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Safety Case for the Disposal of Spent Nuclear Fuel at Olkiluoto
- Design Basis 2012

Posiva Oy

December 2012
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## Tiivistelmä – Abstract

The Design Basis report sits within Posiva Oy’s Safety Case “TURVA-2012” portfolio and has the objective of presenting the design basis for the KBS-3V concept from the long-term safety point of view and is based on Posiva's requirements management system (VAHA). This provides a rigorous, traceable method of translating the safety principles and the safety concept to a set of safety functions, performance requirements, design requirements and design specifications for the various barriers, i.e. a specification for enactment of the concept at the Olkiluoto site.

This report, Design Basis presents the legal and regulatory requirements that guide repository research, design and development; the safety concept and safety functions for each barrier and host rock; the performance targets and target properties for host rock derived for the safety functions and finally the design requirements. Presentation of the reasoning and rationale for derivation of the performance and design requirements is a key aspect of the report.

The requirements arising from legislation, from regulators and other stakeholders set targets and constraints for the acceptability of the disposal of spent nuclear fuel. The design basis is formulated based on the repository concept, the properties of the site and the expected loads and interactions affecting during the expected future lines of evolution. The performance targets and target properties, together with the derived technical design requirements and the underlying design basis scenarios, form the design basis of the repository.

The requirements presented guide the design of the engineered barrier system components (EBS) and repository layout that are presented in the Production Line reports. The compliance of the design with these requirements is assessed in the Performance Assessment report of the TURVA-2012 safety case.

## Avainsanat - Keywords

KBS-3V, design basis, spent nuclear fuel disposal, Olkiluoto, safety case
TURVALLISUUSPERUSTELU KÄYTETYN YDINPOLTTOAINEEN LOPPUSIJOITUKSEILLE OLKILUODOSSA -SUUNNITELUPERUSTEET 2012

Design Basis-raportti esittää laeista ja viranomaisvaatimuksista nousevat vaatimukset, jotka ohjaavat loppusijoituslaitoksen suunnitteluun Olkiluodossa. Posiva on kehittänyt robustin vaatimusten hallintajärjestelmän (VAHA) käytetyn ydinpolttoaineen geologisen loppusijoituslaitoksen suunnittelun Olkiluodoon. VAHA on mahdollistanut täsmällisen ja jäljitettävän menetelmän, jolla turvallisuusperiaatteista ja turvallisuuskonseptista on johdettu turvallisuustoiminnot, toimintakykytavoitteet ja tavoiteominaisuudet, suunnitelluvaatimukset sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnittelusopimusten sekä suunnitel
TABLE OF CONTENTS

ABSTRACT

TIIVISTELMÄ

1 INTRODUCTION ...................................................................................................................................... 7
  1.1 Background .................................................................................................................................... 7
  1.2 The KBS-3 method ...................................................................................................................... 7
  1.3 Posiva’s programme for developing a KBS-3 repository at Olkiluoto .......................... 9
  1.4 Regulatory context for the management of spent nuclear fuel ............................................. 10
  1.5 TURVA-2012 Safety Case portfolio ......................................................................................... 12
  1.6 Quality assurance ....................................................................................................................... 16
  1.7 Aims and status of the report ..................................................................................................... 18
  1.8 Terminology ............................................................................................................................... 18
  1.9 Approach .................................................................................................................................... 21
  1.10 Structure of the document ......................................................................................................... 21
  1.11 Requirements management system VAHA ............................................................................... 22

2 LEGAL AND REGULATORY REQUIREMENTS ................................................................................. 23
  2.1 Laws and Decrees regulating the long-term safety of disposal .............................................. 23
  2.2 Decision-in-Principle/Government resolution ........................................................................... 25
  2.3 Regulatory requirements on disposal of nuclear waste ......................................................... 26

3 THE REPOSITORY SYSTEM .............................................................................................................. 29
  3.1 Spent nuclear fuel ....................................................................................................................... 29
    3.1.1 Fuel types and amounts ......................................................................................................... 29
    3.1.2 Cooling times and decay heat output limits ......................................................................... 30
    3.1.3 Material composition and geometry .................................................................................. 32
    3.1.4 Radionuclide inventory ...................................................................................................... 33
  3.2 Reference KBS-3V repository components .............................................................................. 34
    3.2.1 Canister ............................................................................................................................... 35
    3.2.2 Buffer ................................................................................................................................. 37
    3.2.3 Deposition tunnel backfill and plug ................................................................................. 38
    3.2.4 Closure .............................................................................................................................. 38
  3.3 Host rock and underground openings ....................................................................................... 39
    3.3.1 Repository layout ................................................................................................................ 39

4 THE OLKILUOTO SITE .................................................................................................................. 41
  4.1.1 Geological setting and host rock ............................................................................................ 41
  4.1.2 Hydrogeology and hydrogeochemistry ............................................................................... 43
  4.1.3 Surface environment ............................................................................................................. 47
5 DESIGN BASIS..................................................................................................... 51
  5.1 Safety concept and safety functions ........................................................... 51
    5.1.1 The safety concept .......................................................................... 51
    5.1.2 Safety functions ............................................................................. 53
    5.1.3 Derivation of performance targets and target properties ................. 54
  5.2 Introduction to the design basis ................................................................. 56
6 HOST ROCK AND UNDERGROUND OPENINGS .............................................. 59
  6.1 Definition and objectives ......................................................................... 60
  6.2 General requirements .............................................................................. 60
    6.2.1 Repository depth ........................................................................... 60
  6.3 Target properties ..................................................................................... 62
    6.3.1 Chemical composition of groundwater - canister corrosion .......... 62
      6.3.1.1 Reducing conditions ............................................................... 62
      6.3.1.2 Groundwater conditions to prevent chloride corrosion .......... 62
      6.3.1.3 Limited concentration of solutes with detrimental effect on EBS performance and on radionuclide transport......................... 63
    6.3.2 Chemical composition of the groundwater - buffer and backfill performance ..................................................................................... 64
      6.3.2.1 Sufficiently high ionic strength .............................................. 64
      6.3.2.2 Limited salinity ...................................................................... 65
      6.3.2.3 Groundwater conditions to prevent montmorillonite dissolution ... 66
      6.3.2.4 Limited concentration of detrimental solutes ......................... 67
    6.3.3 Chemical composition of the groundwater - radionuclide release and transport .................................................................................. 68
      6.3.3.1 Reducing groundwater conditions ........................................ 68
      6.3.3.2 pH for sorption ...................................................................... 69
      6.3.3.3 Low colloid and organic content .......................................... 69
    6.3.4 Groundwater flow and solute transport .......................................... 70
      6.3.4.1 Low flow rate around the deposition holes ......................... 70
      6.3.4.2 Sufficient transport resistance ............................................. 71
      6.3.4.3 Limited flow to protect backfill .......................................... 72
      6.3.4.4 Favourable retention properties .......................................... 72
    6.3.5 Mechanical stability ......................................................................... 73
  6.4 Design requirements for the underground openings ................................ 74
    6.4.1 Definitions .................................................................................... 74
    6.4.2 Performance - All subsurface rooms ........................................... 75
      6.4.2.1 Limitation of damage to rock ............................................. 75
      6.4.2.2 Avoidance of layout determining features ......................... 75
6.4.2.3 Avoidance of drillholes ................................................................. 76
6.4.2.4 Limitation of use of foreign materials ....................................... 77
6.4.2.5 Limitation of inflow to open repository rooms ......................... 77
6.4.2.6 Limitation of formation of EDZ ............................................... 78
6.4.3 Performance - Access routes ....................................................... 78
6.4.3.1 Avoidance of head differences in access routes ....................... 78
6.4.3.2 Avoidance of potential deposition tunnel locations in access route construction .................................................. 79
6.4.4 Performance - Deposition tunnels ................................................ 79
6.4.4.1 Avoidance of intersections with LDFs ...................................... 79
6.4.4.2 Limitation of inflow to deposition tunnels ............................... 80
6.4.5 Performance - Deposition holes .................................................. 80
6.4.5.1 Limitation of inflow to deposition holes ................................... 80
6.4.5.2 Avoidance of hydrogeological zones ....................................... 81
6.4.5.3 Avoidance of shear fractures ................................................... 81
6.4.5.4 Avoidance of brittle deformation zones .................................... 82
6.4.5.5 Straightness of deposition holes .............................................. 82
6.4.5.6 Allowance of installation of buffer and canister ........................ 82
6.4.5.7 Avoidance of respect volumes of LDFs .................................... 83
6.4.5.8 Limitation of temperature in repository ................................... 83
6.4.6 Performance - Demonstration tunnels ....................................... 84

7 CANISTER ............................................................................................................ 85
7.1 Performance targets for the canister ................................................... 85
7.1.1 Definition ......................................................................................... 85
7.1.2 Containment .................................................................................... 85
7.1.2.1 Canister intactness ................................................................. 85
7.1.2.2 Canister's service lifetime ....................................................... 86
7.1.3 Chemical resistance ....................................................................... 87
7.1.3.1 Ability to withstand corrosion ................................................ 87
7.1.4 Mechanical resistance ................................................................. 89
7.1.5 Compatibility with other barriers and host rock performance ........ 89
7.1.6 Subcriticality .................................................................................. 90
7.1.7 Handling before disposal ............................................................. 91
7.1.8 Retrievability ............................................................................... 91

7.2 Design requirements for the canister ............................................ 92
7.2.1 Definition ......................................................................................... 92
7.2.2 Performance .................................................................................. 92
7.2.2.1 Chemical resistance ............................................................... 92
7.2.2.2 Mechanical strength ................................................................. 93
7.2.2.3 Subcriticality .......................................................................... 94
7.2.2.4 Limitation of radiation level .................................................. 95
7.2.2.5 Limitation of heat generation ................................................... 96
7.2.2.6 Thermal conductivity ................................................................. 97
7.2.2.7 Canister geometry ................................................................. 97
7.2.3 Copper overpack ....................................................................... 97
7.2.3.1 Corrosion resistance ............................................................... 98
7.2.3.2 Lifting and transfer ................................................................. 99
7.2.3.3 Copper overpack ductility ......................................................... 99
7.2.4 Cast iron insert ......................................................................... 100
7.2.4.1 Subcriticality ....................................................................... 100
7.2.4.2 Mechanical strength ............................................................... 100
8 BUFFER ............................................................................................. 101
8.1 Performance targets for the buffer .................................................. 101
8.1.1 Definition .................................................................................. 101
8.1.2 Performance ............................................................................ 102
8.1.2.1 Limitation of amounts of substances harmful to other components 102
8.1.2.2 Preserve required properties in repository conditions ............. 102
8.1.2.3 Heat transfer ........................................................................ 103
8.1.2.4 Gas transfer .......................................................................... 104
8.1.2.5 Chemical protection ............................................................... 104
8.1.2.6 Mitigation of rock shear damage on canister .......................... 105
8.1.2.7 Limitation of mass flows from and onto the canister ............... 105
8.1.3 Support of the other systems ...................................................... 106
8.1.3.1 Support to deposition holes ................................................... 106
8.1.3.2 Keeping the canister in position ............................................. 106
8.2 Design requirements for the buffer ................................................ 107
8.2.1 Definition .................................................................................. 107
8.2.2 Performance ............................................................................ 107
8.2.2.1 Self-sealing ........................................................................ 107
8.2.2.2 Chemical protection ............................................................... 108
8.2.2.3 Mechanical protection .......................................................... 109
8.2.2.4 Limitation of mass flows to and from canister ....................... 109
8.2.2.5 Heat transfer ...................................................................... 110
8.2.3 Support of other system components ....................................... 110
9 BACKFILL ......................................................................................... 113
9.1 Performance targets for deposition tunnel backfill and plugs ............ 113
10.2.2.2 Ability to withstand conditions during expected evolution .......... 130
10.2.2.3 Transport properties ........................................................................ 131
10.2.2.4 Ability to keep backfill in place .................................................... 131
10.2.2.5 Chemical properties ........................................................................ 132
11 REFERENCES .............................................................................................. 133
APPENDIX A. REQUIREMENT TABLES ............................................................. 153
1 INTRODUCTION

1.1 Background

On assignment by its owners, Fortum Power and Heat Oy and Teollisuuden Voima Oyj, Posiva Oy will manage the disposal of spent nuclear fuel from the Loviisa and Olkiluoto nuclear power plants. At Loviisa, two pressurised water reactors (VVER-440) are in operation; at Olkiluoto, two boiling water reactors are operating and one pressurised water reactor is under construction. Plans exist also for a fourth nuclear power unit at Olkiluoto. At both sites there are facilities available for interim storage of the spent nuclear fuel before disposal.

