository, particularly 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 2011), it is stated that RK&M is needed to support lengthy and complex decision-making processes across long operational and post-operational lifetimes of radioactive waste repositories. Long-term projects of any nature are vulnerable to risks of RK&M loss. The reasons and mechanisms leading to loss of RK&M are very diverse, but preserving RK&M is a fundamental aspect of quality in establishing and running any long-term project. NEA (2011) states that RK&M must be taken into account in implementing national radioactive waste disposal programmes in order to:

- Maintain confidence in the safety and security of the system by allowing for accurate and reliable review by the authorities and providing for visible and transparent oversight of disposal projects across time.
- Address concerns and answer requests from the public, especially local communities.
- Ensure that future generations can base their decisions on relevant and pertinent data.
- Promote awareness of past activities.

Several studies have been undertaken in the past decades, both on the national and international level, to explore a variety of methods for preserving RK&M across different timescales, for example (Jensen 1993, NEA 2011).

The key issue in the current context is how long institutional measures can be relied upon to remove any chance of FHA disrupting 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 2010b). 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 of 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 human intrusion is selected based on following conservative assumptions: the existence and location of the repository are forgotten, and the level of technology is the same as today.

Inclusion/exclusion in scenario development
The knowledge of the repository is an important FEP to include in scenario development since only inadvertent actions are to be included in FHA analysis. For this assessment, although longer time periods have been suggested in assessments in other countries, FHA are assumed to occur at 300 years or thereafter, when it is assumed that knowledge has been lost. It is noted that 300 year is a shorter time span than until the entire repository is situated below land and not sea. In reality, although exploratory drilling are technically possible below sea, the lack of natural resources in the area leads to that FHA are not expected until the repository is situated under land, i.e. about 3000 AD (see Section 4.3.8 and the **Biosphere synthesis report**).

4.4.2 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 which 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 the technical means for directly disruptive FHA, such as deep drilling. By the same token, it can be acknowledged that those with the capability to deep drill would 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 have to 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 particular single 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 on the basis of continued current day social conditions and technical capabilities.

4.4.3 Technological development (FHA03)

Premises

Considerations here are included in discussion of societal development.

Inclusion/exclusion in scenario development

Technical development is included on the basis of continued current day social conditions and technical capabilities. This has significant implications for the consideration of technical FEPS, as follows.

4.4.4 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 is 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, mechanical and thermal state variables and processes in the geosphere. The extent and nature of the changes depends on how the store is designed and constructed. The construction of a heat store 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 a risk of intrusion into the repository and the FEP is considered in scenario selection. It is assumed that such drilling and other investigations 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 contaminated material brought to the surface (as part of a drilling scenario), but development of a heat store itself is not considered further as this would involve intentional intrusion (see Section 4.1).

4.4.5 Heat pump system (FHA05)

Premises

Ground-source heat pump systems are addressed here. 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 is only used where there are large aquifers like eskers or in areas with limestone. Thus, in Forsmark open system can only be expected in Börstilsåsen while the rest of the area that are made up for granite are only suitable for closed heat pump systems.

Technology

The technology is available today and many systems are in operation. Systems for small buildings, with boreholes in which a heat transfer fluid circulates in a closed loop, are common. One 100–200 metres deep borehole can supply a single-family home with its energy needs, but larger houses may require two such boreholes. 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 considered to be limited. However, since the heat pump system includes 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 would include drilling there is a risk of 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 material brought to the surface and can be treated as part of a drilling scenario (see Section 4.1). Development of a heat pump system is not considered further in the FHA assessment since only closed heat pump systems are suitable for the Forsmark area and thus radionuclides would not be brought to the surface via the heat pump system.

4.4.6 Geothermal energy (FHA06)

Premises

By "geothermal energy" is meant here 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, such systems require temperatures of at least 150–200°C. At Forsmark, such high temperatures are expected only at depths of about 10,000 m. 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 flux at great depth in crystalline rock is limited, the latter option is more likely.

Technology

The technology exists today, but is not capable of application at the great depths as would be required at Forsmark. 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 in areas where the temperature increases rapidly with depth. However, as already stated, no system exists today at the great depths that would be required at Forsmark. There are boreholes drilled to these depths for exploratory purposes. If geothermal energy were to be utilised at Forsmark, drilling techniques would have to be developed substantially to make this a routine technological activity.

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 are considered to be low. However, a borehole directly into the repository would affect the repository safety functions.

Inclusion/exclusion in scenario development

This FHA FEP was considered already in siting so this FEP should not need to be considered in scenario selection. However, even a failed geothermal energy project may involve exploration drilling which is included in the drilling scenario.

4.4.7 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 scenario development.

4.4.8 Drilled well (FHA08)

Premises

Rock wells where the water is abstracted for drinking water or for irrigation are drilled through water-conducting zones. Their depth is generally no greater than 50 to 100 m, but some wells reach down to 130–150 metres (Werner et al. 2014). 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, **Main report**) the area will not be a favourable location for wells within the future landscape (see further discussion in Werner et al. 2014). However, it cannot be ruled out entirely.

Technology

The technology exists, and there are rock wells in the country and in the county Uppland where Forsmark is situated (Werner et al. 2014).

Potential impact on the repository and its functions

A drilled well into the repository would affect the safety functions of the repository and could lead to release of radionuclides ending up in the well.

Inclusion/exclusion in scenario development

Evaluating the effect of abstracting water from a well drilled into the repository is included in the post-closure safety assessment. This is handled outside the FHA study (**Main report**, **Radionuclide transport report**), but the discussion has been included for completeness of the documentation of FHA FEPs. The other consequences of the drilling are subsumed in the treatment of FHA11 (Section 4.4.11 below).

4.4.9 Water management (FHA09)

Water management is taken to include a number of actions affecting hydrology, e.g. building dams, change of the course or extent of surface water bodies, building hydropower plants, and building drainage/infiltration systems.

Premises

Dams are built to create a water reservoir, if topography and other ground conditions are suitable. The reservoir 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, see FHA10, Section 4.3.10.

Surface water bodies can be altered by changes in land use associated with e.g. 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 fill with water. Near surface layers may be drained to make the areas 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. Also the technique for building hydropower plants and irrigation/drainage system are well known today and the same technology as for dams are needed but may also include technology for underground construction, see FHA 12, Section 4.3.12.

Potential impact on the repository and its functions

Water management activities may locally affect hydraulic gradients thereby affect the safety function low flow in the bedrock. Areas that have previously been groundwater recharge areas can become discharge areas, and vice versa. The conditions for groundwater infiltration are changed. For most actions related to this FEP, such as building dams or altering the route of streams, the effects on the capacity of the rock to provide favourable hydrological and transport conditions are judged to be small. However, large scale construction activities affecting hydrology may have an effect at repository depth and for example, there has been a discussion whether the pier to SFR will remain or be taken away.

Inclusion/exclusion in scenario development

Small scale activities such as creating a dam should not have an effect on the hydrology at repository depth. However, large scale activities such as large construction at the site may have an effect and are included in scenario development.

4.4.10 Altered land use (FHA10)

Premises

Land use refers to the different ways humans utilise the environment, e.g. by forestry or agriculture. Changes in land use can 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 ground water level will be altered, or if land surface areas are built on and/or covered with some relatively impermeable coating, groundwater recharge will be reduced. This affects the ground conditions and can lead to subsidence damage to buildings as well as landslides. 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 of radionuclides in the biosphere but should have insignificant effect on the safety functions of the repository system due to the depth of SFR.

Inclusion/exclusion in scenario development

Land use changes are part of the biosphere description (**Biosphere synthesis report**) but since there are no expected effects on the safety functions of the repository it is not needed to be included in the FHA scenarios.

4.4.11 Drilling (FHA11)

Premises

SKB consider drilling as a key FEP when addressing the potential impact on the repository of FHA; although deemed unlikely to occur, deep geological drilling on the site post-closure and after knowledge of the site has been lost, is the FHA FEP assumed to be 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 forum (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) 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).

The reason for future humans to decide to drill at the Forsmark site is not possible to predict reliably. Table 4-5 lists a range of present-day human actions involving geological drilling, not necessarily limited to the Forsmark site. In summary, they are related to drilling wells (FHA08), interest in mining (FHA12, FHA13), geothermic energy (FHA06), oil and gas exploration and exploitation, and geological investigations for scientific research and special constructions such as future waste disposals (FHA16). Concerning Forsmark specifically, the evaluation of the potential for ore and industrial minerals in the Forsmark area shows that the area contains several minor mineralizations that might be explored in the future (Lindroos et al. 2004). These areas are situated in the vicinity of the repository but several kilometres away from the repository footprint. In addition, the repository itself comprises a heterogeneity in the rock and, if mineral explorations is commenced in the area, may be detected with investigations. This could attract the interest of the people performing the mineral exploration, and non-intrusive investigations may be followed by drilling on targets of interest.

Table 4-5. Reasons for future humans to conduct geological drilling, with comments on drilling depths and geological formations (reproduced 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 disposals location (toxics and/or radioactive)	Shallow and deep.	Not fractured crystalline rocks and sedimentary formations with low permeability.
Oil/gas exploration and exploitation	Shallow and deep.	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.

Although it has been argued that such scenarios are highly 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 in order to investigate the viability of radioactive waste disposal.

Technology

The art of drilling deep holes in rock has existed for thousands of years. Drilling methods commonly used nowadays are presented in Table 4-6. Although present technologues can reach to extensive depths, a typical depth in rock for a water-supply well is estimated to be 60 m in the Forsmark area (Werner et al. 2014).

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 drilling method. Cable tool drilling was probably the earliest method used and has been in continuous use for some 4,000 years. Cable tool rigs operate by repeatedly raising and dropping a drill string of a heavy drilling bit. The drill bit breaks or crushes consolidate rock into small fragments. During the drilling process, the drill string is periodically removed from the borehole and a bailer is lowered into the borehole 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 has largely been replaced with faster drilling techniques.

Table 4-6. Characteristics of current drilling techniques (reproduced 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 few compact materials: clay, loam, limestone, etc. Compact materials: fractured or karstic.
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 1900's. The concept for 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 km may be reached with the rotary drilling technique.

Reverse circulation drilling is a relatively new method, development for sampling in the early 1970s. Reverse circulation uses dual wall drill rods that comprise an outer drill rod, with inner tubes located inside the drill rod. 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 string. 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 rods and collected at 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, so as 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 deep holes are drilled in the future in the Forsmark region, it cannot be 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 also form a 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.

4.4.12 Underground constructions (FHA12)

Premises

One reason for building tunnels and shafts in the rock is for mining purposes, i.e. 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 placing 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, 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 FHA 06). A rock cavern can also be built for the purpose of obtaining a water head in order 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 affect the capability of the geosphere to provide favourable hydrological and transport conditions i.e. affecting the safety function low flow in the bedrock. If the rock cavern is kept dry, water flux and conditions for transport of substances with the groundwater will be affected. Abandoned rock caverns, tunnels, shafts and boreholes are potential transport pathways for undesirable substances to and from the repository. A rock cavern may also affect the capability of the geosphere to provide chemically favourable conditions. For example, during operation of a sub-surface facility close to the repository, salinity can increase at repository depth. The temperature in the bedrock will also be affected, but it is judged unlikely that it will fall below 0°C or rise above 100°C. The closer to the repository the rock cavern is located, the more the repository is affected.

Inclusion/exclusion in scenario development

Rock caverns in the vicinity of the repository are considered in the selection of FHA scenarios.

4.4.13 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 are 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 to mine near the surface and crystalline rock is plentiful, it is likely that the depth of the quarry would be limited to 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 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. 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 result 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 function.

Inclusion/exclusion in scenario development

Sites with unusually high quality (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, and thus this FEP does not have to be further included in selection of FHA scenarios.

4.4.14 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 measures in the form of drainage, sealing layer and the like. However, a release of substances from a landfill would have to be very extensive in order to affect the chemical conditions in the repository and the landfill itself would probably entail large consequences in human health and environment

Inclusion/exclusion in scenario development

It is unlikely that a landfill would have an effect on the mechanical load of the repository due to the depth of SFR. It is also highly unlikely that the landfill would affect the chemical composition of the groundwater to such a degree that changed chemical conditions at repository depth affect the safety functions. If such releases occur, other health problems related to the releases at the surfaces would most probably make any further release from SFR negligible in comparison. Nevertheless, the upper limit of the dose consequence of this FEP can be estimated from the scenario “loss of barrier function – no sorption in the repository” (in the **Main report** and the **Radionuclide transport report**) and thus this FHA FEP is indirectly handled in the assessment and is not further considered in the FHA scenarios.

4.4.15 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 considered to be 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 in wartime or if the site is used as a weapons testing site. A bomb that detonates near the ground surface could create a crater and the rock fractures locally.

Technology

Besides blasting, this FEP is primarily related to accidents, i.e. there is rather a failure in technique for a crash to occur at the site but accidents like crashes and explosions do occur at present from time to time, though major disruptive accidents are rare.

Potential impact on the repository

It is assumed that the safety of the repository would normally not be affected, as the changes would only penetrate to a few metres or, at most, tens of metres. A bomb that could threaten the repository would have to have a very powerful pressure wave. If such a bomb were to detonate on the surface, the consequences would be disastrous regardless of whether they lead to a release of radionuclides from the repository or not. Testing of such large bombs in peacetime is unthinkable. If bombs of this size were dropped in wartime, the consequences would probably be such that the impact of any radionuclide releases from a deep repository can be regarded as minor compared with the damage caused by the bombing.

Inclusion/exclusion in scenario development

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

4.4.16 Hazardous waste facility (FHA16)

Premises

If the site is selected for disposal of some type of waste, the choice will have been carefully considered, consistent with a desire to dispose of the waste safely. 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 of in this manner. Facilities for geological disposal of radioactive waste are in operation and repositories for spent nuclear fuel are planned in a number of countries. There are also plans to dispose of mercury in rock caverns. Technologies to inject radioactive waste exist and have been employed in the US 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 a risk of 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 4.1).

4.4.17 Contamination with chemical substances or altering chemical conditions (FHA17)

Premises

This FEP can include a number of activities that in the end affect the chemical conditions, e.g. construction of a sanitary landfill, 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 extensive in order 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 are affected, retardation of radionuclides from the repository could be decreased. However, as stated above, the release of chemical substances would have to be very extensive in order to affect the chemical conditions in the repository and the contamination itself would probably entail more significant consequences on human health and environment.

Inclusion/exclusion in scenario development

It is unlikely that chemicals would be released in such quantities that the chemical conditions at repository depth to such a degree that the safety functions would be affected. If such releases occur, other health problems related to the chemical releases at the surfaces would most probably make any further release from SFR negligible in comparison. Nevertheless, an upper limit of the dose consequence of this FEP can be estimated from the scenario "loss of barrier function – no sorption in the repository" (in the **Main report** and the **Radionuclide transport report**) and thus this FHA FEP is indirectly handled in the assessment and is not further considered in the FHA scenarios.