In 2001, the Parliament of Finland endorsed a Decision-in-Principle (DiP) whereby the spent nuclear fuel generated during the operational lives of the operating Loviisa and Olkiluoto reactors will be disposed in a geological repository at Olkiluoto. This first DiP allowed for the disposal of a maximum amount of spent nuclear fuel corresponding to 6500 tonnes of uranium (tU) initially loaded into the reactors. Subsequently, additional DiPs were issued in 2002 and 2010 allowing extension of the repository (up to 9000 tU) to also accommodate spent nuclear fuel from the operations of the OL3 reactor and the planned OL4 reactor. OL4 spent nuclear fuel is handled in the TURVA-2012 safety case assuming it to be similar to OL3 spent nuclear fuel.

1.2 The KBS-3 method

The 2001 DiP states that disposal of spent nuclear fuel shall take place in a geological repository at the Olkiluoto site, developed according to the KBS-3 method. In the KBS-3 method, spent nuclear fuel encapsulated in water-tight and gas-tight sealed copper canisters with a mechanical-load-bearing insert is emplaced deep underground in a geological repository constructed in the bedrock. According to the DiP, the repository shall be located at minimum depth of 400 m. In Posiva’s current repository design, the repository is constructed on a single level and the floor of the deposition tunnels is at a depth of 400–450 m in the Olkiluoto bedrock.

Posiva’s reference design in the construction license application is based on vertical emplacement of the spent nuclear fuel canisters (KBS-3V; Figure 1-1). Currently, an alternative horizontal emplacement design (KBS-3H) is being jointly developed by the Swedish Nuclear Fuel and Waste Management Company (SKB) and Posiva.

The KBS-3V design is based on a multi-barrier principle in which copper-iron canisters containing spent nuclear fuel are emplaced vertically in individual deposition holes bored in the floors of the deposition tunnels (see inset in Figure 1-1). The canisters are to be surrounded by a swelling clay buffer material that separates them from the bedrock. The deposition tunnels and the central tunnels and the other underground openings are to be backfilled with materials of low permeability.
In the TURVA-2012 safety case documentation, the spent nuclear fuel, EBS and the host rock are jointly termed the *repository system*, whereas the term *disposal system* is used when the repository system and the surface environment are both considered, see Figure 1-2.

**Figure 1-1. Schematic presentation of the KBS-3V design.**

**Figure 1-2. The components of the disposal system.**
1.3 Posiva´s programme for developing a KBS-3 repository at Olkiluoto

The Olkiluoto site, located on the coast of south-western Finland (Figure 1-3) has been investigated for over 25 years. During the past few years, key activities in the programme have been related to:

- completion of the investigations for site confirmation at Olkiluoto both through analyses of data from surface-drilled characterisation holes and surveys, and studies carried out in the ONKALO underground research facility,
- the design of the required surface and sub-surface disposal facilities,
- the development of the selected disposal technology to the level required for the construction license application, and
- demonstration of the long-term safety of the disposal of spent nuclear fuel including the preparation of a safety case (Section 1.5) presented as a portfolio of reports, including the present report.

Posiva’s RTD (research, development and technical design) phase for the years 2010–2012 was introduced in the TKS-2009 report (Posiva 2009b), which also provides insight into developments from previous RTD phases. In 2012, a new RTD programme (YJH-2012, Posiva 2012a) for 2013–2015 has been published. In Figure 1-4, a general timeline of Posiva’s programme is presented.

Figure 1-3. Olkiluoto Island is situated on the coast of the Baltic Sea in south-western Finland. Photograph by Helifoto Oy.
Figure 1-4. Overall schedule for nuclear waste management relating to the Loviisa and Olkiluoto reactors until 2020. The target is to begin disposal of spent nuclear fuel around 2020.

The repository will be located in the bedrock of the Olkiluoto Island taking into account the host rock properties as well as the restrictions set by urban planning in the Eurajoki municipality. In Figure 1-5 the current reference layout is presented.

1.4 Regulatory context for the management of spent nuclear fuel

According to the law, the Finnish Ministry of Employment and the Economy (TEM; previously the Ministry of Trade and Industry, KTM) decides on the principles to be followed in waste management of spent nuclear fuel and other nuclear waste.

The schedule for the disposal of spent nuclear fuel was established in the KTM’s Decision 9/815/2003. According to this Decision, the parties under the nuclear waste management obligation shall, either separately, together or through Posiva Oy, prepare to present all reports and plans required to obtain a construction license for a disposal facility for spent nuclear fuel as stated in the Nuclear Energy Decree by the end of 2012. The disposal facility is expected to become operational around the year 2020.
The legislation concerning nuclear energy was updated in 2008. As part of the legislative reform, a number of the relevant Government Decisions were replaced with Government Decrees (GD). The Decrees entered into force on 1st December 2008. The Government Decision (478/1999) regarding the safety of disposal of spent nuclear fuel, which particularly applied to the disposal facility, was replaced by the Government Decree 736/2008, issued 27 November 2008.

Currently, the valid Regulatory Guides pertaining to nuclear waste management are Guides YVL 8.1–8.5; additionally, a number of other YVL Guides may be applied in part to nuclear waste management. The Radiation and Nuclear Safety Authority (STUK) is in the process of updating its YVL Guides to comply with the new legislation. According to the current drafts, the Guides pertaining to the disposal of spent nuclear fuel will belong to the YVL-D series consisting of a total of five Guides. Guide YVL D.1 will deal with nuclear non-proliferation control, D.2 with the transport of nuclear material and nuclear waste, D.3 with the processing, storage and encapsulation of spent nuclear fuel, D.4 with nuclear waste management and decommissioning activities and D.5 with the disposal of nuclear waste. The latest draft of the Guide YVL D.5 (Draft 4, 17.3.2011 in Finnish only) was consulted for the preparation of the TURVA-2012 safety case (see Section 1.5).

Figure 1-5. The current reference layout (green). Dark grey areas are not suitable for deposition tunnels based on Rock Suitability Classification (RSC). Red ovals denote respect distances to drillholes. Red line surrounding the repository shows the area reserved for the repository in urban planning.
1.5 TURVA-2012 Safety Case portfolio

A safety case for a geological disposal facility documents the scientific and technical understanding of the disposal system, including the safety barriers and safety functions that these are expected to provide, results of a quantitative safety assessment, the process of systematically analysing the ability of the repository system to maintain its safety functions and to meet long-term safety requirements, and provides a compilation of evidence and arguments that complement and support the reliability of the results of the quantitative analyses.

As stated in Guide YVL D.5, A01: Compliance with the requirements concerning long-term radiation safety, and the suitability of the disposal method and disposal site, shall be proven through a safety case that must analyze both expected evolution scenarios and unlikely events impairing long-term safety. The safety case comprises a numerical analysis based on experimental studies and complementary considerations insofar as quantitative analyses are not feasible or involve considerable uncertainties (GD 736/2008).

The TURVA-2012 safety case for the disposal of spent nuclear fuel at Olkiluoto is compiled in a portfolio of main reports with supporting documents (Figure 1-6). In this report, all TURVA-2012 portfolio reports are referenced using the report title (as below) in *italics*. The full titles and report numbers are listed at the beginning of the reference list.

The main reports and supporting documents of the TURVA-2012 portfolio are briefly described in the following.

*Synthesis* provides a summary of the TURVA-2012 safety case, building on the key results from all main safety case reports. It represents a synthesis of the assessment of both the repository system and the surface environment (biosphere). It provides a description of the overall safety case methodology, brings together quantitative evidence and other lines of argument, a statement of confidence and the evaluation of compliance with long-term safety constraints.

*Site Description* and *Biosphere Description* are the two main supporting documents that describe the relevant characteristics of the site’s geosphere and surface environment, respectively. In addition to present-day conditions, they discuss the past evolution of the site and future evolution of the surface environment and highlight the most important characteristics to be represented in geosphere and biosphere modelling.

*Description of the Disposal System* summarises the initial state of the repository system components (spent nuclear fuel, EBS and host rock) and of the surface environment. The descriptions of the engineered barriers and underground openings are based on the *Production Line reports*, whereas the descriptions of the host rock and the surface environment are based on *Site Description* and *Biosphere Description*, respectively. The initial state of the spent nuclear fuel is also presented. The report provides the main characteristics of the components of the disposal system to be used as input to the safety assessment.
Features, Events and Processes identifies and describes the various features, events and processes (FEPs) that need to be taken into account when assessing the long-term safety of the Olkiluoto spent nuclear fuel repository, thus feeding into the performance assessment, the formulation of radionuclide release scenarios, the assessment of the scenarios for the repository system and the biosphere (see below).

In the review of the pre-licensing documentation, STUK emphasises the importance of defining performance targets and target properties, giving the reasoning behind them, and providing an assessment of how they are fulfilled by the repository system. Details on the reasoning and rationale behind the definition of the performance targets for the EBS components and target properties of the host rock are specified in Design Basis. The report is supported by the Production Line reports (for the canister, buffer, backfill, closure and underground openings), which present the detailed design specifications for the repository components, combined with a description of their production and initial state.
**TURVA-2012**

**Synthesis**
Description of the overall methodology of analysis, bringing together all the lines of arguments for safety, and the statement of confidence and the evaluation of compliance with long-term safety constraints

<table>
<thead>
<tr>
<th>Site Description</th>
<th>Biosphere Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Understanding of the present state and past evolution of the host rock</td>
<td>Understanding of the present state and evolution of the surface environment</td>
</tr>
</tbody>
</table>

**Design Basis**
Performance targets and target properties for the repository system

**Production Lines**
Design, production and initial state of the EBS and the underground openings

**Description of the Disposal System**
Summary of the initial state of the repository system and present state of the surface environment

**Features, Events and Processes**
General description of features, events and processes affecting the disposal system

**Performance Assessment**
Analysis of the performance of the repository system and evaluation of the fulfillment of performance targets and target properties

**Formulation of Radionuclide Release Scenarios**
Description of climate evolution and definition of release scenarios

<table>
<thead>
<tr>
<th>Models and Data for the Repository System</th>
<th>Biosphere Data Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Models and data used in the performance assessment and in the analysis of the radionuclide release scenarios</td>
<td>Data used in the biosphere assessment and summary of models</td>
</tr>
</tbody>
</table>

**Biosphere Assessment: Modelling reports**
Description of the models and detailed modelling of surface environment

**Assessment of Radionuclide Release Scenarios for the Repository System**
Analysis of releases and calculation of doses and activity fluxes.

**Complementary Considerations**
Supporting evidence incl. natural and anthropogenic analogues

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**Figure 1-6.** TURVA-2012 safety case portfolio including report names (coloured boxes) and brief descriptions of the contents (white boxes). **Disposal system = repository system + surface environment.**
Performance Assessment replaces the previous reports dealing with the expected evolution of a spent nuclear fuel repository (Crawford & Wilmot 1998, Pastina & Hellä 2006), in which the EBS and geosphere uphold their safety functions with no releases of radionuclides for at least 10,000 years and even after 100,000 years. The fulfilment of the performance targets and target properties during the expected evolution of the repository system is evaluated in Performance Assessment. Performance Assessment covers the performance of the system for the entire assessment time frame of one million years with a special focus on the containment safety function of the canister and isolating safety function of other EBS components and the geosphere in the first 10,000 years (as required by YVL D.5). The main focus of the report is the expected evolution and performance, but it is also shown that there are some plausible conditions, and some unlikely events and processes, that could lead to reduction of one or more safety functions and, potentially, give rise to radionuclide releases. Thus, Performance Assessment presents the expected evolution of the repository in which the majority of the canisters in the repository provide complete containment of radionuclides throughout the assessment time frame.

The performance assessment identifies uncertainties in the initial state of the barriers and/or in the evolution of the repository system that could lead to radionuclide releases. These deviations from the desired initial state or expected evolution are propagated to Formulation of Radionuclide Release Scenarios, which defines the scenarios and the calculation cases for both the repository system and the surface environment. The aim of Formulation of Radionuclide Release Scenarios is to systematically define a set of scenarios that encompass the important combinations of initial conditions, expected evolution and disruptive events.

In past assessments by Posiva, the case of a canister with an initial defect has been assessed as a case to test the performance of the other engineered barriers and host rock. While this is not necessarily the most likely feature that could lead to release of radionuclides, it is the reference case in Formulation of Radionuclide Release Scenarios that also complies with the GD 736/2008. Thus, in TURVA-2012, the base scenario addresses the most likely lines of evolution and takes into account the incidental possibility of one or a few canisters with initial undetected penetrating defects. The classification of scenarios emphasises that incidental deviations that may lead to radionuclide release (e.g. an initial defect of a canister) have low probability. The design aim for the repository and expected outcome is that the majority of the canisters in the repository will provide complete containment of radionuclides throughout the assessment time frame (as shown in Performance Assessment) and there will be no releases of radionuclides from the canisters for at least several hundreds of thousands of years. The assumption that no more than a few canisters have initial penetrating defects is based on expert judgement concerning the canister welding method (electron beam welding – EBW) and non-destructive testing (NDT) capabilities. With continued testing it seems practicable in the future to show that the probability of more than one initially defective canister in the repository is less than one per cent. At the moment, therefore, the number of defective canisters is assumed to be one canister out of 4500 in the reference case realisation of the base scenario.
The analyses of the releases and calculated activity fluxes and doses are presented in *Assessment of Radionuclide Release Scenarios for the Repository System* and in *Biosphere Assessment*.

*Models and Data for the Repository System* summarises the models and the data used in the performance assessment and the analysis of radionuclide release scenarios for the repository system. As to the surface environment, the data used in the biosphere assessment are summarised in *Biosphere Data Basis*, and the models are discussed in *Terrain and Ecosystems Development Modelling, Surface and Near-Surface Hydrological Modelling, Biosphere Radionuclide Transport and Dose Assessment* and *Dose Assessment for Plants and Animals*.

*Complementary Considerations* supports the safety case by presenting complementary evidence for the safety of nuclear waste disposal in crystalline bedrock according to the KBS-3 method. In particular, it provides evidence for the reliable performance and longevity of the engineered barrier materials, and suitability of the Olkiluoto site to provide the necessary conditions for long-term safety, focusing on qualitative supporting arguments.

The TURVA-2012 safety case portfolio is based on the safety case plan published in 2008 (Posiva 2008c), which updates an earlier plan published in 2005 (Vieno & Ikonen 2005). In the updated safety case plan, further details are provided on quality assurance and control procedures and their documentation, as well as on the consistent handling of different types of uncertainties. Since 2008, the safety case plan has been iterated based on the feedback received from the authorities, and the contents of the safety case portfolio TURVA-2012 are now as presented in Figure 1-6.

### 1.6 Quality assurance

The quality assurance (QA) procedures for the TURVA-2012 safety case (see Figure 1-6) have been carried out following Posiva’s quality management system, which complies with the ISO 9001:2008 standard and considers relevant regulatory requirements. Even though the quality assurance is based on management according to the standard ISO 9001:2008, a graded approach proposed for nuclear facilities is adopted, i.e. the primary emphasis is on the quality control of the safety case, particularly those activities that have a direct bearing on long-term safety whereas standard quality measures are applied in the supporting work. This means, in practice, that the main safety case reports are subject to stricter quality demands than general research activities. The input from Posiva’s own RTD activities and other research also fulfil the ISO 9001 quality standards.

The general quality guidelines of Posiva are also applied; the composition and quality management of portfolio reports and the recruitment of expert reviewers are controlled according to the respective guidelines. In addition, special attention is paid to the management of the processes that are applied to produce the safety case and its foundations, which is the basis for the whole safety case process and organisation of the work. The purpose of this enhanced process control is to provide full traceability and transparency
of the data, assumptions, models, calculations and results. The safety case production process is a part of Posiva’s RTD process and is linked to Posiva’s Production lines, Facility design and other main processes. The main customer is the Strategy process and the Licensing sub-process. The aim of the safety case production process is to produce the long-term safety documentation for the construction license application. The safety case production process is owned by the research manager of Posiva’s Long-term Safety Unit in Posiva’s Research Department.

The overall plan, main goals and constraints for the safety case production process are presented in the Safety Case Plan (Posiva 2008c). The details of how the Safety Case Plan 2008 is being implemented are described in the SAFCA project plan. The organisation of the TURVA-2012 safety case production process is referred to as SAFCA. The work is managed and coordinated by a SAFCA project group and supervised by a steering group.

The safety case production process is divided into four main sub-processes: Conceptualisation and Methodology, Data Handling and Modelling, Safety Assessment, and Evaluation of Compliance and Confidence.

The Data Handling and Modelling sub-process constitutes the central linkage between Posiva’s main technical and scientific activities and the production of the safety case. It is a clearinghouse activity between the supply of, and demand for, quality-assured data for the safety case. Data are produced by Posiva’s planning, design and development processes for the EBS (Engineered Barrier System), by the site characterisation process for the geoscientific data and through the biosphere description of the Olkiluoto area.

A SAFCA quality co-ordinator (QC) has been designated for the activities related to the quality assurance measures applied to the production of the safety case contents. The QC is responsible for checking that the instructions and guidelines are followed and improvements are made in the process as deemed useful or necessary. The QC is also responsible for the coordination of the external expert reviews, maintenance of schedules, review and approval of the products, and the management of the expert elicitation process. The QC also leads the quality review of models and data used in the Data Handling and Modelling sub-process. Regular auditing of the safety case production process is done as part of Posiva’s internal audit programme.

Data sources and quality aspects of the sources are documented according to a specific guideline. Individual data and databases are approved through a clearance procedure supervised by the SAFCA Quality Co-ordinator. In line with the ISO 9001 standard the process owner checks and approves the data and the QC checks and approves the procedure. Data used may also be approved using other Posiva databases such as VAHA or POTTI and the respective approval processes. A clearance procedure has been applied to all key data used in the performance assessment (i.e. showing compliance with performance targets and target properties), and in the safety assessment (i.e. radionuclide transport analyses and dose calculations).

The control and supervision of the safety case products (i.e. main portfolio reports) has been done in two steps, first an internal review by safety case experts and subject-matter
experts within Posiva’s RTD programme and then the second step by external expert reviewers. A group of external experts covering the essential areas of knowledge and expertise needed in safety case production has been set up. The review process is based on review templates, which record each review comment and how it has been addressed. Upon completion, this template is checked and approved according to the quality guidelines of Posiva.

The expert elicitation process has been applied to specific cases when the understanding or data basis is conflicting and consensus is needed for the selection of key data (e.g. solubility and sorption data) to identify the main sources of uncertainty and determine whether different views may have to be propagated through the safety assessment. This expert elicitation process has been initiated, recruited, documented and managed by the SAFCA Quality Coordinator.

QA issues are discussed further in Synthesis. Quality assurance and quality control measures related to the production and operation of the repository are discussed in detail in production line reports (Canister, Buffer, Backfill, Closure and Underground Openings Production Line).

1.7 Aims and status of the report

This report focuses on the design aspects of the repository design that are relevant to long-term safety. Plant design and manufacturing design basis are discussed in the Plant Design reports (Saanio et al. 2012 and Kukkola & Koskinen 2012) and Production Line reports, where detailed requirements for manufacturing of engineered barrier system components are discussed. This report focuses on the KBS-3V design alternative and does not consider the loads and interactions that are specific for KBS-3H, and are to be discussed in the KBS-3H topical report. The aim of this report is to identify and characterise relevant processes and sources of loads and interactions that the disposal plant designers need to take into account when designing the disposal systems and layouts for the construction and operating license applications. The requirements gathered in this report represent a data-freeze of Posiva’s requirements management system VAHA for the construction license application. The fulfilment of the requirements at the initial state, i.e. the state in which a given component has been emplaced according to its design and remains after intentional engineering measures have been completed, is discussed in the Production Line reports for each engineered barrier system (EBS) component. As stated previously, the fulfilment of the requirements during the evolution of the repository and site is discussed in the Performance Assessment report.

1.8 Terminology

Posiva’s terminology
The system design premises comprise the objectives set for the whole system, the limitations set by the environment, technology and knowledge and the existing operating environment (regulations, responsibilities, organisations, resources). These form the starting point for the definition of the design basis of disposal operations.
The design basis refers to the current and future environmentally induced loads and interactions that are taken into account in the design of the disposal system, and, ultimately, to the requirements that the planned disposal system must fulfill in order to achieve the objectives set for safety (i.e. the design premises).

In defining the design basis, Posiva must, by regulation, on the one hand, assess the likelihood of different scenarios and, on the other hand identify those deemed reasonable, and assess those that may be possible but are considered highly unlikely. Although only scenarios deemed reasonable are used as design basis scenarios, scenarios that are deemed unlikely also need to be assessed in the safety case.

According to regulations (STUK YVL D.5, paragraph 407), targets shall be specified for the performance of each safety function. Safety functions are the main roles for each barrier, from which performance targets for the engineered barriers and target properties for the host rock are defined considering their respective safety functions. The actual design requirements and design specifications are ultimately defined so as to enable the achievement of the performance targets in the expected scenarios (Figure 1-7).

The performance targets have been set so that individual deviations or deficiencies will not endanger the long-term safety of the whole disposal system. The performance targets form the basis for the definition and implementation of the design requirements. The initial state of the disposal system can be affected through the design requirements and system implementation practices (up to the closing and sealing of each deposition hole or tunnel); the degree to which the performance targets are met is evaluated through the performance assessment; the capability of the system as a whole to effectively isolate the radionuclides from the living environment is further studied in the assessment of release scenarios.

The requirements management system project VAHA has resulted in the creation of a hierarchical requirements management database that will be continuously maintained and updated. The purpose of the database is to ensure that all requirements have been sufficiently taken into account in the development of the disposal system and the establishment of the design basis of the nuclear waste facility. During the system development work, Posiva collaborates closely with the Swedish Nuclear Fuel and Waste Management Company (SKB) which is currently developing a similar system for its own purposes.
Figure 1-7. The development of the repository system as an iteration between requirements, designs and safety assessments.

**SKB's terminology**

The KBS-3-method has been developed in collaboration between SKB and Posiva. The implementation of the method in both Sweden and Finland is quite similar due to similarities in general geological properties of the sites. Major conclusions made by SKB can often be applied also to the Olkiluoto site. Therefore, SKB reports are often referenced to in this report. It should be noted that the terminology used by SKB differs from that used by Posiva. Some differences arise also from regulatory requirements, e.g. the Swedish regulatory criteria for the acceptance of radiological consequences are related to the radiological risk arising from doses assessed for different scenarios, whereas the Finnish criteria are related to the estimated radiation doses.

*Design premises* for the Swedish implementation of KBS-3 are defined in SKB (2009a). They primarily correspond to the “design requirements and system specifications” in Posiva terminology. The design premises are used as input to the documents, called production reports, which present the reference design analysed in the long-term safety assessment SR-Site (SKB 2011a). The aim is that the SKB's production line reports should verify that the chosen design complies with the design premises, whereas justifying why these design premises are relevant is presented in SKB (2009a). SR-Site (SKB 2011a) gives feedback to the design premises based on the findings of the assessment of the performance and safety of the repository.

In SKB's context, a safety function is defined qualitatively as a role through which a repository component contributes to safety. SKB expresses safety functions preferably
in a quantitative way which can be measured through safety function indicators. In order to determine whether a safety function is maintained or not, SKB defines quantitative safety function indicator criteria against which the safety function indicators are evaluated over the time period covered by the safety assessment. For a more thorough discussion see SKB (2011a), Section 8.2.

1.9 Approach

The design basis compiled in this report related to the reference design for a KBS-3V-type repository located at Olkiluoto. The design basis aims to fulfill the following objectives:
- Provide the rationale for the requirements,
- Identify the sources of loads and their ranges of magnitude, and
- Quantify the loads to be taken into account in design, if possible.

First, the requirements arising from legislation, and from regulators and other stakeholders are reviewed. Then, the disposal site and system are described, emphasising those aspects that are pertinent to complying with the requirements for achieving safety through appropriate design. The design basis is formulated based on the repository concept, the properties of the site and its expected future evolution.

The site and system descriptions and design basis justifications are gathered mainly from Posiva's documents and SKB's safety case documents, when applicable.

1.10 Structure of the document

This design basis report begins with an introductory chapter which presents the terminology and purpose of the report.

The second Chapter discusses the requirements for the long-term safety of a spent nuclear fuel repository arising from laws and other regulatory requirements, including the Decision-in-Principle given to Posiva on 21st December 2000. These requirements form the framework for the design work and the operations of Posiva. Posiva has gathered the relevant requirements into its requirements management system VAHA.

The third Chapter describes the reference KBS-3V disposal system briefly. The components of the KBS-3V system are the underground openings, the canister, the buffer, backfill, and structures and materials introduced as part of the process of repository closure. Aspects closely related to the system description are included in Chapter 3. The spent nuclear fuel and its properties are described. The fuel properties are given and for them one cannot define any design premises.