5 FHA scenarios

5.1 Basis for scenario selection

In the FEP analysis (Chapter 4) a set of FHA was identified that have a potential impact on post-closure safety of the repository and that should be taken into account in FHA scenario development. This chapter uses the results of Chapter 4 to identify 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 manageable set of scenarios that covers the actions with greatest 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). SSMFS 2008:37 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 1998) 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."

Accordingly, the scenario selection is not intended to identify the reason for the FHA but to identify the potential consequences. The results from Chapter 4 are summarised in Tables 5-1 with a link to selected FHA scenarios. In Table 5-2 the scenarios are summarised with a link to identified calculation cases and qualitative analyses to be made for the identified FHA scenarios. The scenario descriptions, calculations and results are further expanded in the following Sections 5.2 to 5.4.

5.2 Drilling Scenario

Drilling (FHA11) is considered to be a credible action that may lead to direct intrusion into the repository; it is judged at the same time being as being inadvertent, technically possible and practically feasible, plausible, and conceivable in the societal context. The reasons for drilling may vary; as shown in Table 5-1. Therefore, this scenario in addition to FHA11, also includes part of FHA04, FHA05, FHA06, FHA12 and FHA16.

5.2.1 Scenario description

The precise reason for future humans to drill at the Forsmark site is not an important driver for the scenario description. The selection of FHA scenarios aims to comprise 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. Hence, all future human actions that may involve drilling are here embraced by one drilling scenario. The premises for this scenario is that the technology to drill to repository depth exists (as detailed in Section 4.3.11), that the knowledge of the location and purpose of the repository is lost, that the intruders do not initially recognise the radioactive nature of drilling material with which they may come into contact. As described in section 4.2.1 the main safety principles of SFR is limitation of the activity of long-lived radionuclides and 'retention of radionuclides'. One drill whole into the repository is not assumed to have a significant effect on these safety functions but the main concern in this scenario is if future humans would be exposed to radioactive waste brought back to the surface.

Assumptions

The main assumption for the drilling scenario is that the borehole directly intersects the repository and brings contaminated materials up to the surface. To maximise the potential dose consequences to humans, it is assumed that the borehole penetrates disposed radioactive waste packages. For any drilling method, it is likely that the drilled material presented by the components of the SFR repository will be discovered and the drilling stopped for further investigation which could lead to recognition of the purpose of the underground facility (SFR). Material brought to the surface may then give rise to exposure of drilling crew workers who might examine the drilled material, before its hazardous nature is recognised.

Table 5-1. Linking of FHA FEPs to selected FHA scenarios.

FEP number	Name	Scenario	Comment
FHA01	State of knowledge	All scenarios	It is assumed that the memory of the repository is lost after 300 years. Continuing support for assumptions made here will be available from the NEA Records, Knowledge and Memory (RK&M) project, on-going (NEA 2011).
FHA02	Societal development	All scenarios	Strongly linked to state of knowledge. It is assumed that the societal development allows for loss of memory of the repository.
FHA03	Technological development	All scenarios	Strongly linked to societal development. It is assumed that present day level of technology applies in all scenarios.
FHA04	Heat storage	Drilling into the repository	A heat storage system would only be constructed after geological investigation, potentially including drilling. Given current day technology this would result in discovery of the radioactive contamination and SFR. Thereafter any intrusion would be intentional and intruders are responsible for their own actions.
FHA05	Heat pump system	Drilling into the repository	With current technology water is not brought to the surface but drill cuttings are covered in drilling scenario.
FHA06	Geothermal energy	Drilling into the repository	Unlikely to occur, but exploratory drilling may be performed.
FHA07	Heating/cooling plant	No scenario selected.	Would require oher technology than available at present.
FHA08	Drilled well	No FHA-scenario for abstracting and use of well water. Effects of drilling the well subsumed with FHA11.	Well water abstraction and use is included in the main calculation cases (**Main report**) and not considered further here.
FHA09	Water management	Water management	Large scale activities are considered.
FHA10	Altered land use	No scenario selected.	Treated in the biosphere analysis **(Biosphere synthesis report)**.
FHA11	Drilling	Drilling into the repository	A key case for FHA.
FHA12	Underground constructions	Drilling into the repository Underground constructions	Includes exploratory drilling direct into the repository but also effects of a rock cavern in the vicinity of the repository.
FHA13	Quarry	No scenario selected.	Quarries to a few tens of metres are unlikly to have an impact on the repository. In addtition, the quality of the bedrock was considered in siting to avoid the use of a site suiatble for quarries. Mining is considered in FHA 12.
FHA14	Landfill	No FHA scenario selected.	Unlikely that releases at a landfill would have an impact at the repository depth. Nevertheless, the upper limit of the dose consequence of this FEP can be estimated from the scenario 'Loss of barrier function – no sorption in the repository' and thus does not has to be further evaluated in the FHA analysis.
FHA15	Bombing, blasting, explosions and crashes	No scenario selected.	Due to the large depths of SFR, explosions and crashes are considered highly unlikely to have any effect on the repository.
FHA16	Hazardous waste repository	Drilling into the repository	Similar argument to that for heat storage.
FHA17	Contamination with chemical substances or altering chemical conditions	No FHA-scenario selected.	Unlikely that releases of chemicals would have an impact at the repository depth. Nevertheless, the upper limit of the dose consequence of this FEP can be estimated from the scenario 'Loss of barrier function – no sorption in the repository' and thus does not has to be further evaluated in the FHA analysis.

Table 5-2. FHA-scenarios in SR-PSU with calculation cases and qualitative analyses. (FHACC = Future human action calculation case).

Scenario	Calculation cases	Comment
1 Drilling into the repository	FHACC1 On-site crew during drilling	This calculation case assumes that a waste package is hit when drilling. Potential consequences is evaluated by calculating doses to the drill crew directly exposed during drilling.
	FHACC2 Construction on drilling detritus landfill	This calculation case assumes that a waste package is hit when drilling and that waste is brought to the surface (drilling detritus) and left on a landfill. It is assumed that humans, after the borehole is abandoned, utilise the landfill for construction. Potential consequences is evaluated by calculating the dose to a worker during construction on the landfill containing drilling detritus.
	FHACC3 Cultivation on drilling detritus landfill	This calculation case assumes that a waste package is hit when drilling and that waste is brought to the surface (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 is evaluated by calculating the dose to a farmer working on, and eating the crops grown on the landfill containing drilling detritus.
	Intrusion wells calculation case (CC 10 in the **Main report**)	This calculation case assumes that future generations will use a geological well where the borehole has hit directly into the repository. The calculation case is performed to assess the dose consequences of use of the abstracted water. This calculation case is included in the main calculation cases for SR-PSU and are not described in the current **FHA report**.
2 Water management	FHACC4 Pier to SFR removed	Hydrological modelling to evaluate the effect of changes or removal of the pier to SFR. Included in uncertainties in hydrological modelling (Odén et al. 2014, **Main report**).
3 Underground constructions	FHACC5 Road/rail tunnel in the vicinity of the repository	Hydrological modelling to evaluate the effect of changes or removal of the pier to SFR. Included in uncertainties in hydrological modelling (Odén et al. 2014, **Main report**).
	FHACC6 A mine in the vicinity of the Forsmark site	Qualitative assessment.

In addition, the contaminated drilling detritus is assumed to be disposed of in a near-by landfill. This landfill is assumed also to be subject for human utilisation, without people having understanding of the potential radiological hazard.

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

Calculation cases identified to analyse the drilling scenario

Four aspects related to radiation exposure due to drilling into the repository are considered when identifying calculation cases for analysing the drilling scenario: 1) exposure to drilling crew workers during the drilling event, 2) exposure of people utilising the contaminated drilling detritus landfill for construction, 3) Exposure of people cultivating on a garden plot where the contaminated drilling detritus landfill has been disposed, and 4) direct exposure of humans utilising the borehole as a geological well, i.e. four calculation cases have been identified:

- FHACC1. Exposure of the on-site crew during the drilling event
- FHACC2. Exposure during construction on drilling detritus landfill
- FHACC3. Exposure due to cultivation on drilling detritus landfill
- Intrusion wells calculation case. Exposure due to utilising a well sunk into the repository (intrusion well). As indicated above, this calculation case is not evaluated in the present report but in the **Main report** and the **Radionuclide transport report**.

5.2.2 Calculation case on-site crew during drilling (FHACC1)

In this calculation case, it is assumed that a deep borehole is drilled, that the drill penetrates a waste package in the repository, selected to be either into the silo, or into one of the 1BMA, 1BLA or 2BMA vaults. Consequently, radioactive material is brought to the surface in the drill detritus, which causes exposure of workers at the drill site. Consideration is given to 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 among the more likely techniques for deep drilling in crystalline rock, or rotary drilling using air, which likely results in highest doses (Smith et al. 2013). 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 problem in all parts of the repository and bring back cores to the surface that would not alert the drilling personnel that they have hit something unusual. When analysing this calculating case, it is assumed that 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 conservative assumption that may be particularly unlikely if the drill hits a piece of stainless steel, e.g. in the1 BLA.

Furthermore, in reality, there is a pronounced heterogeneity in the spatial distribution of radionuclides and their activities within the repository. When analysing this calculating case, the simplified assumption is made that the radionuclide inventory in a repository part is uniformly distributed.

The exposure to the on-site-crew driller 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 SR-PSU are the waste inventory of the repository (described in the section 'Inventory and weight of waste').

Models and data applied

As stated above, this calculation case estimates 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 consequence due to unit activity inventory concentrations (1 Bq g^{-1}) and comprise a range of relevant radionuclides assumed to be present in 1 m length cores 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 be multiplied with activity concentrations in the waste of a specific assessment as long as the underlying assumptions are regarded relevant for the assessment. The case estimating doses to drillers, assuming diamond core drilling with water and that material excavated consist of concrete is in Smith et al. (2013) denoted DCW_CO_D (Diamond Core, Water, COncret, Driller) and the case estimating doses to drillers assuming rotary drilling with air is denoted RA_CO_D (Rotary, Air, COncret, Driller). The same abbreviations are used in this report.

Table 5-3 to 5-5 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 (DCF) is then calculated by summing the three pathway-specific dose contributions, according to:

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

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

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

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

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

Parameters are explained in Tables 5-3 to 5-5.

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 contaminated length of core material is assumed to be taken to the surface for the normalised DCF. For SFR this is a conservative estimate since a typical well drilled in the Forsmark area (for water supply) is only 60 m deep whereas the waste in the silo is placed at 78 m below surface (62 m rock and 16 m cupola on top of the cylindrical silo, as described in the **Initial state report**). However, drilling could also be performed for other reasons than water supply and the implications of longer cores are considered in Section 'Results' below, alongside other discussion of the results, bearing in mind that the doses vary linearly with the length of contaminated core or time exposed. The input data from Smith et al. (2013) are judged appropriate to use also for SR-PSU and the dose to drilling crew is calculated in this calculation case by the following equation:

$$D_{RA\_CO\_D} = DCF_{FHACC1RA\_CO\_D} \times A_i \qquad \text{or} \qquad D_{DCW\_CO\_W} = DCF_{FHACC1RA\_CO\_D} \times A_i$$

Where:

$D_{RA\_CO\_D}$ is the dose to drilling personnel using the drilling technique rotary drilling with air, Sv

$D_{DCW\_CO\_W}$ is the dose to drilling personnel using the drilling technique diamond core drilling, Sv.

$DCF_{FHACC1RA\_CO\_D}$ and $DCF_{FHACC1RA\_CO\_D}$ 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 5-3 to 5-5. The DCFs applied are summarised in Table 5-6.

A_i is the average activity concentration of a radionuclide in the sample, described under 'Inventory and weight of waste' below and summarised in Table 5-7.

Table 5-3. Data for calculation of the effective dose from external irradiation (D_{ext}) (cf. Section 4.2 in Smith et al. 2013). RA_CO_D – Rotary drilling with air, DCW_CO_D – Diamond core drilling with water.

Parameter or constant		Value	Unit
$1.4 \cdot 10^{-13}$	Constant relating exposure rate to source size and distance. Here, R refers to the exposure, in roentgens.	$1.4 \cdot 10^{-13}$	(100R m²)/(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 each radionuclide of interest	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)	2,400	kg m^{-3}
V	Volume of sample (m³) where, $V = \pi \cdot r^2 \cdot h$	0.34 (RA_CO_D) 0.02 (DCW_CO_D)	m³
	r Borehole radius	0.33 (RA_CO_D) 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 progeny which are assumed to be in equilibrium with the header radionuclide are given in Table 12 in Smith et al. (2013).

b) For the normalised DCF derived in Smith et al. (2013) a number of 1 Bq g^{-1} waste was applied. For the SR-PSU assessment, the activity concentrations for each radionuclide in the waste from the different repository parts assessed are summarised in Table 5-7.

Table 5-4. Parameter data for calculation of the effective dose from inhalation (D_{inh}) (cf. Section 4.2 in Smith et al. 2013). RA_CO_D – Rotary drilling with air, DCW_CO_D – 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	$1\cdot10^{-2}$ (RA_CO_D) $2.0\cdot10^{-3}$ (DCW_CO_D)	$g\ m^{-3}$
$I_{inh,i}$	Dose per unit intake by inhalation of each radionuclide i	Radionuclide dependent [(a)]	$Sv\ Bq^{-1}$
S_i	Average activity concentration of a 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 in ICRP (1996). 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 number of 1 $Bq\ g^{-1}$ waste was applied. For the SR-PSU assessment the activity concentration in the waste from the different repository parts assessed are summarised in Table 5-7.

Table 5-5. Data for calculation of the effective dose from inadvertent ingestion (D_{ing}), (cf. Section 4.2 in Smith et al. 2013). RA_CO_D – Rotary drilling with air, DCW_CO_D – Diamond core drilling with water.

Parameter		Value	Unit
t_{exp}	Exposure time	1	h
m	Intake by ingestion	$8x10^{-4}$ (RA_CO_D) $1.7x10^{-2}$ (DCW_CO_D)	$g\ h^{-1}$
$I_{ing,i}$	Dose per unit intake by ingestion of each radionuclide i	Radionuclide dependent [(a)]	$Sv\ Bq^{-1}$
S_i	Average activity concentration of a 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 (1996).

b) For the normalised DCF derived in Smith et al. (2013) a number of 1 $Bq\ g^{-1}$ waste was applied. For the SR-PSU assessment the activity concentration in the waste from the different repository parts assessed are summarised in Table 5-7.

Table 5-6. Dose conversion factor (DCF, Sv per $Bq\ g^{-1}$) used for the different FHA calculation cases in SR-PSU. DCF_FHACC1_DCW_CO_D = DCF for drilling personnel using Diamond core driller with water, DCF_FHACC1_RA_CO_D = DCF for drilling personnel using Rotary drilling with air, DCF_FHACC2_RA_CO_D = DCF for construction worker utilising a landfill with drilling detritus, DCF_FHACC3_ RA_CO_D = DCF for utilising a landfill as garden plot growing food. The references for the different DCFs are described in the text.

	FHACC1 Drilling case		FHACC2 construction case	FHACC3 cultivation case
	DCF_FHACC1_DCW_CO_D	DCF_FHACC1_RA_CO_D	DCF_FHACC2_RA_CO_D	DCF_FHACC3_ RA_CO_D
Ba-133	4.4E–11	9.4E–11	3.1E–06	2.1E–06
Am-243	2.5E–07	1.2E–06	1.0E–04	2.6E–06
C-14-inorg	2.2E–11	6.1E–11	3.1E–06	9.8E–07
C-14-ind	2.2E–11	6.1E–11	3.1E–06	9.8E–07
Ag-108m	5.9E–09	1.3E–07	1.1E–03	1.4E–05
Ac-227	3.4E–06	1.7E–05	1.4E–03	3.1E–05
Am-242m	2.3E–07	1.1E–06	1.0E–04	1.1E–06
Am-241	2.6E–07	1.3E–06	1.0E–04	1.2E–06
Ra-226	3.2E–08	2.4E–07	7.6E–04	2.5E–04
Pu-242	2.9E–07	1.4E–06	1.2E–04	7.8E–07
Pu-241	5.5E–09	2.7E–08	2.1E–06	6.1E–09
Pu-240	3.0E–07	1.5E–06	1.2E–04	8.2E–07

	FHACC1 Drilling case DCF_FHACC1_DCW_CO_D	DCF_FHACC1_RA_CO_D	FHACC2 construction case DCF_FHACC2_RA_CO_D	FHACC3 cultivation case DCF_FHACC3_ RA_CO_D
Pu-239	3.0E–07	1.5E–06	1.2E–04	8.3E–07
Pu-238	2.8E–07	1.4E–06	1.1E–04	6.3E–07
Po-210	4.0E–08	1.0E–07	1.4E–05	1.2E–06
Pd-107	1.1E–12	2.6E–12	2.3E–09	3.6E–08
Pb-210	1.9E–08	3.7E–08	6.5E–06	6.0E–04
Pa-231	8.5E–07	4.2E–06	3.4E–04	3.5E–05
Np-237	1.4E–07	7.1E–07	1.2E–04	3.3E–05
Ni-63	5.4E–12	1.5E–11	2.3E–09	1.2E–07
Ni-59	2.9E–12	2.8E–11	2.3E–09	6.1E–08
Nb-94	5.8E–09	1.3E–07	1.1E–03	1.5E–05
Nb-93m	5.1E–12	1.5E–11	6.1E–08	9.0E–09
Mo-93	5.6E–11	2.1E–11	2.3E–09	2.5E–05
Ho-166m	0.0E+00	0.0E+00	0.0E+00	1.6E–05
I-129	2.1E–09	1.2E–09	3.1E–06	1.8E–05
Eu-152	4.3E–09	9.1E–08	1.1E–03	3.9E–06
H-3	5.8E–13	1.4E–12	2.4E–12	3.9E–15
Cs-135	3.8E–11	2.3E–11	3.1E–06	2.4E–06
Cs-137	2.3E–09	4.5E–08	2.4E–04	1.2E–05
Cm-246	2.3E–07	1.1E–06	1.2E–04	2.9E–06
Co-60	9.2E–09	2.0E–07	1.1E–03	4.8E–06
Cm-244	1.6E–07	8.1E–07	3.1E–06	7.4E–07
Cm-245	2.3E–07	1.1E–06	1.2E–04	3.4E–06
Cm-242	0.0E+00	0.0E+00	0.0E+00	2.1E–09
Cm-243	0.0E+00	0.0E+00	0.0E+00	1.7E–06
Cd-113m	0.0E+00	0.0E+00	0.0E+00	1.9E–04
Cl-36	6.0E–11	2.3E–10	3.1E–06	9.0E–05
C-14-org	2.2E–11	6.1E–11	3.1E–06	9.8E–07
Ca-41	3.8E–12	3.9E–12	2.3E–09	1.3E–06
Zr-93	7.9E–11	3.0E–10	6.1E–08	1.8E–07
Th-230	8.8E–08	4.2E–07	3.4E–05	2.7E–06
Th-232	1.5E–07	7.5E–07	5.9E–05	3.0E–06
U-232	5.2E–08	2.3E–07	1.2E–04	5.5E–05
U-233	2.2E–08	1.1E–07	8.7E–06	1.1E–05
U-234	2.2E–08	1.1E–07	8.4E–06	1.0E–05
U-235	2.0E–08	1.1E–07	5.3E–05	1.1E–05
U-236	2.0E–08	9.6E–08	7.6E–06	9.9E–06
U-238	1.8E–08	8.9E–08	1.8E–05	1.0E–05
Ra-228	3.1E–08	1.5E–07	4.1E–04	9.7E–05
Se-79	5.6E–11	3.5E–11	6.1E–08	1.4E–06
Sm-151	2.6E–11	1.2E–10	1.1E–08	3.9E–09
Sn-126	7.1E–09	1.5E–07	1.1E–03	1.8E–05
Sr-90	7.6E–10	1.3E–09	3.1E–06	1.3E–04
Tc-99	3.5E–11	1.2E–10	6.1E–08	1.9E–06
Th-228	2.7E–07	1.4E–06	7.8E–04	9.7E–07
Th-229	5.3E–07	2.6E–06	2.8E–04	1.0E–05

Table 5-7. Reference radionuclide inventory [Bq] in the four considered waste vault at closure of SFR i.e. 2075 according to the initial state report. A_i is the concentration calculated by dividing the inventory by the weight of cement and concrete in the silo, 1BMA and 2BMA ($2.39 \cdot 10^{10}$ g, $1.29 \cdot 10^{10}$ g, and $1.78 \cdot 10^{10}$ g, respectively) and for the weight of iron and steel and organic material for 1BLA ($5.66 \cdot 10^{9}$). Radionuclides with a half life less than 10 year are not included in the dose calculations. Also Be^{-10} is excluded due to the very low activity concentrations in the waste waults (maximum of about 4E-5 Bq g^{-1} found in the silo).

Radionuclides	Silo		1BMA		2BMA		1BLA	
	inventory [Bq]	A_i [Bq/g]	inventory [Bq]	A_i [Bq/g]	inventory [Bq]	A_i [Bq/g]	inventory [Bq]	A_i [Bq/g]
H-3	8.97E+09	3.75E–01	8.09E+08	6.28E–02	3.31E+12	1.87E+02	2.00E+08	3.54E–02
Be-10	9.89E+05	4.14E–05	2.21E+05	1.71E–05	2.19E+04	1.24E–06	6.53E+02	1.15E–07
C-14-org	7.56E+11	3.16E+01	1.47E+11	1.14E+01	3.96E+09	2.24E–01	7.91E+07	1.40E–02
C-14-inorg	2.72E+12	1.14E+02	1.90E+12	1.47E+02	1.44E+10	8.13E–01	4.03E+09	7.12E–01
C-14 ind	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.09E+09	2.87E–01	0.00E+00	0.00E+00
Cl-36	8.94E+08	3.74E–02	3.34E+08	2.59E–02	2.02E+08	1.14E–02	2.17E+07	3.83E–03
Ca-41	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.56E+10	8.80E–01	0.00E+00	0.00E+00
Fe-55	2.73E+12	1.14E+02	5.35E+10	4.15E+00	1.05E+11	5.91E+00	8.78E+06	1.55E–03
Co-60	1.29E+13	5.38E+02	4.08E+11	3.16E+01	1.99E+12	1.12E+02	1.03E+09	1.81E–01
Ni-59	6.85E+12	2.87E+02	2.10E+12	1.63E+02	9.50E+11	5.37E+01	3.99E+09	7.06E–01
Ni-63	5.48E+14	2.29E+04	1.47E+14	1.14E+04	9.23E+13	5.21E+03	3.04E+11	5.37E+01
Se-79	1.05E+09	4.40E–02	2.10E+08	1.63E–02	7.29E+06	4.12E–04	4.00E+05	7.07E–05
Sr-90	3.61E+12	1.51E+02	5.49E+11	4.26E+01	3.60E+11	2.03E+01	7.42E+08	1.31E–01
Zr-93	4.48E+09	1.87E–01	3.68E+08	2.85E–02	1.06E+09	5.99E–02	1.09E+06	1.92E–04
Nb-93m	9.33E+12	3.91E+02	1.73E+10	1.34E+00	1.31E+13	7.39E+02	7.68E+07	1.36E–02
Nb-94	8.67E+10	3.63E+00	3.67E+09	2.85E–01	9.12E+10	5.15E+00	3.14E+07	5.54E–03
Mo-93	1.96E+10	8.20E–01	1.46E+09	1.13E–01	4.52E+09	2.54E–01	1.01E+08	1.79E–02
Tc-99	5.00E+10	2.09E+00	6.22E+09	4.83E–01	1.42E+09	8.03E–02	1.85E+09	3.28E–01
Pd-107	2.75E+08	1.15E–02	5.25E+07	4.07E–03	2.55E+09	1.44E–01	1.00E+05	1.77E–05
Ag-108m	2.30E+11	9.62E+00	1.95E+10	1.51E+00	4.06E+10	2.30E+00	1.94E+08	3.42E–02
Cd-113m	9.58E+09	4.01E–01	7.98E+08	6.19E–02	9.32E+07	5.27E–03	1.96E+06	3.47E–04
Sn-126	2.05E+08	8.59E–03	2.62E+07	2.03E–03	1.75E+07	9.87E–04	5.00E+04	8.84E–06
Sb-125	1.32E+11	5.53E+00	4.37E+07	3.39E–03	2.62E+08	1.48E–02	4.74E+05	8.37E–05
I-129	9.84E+08	4.12E–02	1.46E+08	1.13E–02	7.67E+06	4.34E–04	4.35E+05	7.68E–05
Cs-134	2.20E+11	9.20E+00	1.45E+08	1.12E–02	2.26E+08	1.27E–02	1.58E+04	2.79E–06
Cs-135	4.47E+09	1.87E–01	8.41E+08	6.52E–02	5.33E+07	3.01E–03	3.07E+06	5.42E–04
Cs-137	5.97E+13	2.50E+03	8.15E+12	6.32E+02	8.95E+11	5.06E+01	1.84E+10	3.24E+00
Ba-133	6.16E+08	2.58E–02	4.89E+07	3.79E–03	1.43E+08	8.07E–03	2.20E+05	3.89E–05
Pm-147	3.59E+11	1.50E+01	3.71E+08	2.88E–02	4.06E+08	2.30E–02	3.02E+05	5.34E–05
Sm-151	4.63E+11	1.94E+01	8.26E+10	6.40E+00	3.55E+10	2.01E+00	1.68E+08	2.97E–02
Eu-152	8.64E+08	3.62E–02	9.47E+07	7.34E–03	1.33E+11	7.53E+00	1.02E+08	1.80E–02
Eu-154	5.24E+11	2.19E+01	2.33E+10	1.81E+00	6.83E+09	3.86E–01	4.01E+07	7.08E–03
Eu-155	9.96E+10	4.17E+00	1.02E+09	7.93E–02	3.74E+08	2.11E–02	1.54E+06	2.73E–04
Ho-166m	6.83E+09	2.86E–01	1.41E+09	1.09E–01	5.22E+08	2.95E–02	4.18E+06	7.39E–04
U-232	6.20E+05	2.59E–05	8.85E+04	6.86E–06	1.46E+05	8.26E–06	2.34E+03	4.14E–07
U-234	3.58E+07	1.50E–03	6.66E+06	5.16E–04	3.04E+06	1.72E–04	1.33E+05	2.35E–05
U-235	1.42E+07	5.92E–04	3.00E+06	2.33E–04	7.82E+04	4.42E–06	2.98E+08	5.26E–02
U-236	1.58E+07	6.63E–04	2.64E+06	2.05E–04	6.00E+06	3.39E–04	3.99E+04	7.05E–06
U-238	3.28E+07	1.37E–03	5.95E+06	4.61E–04	1.23E+06	6.94E–05	7.33E+08	1.30E–01
Np-237	5.36E+08	2.24E–02	2.73E+07	2.11E–03	7.68E+06	4.34E–04	6.75E+04	1.19E–05
Pu-238	7.29E+10	3.05E+00	7.52E+09	5.83E–01	4.42E+10	2.50E+00	3.47E+08	6.13E–02
Pu-239	1.70E+10	7.11E–01	2.77E+09	2.15E–01	6.78E+09	3.83E–01	6.60E+07	1.17E–02
Pu-240	2.39E+10	9.99E–01	3.87E+09	3.00E–01	9.21E+09	5.20E–01	6.74E+07	1.19E–02
Pu-241	3.07E+11	1.28E+01	2.40E+10	1.86E+00	1.66E+11	9.38E+00	1.29E+09	2.28E–01
Pu-242	1.23E+08	5.14E–03	2.00E+07	1.55E–03	5.02E+07	2.84E–03	3.99E+05	7.04E–05
Am-241	2.32E+13	9.69E+02	2.91E+10	2.25E+00	4.12E+10	2.33E+00	5.23E+08	9.25E–02
Am-242m	3.22E+08	1.35E–02	4.46E+07	3.46E–03	1.83E+08	1.04E–02	1.02E+06	1.81E–04
Am-243	1.60E+09	6.68E–02	2.02E+08	1.56E–02	6.62E+08	3.74E–02	4.00E+06	7.07E–04
Cm-243	1.89E+08	7.89E–03	1.85E+07	1.43E–03	1.03E+08	5.80E–03	7.58E+05	1.34E–04
Cm-244	9.26E+09	3.88E–01	6.73E+08	5.22E–02	1.07E+10	6.05E–01	5.39E+07	9.53E–03
Cm-245	1.49E+07	6.23E–04	1.99E+06	1.54E–04	1.01E+07	5.71E–04	3.97E+04	7.01E–06
Cm-246	4.29E+06	1.80E–04	5.27E+05	4.09E–05	3.34E+06	1.89E–04	1.05E+04	1.86E–06

Inventory and weight of the waste

The inventory and concentrations of the radionuclides in the silo, 1BMA, 2BMA, and 1BLA in 2075 are given in Table 5-7. The radionuclides included are those which present an inventory of above 1 MBq in any of the mentioned SFR components. It is noted that, given the masses of the wastes, radionuclides are only excluded if their concentrations are substantially lower than the most restrictive exemption level for any radionuclide in bulk amounts of radionuclides, i.e. 0.1 Bq g^{-1}, as given in IAEA (2005).