The fourth Chapter discusses briefly the site conditions at Olkiluoto that affect the design of the repository and EBS components. The geology, geochemistry and geohydrology along with postulated climatic and landscape evolution are discussed based on the Site Description and supporting reports on climate evolution. The site properties give the boundary conditions to which the reference design must be adapted. The possible future evolution of the Olkiluoto site is briefly discussed, because major climate changes form an important source of design basis loads.
The fifth Chapter presents the safety functions of the KBS-3V EBS components and host rock, and discusses the performance targets, target properties and derivation of the design basis. The design basis is underpinned by Posiva's requirements management system and is described in Chapters 6 to 10 for the host rock, canister, buffer, backfill and closure. The host rock and underground openings are described in Chapter 6, the canister in Chapter 7, the buffer in Chapter 8, deposition tunnel backfill and plug in Chapter 9, and closure in Chapter 10. The requirements are presented in table format in Appendix A in their exact requirements management system form.

1.11 Requirements management system VAHA

Posiva's requirements management system VAHA is an information system designed in Posiva to manage the requirements related to the geological disposal of spent nuclear fuel. VAHA aims to include all relevant requirements, origin and their rationale with existing solutions to fulfil them, and enables an effective review of compliance and dependencies between separate specifications and requirements.

The VAHA database is organised into five levels:

I. Level 1 consists of the Stakeholder requirements. These are the requirements arising from laws, regulatory requirements, decisions-in-principle and other stakeholder requirements.

II. Level 2 consist of the System requirements as defined by Posiva on the basis of Posiva's owners' requirements and the legal and regulatory requirements listed on Level 1. Level 2 requirements define the EBS components and the functions of the EBS and host rock.

III. Level 3 consists of the Subsystem requirements which are specific requirements for the canister, buffer, backfill, closure and host rock and underground openings. The requirements of level 3 are mostly general and set qualitative requirements (performance targets and target properties) for EBS and host rock performance.

IV. Level 4 Design requirements further clarify and provide more details to the requirements of Level 3.

V. Level 5 presents the Design specifications. These are the detailed specifications to be used in the design, construction and manufacturing.

Each requirement has its on ID on the requirements management system VAHA, which is based on the requirement level, system and requirement number. For example L3-ROC-2 relates to the Level 3 requirement on host rock and underground openings, VAHA requirement 2. See Appendix A for requirement tables for levels 1-4. Level 5 requirements (design specifications) are presented in the Production Line reports.
2 LEGAL AND REGULATORY REQUIREMENTS

2.1 Laws and Decrees regulating the long-term safety of disposal

The basis for the use of nuclear energy in Finland is given in the Nuclear Energy Act 990/1987. According to its Section 7h, "Nuclear waste shall be managed so that after disposal of the waste no radiation exposure is caused, which would exceed the level considered acceptable at the time the final disposal is implemented."

The disposal of nuclear waste in a manner intended as permanent shall be planned giving priority to safety and so that ensuring long-term safety does not require the surveillance of the final disposal site".

The safety of the disposal of nuclear waste is regulated in more detail in the Government Decree (736/2008) on the safety of disposal of nuclear waste. The following sections regulate the long-term safety of the disposal of spent nuclear fuel:

- Section 4 Long-term radiation impacts of disposal
  Disposal of nuclear waste shall be planned so that radiation impacts arising as a consequence of expected evolution scenarios will not exceed the constraints given in subsections 2 and 3.

  In any assessment period, during which the radiation exposure of humans can be assessed with sufficient reliability, and which shall extend at a minimum over several millennia:

  1) the annual dose\(^1\) to the most exposed people shall remain below the value of 0.1 mSv; and

  2) the average annual doses to other people shall remain insignificantly low.

  During assessment periods after the period referred to above in subsection 2, average quantities of radioactive materials over long time periods, released into the living environment from the disposed nuclear waste, shall remain below the maximum values specified separately for each radionuclide by the Radiation and Nuclear Safety Authority (STUK). These constraints shall be specified so that:

  1) at a maximum, radiation impacts caused by disposal can be equivalent to those caused by natural radioactive materials in earth’s crust; and

  2) on a large scale, the radiation impacts remain insignificantly low.

- Section 5 Consideration of unlikely events
  The significance of unlikely events impairing long-term safety shall be assessed by evaluating the reality, probability and possible consequences of each event. Whenever possible, the acceptability of the expectancies of radiation impacts caused by such events shall be evaluated in relation to the

\(^1\) Effective annual doses (ICRP 2007).
annual dose and release rate constraints of radioactive materials, as referred to in section 4.

Chapter 3 of the Decree gives the design requirements for a nuclear waste facility. Some of the requirements are important for long-term safety. In Section 9 it is stated that

- The disposal package containing spent nuclear fuel shall be designed so that no self-sustaining chain reaction of fissions can occur, even in the disposal conditions.

Chapter 4 of the Decree focuses on the long-term safety of disposal.

- Section 10 General requirements concerning disposal
  
  Disposal shall be implemented in stages, with particular attention paid to aspects affecting long-term safety. The planning of the construction, operation and closure of a disposal facility shall take account of reduction of the activity of nuclear waste through interim storage, the utilisation of high-quality technology and scientific data and the need to ensure long-term safety via investigations and monitoring. However, the implementation of the various stages of disposal shall not be unnecessarily postponed.

- Section 11 Multibarrier principle
  
  The long-term safety of disposal shall be based on safety functions achieved through mutually complementary barriers so that a deficiency of an individual safety function or a predictable geological change will not jeopardise the long-term safety.

  Safety functions shall effectively prevent releases of disposed radioactive materials into the bedrock for a certain period, the length of which depends on the duration of the radioactivity in waste. For short-lived waste, this period shall be at least several hundreds of years, and for long-lived waste, at least several thousands of years.

- Section 12 Disposal site
  
  The geological characteristics of the disposal site shall, as a whole, be favourable to the isolation of the radioactive substances from the environment. Any area with a feature that is substantially adverse to long-term safety shall not be selected as the disposal site.

  The planned final disposal site shall contain sufficiently large, intact rock volumes that facilitate the construction of the waste emplacement rooms. For the purposes of disposal facility design and acquiring data required for safety assessments, the geological characteristics of the host rock at the site shall be characterized through investigations at the intended disposal depth, in addition to surface based investigations. The layout, excavation, construction and closure of underground facilities shall be implemented so that the characteristics of the host rock deemed important in terms of long-term safety are retained, as far as possible.

  The depth of the waste emplacement rooms shall be selected appropriately as regards the waste type and local geological conditions. The goal related to disposal depth shall be that any impacts on the long-term safety of above-ground events, activities and environmental changes will remain
minor and that intrusion into the waste emplacement rooms will be difficult.

Chapter 5 of the Decree covers the demonstration of compliance with safety requirements. Section 14 states that

Compliance with the requirements concerning long-term radiation safety, and the suitability of the disposal method and disposal site, shall be proven through a safety case that must analyse both expected evolution scenarios and unlikely events impairing long-term safety. The safety case comprises a numerical analysis based on experimental studies and complementary considerations insofar as quantitative analyses are not feasible or involve considerable uncertainties. Compliance with the radiation exposure constraints for the most exposed people, as referred to in section 4 above, shall be proven by considering a community that derives nutrition from the immediate surroundings of the disposal site and is most exposed to radiation. In addition to impacts on people, possible impacts on flora and fauna shall be analysed.

Section 15 Reliability of the safety case

The input data and models utilised in the safety case shall be based on high-quality research data and expert judgement. Data and models shall be validated as far as possible, and correspond to the conditions likely to prevail at the disposal site during the assessment period. The basis for selecting the computational methods used shall be that the actual radiation exposure and quantities of radioactive materials released remain below the results of safety analyses, with a high degree of certainty. The uncertainties involved in the safety analysis, and their significance, shall be separately assessed.

2.2 Decision-in-Principle/Government resolution

The Nuclear Energy Act requires a Decision-in-Principle for the construction of a nuclear facility of considerable general significance, including facilities serving as repositories for nuclear waste. Posiva applied for its first DiP in 2000 when the site selection process was being finalised. The Government decided that the application was in line with the overall good of the society. The process is described in further detail in TKS-2009 Chapters 1 and 2 (Posiva 2009b) The Decision-in-Principle (DiP) of December 2000 gives some requirements which need to be taken into account as design basis. The amount of spent nuclear fuel that can be disposed of at Olkiluoto has been stated in the Government resolutions. The latest Government resolution (M 3/2010 vp, 6.5.2010) grants to Posiva a permit to prepare the disposal for 9000 tonnes of spent nuclear fuel, corresponding to the amount of spent nuclear fuel from operating and planned power plant units of TVO and Fortum.

The DiP given to Posiva states that the construction of a disposal facility for the spent nuclear fuel generated in the operation of the current Finnish nuclear power plants, according to the key operational principles and solutions related to the verification of safety presented in the facility description of the application, at Olkiluoto in Eurajoki
municipality is in accordance with the overall good of the society. The facility description in the DiP application was based on a KBS-3 type repository.

The requirement of retrievability, although no longer found in the renewed Nuclear Energy Act, is on the DiP 2000 and DiP 2001 (17.1.2002) and therefore has to be taken into account. It is required that disposal shall be designed in such a way that the closed repository can be reopened, without unnecessary difficulty, if found necessary in the future if advances are made in waste management techniques. The canisters have to be retrievable for a long enough time, but at the same time retrievability shall not endanger the safety of the disposal.

The DiPs M 7/2000 vp (21.12.2000) and M 5/2001 vp (17.1.2002) state that structural solutions shall be designed to prevent an uncontrollable chain reaction fed by neutrons, i.e. the spent nuclear fuel packages shall be designed to prevent the spent nuclear fuel from going critical in repository conditions.

STUK also states in the preliminary safety assessments in DiPs M 7/2000 vp (21.12.2000) and M 5/2001 vp (17.1.2002) that in scheduling the disposal operations, the best available technique, or best available forthcoming technique, is to be taken into account.

2.3 Regulatory requirements on disposal of nuclear waste

The detailed long-term safety requirements for spent nuclear fuel disposal are given in STUK’s YVL Guide 8.4. However, the Guide is currently under revision and will soon be replaced by a new YVL Guide D.5. Therefore, Posiva and STUK have agreed that Posiva’s license application can be based on the Level 4 draft version of the forthcoming Guide (which is available on STUK’s website). For simplicity, we will hence call this draft YVL D.5 version simply as D.5.

The Guide gives the principles according to which the disposal method and facility must be designed, built and operated. The appendix of D.5 gives the framework for the safety case which aims to show compliance with the long-term radiation protection requirements and suitability of the disposal method disposal. The first Chapters of the Guide YVL D.5 are introductory and define the areas regulated in the guide.

The third Chapter of YVL D.5 defines the radiation safety requirements based on GD 736/2008:

Disposal of nuclear waste shall be planned so that as a consequence of expected evolution scenarios
- the annual dose to the most exposed people shall remain below the value of 0.1 mSv; and
- the average annual doses to other people shall remain insignificantly low.

These limits are applied to timescales for which the radiation impact on humans can be estimated with high enough certainty, for at least several thousand years. The dose as-
essment shall take into account changes in the environment which result from the elevation of either sea level or land uplift. The climate, human behaviour and needs can be presumed to stay unchanged. The analysis shall take into account the use of contaminated water and use of contaminated agricultural and natural products. For timescales exceeding several thousand years, radionuclide release limits are imposed. The releases can be averaged over one thousand years in safety assessments.

The unlikely events that need to be analysed are defined. These include: rock movements which may damage the canisters, drilling of a medium-deep drill well on the repository site, and exploratory drilling hitting a canister.

It is also stated that the disposal shall not cause harmful effects on non-human biota due to radioactivity. The doses caused to the non-human biota shall stay well below the limits which could endanger the diversity of nature or cause notable harm to some biotic community.