In the silo, it is assumed that the inventory of each radionuclide is uniformly distributed within the dominant materials in the waste packages, consisting of concrete and cement, i.e. $2.39 \cdot 10^7$ kg (**Initial state report)**. In the 1BMA and 2BMA vaults, the same approach is used assuming distribution in concrete and cement, i.e. the inventories is distributed in a mass of $1.29 \cdot 10^7$ kg and $1.77 \cdot 10^7$ kg respectively (**Initial state report)**. For the 1BLA vault, it is also assumed that the inventory of each radionuclide is uniformly distributed within the dominant materials consisting in this case of iron/steel and organic material (bitumen, cellulose and other organics) amounting to $5.66 \cdot 10^6$ kg (**Initial state report)**. This approach marginally understates the mass, and hence over-estimates the concentrations, and is thus marginally conservative. Later in the dose calculation, the density of material has to be taken into account. This marginally conservative approach avoids introducing the complexity of dealing with the inventory of each radionuclide in each material and then considering the density of each material[6].

These concentrations have been decayed through, also allowing for ingrowth of radioactive progeny in radioactive waste. This requires the inclusion of additional radionuclides in the decay chains. Branching ratios are also noted as these affect the summation over these chains. Data are taken from ICRP (2008). The decay and ingrowth of some of these radionuclides need to be assessed explicitly, in cases where they are relatively long-lived. Other are so short-lived that they can be assumed to be in secular equilibrium with their nearest long-lived progenitor. Short-lived here is taken to be the same as given in Smith et al. (2013), i.e. radionuclides having a half-life less than 30 days. The radiation effects of these relatively short-lived radioactive progeny are added into those of the nearest parent.

Results

Doses to on-site drilling crew were assessed for two different drilling techniques (Rotary drilling with air RA_CO_D, and diamond core drilling DCW_CO_W) and for four repository parts (SILO, 1BMA, 2BMA and 1BLA) i.e. results are achieved for 8 different calculation cases for FHACC1:

- FHACC1_RA_CO_D_SILO (Rotary drilling with air into the silo).
- FHACC1_DCW_CO_W_SILO (Diamond Core drilling with water into the silo).
- FHACC1_RA_1BMA (Rotary drilling into 1BMA).
- FHACC1_DCW_1BMA (Diamond Core drilling into 1BMA).
- FHACC1_RA_2BMA (Rotary drilling into 2BMA).
- FHACC1_DCW_2BMA (Diamond Core drilling into 2BMA).
- FHACC1_RA_1BLA (Rotary drilling into 1BLA).
- FHACC1_ DCW_CO_W_1BLA (Diamond Core drilling into 1BLA).

[6] The dose implications of heterogeneity are further discussed below.

The highest dose for on-site drilling crew was achieved for drilling into the silo using Rotary drilling with air at year 3000 AD (Figure 5-1). The highest dose for intrusion into the repository is seen for year 3000 AD in the silo and in the BMA rock vaults. In BLA, the highest dose is achieved at the end of the assessment period, due to ingrowth of Ac-227 and Pa-231. For all repository parts (except BLA) the highest dose would be achieved directly upon repository closure but as described earlier, drilling into the repository is not expected to occur until 3000 AD at the earliest (see Section 4.4.11). For the first 45,000 years, the highest dose is seen for FHACC1_RA_CO_D_SILO. Thereafter, intrusion case FHACC1_RA_1BLA would give rise to the highest doses. However, at this point in time, the dose is orders of magnitudes lower than at 3000 AD.

The dose at 3000 AD is 0.25 mSv for FHACC1_RA_CO_D_SILO. The doses at around 3000 AD and for several thousand years thereafter are, for this calculation case, dominated by Am-241 (Figure 5-2a). With time, the contribution from Pu-239, Np-237, and Th-229 to total dose increases as Am-241 decays, but, as seen in Figure 5-2a, not with any dose significance. The doses presented are those due to the presence of each radionuclide in the waste at the time of intrusion[7], not to the amount of said radionuclide deposited in the silo. Thus, this Am-241 includes the effects of any Am-241 present in, say 3000 AD, due to the decay of initial Pu-241 into Am-241 (although in this case, this makes a negligible contribution, as would be expected given inspection of the initial 2075 inventory shown in Table 5-7).

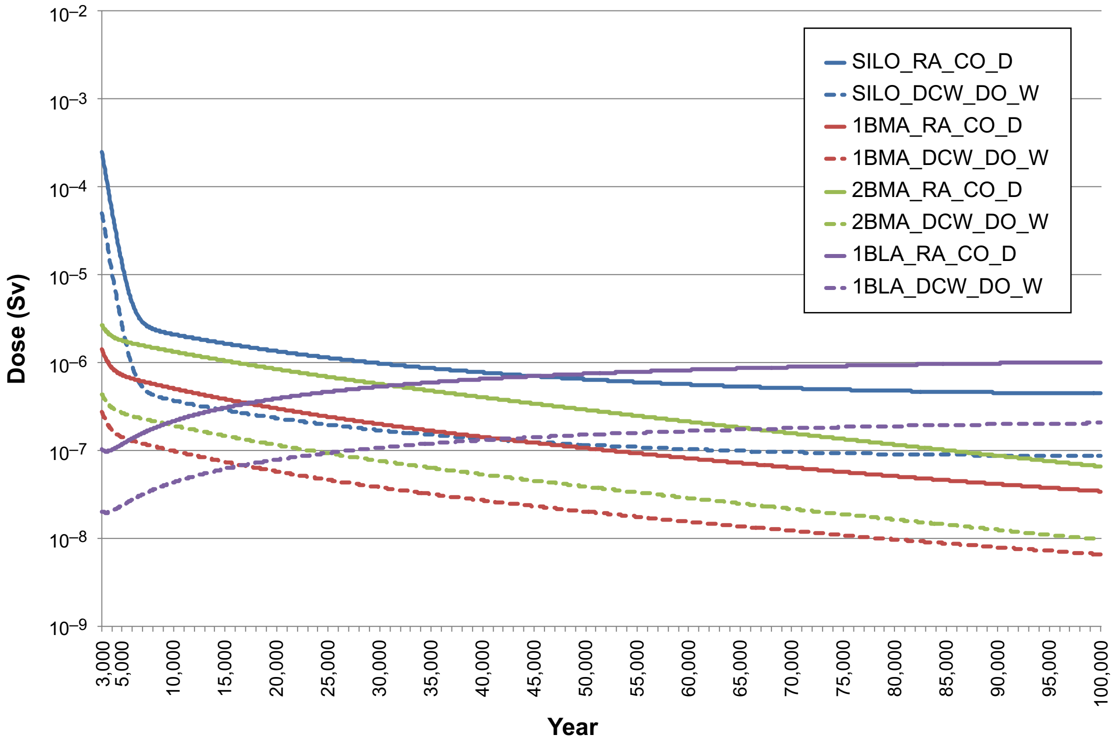

Figure 5-1. *Dose to drilling personnel working in the contaminated area after drilling into the different repository parts (silo, 1BMA, 2BMA and 1BLA) using the different techniques rotary drilling with air (RA_CO_D) or diamond core drilling with water (DCW_CO_W). Doses are shown as a function of time from 3000–100,000 AD.*

[7] Plus the contributions of short-lived radionuclides assumed to be in secular equilibrium with the named radionuclide, as discussed in Section 5.2.3 Inventory and weight of the waste.

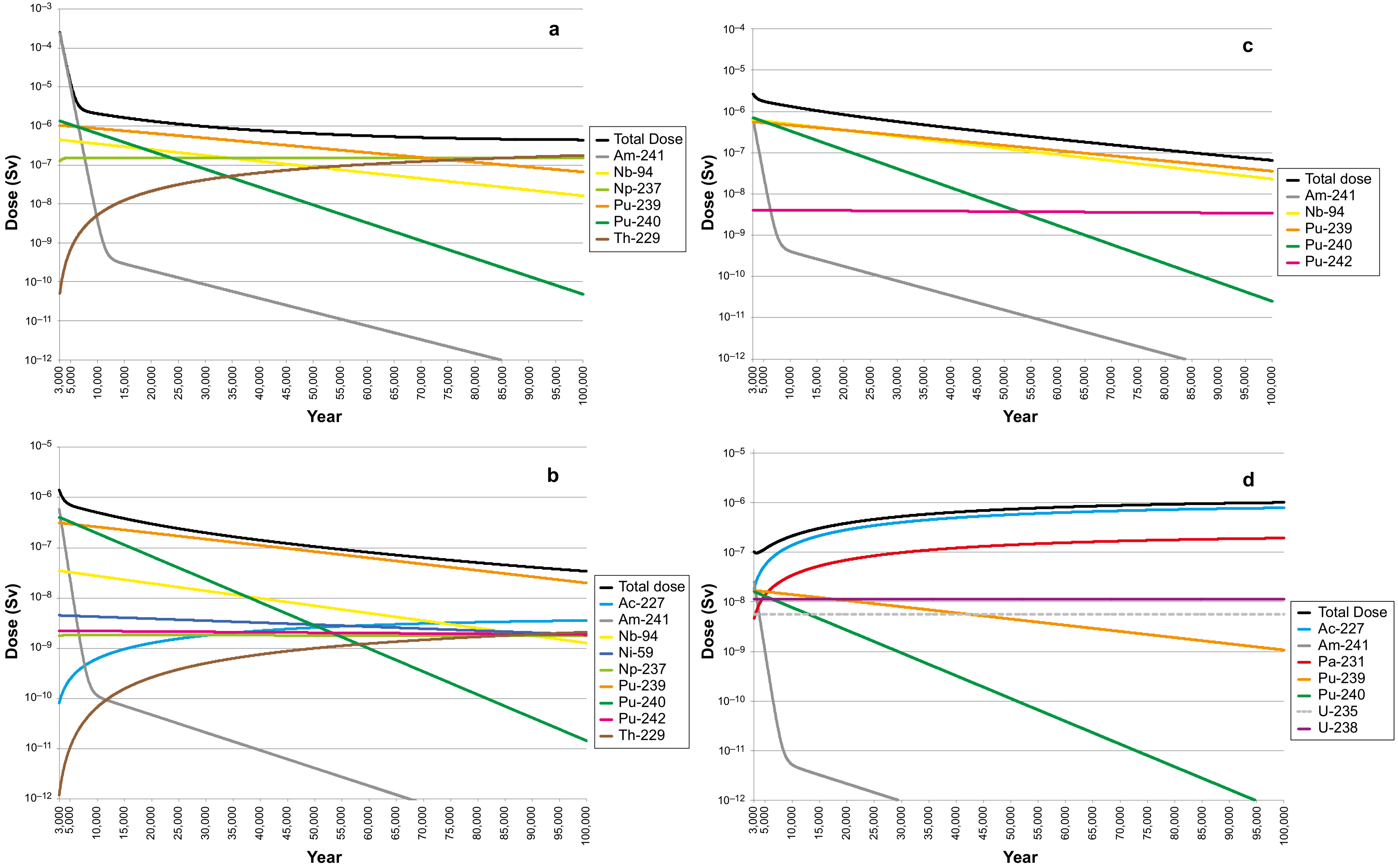

Figure 5-2. *Contribution of different radionuclides to the total dose rate to drilling personnel working in the contaminated area after drilling into the repository as a function of time using rotary drilling with air. a) FHACC1_RA_CO_D_SILO, b) FHACC1_RA_CO_D_1BMA, c) FHACC1_RA_CO_D_2BMA, and d) FHACC1_RA_CO_D_1BLA. The pattern of contribution of different radionuclides to total dose is similar for diamond core drilling technique but doses are lower.*

The dose at 3000 AD for FHACC1_DCW_SILO is 0.05 mSv, i.e. one order of magnitude lower than for FHACC1_RA_CO_D_SILO. The results here show similar features regarding dominating radionuclides, but reduced dose levels because the diamond core drilling technique brings less detritus or core material to the surface.

Intrusion into the 1BMA, 2BMA and 1BLA[8] using the same RA and DCW drilling techniques result in doses 2 or 3 orders of magnitudes lower than intrusion into the silo at year 3000 AD (Table 5-8). The results show moderately different characteristics because of the different proportions of radionuclides in the respective wastes. The lower doses compared to the silo are expected since the silo is designed for waste containing higher concentrations of radionuclides. In 1 BMA, Am-241, Pu-240, and Pu-239 dominate the dose at 3000 AD, but as Am-241 declines Pu-239 makes up the major part of dose, for most of the assessment period, but as seen in Figure 5-2b, not with any dose significance. In 2BMA, Am-241, Pu-239, Pu-240 and Nb-94 makes up roughly one quarter each of the total dose at 3000 AD (Table 5-8). Pu-239 and Nb-94 makes up major part of dose in late part of the assessment, but as seen from Figure 5-2c, not with any dose significance.

Drilling into 1BLA results in doses roughly the same as for drilling into the BMA vaults and two orders of magnitude lower than drilling into the silo at 3000 AD (Figure 5-2d, Table 5-8). At 3000 AD, Pu-240, Pu-239, Am-241, and Ac-227 dominates dose. The dose from Pu-240, Pu-239, and Am-241 decreases over time whereas Ac-227 and Pa-231 increases with time (Figure 5-2d). Due to the increase of Ac-227 and Pa-231, dose increases throughout the entire assessment period for FHACC1_RA_1BLA and FHACC1_DCW_1BLA and doses do not decline as for the other rock vaults.

In all calculation cases above, doses could be larger, if exposure time is increased or if a longer length of contaminated core material were brought to the surface, e.g. 5 m instead of 1 m. However, although stated already in Section 'Models and data applied', that there may be several reasons for drilling, the most likely reason for drilling based on records from the area today, would be for a well and then, drilling to shallower depths is expected. Thus, a 1 metre core can be seen as a cautious assumption. Another aspect of the results is that they are based on the assumption that activity in each component of the SFR is uniformly mixed. In reality, the drill may hit a more or less radioactive item of waste, and the resulting dose could be proportionately higher or lower.

Table 5-8. Dose at 3000 AD for FHACC1 with dose contribution from different radionuclides in %. Note from Figure 5-2 that other nuclides may become more important over time.

Radionuclide	Silo		1BMA		2BMA		1BLA	
	RA	DCW	RA	DCW	RA	DCW	RA	DCW
Total Dose [Sv]	**2.50E–04**	**5.05E–05**	**1.42E–06**	**2.77E–07**	**2.68E–06**	**4.35E–07**	**1.01E–07**	**2.02E–08**
Dose contributions [%]								
Am-241	99	99	41	43	25	31	25	25
Pu-240	1	1	29	30	26	33	16	16
Pu-239	<1	<1	22	23	21	26	17	17
Ag-108	<1	<1	3	<1	2	<1	<1	<1
Nb-94	<1	<1	2	1	24	7	<1	<1
Am-243	<1	<1	1	1	2	2	<1	<1
C-14	<1	<1	<1	1	<1	<1	<1	<1
Ac-227	<1	<1	<1	<1	<1	<1	18	18
U-238	<1	<1	<1	<1	<1	<1	11	12
U-235	<1	<1	<1	<1	<1	<1	6	5
Pa-231	<1	<1	<1	<1	<1	<1	5	5

[8] The 1BLA calculations were for concrete, although much of the material in the 1BLA is iron or steel or organic waste. This approach was adopted for simplification. The complete approach would require allocating each waste type its own density and allocation of the inventory in the BLA to each waste type. The affect here is to under-estimate the concentration of activity in the 1BLA wastes by about a factor of about 2. This is not ignored, but considered small in the overall consideration of results.

The most significant result from this set of calculations is that all the results, even for the most pessimistic drilling technique are below the (ICRP 2013) ranges of reference levels indicative of system robustness, i.e. for an existing exposure situation, a few mSv per year, and for an emergency exposure, 20–100 mSv. That is, these pessimistic illustrative results do not give rise to concern relative to reference levels set in either existing situations or emergency situations. This is a clear indicator of safety system robustness to FHA linked to human intrusion by drilling.

Similar conclusions can be drawn in comparison with the recommendations of IAEA (2011a). That is, even the largest doses fall below 1–20 mSv, whereby 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 repository's design.

5.2.3 Calculation case construction on drilling detritus landfill (FHACC2)

In this calculation case, it is assumed that a borehole is drilled that penetrates a waste package in the repository (as in FHACC1). Thereafter, radioactive material is assumed to be brought to the surface as drill core detritus and is assumed to be disposed in a shallow uncovered landfill at the drill site. Potential dose consequences 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'.

The same assumptions are adopted regarding the drilling techniques and activity concentrations in the drilling detritus from the different rock vaults and silo as in the case FHACC1, except the calculations are limited to only include the rotary drilling with air. This calculation case is only dependent on the amount of contaminated materials brought to the surface and mixed with soil in a landfill, and it is sufficient to only include the rotary drilling technique since the volume of drilling detritus per drilled metre is about 20 times larger compared to the diamond core drilling technique. As for the case FHACC1, it is assumed that the drilling brings radioactive waste to the surface due to drilling 1 m into the waste in the silo or the 1BMA, 2BMA, or 1BLA rock vaults. For discussion on core length, see FHACC1 above.

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

Models and data applied

Conservatively, no allowance is made for loss of activity from the contaminated landfill area in the time between when the landfilling takes place and use of the land for construction takes place.

As stated above, this construction worker scenario is based on the 'Construction scenario' in Oatway and Mobbs (2003). There, the radioactivity in drilling detritus from a 1 m core is uniformly distributed in the volume of a 2,000 m^3 landfill. Basically the same assumption as in Oatway and Mobbs (2003) are assumed for the constructer worker scenario is applied and therefore a normalised dose conversion factor from Oatway and Mobbs (2003) can be used to calculate the dose to a construction worker. The assessment specific assumptions needed in this calculation case are the volume of the contaminated landfill, the activity concentration of radionuclides in the excavated material, and the exposure 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 140 m^2 and to a depth of 1 m, hence the contaminated land has a volume of 140 m^3 (the relatively small construction area is chosen in order to be comparable to the agricultural land in FHACC3). This landfill is then assumed to be redeveloped for either residential or commercial use, alongside other surrounding land. Noting the small size of the contaminated area, it is assumed that a worker stays in this area no longer than 200 h 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:

$$D_{con} = DCF_{con} \cdot Exp\_frac \cdot A_{i,core} \cdot \frac{V_{excavated}}{V_{mixed}}$$

Where:

DCF_{con} is the dose conversion factor, Sv/y 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 4.2.2 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 exemption of individual radionuclide in IAEA (2005). The resulting DCFs are presented in Table 5-6.

Exp_frac 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 2,000 h (Exp_frac= 0.1).

Aicore is the radionuclide concentration in the drilling detritus (i.e. drill core).

$V_{\mathrm{excavated}}$ is volume of the contaminated drilling detritus (0.34 m^3, cf. Table 5-3).

V_{mixed} is volume of the landfill the detritus is mixed in (140 m^3).

Inventory

The inventory and concentrations assumed are the same as for FHACC1, see Table 5-7.

Results

Effects on a construction worker utilising a landfill containing drilling detritus are evaluated for one drilling technique (RA_CO_D rotary drilling with air) with drilling detritus from the silo, 1BMA, 2BMA and 1BLA, i.e. results are provided for 4 calculation case for FHACC2:

- FHACC2_RA_CO_D_SILO (Rotary drilling with air into the silo).
- FHACC2_RA_1BMA (Rotary drilling with air into 1BMA).
- FHACC2_RA_2BMA (Rotary drilling with air into 2BMA).
- FHACC2_RA_1BLA (Rotary drilling with air into 1BLA).

The construction worker utilising the landfill containing drilling detritus receives a small dose in a year of work compared to the dose assessed for the on-site drilling personnel (cf. Section 5.2.2). Similar to FHACC1, the doses are highest for the calculation case related to the silo at 3000 AD (FHACC2_ RA_CO_D_SILO , $6 \cdot 10^{-3}$ mSv in a year). The dose rate at 3000 AD in FHACC2_ RA_ CO_D_SILO is primarily due to Am-241, but is falling thereafter. At 4900 AD, the dose related to 2BMA (FHACC2_RA_2BMA) exceeds the dose for FHACC2_RA_CO_D_SILO AD (Figure 5-3).

Similar to FHACC1, the highest doses occurs at 3000 AD for FHACC2 for the silo, 1BMA and 2BMA whereas drilling detritus from 1BLA gave highest dose at the end of the assessment period due to ingrowth of radioactive progeny. The dominating radionuclides in FHACC2 vary from those for FHACC1. For the silo, Am-241, dominates the dose at 3000 AD but thereafter Nb-94 contributes most to dose during the rest of the assessment period (Figure 5-4a). For the rock vaults 1BMA, 2BMA and IBLA, the dose at 3000 AD is dominated by C-14, Nb-94, and Ag-108m, respectively (Table 5-9, Figure 5-4b-d).

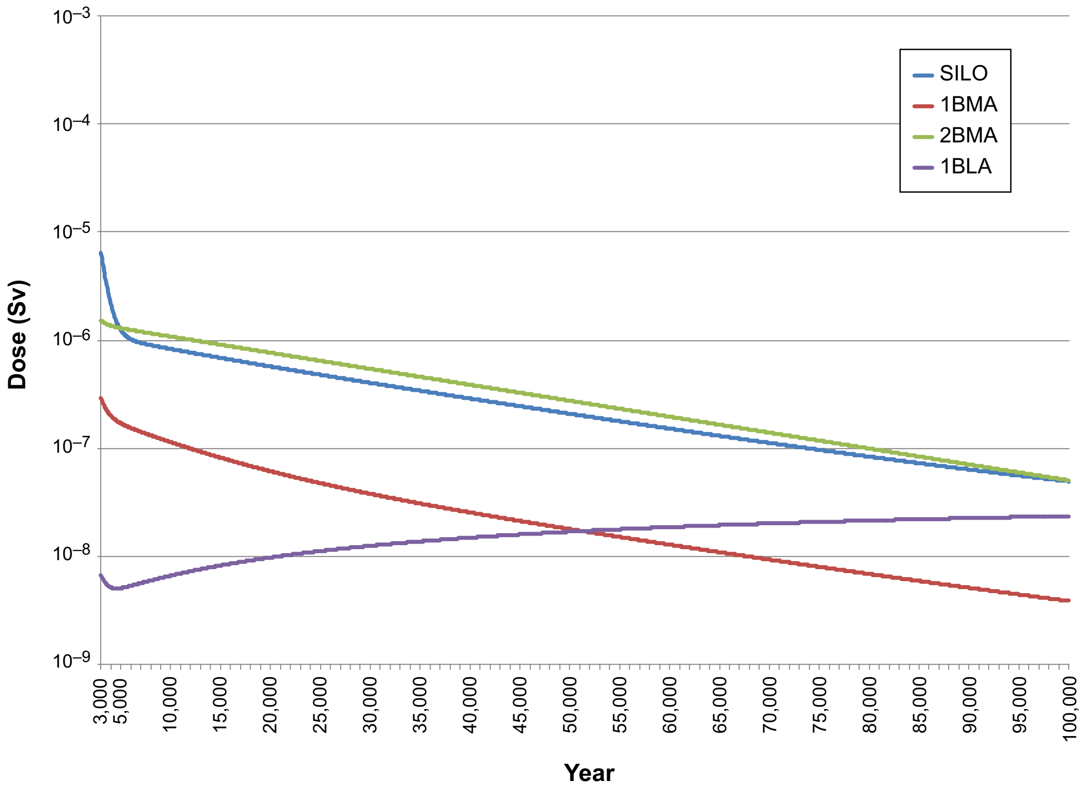

Figure 5-3. *Doses in a year for a construction worker from external radiation, inhalation and ingestion during construction on a landfill containing drilling detritus from the different repository parts, silo, 1BMA, 2BMA and 1BLA.*

Table 5-9. Dose in year 3000 AD for FHACC2, constructing on a landfill containing drilling detritus, with dose contribution from different radionuclides in %. Note from Figure 5-4 that other radionuclides may become more important over time.

	SILO	1BMA	2BMA	1BLA
Total Dose [Sv]	**6.5E–06**	**2.9E–07**	**1.5E–06**	**6.7E–09**
Dose contribution [%]				
Am-241	75	4	<1	7
Nb-94	15	26	89	22
Ag-108m	8	29	8	28
C-14	1	36	<1	7
Pu-240	<1	3	<1	5
Pu-239	<1	2	<1	5
U-238	<1	<1	<1	8
U-235	<1	<1	<1	10
Ac-227	<1	<1	<1	6
Pa-231	<1	<1	<1	1

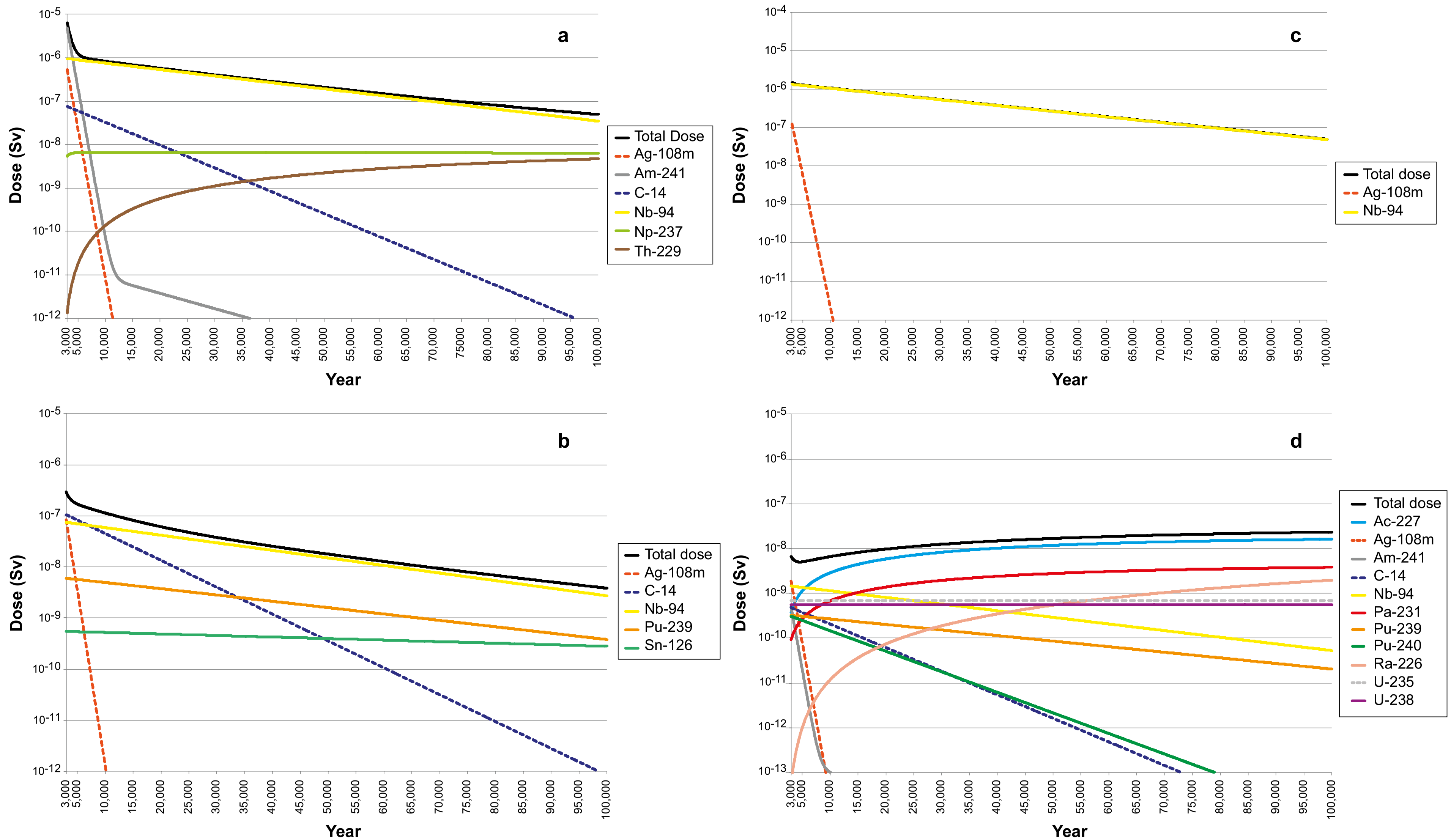

Figure 5-4. *Contribution of different radionuclides to the total dose in a year for constructing on a landfill containing drilling detritus.a) FHACC2_RA_CO_D_SIL b) FHACC2_RA_1BMA, c) FHACC2_RA_2BMA, and d) FHACC2_RA_1BLA.*

5.2.4 Calculation case cultivation on drilling detritus landfill (FHACC3)

This calculation case considers the same uncovered contaminated landfill as in FHACC2, including the same radionuclide concentrations. A family is assumed to move into the area and utilise the contaminated landfill for a life time (50 years). Potential dose consequences are calculated for a member of a family using the contaminated landfill as a garden plot for cultivating vegetables. The area of the garden plot is selected to the same area as used in the biosphere calculation case for a household garden plot (see the **Biosphere synthesis report** and Saetre et al. 2013). This is sufficient to support a family of five with their own cultivated vegetables and tubers. As for the case FHACC2, this calculation case only includes the rotary drilling technique.

Models and data applied

Conservatively, no allowance is made for loss of activity from the contaminated landfill area in the time between when the landfilling takes place and use of the land for a garden plot. As stated above, the area of the FHA garden plot is set to the same size as in the Biosphere garden plot model. However, the depth of the landfill the drilling detritus is mixed in is assumed to be 1 metre. This soil layer is thicker than the 25 cm deep upper regolith specified in the biosphere model (Saetre et al. 2013). Drilling detritus in a landfill would probably have to be mixed to an even higher degree to make the soil appropriate for agriculture but by assuming a 1 metre deep soil layer a conservative estimate is made and in addition the results can be easily compared with the construction calculations case (FHACC2). The garden-plot household model in the biosphere is used to calculate the doses from using the contaminated soil for cultivation vegetables (see Section 7.3 in Saetre et al. 2013). The only difference here, compared with how it is used in the biosphere model, is that the soil initially contains radionuclides from the drilling core and that is the only source of contamination. In the biosphere garden plot model, the garden plot initially does not contain radionuclides but radionuclides are added to the garden plot by fertilisation or irrigation with material and water containing radionuclides.