The present report is intended to respond to Section 4.2 of D.5, which requires the implementer to describe the safety functions of the disposal system and to define the performance targets associated with them. The discussion of the performance targets (or target properties) in Chapters 5 to 10 forms the main contents of the report; before that the planned repository system and the intended repository site are briefly described in Chapters 3 and 4, respectively.
3 THE REPOSITORY SYSTEM

3.1 Spent nuclear fuel

3.1.1 Fuel types and amounts

Several types of spent nuclear fuel are planned for disposal in the Olkiluoto repository. These types originate from the Finnish nuclear power plants operated by TVO and Fortum:

- BWR spent nuclear fuel from the boiling water reactors Olkiluoto 1 and 2 (OL1 and OL2);
- PWR spent nuclear fuel from the pressurised water reactors Loviisa-1 and -2 (LO1 and LO2), which comprises two sub-types: TVEL VVER-440 and BNFL VVER-400;
- PWR-type spent nuclear fuel from the EPR reactor OL3, currently under construction.
- fuel of currently unknown type from Olkiluoto 4 (OL4), assumed in the safety analysis to be similar to OL3.

The amount of spent nuclear fuel mentioned in the Decision-in-Principle 2001 was 6500 tU. A new DiP was granted in 17.1.2002 to extend the repository for the amount of spent nuclear fuel from OL3 (2500 tU). Similarly, a DiP (6.5. 2010, M 3/2010 vp) was also granted for the application to extend the repository to accommodate the spent nuclear fuel from OL4 (2500 tU). The spent nuclear fuel inventory considered in the recent radionuclide transport reports (RNT-2008, Posiva 2008a), i.e. 5468 (rounded up to 5500 tU), is based on estimates of the amount of spent nuclear fuel to be produced in OL1, 2 and 3 and LO1 and 2 (see Table 3-1). It has been estimated that the total amount of fuel to be disposed of will be 9000 tU when the fuel of the planned OL4 is taken into account.

These estimates are, however, subject to change depending on the operational lifetimes of the reactors and potential extensions to those lifetimes. The long-term safety and other implications of the disposal of a larger fuel amount are discussed in the Environmental Impact Assessment of 2008 (Posiva 2008b). For future safety assessments, the assumptions concerning the radionuclide inventory and other aspects of the spent nuclear fuel specifications will be decided on the basis of the status of plans and Government decisions in 2010 - 2011. The safety case for the construction license application in 2012 will be performed for a fuel amount of 9000 tU, corresponding to 4500 canisters.

Table 3-1 shows the anticipated operational lifetime, spent nuclear fuel element accumulation, and average burn-up estimates for the nuclear power plants at Olkiluoto and Loviisa. (Canister Production Line). In the future, the maximum burn-up is estimated to be 50 MWd/kgU for OL1, 2, and 3 and 57 MWd/kgU for LO1 and 2. The design value for maximum assembly average burn-up is 60 MWd/kgU in the dimensioning of the KBS-3 system and encapsulation plant.

Current understanding of the characteristics of spent nuclear fuel has been summarised in reports by Anttila (2005b) and Raiko (2005). Nuclear fuel consists of sintered ura-
nium dioxide (UO$_2$) pellets enriched with roughly 3 - 5 % U-235. The pellets are stacked, according to each nuclear core's design specifications, into sealed cladding tubes of corrosion-resistant metal alloy (zirconium alloy). In a nuclear power reactor, the resulting fuel rods are grouped in assemblies that are used to build the nuclear fuel core.

Irradiation of the fuel assemblies produces a large number of radionuclides. These radionuclides include those produced by the fission of uranium and plutonium in the fuel pellets (fission products), as well as activation products arising from neutron absorption. The majority of fission products and higher actinides in spent nuclear fuel exist as a solid solution in the uranium dioxide matrix. However, some of the activation products, such as C-14 and Cl-36, are present in both the fuel pellets and in structural materials. Certain radionuclides (e.g. I-129, C-14, Cl-36 and Cs) are also enriched at grain boundaries in the fuel, at pellet cracks and in the fuel/cladding gap as a result of thermally driven segregation during irradiation of the fuel in the reactor (see Posiva 2010a Part II, Section 1.3.1).

Table 3-1. Anticipated operational lifetime, spent nuclear fuel elements accumulation, average burn-up, and uranium mass estimates for the nuclear power plants at Olkiluoto and Lovisa. Values in parentheses are preliminary estimates that depend on the type of reactor selected for OL4 (From Canister Production Line, Table 4-5).

<table>
<thead>
<tr>
<th></th>
<th>OL1–2</th>
<th>OL3</th>
<th>OL4</th>
<th>LO1–2</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planned operating life (a)</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>50</td>
<td>-</td>
</tr>
<tr>
<td>Predicted accumulation of assemblies (pcs)</td>
<td>14,034</td>
<td>3816</td>
<td>3781</td>
<td>7752</td>
<td>29,383</td>
</tr>
<tr>
<td>Average discharge burnup of all assemblies (MWd/kgU)</td>
<td>39.5</td>
<td>45.0</td>
<td>(45.2)</td>
<td>40.6</td>
<td>(42.7)</td>
</tr>
<tr>
<td>Predicted number of canisters</td>
<td>1170</td>
<td>954</td>
<td>946</td>
<td>646</td>
<td>3716</td>
</tr>
<tr>
<td>Predicted tonnage (tU)</td>
<td>2460</td>
<td>2030</td>
<td>2023</td>
<td>950</td>
<td>7463</td>
</tr>
<tr>
<td>Dimensioning number of canisters</td>
<td>1400</td>
<td>1175</td>
<td>1175</td>
<td>750</td>
<td>4500</td>
</tr>
<tr>
<td>Dimensioning tonnage (tU)</td>
<td>2950</td>
<td>2500</td>
<td>2500</td>
<td>1050</td>
<td>9000</td>
</tr>
</tbody>
</table>

3.1.2 Cooling times and decay heat output limits

After discharge from the reactor, the fuel is stored under water until the radiation intensity and decay heat decrease sufficiently for transport, encapsulation and disposal. In the cooling pool, the temperature of the cladding is slightly higher than the water temperature. The average precooling time needed for the spent nuclear fuel before encapsulation is between 30 and 50 years, depending on burn-up. A minimum cooling time of 20 years is used for single fuel elements in canister design (Canister Production Line report).

The canister's decay heat power is limited for each fuel type, see Table 3-2. The heat load limits are used for repository dimensioning purposes and to ensure that the maximum temperature in the buffer surrounding the canister is less than 100 °C. At this temperature at repository depth groundwater boiling is also prevented. The thermal dimensioning of the Swedish canisters specifies a maximum heat decay power of 1 700 W,
which is approximately 100 W/m² per canister and that the temperature in the canister surface should not be significantly above 100 °C. SKB's temperature limit is equal to that of Posiva (SKB 2009a). SKB’s canister length is 4.84 metres and the outer diameter is 1.05 metres.

The decay heat powers (W/tU) for activation products (e.g. from trace elements in structural materials), actinides and fission products, and the total values at 51 calculated time points after discharge are presented in Anttila (2005b). Over 100 calorimetric measurements have been performed on Swedish BWR- and PWR-fuel assemblies stored in the CLAB interim storage facility. The results have been used to verify the decay heat estimates calculated using the code ORIGEN-S, which was the approach adopted by Anttila (2005b).

The decay heat evolution is used as input for the thermal dimensioning of the repository. The evolution of temperatures over time in the repository have been reported in Ikonen and Raiko (2012), see Figure 3-1.

![Figure 3-1. Canister surface temperature estimates in repository (central area) as a function of time since emplacement using the two extreme saturation degrees for the bentonite buffer. OL3 PWR-type canister, average burnup 50 MWd/kgU, canister distances in repository 10.5 m / 25 m, buffer conductivity is 1.0 W/m/K in initial condition and 1.3 W/m/K in saturated condition. In initial condition, there is a 10 mm air gap between the canister and the buffer, in saturated condition the gap is closed. The outer 50 mm gap between buffer and rock is assumed to be filled with bentonite pellets that have conductivity of 0.2 W/m/K in initial condition and 0.6 W/m/K when saturated. Based on the results of Ikonen & Raiko (2012).](image)
3.1.3 Material composition and geometry

Geometry
The geometry of the spent nuclear fuel elements depends on the reactor type and the manufacturer of the fuel element. The dimensions of the fuel elements for the different reactors have been described in Raiko (2011), see also Table 3-2.

Spent nuclear fuel pellets
The BWR, VVER and PWR spent nuclear fuel pellets are, from a chemical point of view, made of the same type of sintered UO₂. However, the fuel assembly geometry, U-235 content and burnable poison (absorber) proportion, cladding material as well as other components of the assembly are different depending on the fuel type. The average U-235 enrichment of a fuel assembly may vary roughly between 3–4 %, but within a single fuel rod/pellet the enrichment could be nearly 5 %. In the future, the assembly average enrichment could be over 4 %, enabling higher burnup to be achieved.

A fuel pellet goes through strong temperature gradients during its service in the reactor, particularly during the power ramping up and ramping down periods. These temperature gradients lead to fracturing of the pellet and an increased specific surface of the material. The microstructure of the pellet is also affected by the radiation field it experiences while in the reactor. The increase in density that occurs at first is compensated for by the expansion caused by cracks and an increasing amount of fission products; in the end, the diameter of the pellet is greater than at the beginning, and the density is correspondingly lower. The microstructure can be divided into two zones: a central zone with radial fractures and a homogeneous porosity due to fission gases developing with time, and a rim zone caused by the accumulation of Pu-239. This rim zone usually appears if the burnup is higher than 45 MWd/kgU. The rim zone, in comparison to the central zone, is characterised by higher porosity, smaller grains and higher concentrations of fission products and actinides.

Fuel cladding
Fuel cladding is usually made of different types of zirconium alloys (e.g. various grades of zirconium alloy) because the zirconium cross-section for thermal neutrons is very small and because zirconium alloys typically have great mechanical strength and good corrosion resistance.

Other metal parts
The other structural elements of the fuel assemblies (e.g. upper and lower tie-plates, end plug, spacer grid, and channel and nose piece) are fabricated from stainless steel, zirconium alloy or nickel-based alloys.
**Table 3-2.** A summary of the fuel characteristics for BWR, VVER 440 and OL3 PWR fuel. Minor fuel details may vary depending on fuel manufacturer but main data are constant (Table 28 from Raiko 2011).

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>Asea-Atom BWR</th>
<th>VVER-440 PWR</th>
<th>OL3 PWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assembly sectional configuration</td>
<td>square</td>
<td>hexagonal</td>
<td>square</td>
</tr>
<tr>
<td>Length of assembly (m)</td>
<td>4.127</td>
<td>3.217</td>
<td>4.865***</td>
</tr>
<tr>
<td>Sectional dimension (mm)</td>
<td>139*</td>
<td>144**</td>
<td>215</td>
</tr>
<tr>
<td>Number of rods per assembly</td>
<td>63 - 96</td>
<td>126</td>
<td>265</td>
</tr>
<tr>
<td>Mass of uranium (kg)</td>
<td>172 - 180</td>
<td>120 - 126</td>
<td>530 - 533</td>
</tr>
<tr>
<td>Total assembly mass (kg)</td>
<td>292 - 331</td>
<td>210-214</td>
<td>785</td>
</tr>
<tr>
<td>Flow channel dimension (mm)</td>
<td>139 (square)</td>
<td>144 (hexagonal)</td>
<td>No channel</td>
</tr>
<tr>
<td>Total length with flow channel (m)</td>
<td>4.398</td>
<td>3.217</td>
<td>4.865***</td>
</tr>
<tr>
<td>Anticipated maximum average burnup of a fuel assembly (MWd/kgU)</td>
<td>50</td>
<td>55</td>
<td>50</td>
</tr>
<tr>
<td>Estimated average burnup of all the fuel (MWd/kgU)</td>
<td>38 - 39</td>
<td>39 - 40</td>
<td>46 - 47</td>
</tr>
<tr>
<td>Typical enrichment U-235 (%)</td>
<td>3.3 – 4.4</td>
<td>3.6 - 4.4</td>
<td>3.6 - 4.2</td>
</tr>
<tr>
<td>Minimum cooling time of a single bundle (years)</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Minimum average cooling time with average burnup (years)</td>
<td>43.7</td>
<td>31.5</td>
<td>56.5</td>
</tr>
<tr>
<td>Allowable average decay heat at disposal (full canisters) (W/tU)</td>
<td>806</td>
<td>950</td>
<td>862</td>
</tr>
<tr>
<td>Heat decay power limit per canister (W)</td>
<td>1700</td>
<td>1370</td>
<td>1830</td>
</tr>
</tbody>
</table>

*) The top end handle of the BWR fuel assembly has some more extensive details; max sectional dimension is 151 mm.

**) Overall width across flat edges.

***) The fuel element has leaf springs on the top tie-plate that extends the total length with some tens of millimetres. Geometric details of the fuel element are to be confirmed later. Control rod crown is not included in the OL3 PWR fuel elements that are to be disposed. The weight of a set of 24 absorber rods is roughly 55 kg.

### 3.1.4 Radionuclide inventory

The radionuclide inventory in spent nuclear fuel depends among other considerations on the burnup history of the fuel, and the time elapsed since the end of its irradiation. The radionuclide inventories used in the radionuclide transport analyses are based on Anttila (2005b), where the composition and radioactive characteristics of the spent nuclear fuel from the Finnish nuclear power plants have been estimated with the ORIGEN-S computer code of the SCALE-5 program package. The inventories calculated in Anttila (2005b, App. 2 and 3) are based on data provided by TVO and Fortum (see Anttila 2005b or the Models and Data for the Repository System report for details).
The activity inventories for the source term from a single canister containing BWR, VVER and OL3 PWR fuel are reported in Posiva (2008a, Tables 6-8, 6-9 and 6-10, respectively). Initial activities used as input to radionuclide transport calculations are those after 30 years of cooling (Anttila 2005b).

The radionuclides are embedded
- within the fuel matrix, including its microstructures,
- within the gap between the fuel pellets and the cladding, and
- within the cladding and other metal parts.

In the fuel matrix the radionuclide inventory is partitioned between
- a solid solution of mixed fissionable and fertile materials (principally UO$_2$) homogeniously distributed in the UO$_2$ matrix, and
- a mobile fraction located in grain boundaries, fractures and the rim zone of fuel pellets.

Radioactive gases are part of the mobile fraction and can be readily released. The mobile fraction in the void spaces within the matrix typically includes high mobility radionuclides (e.g. I-129, C-14, Cl-36) that are readily available for release, hence the term “instant release fraction” or IRF.

Radionuclides can be released from fuel by a number of processes. Once in contact with groundwater, there will be rapid release of the IRF, followed by a slow congruent release from the fuel matrix by dissolution and alteration reactions. As the burnup of fuel increases, the structure of fuel pellets evolves to more altered states and higher IRF (Features, Events and Processes report, FEP 3.2.9).

Radionuclide release from fuel is mainly affected by the following factors:
- Radionuclide inventory, in particular the IRF, which is affected by the irradiation history of the fuel;
- Redox and chemical conditions inside the canister which affect the solubility and speciation of the radionuclides;
- The mass transport of water in and outside the canister.

Additionally, if the fuel pellets are in contact with water after canister failure, especially alpha radiolysis can split water in oxygen and hydrogen. If hydrogen is transported out of the canister, the uranium may then oxidise from state U(IV) to U(VI) which is more soluble. The process may, however, be counteracted by corrosion of the canister insert, which produces hydrogen.

3.2 Reference KBS-3V repository components

Posiva’s safety concept consists of the principles of isolation and containment of the hazardous materials contained in the spent nuclear fuel. The safety concept is based on the properties of the Olkiluoto site and on the KBS-3 method, which is the selected geological disposal method for the given spent nuclear fuel inventory.

The KBS-3 method relies on stable and favourable conditions of the bedrock, durable canisters containing the spent nuclear fuel and the buffering properties of the clay sur-
rounding the canister. Currently, two alternatives of the KBS-3 method are under consideration: KBS-3V and KBS-3H. The KBS-3V alternative, shown in Figure 1-1, is the reference design for the construction license application and the safety case supporting it, whereas the KBS-3H alternative is presented as an alternative potentially becoming available in the future. These alternatives have similar components in the near field and both can be implemented at Olkiluoto; so much of the system description applies to both. A schematic view of KBS-3V repository design components was shown in Figure 3-2. The safety concept and safety functions are discussed in detail in Section 5.1.

3.2.1 Canister

The canister is described in detail in the Canister Production Line report and in the Description of the Disposal System report. The canister structure consists of a massive cast iron insert covered by a 5 cm thick copper overpack. Copper has been chosen as the overpack material because of its well-known characteristics, including its good thermal and mechanical properties, and its resistance to corrosion in reducing environments. Cast iron has been chosen for the insert to provide mechanical strength, radiation shielding and to maintain the fuel assemblies in the required configuration. The design and dimensioning analyses of the copper-iron canister for spent nuclear fuel are presented in Raiko (2005, 2012). There are currently three versions of the canister, one for each fuel type (Figure 3-3). The canister for OL-4 fuel will be designed after the power plant type has been selected. The design basis for the canister is given in Chapter 7. The spent nuclear fuel is sealed in the canisters as whole fuel assemblies including the flow channel outside the VVER-440 and BWR fuel bundles. Further information on the canister material properties relevant to the analysis of scenarios is presented in Part II, Chapter 2 of Posiva (2010a). See also Models and Data for the Repository System and Description of the Disposal System reports.
Figure 3-2. Schematic view of KBS-3V repository design components: canister, buffer, and deposition tunnel backfill (deposition tunnel plug not shown).
Figure 3-3. Copper-iron canisters for the spent nuclear fuel from the Loviisa 1-2 (VVER-440), Olkiluoto 1-2 (BWR) and Olkiluoto-3 (EPR) reactors from left to right (Raiko 2005). All versions of the canister have the same outer diameter of 1.05 m. The height ranges from 3.6 to 5.25 m.

The canisters are designed for long-term integrity, i.e. gas and water-tightness, and have a design lifetime of hundreds of thousands of years except for incidental deviations. Incidental deviations refer to manufacturing defects and operating errors that may reduce the lifetime for a few canisters. This canister design lifetime corresponds to the minimum time that the canisters are designed to maintain their integrity taking into account the loads that are considered likely to take place in the repository over the assessment period. The design lifetime does not mean that the canister will fail beyond this period. The possibility paths of canister evolution will be assessed in the Formulation of Radionuclide Release Scenarios and in the Performance Assessment.

3.2.2 Buffer

The buffer is described in detail in the Buffer Production Line report and in the Description of the Disposal System report. The canister will be surrounded by rings and blocks (at the top and bottom) of highly compacted bentonite, referred to as the "buffer" (Figure 3-2). The uppermost metres of the deposition hole will be backfilled with blocks of compacted bentonite. The installation gap between the canister cylinder and buffer is approximately 10 mm and that between the buffer and the rock is approximately 50 ± 25 mm (Buffer Production Line report, Table 2-3).

MX-80 sodium bentonite from Wyoming, USA is the reference buffer material in the design and is the material considered in the previous radionuclide release and transport calculations. The properties of MX-80 are discussed in the Buffer Production Line re-
port and its initial state is given in the *Description of the Disposal System* report. The gap between the bentonite block and rings and the rock wall will be filled with bentonite pellets.

### 3.2.3 Deposition tunnel backfill and plug

The backfill is described in detail in the *Backfill Production Line* report and in the *Description of the Disposal System* report. The deposition tunnel leading to the deposition holes will be backfilled to limit the hydraulic conductivity of the tunnels, prevent the loss of buffer density due to expansion of the buffer into the deposition tunnel and provide mechanical stability to the tunnels. The current backfilling method is based on the block concept, comprising filling the majority of the tunnel with pre-compacted backfill blocks and the remaining volume with bentonite pellets. The reference backfill material is Friedland clay, which is a German bentonite material from Neubrandenburg area, which has less swelling minerals than MX-80 (Karnland et al. 2006).

The deposition tunnels will be plugged after the backfilling is completed to avoid significant water inflows and to keep the backfill and buffer in place. The plug shall be designed to withstand the hydrostatic pressure at the disposal depth and the swelling pressure of the backfill.

Plans for the plug structures for deposition tunnels have been presented in the *Backfill Production Line* and in the *Description of the Disposal System* reports. The cement used in the concrete plug should be compatible with saline water and generate minimal heat during its hydration.

### 3.2.4 Closure

The design of the approach to closure is on-going and the latest design and background information for the selected approach can be found in the *Closure Production Line* report and in Dixon et al. (2012), respectively. The closure components of the repository are designed by adopting a compartmental concept that allows the closure structures to be adjusted taking into account the demands of different environments within the repository. Depending on their location and function, several types of plugs and seals are used for closure. The plugs and seals are described in the *Closure Production Line* report.

The aim of the closure is to prevent the underground openings from compromising the long-term isolation of the repository from the surface environment and normal habitats for humans, plants and animals, to contribute to favourable and predictable geochemical and hydrogeological conditions for the other engineered barriers by preventing the formation of significant water conductive flow paths through the openings, and to limit and retard inflow to and release of harmful substances from the repository. Openings of the disposal facility that need to be backfilled are the central tunnels, shafts, technical rooms, characterisation drillholes and investigation niches as well as the access tunnel. Specific plans for backfilling these openings are ongoing. Similar backfilling material and techniques to those used in the deposition tunnels may be used in these other cavities.
3.3 Host rock and underground openings

3.3.1 Repository layout

The current repository layout has been prepared for 9000 tU from the two Loviisa power plant units and four Olkiluoto units. The conceptual layout is presented in Figure 3-4. The layout is described in detail in Saanio et al. (2012).

Figure 3-4. An example of the disposal facility layout at Olkiluoto (z = -410 m). The layout is for 9000 tU. This layout has a reserve of 20 % to take into account the possibility that some tunnel sections may not be usable. White areas are available for repository layout, layout determining features and their respect distances restricting the repository layout are shown in dark grey, and intersections of surface-based drillholes with their respect distances in red. Respect distances are distances near major fracture zones inside which deposition tunnels cannot be constructed in order to protect the deposition canisters.
4 THE OLKILUOTO SITE

Olkiluoto Island (about 10 km² in area), which has been selected as the site for the spent nuclear fuel repository, is located on the Baltic Sea coast in the south-western part of Finland (Figure 1-3).

The Olkiluoto site, as seen today, has developed as a consequence of events and processes that have taken place over billions of years, from those reflected in the geological properties of the rocks forming the geosphere, to those much shorter-term changes due to climate-driven processes (influencing mainly groundwater flow and groundwater composition) and the geomechanical effects of isostatic rebound. A detailed description of the Olkiluoto site is given in the Site Description report concentrating on the host rock and in the Biosphere Description for the surface environment.

4.1.1 Geological setting and host rock

The crystalline bedrock of Finland is a part of the Precambrian Fennoscandian Shield which, in south-western Finland, consists mainly of Early Palaeoproterozoic metamorphic and igneous rocks, belonging to the Svecofennian Domain. This domain developed between 1930 Ma and 1800 Ma ago, either during one long Svecofennian orogeny, or during several, separate orogenies. The rocks of Olkiluoto can be divided into two major classes (Aaltonen et al. 2010). The first are supracrustal high-grade metamorphic rocks including various migmatitic gneisses, tonalitic-granodioritic-granitic gneisses, mica gneisses, quartz gneisses, and mafic gneisses, and the second are igneous rocks including pegmatitic granites and diabase dykes. The metamorphic supracrustal rocks have been subjected to polyphase ductile deformation producing thrust-related folding, shearing, strong migmatisation and pervasive foliation. The most important rock-forming minerals in the Olkiluoto rocks are quartz, potassium feldspar, plagioclase, biotite (± other micas) and hornblende (± other amphiboles).
Figure 4-1. A bedrock surface geological map of Olkiluoto Island showing lithology and the fault zones (brittle deformation zones) defined as layout-determining features.

The bedrock at Olkiluoto has been subjected to extensive hydrothermal alteration processes, which are estimated to have taken place at temperatures from slightly over 300 °C down to 50 °C (Gehör et al. 2002). Based on the grade of alteration, two different types of hydrothermal alteration can be distinguished: a fracture-controlled type and a pervasive (or disseminated) type. The fracture-controlled alteration indicates that hydrothermal fluids have passed through the rock along planar features, with the alteration being restricted to incipient fractures or narrow zones adjacent to them. The pervasive alteration is the strongest type of alteration - it occurs as spots or is finely disseminated throughout the rock and in the fracture fillings. The main hydrothermal alteration minerals in the Olkiluoto bedrock are illite, kaolinite, sulphides and calcite. The overall trend of alteration at Olkiluoto is the replacement of framework silicates by sheet silicates. Typically the cyclic alteration at Olkiluoto has increased the concentrations of CO₂ and Ca of the whole rock composition, and the altered rocks at Olkiluoto have undergone K-metasomatism; K gain and Na+Ca loss.

The fault zones at Olkiluoto are mainly SE-dipping thrust faults formed during contraction in the latest stages of the Svecofennian orogeny, approximately 1800 Ma ago, and were reactivated in several deformation phases. In addition, NE-SW striking strike-slip faults are also common (see Figure 4-1). The occurrence of fracturing varies between different rock domains, but the following three fracture sets are typical for the site (i) east-west striking fractures with generally subvertical dips to both the north and south, (ii) north-south striking fractures with generally subvertical dips to both the east and the
west and (iii) moderately-dipping to gently-dipping fractures with strikes that are generally sub-parallel to the aggregate foliation directions in a particular fracture domain.