DCFs for the FHA garden plot were produced by first calculating the integrated concentration in the upper soil layers assuming that the garden plot is utilised for 50 years. The equations specific for the FHA garden plot are given in Appendix B. The integrated concentration in the upper regolith was then used to calculate a normalised dose conversion factor by applying the same input parameters as for the biosphere garden plot including external exposure, inhalation and ingestion of vegetables and tubers. That is, from the radionuclide concentrations in the upper soil layers, atmosphere concentration were calculated by using atmosphere model, and concentrations in vegetables and tubers were calculated with concentration ratios parameter values and external and internal exposure was calculated by applying parameter values for consumption, and duration spent on the garden plot. The garden plot model and input parameters are further described in Saetre et al. (2013) and Grolander (2013). The DCFs were used to calculate dose to humans utilising the land fill for a garden plot by the following equation:

$$D_{GP} = DCF_{GP} \cdot A_{i,core} \cdot \frac{V_{excavated}}{V_{mixed}}$$

Where

DCF_{GP} is the Dose conversion factor described above and tabulated in the final column in Table 5-6.

A_{icore} is the average activity concentration of each radionuclide in the drill core.

$V_{excavated}$ is the volume of the contaminated drilling detritus (0.34 m^3, cf. Table 5-3).

V_{mixed} is the volume of the landfill the detritus is mixed in (140 m^3).

Inventory

The inventory applied is same as for FHACC1, see Table 5-7.

Results

Doses to humans utilising a landfill containing drilling detritus as a garden plot is evaluated for one drilling techniques (RA_CO_D rotary drilling with air) with drilling detritus from the silo, 1BMA, 2BMA and 1BLA. Thus results are achieved for 4 calculation cases for FHACC3:

- FHACC3_RA_CO_D_SILO (Rotary drilling with air into the silo).
- FHACC3_RA_1BMA (Rotary drilling with air into 1BMA).
- FHACC3_RA_2BMA (Rotary drilling with air into 2BMA).
- FHACC3_RA_1BLA (Rotary drilling with air into 1BLA).

The assessed doses in a year to humans in calculation case FHACC3 are low compared to those for FHACC1 (Section 5.2.2) The highest dose for FHACC3 occurs at 3000 AD for the silo calculation case (FHACC3_RA_CO_D_SILO, $1 \cdot 10^{-3}$ mSv in a year). Due to decay, doses decline for FHACC3_silo, FHACC3_1BMA, FHACC3_2BMA. For FHACC3_1BLA, on the other hand, dose increases over time due to ingrowth of radioactive progeny with higher DCFs. Still, as seen in Figure 5-5, the dose rate for FHACC3_1BLA is still lower than the dose for FHACC3_ RA_CO_D _SILO at the end of the assessment.

The dominating radionuclides for FHACC3_ RA_CO_D _SILO are Am-241, C-14 and Nb-94 in the beginning (at dose maximum) but Am-24 declines fast and at the end of the assessment period Ni-59 and Np-237 contributes most to dose (Table 5-10, Figure 5-6a). For the rock vaults the dominating radionuclides at 3000 AD were C-14 for 1BMA, Nb-94 for 2BMA, and U-238 for 1BLA (Table 5-10 and Figure 5-6b-d).

Table 5-10. Dose in a yearat 3000 AD for FHACC3 with dose contribution from different radionuclides in %. Note from Figure 5-6 that other radionuclides become more important over time.

	SILO	1BMA	2BMA	1BLA
Total Dose [Sv year^{-1}]	**1.2E–06**	**4.1E–07**	**2.4E–07**	**1.0E–08**
Radionuclide contribution [%]				
Am-241	48	<1	<1	<1
C-14	25	83	1	15
Nb-94	10	3	78	2
Ag-108m	5	3	7	2
Ni-59	3	6	3	1
Mo-93	3	1	6	9
Cl-36	1	1	1	8
Np-237	1	<1	<1	<1
Tc-99	<1	1	<1	14
Ca 41	<1	<1	1	<1
Ac-227	<1	<1	<1	1
Pa-231	<1	<1	<1	1
U-238	<1	<1	<1	32
U-235	<1	<1	<1	14
U-235	<1	<1	<1	14

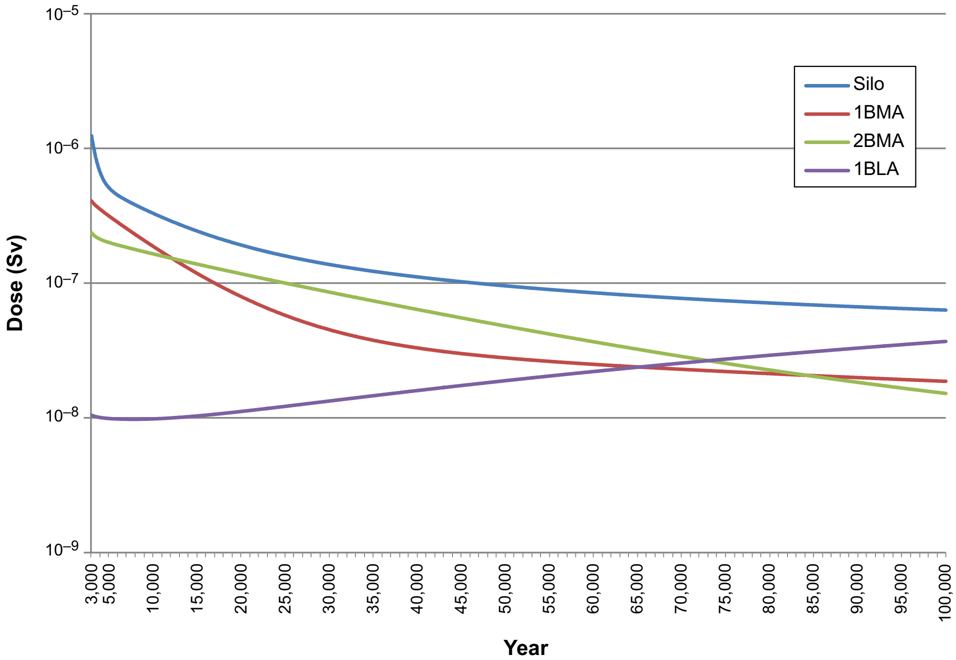

Figure 5-5. Calculated annual effective dose due to exposure following use of contaminated soil for domestic farming and through spending time in the contaminated area.

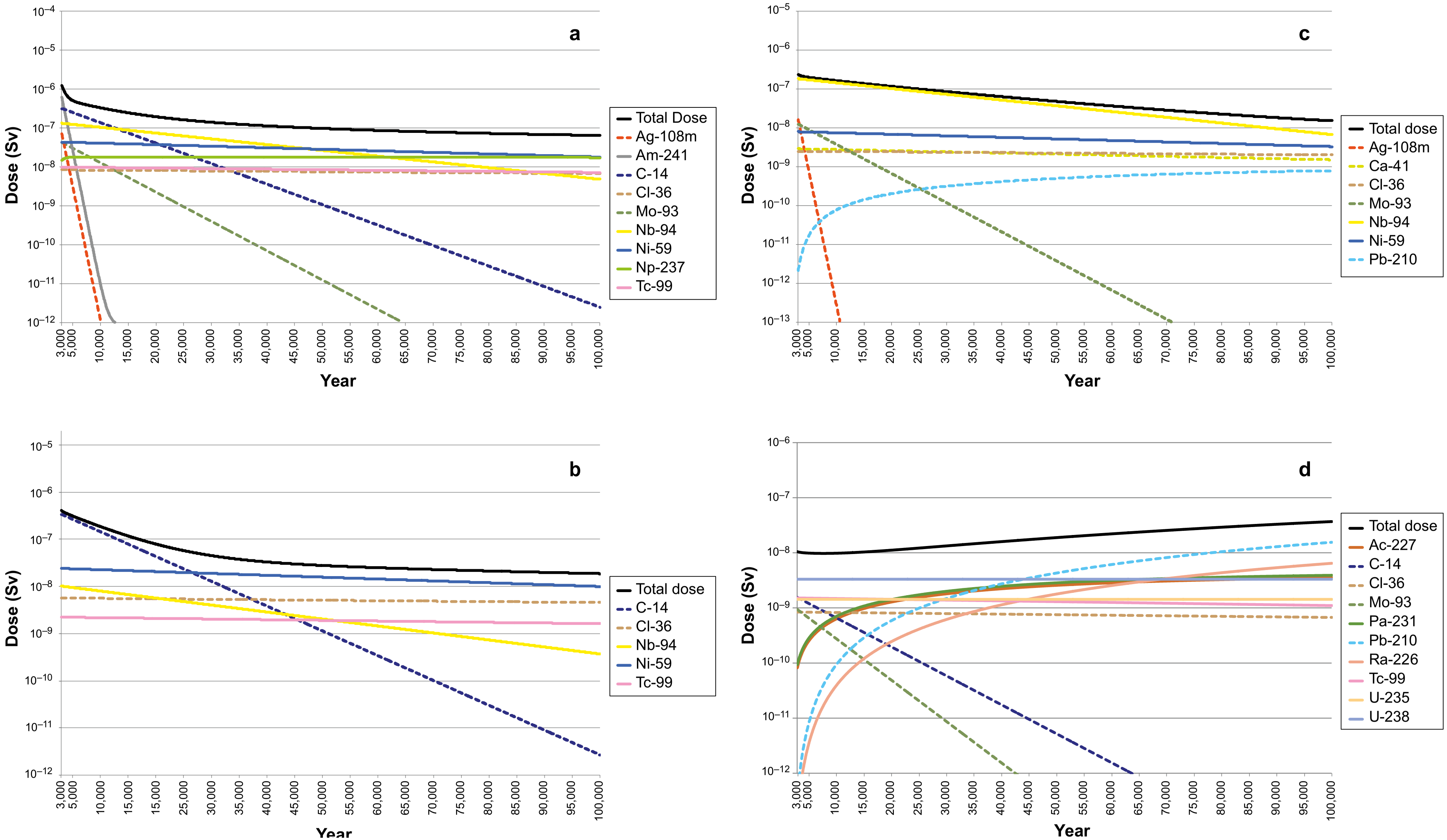

Figure 5-6. *Contribution of different radionuclides to the total dose to humans utilising a landfill with drilling detritus as a garden plot. a) FHACC3_RA CO_D_SILO b) FHACC3_RA CO_D_1BMA, c) FHACC3_RA CO_D_2BMA, d) FHACC3_RA CO_D_1BLA.*

5.3 Water management scenario

Water management (FHA09) is considered to be a credible action that may lead to altered geohydrological fluxes at repository depth.

5.3.1 Scenario description

Water management activities may locally affect hydraulic gradients. As stated in Section 4.3.9 the impacts of water management activities on the capacity of the rock to provide favourable hydrological and transport conditions are judged to be in most cases small, although large scale construction activities affecting hydrology may have an effect at repository depth. Here, the large scale activity of removal or modifications to the pier to SFR is considered.

Assumptions

The main assumption in this scenario is that the pier above SFR is removed and this work will alter the hydrogeological conditions.

Calculation cases identified to analyse the water management scenario

One calculation case, removal or modifications to the pier to SFR has been identified as representative of major possible water management FHA. Removal of the SFR pier is not strictly a water management activity but may lead to altered hydrological flexes.

5.3.2 Calculation case Pier to SFR removed (FHACC4)

If the pier above SFR is affected by removal or construction etc, this may lead to altered hydrogeological fluxes. The SFR pier itself is constructed from coarse, high-permeable materials (sand, gravel, and blocks). The pier is not entirely man made but is constructed on a natural topographic ridge. Groundwater levels in stand pipes demonstrate that the current groundwater table is very close to sea level. There are no data indicating that the future groundwater level in the SFR pier should rise significantly above sea level, or the natural ridge. Therefore the removal or levelling of highly permeable filling masses of the SFR pier is not expected to have a significant effect on the local flow pattern at SFR.

The significance of SFR pier-groundwater levels for performance measures in SR-PSU is demonstrated by comparing two model representations:

1) High SFR pier groundwater level (pessimistic): the SFR pier is modelled to hold groundwater above future sea level and its hydraulic contact with the underlying bedrock is assumed to be unconstrained.
2) Realistic SFR pier groundwater level (realistic): the SFR pier is modelled to hold a low groundwater level and its hydraulic contact to the underlying bedrock is assumed to be restricted by the existence of natural sediments.

Results

The action of removing the pier would result in somewhat altered hydrological water flow (Oden et al. 2014). However, the difference was limited and, therefore, the effects of altered hydrological flow due to this and other water management actions can be assumed to be addressed by the *high flow in the bedrock scenario* described in the **Main report** and no specific FHA dose calculation case is set up for this FHA scenario.

5.4 Underground construction scenario

The FEP 'Underground constructions' (FHA12) is considered to be a plausible action that may lead to altered hydrological fluxes.

5.4.1 Scenario description

Assumptions

The main assumption is that a major underground excavation is made near the SFR, as follows:

- FHACC6 – Road or rail tunnel is constructed in the vicinity of the repository. A tunnel into, above or below the SFR repository would include exploratory drilling and thereby the repository would be recognised and ruled out for rock cavern. However, a tunnel could be built in the vicinity of the repository and thereby affect water fluxes.
- FHACC7 – A mine in the vicinity of the Forsmark site could affect water fluxes.

5.4.2 Qualitative consideration of road or rail tunnel in the vicinity of the repository (FHACC5)

The impact on the repository of the construction of a tunnel in the vicinity of the repository will depend on the location, depth and size of the tunnel.

A tunnel west of the Singö deformation zone 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 tunnel north, south or east of the repository could result in somewhat larger hydraulic gradients and hence larger flow through the disposal rooms. However, grouting would considerably limit the impact of the tunnel on the hydrogeology in the surrounding rock.

Results

From the discussion above it is evident that a tunnel in the vicinity of Forsmark is likely to not have a negative effect on the SFR repository. Nevertheless, it cannot be excluded that a tunnel south or east of the repository would affect the hydraulic gradient. The effects on hydrological flow due to a tunnel construction can be assumed to be addressed by the *high flow in the bedrock scenario* described in the **Main report** and this FHA scenario is not further analysed.

5.4.3 Qualitative consideration of a mine in the vicinity of the Forsmark site (FHACC6)

The ore potential at Forsmark has been analysed within the site investigations for a respository for spent fuel. In an area south-west of the Forsmark site a felsitic to metavolcanic rock, judged to have a potential for iron oxide mineralisation, has been identified (Lindroos et al. 2004) (Figure 5-7). 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 SFR repository, it may be assumed that the greatest influence on the repository would occur if the construction took place in close proximity to the repository. For the planned repository for spent nuclear fuel it was concluded that the repository and a hypothetical mine in the potential area for mineralisation would be on the order of 3 km and too far away to influence the repository (SKB 2010b). The distance between SFR and the planned repository for spent fuel at Forsmark is on the order of 2 km, hence, it can be assumed that the potential influence on the repository from a future mine would be less than that from the planned repository for spent fuel.

The influence on the SFR repository from the planned repository for spent fuel has been analysed 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.

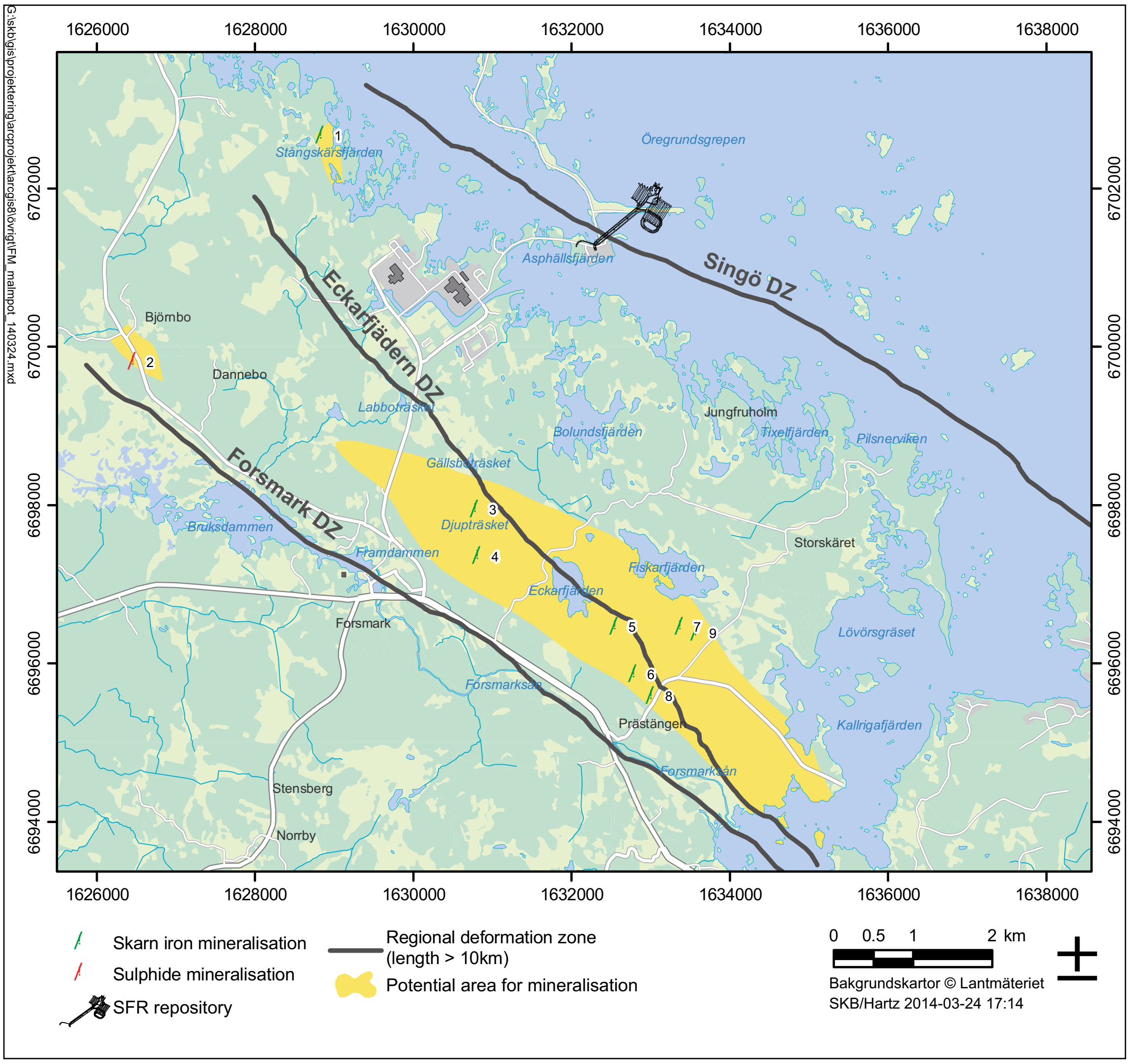

***Figure 5-7.** Map showing the areas on the surface that are judged to have some exploration potential for mineral deposits (modified after Figure 6-5 in SKB 2010b).*

6 Summary and conclusions

Review of general issues associated with future human actions

FHAs have been included in geological repository safety assessments for many years because they may result in impairment or loss of safety functions of the repository systems. FHAs might result in degradation of repository safety functions identified for the SFR, and in extreme cases result in radioactive waste being brought back to the surface, e.g. through drilling activities. While it is a consequence of the general strategy to concentrate and retain radioactive waste that leaves open various such possibilities for future human contact with the radioactive waste; at the same time, such possibilities are very substantially reduced by geological disposal compared with continued storage at the surface.

The review carried out has identified intrinsic methodological difficulties associated with accounting for FHA, notably associated with the unpredictability of human behaviour. This FHA study was able to take advantage of the large amount of work carried out in this area in national assessments (Swedish and foreign) and international co-operations, considering technical as well as social factors. The international work has been in progress since at least 1989 through the OECD/NEA, BIOPROTA, and the latest progress presented in recent guidance issued by both the IAEA and ICRP.

National applications of this work outside Sweden have been considered, both as regards regulatory requirements and the assessments made with a view to demonstrating compliance with protection objectives. It can be seen while the range of issues raised is broadly recognised, no single regulatory or assessment approach is adopted globally to address FHA. It is generally recognised that the possibility of human intrusion presents a special case for setting of criteria and for assessment, but that results need to be considered alongside other safety considerations.

Methodological approach: features, events and processes; future human actions scenarios; quantitative calculations, and qualitative analyses

A FEP analysis of FHA has been carried based on a common understanding of the system safety functions and system behaviour drawn from the rest of the SR-PSU assessment.

FHA FEPS have been identified and described to allow for the screening out from further consideration in the FHA scenarios, or screened in for inclusion for further consideration.

FHA scenarios have either been analysed qualitatively, or recognised as having similar consequences as scenarios in the rest of the SR-PSU, or analysed quantitatively.

Quantitative dose calculations have been made of FHA scenarios linked to drilling into the SFR and radioactive material being brought to the surface, thereby giving rise to exposure of drill crew, or to those involved in construction work or consuming produce grown in areas left contaminated at the drill site. All the calculations can only be regarded as illustrative, but they are inclusive of possible exposure modes and pessimistic assumptions have been made, consistent with international and national assessment experience.

Results and discussion

Qualitative arguments show that the FHA scenarios identified have little radiological significance or, have been considered within scenarios considered in the non-FHA part of SR-PSU.

Concerning the FHA scenarios addressed through calculations, the highest doses for the most pessimistic drilling technique, at the time of expected emergence of the SFR site to land around 3000 AD, are less than 1 mSv. It is considered that the scenarios under which these doses could arise are nevertheless, unlikely to arise. It is always possible to envisage even more extreme circumstances. These possibilities are recognised, albeit at an even lower likelihood of occurrence. The ICRP guidance notes that a fully optimised system may result in a distribution of doses where some are above a reference level (ICRP 2013).

Conclusions

The most significant result from this set of calculations is that both water management, underground construction in the vicinity of the repository or exposure to drilling personnel drilling into the repository will have little influence on safety. The highest doses, results from the most pessimistic assumptions on a drilling technique, occur at the time when the repository foot print is expected to emerge above the shoreline at 3000 AD. The doses are below 1 mSv, and are considered to be very unlikely to occur. Utilising a landfill containing drilling detritus for construction work or for growing vegetables would result in even smaller doses than the drilling personnel and it can be concluded that of the FHA related to drilling, the only action resulting in significant dose rates (above 1 mSv per y) is by utilising the borehole as a well to provide drinking and irrigation water (included in main calculation cases, see the **Radionuclide transport report** and the **Main report**). All the quantitative FHA results included in this report for drilling into the repository are below the (ICRP 2013) ranges of reference levels indicative of system robustness, i.e. for an existing exposure situation, a few mSv per y, and for an emergency exposure, 20–100 mSv. That is, these illustrative and pessimistic results do not give rise to concern relative to reference levels set by ICRP in either existing situations or emergency situations. They are also lower than the ICRP recommendation for the annual individual dose limit for members of the public in planned situations. This is a clear indicator of the robustness of SFR to FHA linked to human intrusion.

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SKB's (Svensk Kärnbränslehantering AB) publications can be found at www.skb.se/publications.
References to SKB's unpublished documents are listed separately at the end of the reference list.
Unpublished documents will be submitted upon request to document@skb.se.

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Unpublished documents

SKBdoc id, version	Title	Issuer, year
1346469 ver 1.0	Hydrogeologisk utredning rörande befintligt SFR och planerad utbyggnad. (In Swedish.)	SKB, 2014

Appendix A

Acronyms and abbreviations

Acronym or abbreviation	Expanded version
FHA	Future Human Actions
HI	Human intrusion
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
RK&M	Records, Knowledge and Memory project
OECD/NEA	Nuclear Energy Agency of the Organisation for Economic Cooperation and Development, Paris

Appendix B

Regulatory and assessment practice for FHA in other countries

Most of the examples of assessments of FHA and inadvertent HI in the assessment of deep geological disposal facilities mentioned in this section were reviewed in Smith et al. (2013, Appendix A). Added to this Appendix, are observations on the assessments Germany (Beuth et al. 2012) and Finland (Smith et al. 2013) as well as results from the European PAMINA project on HI (Galson et al. 2009).

All examples from national assessments refer to geological disposal of radioactive waste illustrating a project specific application of national and international guidance and recommendations. The full references and further explanation are provided in Smith et al. (2013), Beuth et al. (2012) and Galson at al. (2009).

The assessment of human intrusion as part of the safety case methodology in the European PAMINA project

The topic "human intrusion" was one of many other addressed within the integrated European PAMINA project with the aim to provide a current comprehensive overview of safety assessment methodologies summarising workshop results and contributions from participating organisations (Galson et al. 2009).

It was agreed on the terminology, that HI can be understood as human actions which have the potential to directly jeopardise the isolating capacity of the barriers of the disposal system and therefore might have radiological consequences. The situation with respect to regulation of the treatment of human intrusion in a safety analysis is heterogeneous over Europe, but it was concluded that the treatment should be addressed in regulations and guidelines provided by the respective responsible authorities including e.g. the framework of the analysis of HI scenarios, scope of the investigations, constraints and conditions. The scenarios should be identified on a stylised basis (for inadvertent intrusion only), since a systematic development of HI is not possible. These intrinsic uncertainties account e.g. with respect to relevant time frames and probability of scenario occurrence. There were different opinions about where and how HI has to be treated in the safety case. It was stated, that the potential of measures against HI are limited, but also that a sufficient depth of the repository and information preservation (with institutional control) were considered as sufficient measures with respect to safety optimisation requirements. Measures against HI must not compromise other safety aspects of the repository. There were some reservations as to whether the likelihood of an HI event can be really reduced over the long timeframes that have to be considered. With respect to relevant activities leading to HI it was concluded that exploratory drilling is actually the initial event for all other actions like mining or exploitation. Finally, it was agreed that a detection of the repository due to anomalies induced by the repository should be taken account in the assessment based on today's knowledge and technology.

Deep geologic disposal of L/ILW in Canada

Ontario Power Generation's proposed repository is located at 680 m depth in an argillaceous limestone formation (Quintessa and SENES 2011). The groundwater is highly saline below about 200 m, and the rock formations are under-pressured (relative to hydrostatic) around the repository horizon and over-pressured below it. Consistent with the regional geology and its history, there is no significant gas and oil in the area of the repository, but these do occur a few 100 km distant. The repository is not backfilled, and is expected to be mostly dry and contain gas at around hydrostatic pressure due to degradation of wastes.

An inadvertent human intrusion scenario is considered, based on an exploratory borehole intercepting waste packages within the repository. Intrusion is assumed possible after 300 years. The likelihood of intrusion is low, and an indicative estimate of 10^{-10} m^{-2} y^{-1} is suggested, based in part on historical deep drilling rates and on a notional estimate of 1 deep borehole per 10 km × 10 km area per 100 years.

The following exposure routes were considered:

- Direct release to the surface of pressurised gas by drill crew and nearby resident;
- retrieval and examination of core containing waste by core technician;
- exposure to drill core debris left on site by drill crew and by a future site resident, and
- the long-term release of contaminated water from the repository into the permeable geosphere horizons via the exploration borehole.

For the drilling personnel, the following exposure pathways were considered:

- Inhalation of released gas;
- external irradiation from soil contaminated by drill core debris left on site;
- inadvertent soil ingestion; and
- inhalation of suspended dust.

For a site resident, exposure pathways considered were:

- Inhalation of released gas;
- external irradiation from soil contaminated by drill core debris left on site;
- inadvertent soil ingestion;
- consumption of vegetables grown on contaminated soil; and
- inhalation of suspended dust.

The calculated peak dose was around 1 mSv for drill crew or nearby resident. However it was noted that the likelihood of the site occupancy scenario is very low since it assumes that drilling slurry is not managed to current drilling standards and that the soil is used for farming immediately after the intrusion event.

UK geological disposal of ILW

In the UK, the disposal of intermediate level waste (ILW) and that of low level waste (LLW) not suitable for disposal to a near surface repository falls within the remit of the Nuclear Decommissioning Authority Radioactive Waste Management Directorate (NDA RWMD), formerly UK Nirex Ltd (Nirex). No site has yet been selected for the disposal of such wastes and, as such, studies undertaken by NDA RWMD in relation to the disposal concept are generic in relation to both location and geology. Nonetheless, consideration has been given to the potential consequences to members of the public arising from inadvertent human intrusion into a deep geological repository as part of a generic post-closure performance assessment (Nirex 2003).

The inadvertent direct HI scenarios considered were those that were considered plausible based on current economic needs and technology, the current pattern of resource exploitation and an evaluation of frequencies of human activities observed in the recent past. The mode of intrusion assumed was exploratory drilling for natural resources following loss of knowledge of the location of the repository and/or its purpose. Drilling activity was assumed to penetrate the engineered barrier system (EBS) with radioactive waste material being brought to the surface. The frequency of intrusion into the repository was based on the foot print area of the repository and the frequency of drilling that could occur based on current practise in coal, hydrocarbon and mineral extraction industries. No prior loss of activity from the repository was assumed to occur as a result of radionuclide transport, although radioactive decay was taken into account.