The strength and deformation properties of the intact rock, as well as its thermal properties, depend essentially on the mineral composition and structure, i.e. rock type. The rocks with higher quartz content have higher thermal conductivity and diffusivity than the ones consisting of mafic minerals. The heterogeneity of the rock properties at Olkiluoto is, therefore, reflected in the variation of the thermal and rock mechanics properties and seen e.g. in the anisotropic thermal properties due to foliation and gneissic banding. Currently the temperature at the repository level is 11 - 12°C. The thermal conductivity of the rock at 25°C varies over 2.49 - 3.20 W/(mK), the average being 2.91 W/(mK) depending on the rock type. The specific heat capacity at 25°C is on average 712 J/(kg·K).

Olkiluoto is situated away from the active plate margins. In Fennoscandia, the orientation of the major principal stress is attributed to an E-W compression from the mid-Atlantic ridge push and a N-S compression from the Alpine margin, resulting in a roughly NW-SE orientation of major principal stress (Heidbach et al. 2008). This is also supported by the regional in situ data from Olkiluoto and other Finnish sites studied during the site selection programme. Changes in isostatic load due to glaciations and related isostatic adjustment and the existence of brittle deformation zones change the stress regime at the site. Currently, a thrust faulting stress regime is present, i.e. the horizontal stresses are larger than the vertical stress, $\sigma_H > \sigma_h > \sigma_v$ and the principal stresses are approximately oriented horizontally and vertically, respectively. The orientation of $\sigma_H$ at the site is found to vary slightly with depth and at the repository depth is in the range NW-SE and E-W. The vertical stress is predominantly well represented by the weight of the overlying rock mass.

4.1.2 Hydrogeology and hydrogeochemistry

In the crystalline bedrock at Olkiluoto, groundwater flow takes place in hydraulically-active deformation zones (hydrogeological zones) and fractures. The larger scale hydrogeological zones, which are related to brittle deformation zones, carry most of the volumetric water flow in the deep bedrock. There is a general decrease of transmissivity of both fractures and the hydrogeological zones with depth. Under natural conditions, groundwater flow at Olkiluoto occurs mainly as a response to freshwater infiltration dependent on the topography, although salinity (density) variation driven flow also takes place to a lesser extent. The porewater within the rock matrix is stagnant but exchanges solutes by diffusion with the flowing groundwater in the fractures.

The complexity of the fracture groundwater and matrix porewater composition reflects the history of the Olkiluoto area and the effects of periods of glaciation and associated infiltration of fresh meltwater, submersion below sea-level and the influence of marine water, and the slow interaction between the groundwater, porewater and the minerals of the rocks over millions of years. Currently, the groundwater composition over the depth range 0–1000 m at Olkiluoto is characterised by a significant range in salinity and the groundwater forms a relatively layered system (Site Description) (see Table 3-2). Fresh waters (total dissolved solids (TDS) <1 g/L) rich in dissolved carbonate are found at shallow depths, in the uppermost tens of metres. Brackish groundwater, with salinity
(TDS) up to 10 g/L dominates at depths between 30 m and about 400 m. Brackish sulphate-rich waters are common in the depth range 100–300 m, whereas brackish chloride water, low in sulphate, dominates at depths of 300–400 m. Saline groundwaters (TDS >10 g/L) dominate at still greater depths. At the repository depth the initial salinity (TDS) will be about 12 g/L on average (Site Description).

The matrix porewaters are rather different from the groundwater flowing in the fractures, as they are exchanged more slowly: in the upper part of the bedrock (0–150 m), the groundwater and matrix porewater seem to be in equilibrium, suggesting a similar origin and strong interaction between these two groundwater types. However, at deeper levels (150–500 m), the matrix porewater is less saline than groundwater flowing in the fractures and increasingly enriched in $\delta^{18}O$, which has been interpreted to represent fresh water conditions during a warm climate, probably the pre-glacial Tertiary period (Posiva 2009b). Isotope analyses and palaeohydrogeochemistry are discussed in length in Site Description (Chapter 7).

The brackish chloride and saline groundwaters below 300 m depth are thought to be very old and water compositions are missing distinct features from Quaternary glacial cycles, over the last approximately two million years. Shallower groundwaters, in the range down to 300 m depth have been affected by infiltrating waters of glacial, marine and meteoric origin during the alternating periods of glaciations and interglacials. Features in the groundwater related to the latest Weichselian glaciation and postglacial-period are observed above 300 m depth indicating the dynamic hydrogeological characteristics of this upper bedrock compared with the deeper rock. The distribution of the groundwater types is the result of progressive mixing and reactions between various initial water types, which represent some of the major events at the site during its geological history. The initial water types have been recognised to be, from oldest to youngest, (i) brine, (ii) subglacial water, (iii) glacial meltwater, (iv) Littorina seawater, and (v) meteoric water (Site Description, Section 11.4.1). Present-day Baltic seawater, which is basically diluted Littorina seawater, is also recognised from shallow depths. Water-rock interactions, such as carbon and sulphur cycling and silicate reactions, buffer the pH and redox conditions and stabilise the groundwater chemistry. In addition, weathering processes during infiltration play a major role in determining the shallow groundwater composition.
Table 4-1. Ranges of total dissolved solids (TDS) in the water-conductive fracture system, based on EC measurements, which are used to improve the coverage of groundwater samples in the 3-D salinity model. Water types corresponding to TDS ranges, their mixing origin and observed depth ranges are also shown (Posiva 2009b), in addition pH and Eh ranges are presented.

<table>
<thead>
<tr>
<th>Groundwater types; dominant origin and mixing evidence in groundwater samples</th>
<th>Depth range (z), m.a.s.l.</th>
<th>TDS g/L</th>
<th>Redox conditions</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh HCO₃; Meteoric infiltration</td>
<td>+10 – -40</td>
<td>&lt;1</td>
<td>Oxic to Anoxic</td>
<td>5.2–8.1</td>
</tr>
<tr>
<td>Brackish HCO₃; Mixing of meteoric infiltration with Littorina² Sea derived SO₄-rich brackish groundwater</td>
<td>0 – -130</td>
<td>1–3</td>
<td>Sulphidic</td>
<td>7.6–8.1</td>
</tr>
<tr>
<td>Brackish SO₄; Littorina seawater and glacial meltwater mixed with ancient meteoric water-saline groundwater mixture</td>
<td>-60 – -300</td>
<td>4–9</td>
<td>Sulphidic</td>
<td>7.1–8.1</td>
</tr>
<tr>
<td>Brackish Cl; Ancient meteoric water - saline groundwater mixture with minor Littorina seawater component</td>
<td>-100 – -400</td>
<td>2–10</td>
<td>Sulphidic to Methanic</td>
<td>7.3–8.8</td>
</tr>
<tr>
<td>Saline Na-Ca-Cl; Ancient meteoric water - saline groundwater mixture</td>
<td>-320 – -480</td>
<td>10–18</td>
<td>Methanic</td>
<td>7.3–8.2</td>
</tr>
<tr>
<td>Saline Ca-Na-Cl; Ancient saline groundwater - meteoric water mixture</td>
<td>-410 – -570</td>
<td>18–30</td>
<td>Methanic</td>
<td>7.6–8.4</td>
</tr>
<tr>
<td>Highly saline Ca-Na-Cl; Ancient brine³ - meteoric water mixture</td>
<td>below -570</td>
<td>&gt;30</td>
<td>Methanic</td>
<td>7.0–8.1</td>
</tr>
</tbody>
</table>

Redox conditions at Olkiluoto are anoxic except in shallow infiltrating groundwater at a few locations (see Table 4-1). Scarce observations of iron oxyhydroxides on fracture surfaces at depths in excess of ten metres in the bedrock and the lack of corroded pyrites support the assumption of long-term reducing conditions in the deep groundwater. Instead, pyrite and other iron sulphides are common in water conducting fractures throughout the investigated depth range (down to 1000 m), indicating a strong lithologi-

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² During the end of the Weichselian glaciation the Baltic Sea developed to its current stage via alternating lacustrine and marine stages that were Baltic Ice Lake (until 11 590 BP), Yoldia Sea (11 590 – 10 800 BP), Ancylus Ice Lake (10 800 – 9000 BP), Mastogloia Sea (9000 – 8000 BP), Littorina Sea (8000 – 3000 BP) and Baltic Sea (3000 BP–present). Olkiluoto was free of ice cover around 11,000 BP and emerged from Baltic sea around 3000 BP. (Eronen et al. 1995)

³ TDS in brine water is more than 100 g/L.
cal buffer against oxic waters over geological time scales (cf. Site Description). Two natural metastable interfaces are present (Figure 4-2). The upper is located mostly in the overburden, where the conditions change from oxic to anoxic. The other is located at a depth of approximately 250–350 m (Figure 4-2). In this zone, sulphate-rich groundwater is mixed with a methane-rich brackish-Cl – saline groundwater system to give rise, at least locally, to exceptionally high levels of dissolved sulphide as a microbially mediated reaction product (Figure 4-2).

**Figure 4-2.** Illustrative hydrogeochemical site model of baseline groundwater conditions with the main water-rock interactions at Olkiluoto. Changes in colour indicate alterations in fracture hosted water type. The hydrogeologically most significant zones are represented. Blue arrows represent flow directions. Rounded rectangles contain the main sources and sinks affecting pH and redox conditions. Enhanced chemical reactions dominate the infiltration zone at shallow depths, and at the interface between Na-Cl-SO₄ and Na-Cl groundwater types. Note that the illustration depicts hydrogeochemical conditions in the water-conductive fracture system, not in the diffusion-dominated rock matrix (Site Description).
4.1.3 Surface environment

Topography in the Olkiluoto area, and in general in south-western Finland, is flat and soil erosion rates are very low. Glacial erosion features such as glacially smoothed bedrock outcrops and *roche moutonnées* are common. As a result of the last glaciation, the bedrock depressions are filled with a thicker layer of overburden, mainly sandy till and fine-grained till (Huhta 2005, 2007, 2008, 2009, 2010, Lintinen et al. 2003, Lintinen & Kahelin 2003, Lahdenperä et al. 2005, Lahdenperä 2009).

Studies on sorption in soils at Olkiluoto have been carried out since 2008 and results are presented e.g. in Lusa et al. (2009); Söderlund et al. (2011); Virtanen (2011); Söderlund & Lehto (2012); Söderlund et al. (2012). In addition, *in situ* partition coefficient values, from different mineral and organic soil types are presented in *Biosphere Data Basis*, (Section 15.2).

The waters around Olkiluoto Island are shallow, except for a few areas where sea depths reach about 15 m. The seabed west of Olkiluoto is mainly till (about 35-45 %), bedrock (about 30-40 %) and various clay and mud deposits (about 15-25 %). The sea area surroundings of Olkiluoto have a quite large area of gaseous gyttja clay sediments with high organic matter content (Rantataro & Kaskela 2010). This is of particular interest because of the continued land uplift (at present 6 mm/year, Eronen et al. 1995) of the Olkiluoto area which will expose areas of current seabed sediments in the next few thousand years – the time frame for which the spent nuclear fuel repository releases must be quantified in terms of doses to a human population and other biota. In addition, the effects of land uplift are accentuated by eutrophication in the coastal areas, especially in shallow bays (Haapanen & Lahdenperä 2011). The ecosystem succession during uplift, the redistribution of sediments and groundwater flow will influence the areas of potential deep groundwater recharge and discharge from the repository (Haapanen et al. 2007, 2009). The changes in the landscape are, however, affected not only by uplift but also by changes in sea-level that are related to changes in climate, both regionally and globally. The effect of uplift could be, at least to some degree, enhanced or reversed by changes in sea level. This is taken into account in the climate scenarios in the *Biosphere Assessment* report.