Two exposure scenarios were considered – exposure of geotechnical workers and site occupiers – based on the assumption that the nature of the material brought to the surface is not recognised. The impacts of intrusion events on the integrity of the EBS were not considered.

Exposure of geotechnical workers occurs as a result of laboratory work on the drill core, leading to: external exposure during short-term working in close proximity to the core and longer term irradiation at a greater distance; inadvertent ingestion following handling of the core; and, inhalation of dust generated as a result of laboratory analysis techniques and radon generated from the presence of Ra-226 within the core. Results of the scenario were presented in terms of individual risk with a peak risk, corresponding to an intrusion event occurring at 100 years post closure, was calculated to be $6.6 \cdot 10^{-9}$ per year, risk being the product of the dose, the risk per unit dose and the probability in a year of the dose occurring. The latter was based on the area of interest and a midrange value for the drilling frequency, 10^{-10} holes per m^2 per year, which is said to be an appropriate average for mineral exploration in the UK in low-relief, hard rock areas.

The site occupier scenario assumes that radioactive material from drilling spoil is dispersed around the site of the exploratory borehole, which is subsequently inhabited and land used for agriculture. The size of the resource area (that used as arable land) was assumed to be 10,000 m^2. Exposure pathways considered include external exposure to contaminated material in surface soil, ingestion of foodstuffs grown in contaminated soil, and inhalation of dust derived from contaminated soil and of radon generated as a result of the presence of parent material. Risk to site occupiers is cumulative such that as time progresses, the likelihood of exposure is increased due to drilling events in previous years. The peak risk was calculated to be $9.3 \cdot 10^{-7}$ per year, occurring 200,000 years following repository closure. Here the probability of the dose is relatively high because of the possibilities for intrusion in previous years prior to the year of exposure, and the relatively long residence time in soil for at least some of the radionuclides brought to the surface. Thus, while the risk is higher, the dose is not higher than for the laboratory worker.

German Working Group on "Scenario Development": Handling of human intrusion into a repository for radioactive waste in deep geological formations.

On the basis of documentation preserved within German archives on mining, the working group considered that inadvertent HI will only occur from periods of 500 years or more post-closure (ATW 2008). The working group also concluded that it is not possible to quantify consequences associated with HI due to the lack of predictability of boundary conditions and other parameters and, as such, consequences of HI should not be evaluated by means of radiological limit values. The working group recommended that the range of scenarios that should be considered for HI be limited to, for example, exploratory drilling in the host salt rock, construction of a mine and solution mining of caverns, which is consistent with previous consideration of the issue (Hirsekorn 1989).

"Human intrusion" in the preliminary safety analysis of geological disposal at the Gorleben site ("vorläufige Sicherheitsanalyse Gorleben") in Germany

The FHA report for the Gorleben site covers future human actions in the post-closure phase of a repository for heat generating radioactive waste (Beuth et al. 2012). German regulation (BMU 2010) requires the assessment of FHA, but "optimisation with regard to reliable isolation of the radioactive materials from future human activities shall be carried out as secondary priority to [other primary targets]. As future human activities cannot be forecasted, a variety of reference scenarios for unintentional human penetration of the final repository, based on common human activities at the present time, shall be analysed. Within the context of such optimisation, the aim shall also be to reduce the probability of occurrence and its radiological effects on the general public." The report distinguishes activities changing the effectivity of barriers or changing the situation at the site (building of dams, tunnels, installations for groundwater extraction which are assumed to take effect only in the near surface environment with minimal impact on the containment function of the deep geological repository system. These activities are not investigated further. Activities destroying or by-passing the engineered barrier system including the containing host rock (damaging the barrier functions) are considered as human intrusion (deep drilling, leaching out of caverns in salt rock, mining activities in the vicinity). As the development of the human society and technological capabilities are not predictable over longer time frames stylised assessment scenarios assuming today's conditions with respect to human behaviour, state-of-the-art science and technology and current (German) regulatory conditions for the planned activities are applied for the assessment of HI to make the treatment of this type of uncertainty transparent. The scenarios take the feasibility of activities from today's perspective into account and analyse if anomalies caused by the repository are detectable in the course of their execution. It is assumed that inadvertent intrusion does not occur before 500 years after closure of the repository.

HI scenarios are not assessed within the class of less probable alternatives of the main scenarios but as a residual class of its own. Their consequences are not compared against radiological constraints as it is assumed that the quantification of radiological consequences is not reasonable as boundary conditions cannot be reasonably predicted, even though it is recognised that the exposure of persons intruding into the repository might be high.

The human activities analysed are industrial projects comprising drilling, leaching of caverns in salt rock (solution mining e.g. for the purpose of storage of gas or oil) or construction of mines (conventional mining). A major part of the report is dedicated to the possible detection of the repository in the course of the project due to anomalies of porosities, permeabilities, densities or temperature, direct radioactive exposure and the existence of material unusual for the geological formation as e.g. canisters, containers, concrete and radioactive waste.

Measures for the optimisation of the repository system with respect to inadvertent human intrusion are the reduction of probability of intrusion and the reduction of possible radiological consequences. Such measures can be apart from maintaining the knowledge of the existence of a repository as long as possible marking the repository with strong magnets, radiation from a dedicated cocktail of isotopes, acoustic devices, pictograms on waste containers, spherical objects or colours to be identified as anthropogenic or the use of materials and structures making intrusion more difficult. These measures are discussed in the context of the mentioned types of activities concluding that no reasonably applicable measure could be identified to reduce effectively the probability of an inadvertent intrusion into the repository system, even though colours and dedicated materials could be applied to mark the system. The possibility to optimise the system with respect to inadvertent human intrusion is strongly limited and uncertainties are intrinsic. The final conclusion is that regulatory guidance is needed to define procedures or measures how to tackle the issue within a safety case.

Deep geological disposal of LLW and ILW in Switzerland

Several assessments have been carried out on the consequences of human actions on both LLW/ILW and HLW repositories including both direct and indirect effects going as far back as (van Dorp and Vigfusson 1989). A range of possible human actions has been identified that may have implications for the function of repositories, including:

- Borehole drilling for exploration and production of drinking water, mineral resources, hydrocarbons, geothermal energy and/or for storage and waste injection purposes.
- Cavern excavation for the exploitation of mineral resources, for storage, road tunnel and/or military or industrial purposes.

Whether or not these actions should be considered for a particular scenario is dependent upon the site location and the depth of the repository.

It was considered that, in order to evaluate the consequences of human activities, consideration would need to be given to the following:

- The potential for contaminated material to be extracted either directly from the repository or from the surrounding contaminated geosphere.
- Exposure resulting from the extraction of contaminated groundwater from the repository, host rock or a more distant contaminated aquifer.
- The effects of changes in barrier properties and/or hydrogeology on radionuclide transport.

Deep geological disposal in the USA

In relation to the proposed Yucca Mountain HLW repository, the US DoE considered that effects of human intrusion events should focus on credible scenarios including exploratory drilling, groundwater withdrawal and mining and mine-dewatering (Rickertsen and Alexander 1989). The most credible human intrusion scenarios were considered to involve exploratory drilling and two scenarios were developed, according to the scale of drilling:

- Small scale drilling involving three or less boreholes per square kilometre per ten thousand years.
- Large scale drilling which may give rise to between three and thirty boreholes per square kilometre per ten thousand years.

Drilling is considered to either result in the penetration of a waste package leading to the migration of radioactivity from the waste package to the surface in drilling fluid, or result in the penetration of an aquifer beneath the repository that leads to the creation of a preferential pathway for the transfer of radionuclides to the biosphere. The release rate of radionuclides from a waste package is estimated from the groundwater flow rate, the solubility limits for individual radionuclides and the waste form. Travel time to the biosphere is a function of flow rate and both chemical and mechanical retardation properties of the transported radionuclides.

Concerning the Waste Isolation Pilot Plant (WIPP) which is intended, broadly speaking for a range of LLW and ILW, scenarios were considered in relation to inadvertent HI events relating to the WIPP, including drilling and mining activities (Anderson et al. 1989). In the case of drilling, several scenarios have been identified that could result in radionuclides being transported to the biosphere.

- Drilling could result in penetration and connection of WIPP and an underlying reservoir of pressurised brine. Following drilling, the resultant borehole would be plugged, but the assumption made that the plug degrades over time leading to the release of pressurised brine, which has been in contact with radioactive material, to groundwater above the WIPP and subsequent flow to a well.
- Drilling leads to penetration of a repository panel which results in contact between drilling fluid and the waste material. Radioactivity could be transported to the surface either as eroded material in drilling fluid or as cuttings. Cuttings may be examined by a geologist who is the maximally exposed individual. Drilling fluid is deposited in a settling pond which, following cessation of drilling activities, dries due to the arid climate, with radioactivity then being transported as airborne particles downwind to where a hypothetical farming family is located.
- Alternatively, multiple boreholes could result in a pathway for gravity driven flow of radioactive material from the repository to the surface environment.

In all cases considered, a conservative approach was taken to consequence analysis by assuming that no radioactive decay had occurred prior to drilling activities occurring.

“Human instruison” in the context of disposal of spent-fuel in Finland

This recent study (Smith et al. 2013) for the disposal of spent-fuel states that there has not been an international cooperation to develop an approach to assess HI in the context of deep geological disposal, i.e. comparable to the IAEA ISAM programme for near-surface disposal. The study focused on inadvertent HI without referring the broader context of FHA, and had the objectives to:

- Examine the technical aspects of why and how deep geological intrusion might occur,
- consider how and to what degree radiation exposure would arise to the people involved in such intrusion,
- identify the processes which constrain the uncertainties; and hence
- develop and document an approach for evaluation of doses arising from direct HI which addresses the criteria adopted by the IAEA and takes account of other international guidance and human assessment experience.

The scope of the study included:

- Land-based deep geological disposal of all kinds of radioactive waste (i.e. depth greater than 50 m), and
- dose consequences to those directly involved in the intrusion and those directly affected by contaminated material brought to the surface.

The study reviewed the most likely mechanisms for HI considering the range of available drilling technologies and the possible exposure of drilling workers and geologists involved in the activity with simple and stylised models. This approach covered 58 different scenarios. Data were reviewed and selected particularly considering inadvertent ingestion and inhalation of contaminated dust since the data for these exposure pathways was found to be wide ranging. Normalised exposure results are provided potentially applicable in other assessments. The conceptual and data assumptions have been made on a conservative but plausible, realistic basis. Due to institutional control HI is assumed not to occur before 100 years after closure. The likelihood of intrusion has not been part of the study but it is noted that vertical opposed to horizontal displacement of waste in a repository would reduce the chance of a borehole intersecting the waste. A major part analyses drilling scenarios with different drilling technologies and the possible (quantitative) radiological consequences of intrusion from 100 to 100,000 years after closure.

Methods and data described are considered to be consistent with assessment requirements of current international recommendations and guidance on deep geological disposal.

Conclusion from review of international work

It can be seen from the above work that, while the range of issues discussed in Section 2.1 is broadly recognised, no single regulatory or assessment approach is adopted globally to address FHA. It is generally recognised that the possibility of HI presents a special case for setting of criteria and for assessment, but that results need to be considered alongside other safety considerations. International guidance on how to carry out such assessments has been lacking. This situation has given rise to international cooperative work on human intruder dose assessment for deep geological disposal, as reported in Smith et al. (2013) and to further work within the IAEA's HIDRA project, which at the time of writing, is on-going.

Appendix C

Equations for FHACC3

FHACC3 for humans utilising a landfill containing drilling detritus with radionuclides from the repository is based on the garden plot calculation case in the biosphere (**Biosphere synthesis report**, Saetre et al. 2013). The only differences are that the landfill contains radionuclides from the beginning of the assessment and therefore some equations are needed to calculate the concentration in the upper soil layers for the FHA garden plot calculation case as described below. For a full description of the garden plot household calculation and equations, see Saetre et al. (2013).

In mathematical terms the dynamic decay of radionuclide activity concentration in agricultural land can be described by the following ordinary differential equations:

$$\frac{dAC^{14C}_{regoUp}}{dt} = -AC^{14C}_{regoUp}\left(\lambda^{14C} + k^{14C}_{leach} + k^{14C}_{degass}\right)$$

$$\frac{dAC^{RN}_{regoUp,i}}{dt} = -AC^{RN}_{regoUp,i}\left(\lambda^{RN} + k^{RN}_{i,leach}\right), \qquad i = \{vegetables,\ tuber\} \tag{C-1}$$

where AC^{14C}_{regoUp} and $AC^{RN}_{regoUp,\ i}$ denote the concentration of C-14 and other radionuclides respectively in the regoUp-compartment, and λ, k_{leach} and k_{degass} the decay constant and rates for leaching and degassing from the same compartment with details being given in Saetre et al. (2013, Section 7.3).

The solution to the two ordinary differential equations above (C-1) gives us the radionuclide activity concentration [Bq $kgDW^{-1}$] in cultivated soil at any point in time given an initial activity concentration $AC_{regoUp,t0}$ at year t_0 when cultivations starts:

$$AC^{14C}_{regoUp}(t) = AC^{14C}_{regoUp,t_0}\, e^{-\left(\lambda^{14C} + k^{14C}_{leach} + k^{14C}_{degass}\right)t}$$

$$AC^{RN}_{regoUp,i}(t) = AC^{RN}_{regoUp,t_0}\, e^{-\left(\lambda^{RN} + k^{RN}_{i,leach}\right)t} \qquad i = \{vegetables,\ tuber\} \tag{C-2}$$

The average soil activity concentration $AC_{regoUp,aver}$ [Bq $kgDW^{-1}$] for the interval between start of cultivation (t_0) and the following 50 years (t_{50}), is obtained by the integral of $AC_{regoUp}(t)$ as given in equations C-2 from t_0 to t_{50} divided by the time span t_{50}–t_0 of 50 years. The average activity concentration in agricultural soils can then be described by:

$$AC^{14C}_{regoUp,aver} = \frac{\int_{t_0}^{t_{50}} AC^{14C}_{regoUp}(t)dt}{t_{50} - t_0} = AC^{14C}_{regoUp,t_0} \frac{1 - e^{-\left(\lambda^{14C} + k^{14C}_{leach} + k^{14C}_{degass}\right)(t_{50} - t_0)}}{(\lambda^{14C} + k^{14C}_{leach} + k^{14C}_{degass})(t_{50} - t_0)}$$

$$AC^{RN}_{regoUp,i,aver} = \frac{\int_{t_0}^{t_{50}} AC^{RN}_{regoUp,i}(t)dt}{t_{50} - t_0} = AC^{RN}_{regoUp,t_0} \frac{1 - e^{-\left(\lambda^{RN} + k^{RN}_{i,leach}\right)(t_{50} - t_0)}}{(\lambda^{RN} + k^{RN}_{i,leach})(t_{50} - t_0)} \tag{C-3}$$

i = {vegetables, tuber}