At present, freshwater (limnic) ecosystems are few in the Olkiluoto area and there are no natural lakes on the island. The nearby lake basins were isolated during the various stages of the Baltic Sea as a result of isostatic uplift and tilting of the land. The closest rivers are Eurajoki and Lapinjoki, which discharge to the sea north and east of Olkiluoto Island, increasing the concentration of nutrients and solids, especially at the river mouths (Haapanen et al. 2009). The use of lakes and mires – currently absent from the island – in the surrounding region as analogues for conditions that could occur as a result of future biosphere evolution at Olkiluoto is discussed by Haapanen et al. (2010). *Figure 4-3* shows land uplift and an example of surface environment development during 10,000 years after present.
Figure 4-3. Land uplift and an example of the biosphere development through to 10,000 a after the present. Map data: Topographic database by the National Land Survey of Finland (permission 41/MYY/11) and Posiva Oy. Map layout by Jani Helin/Posiva Oy. Note: dates are given as AD, i.e. 12020 is 10,000 years after the reference date of 2020 AD.
4.2 Expected evolution

The long-term safety of the disposal system will be influenced by climate changes during its evolution. The climatic evolution gives the time windows for which climate driven processes in the disposal system may be effective. It must be noted that, for example, current crustal uplift is the consequence of past climate changes (i.e. last glacial maximum during the Weichselian) and that crustal uplift influences hydrogeology and hydrogeochemistry in the entire disposal system, and therefore the performance of the EBS and host rock.

In the report by Pimenoff et al. (2012), two future climate evolution scenarios for the Olkiluoto area and for the next 120,000 years were depicted considering constant CO\textsubscript{2} concentrations in the atmosphere (280 ppm and 400 ppm). The methodology was based on the simulation, with CLIMBER-2 EMIC model, of the last glacial cycle, the Weichselian, for which proxy data and climatic records are available. Current CO\textsubscript{2} concentration in the atmosphere is around 390 ppm (Tans 2010), meaning that the 400 ppm CO\textsubscript{2} scenario (also called greenhouse-emission scenario) would be a prolonged temperate period (boreal climate), i.e. the continuation of a climate similar to the current one. In this scenario no occurrence of ice sheets or temperatures leading to permafrost formation are deemed.

In fact, the two future climate scenarios are recommended to be looked at in a qualitative way, since it is hard to believe that atmospheric CO\textsubscript{2} concentration will stay constant for very long time periods. Nonetheless, and based on the results of several climate simulations for the future (see Pimenoff et al. 2012), it is assumed that the next cold period initiating permafrost will occur at about 50,000 years AP. Thereafter the Weichselian glacial cycle applies (see Appendix 1 in Formulation of Radionuclide Release Scenarios report) until one million years. It is acknowledged that this is a simplistic assumption, since during the last million years none of the glacial cycles can be said to be a repetition of the other. There could be shorter or longer permafrost periods and a smaller or larger ice cover. However, very pessimistic climate conditions are assumed for permafrost to reach repository depth (Hartikainen 2012). Because of the uncertainties in the timing and duration of periods of permafrost, only particular time windows covering permafrost are selected for further studies. The most reliably characterised ice-sheet retreat period at the end of the Weichselian is also selected for further study.
Figure 4-4. A) Schematic representation of the occurrence of permafrost, ice-sheets, and temperate periods during the last glacial cycle (LGC). B) The repetition of the past glacial cycle after 50,000 years after present (AP) and selected climatic evolution for safety assessment.
5 DESIGN BASIS

5.1 Safety concept and safety functions

5.1.1 The safety concept

The long-term safety principles of Posiva’s planned repository system are described at Level 2 of the VAHA (VAHA is Posiva’s requirement management system) as follows.

1. The spent nuclear fuel elements are disposed of in a repository located deep in the Olkiluoto bedrock. The release of radionuclides is prevented with a multi-barrier disposal system consisting of a system of engineered barriers (EBS) and host rock such that the system effectively isolates the radionuclides from the living environment.

2. The engineered barrier system consists of
   a) canisters to contain the radionuclides for as long as they could cause significant harm to the environment
   b) buffer between the canisters and the host rock to protect the canisters as long as containment of radionuclides is needed
   c) deposition tunnel backfill and plugs to keep the buffer in place and help restore the natural conditions in the host rock
   d) the closure, i.e. the backfill and sealing structures to decouple the repository from the surface environment.

3. The host rock and depth of the repository are selected in such as to make it possible for the EBS to fulfil the functions of containment and isolation described above.

4. Should any of the canisters start to leak, the repository system as a whole will hinder or retard releases of radionuclides to the biosphere to the level required by the long-term safety criteria.

The safety concept, as depicted in Figure 1-5, is a conceptual description of how these principles are applied together to achieve safe disposal of spent nuclear fuel in the conditions of the Olkiluoto site. Due to the long-term hazard of the spent nuclear fuel, it has to be isolated from the surface environment over a long period of time. The KBS-3 method provides long-term isolation and containment of spent nuclear fuel by a system of multiple barriers, both engineered and natural, and by ensuring a sufficient depth of disposal (the key safety features of the system in Figure 5-1). All of these barriers have their roles in establishing the required long-term safety of the repository system. These roles constitute the safety functions of the barriers (see Table 5-1). The surface environment is not given any safety functions; instead it is considered as the object of the protection provided by the repository system.

Most radionuclides in the spent nuclear fuel are embedded in a ceramic matrix (UO₂) that itself is resistant to dissolution in the expected repository conditions. The slow release of radionuclides from the spent nuclear fuel matrix is part of Posiva’s safety con-
cept. Moreover, the near-field conditions should contribute to maintaining the low solubility of the matrix.

**Figure 5-1.** Outline of the safety concept for a KBS-3 type repository for spent nuclear fuel in a crystalline bedrock (adapted from Posiva 2003a). Orange pillars and blocks indicate the primary safety features and properties of the disposal system. Green pillars and blocks indicate the secondary safety features that may become important in the event of a radionuclide release from a canister.

Implementation of the KBS-3 method entails the introduction of a number of closure components because of engineering, operational safety or long-term safety needs. Long-term safety needs arise, for example, because implementation involves the construction of a system of underground openings, including the access tunnel and shafts, that would significantly perturb the safety functions of the host rock unless backfilled and sealed at closure of the disposal facility. These closure components with long-term safety functions include:

- backfill of underground openings, including the central tunnels, access tunnel, shafts, and other excavations, and
- drillhole plugs, mechanical plugs, long-term hydraulic plugs at different depths and plugs near the surface.

The safety functions of the EBS components and host rock are summarised in Table 5-1. In the TURVA-2012 safety case documentation, the spent nuclear fuel, EBS and the host rock are jointly termed the repository system, whereas the term disposal system is used when the repository system and the surface environment are both considered (see Figure 1-2).
5.1.2 Safety functions

As described in Section 5.1.1, the long-term safety of disposal is based on a system of natural and engineered barriers which all have their roles in establishing the required long-term safety of the repository system. These roles constitute the safety functions of the barriers. According to YVL D.5, paragraph 405:

“Engineered barriers and their safety functions may consist of waste matrix, in which radioactive substances are incorporated; hermetic, corrosion resistant and mechanically strong container, in which the waste is enclosed; chemical environment around waste packages, which limits the dissolution and migration of radioactive substances; material around waste canisters (the buffer), which provides containment and yields minor rock movements; other containment structures in the emplacement rooms; backfilling materials and sealing structures, which limit transport of radioactive substances through excavated rooms.”

Posiva’s definition of safety functions follows this guidance. However, since an engineered barrier is a barrier that has been designed to provide certain safety function(s) and fulfill certain performance criteria, the spent nuclear fuel matrix is not considered an engineered barrier. In Posiva’s case, the spent nuclear fuel elements are disposed of in the form they are received from the utilities and are not “designed” in any way (e.g. conditioned or reprocessed) before packaging in canisters.

It is acknowledged that most radionuclides in the spent nuclear fuel are embedded in a ceramic matrix (UO₂) that itself is resistant to dissolution in the expected repository conditions. The slow release of radionuclides from the spent nuclear fuel matrix is part of Posiva’s safety concept. Moreover, the near-field conditions should contribute to maintaining the low solubility of the matrix. As these conditions can be constrained by repository design, performance targets and target properties are assigned to the engineered barriers and the host rock. In the safety assessment, the properties of the spent nuclear fuel are taken into account in the release rate of radionuclides from the source term.

The safety functions for each barrier have been presented in Table 5-1. The surface environment is not given any safety functions; instead it is considered as the object of the protection provided by the repository system.
Table 5-1. Safety functions assigned to the barriers (EBS components and host rock) in Posiva’s KBS-3V repository.

<table>
<thead>
<tr>
<th>Barrier</th>
<th>Safety functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canister</td>
<td>Ensure a prolonged period of containment of the spent nuclear fuel. This safety function rests first and foremost on the mechanical strength of the canister’s cast iron insert and the corrosion resistance of the copper surrounding it.</td>
</tr>
</tbody>
</table>
| Buffer                               | Contribute to mechanical, geochemical and hydrogeological conditions that are predictable and favourable to the canister
Protect canisters from external processes that could compromise the safety function of complete containment of the spent nuclear fuel and associated radionuclides
Limit and retard radionuclide releases in the event of canister failure. |
| Deposition tunnel backfill            | Contribute to favourable and predictable mechanical, geochemical and hydrogeological conditions for the buffer and canisters
Limit and retard radionuclide releases in the possible event of canister failure
Contribute to the mechanical stability of the rock adjacent to the deposition tunnels. |
| Host rock                            | Isolate the spent nuclear fuel repository from the surface environment and normal habitats for humans, plants and animals and limit the possibility of human intrusion, and isolate the repository from changing conditions at the ground surface,
Provide favourable and predictable mechanical, geochemical and hydrogeological conditions for the engineered barriers,
Limit the transport and retard the migration of harmful substances that could be released from the repository. |
| Closure                              | Prevent the underground openings from compromising the long-term isolation of the repository from the surface environment and normal habitats for humans, plants and animals.
Contribute to favourable and predictable geochemical and hydrogeological conditions for the other engineered barriers by preventing the formation of significant water conductive flow paths through the openings.
Limit and retard inflow to and release of harmful substances from the repository. |

5.1.3 Derivation of performance targets and target properties

The safety functions described above are implemented in the proposed design through a set of technical design requirements, based on performance objectives that are defined for each barrier of the repository system. The performance objectives are expressed as performance targets (engineered barriers) and target properties (natural barriers) that the system should meet in the long-term to provide the safety level needed. The technical
design requirements of the repository system are expressions of these performance targets and target properties in a form that can be tested or otherwise proven at the stage of implementation through observations and measurements. The potential future conditions that are taken into account in the design process are described through a set of design basis scenarios. As required by regulation, the likelihood of different scenarios is assessed and those that are judged reasonably likely are included in the design basis scenarios. The performance targets and target properties, together with the derived technical design requirements and the underlying design basis scenarios, form the design basis of the repository.

The definition of the performance targets and target properties requires the identification of the different loads and interactions that may act on the repository system at the time of canister emplacement and in the long-term. The loads and interactions are identified through a comprehensive analysis of the features, events and processes (FEPs, see Features, Events and Processes report) that are likely to affect the system in the design basis scenarios. These scenarios are developed from a consideration of the expected evolution of the repository system, and an analysis of the uncertainties involved, given that only limited information can be obtained from observation of conditions in that deposition hole or its near-field once a canister has been emplaced and the buffer installed.

The performance targets and target properties are defined such that, provided they are met by the technical design and the future unveils as expected, the repository will provide the protection level required by the regulations. In addition, the definition of the performance targets takes into account the extra requirement imposed by YVL Guide D.5, paragraph 408:

"The safety approach for disposal of spent nuclear fuel shall be that the safety functions provided by the engineered barriers will limit effectively the release of radioactive substances into bedrock for at least 10,000 years."

Performance assessment is used to show that the system, designed and built according to the specified technical requirements, will be compliant with the performance targets and target properties initially and in the long-term. In case of non-compliance, the system design - or ultimately the whole disposal concept - has to be modified until a technically feasible and long-term safe system can be demonstrated. The development of the disposal system can, therefore, be considered as continuous iteration between performance assessment, evaluation of safety and design basis, as shown in Fig. 1-5.

With the current definitions of performance targets and target properties (Chapters 6 to 10), Posiva aims at complete containment of the radionuclides for several hundreds of thousands of years. However, Posiva must also take into account the possibility of "incidental deviations" in which one or more of the engineered barriers do not meet their performance targets or the properties of the natural barriers deviate from their target values. According to YVL Guide D.5

"The base scenario shall assume the performance targets defined for each safety function, taking account of incidental deviations from the targets values. The influence
of declined performance of single safety function or, in case of coupling between safety functions, the combined effect of declined performance of more than one safety function, shall be analysed by means of variant scenarios."

(Appendix 1)

Pursuant to this guidance, the Base Scenario includes the possibility of initial canister defects that may lead to releases of radioactive substances. Variants of the Base Scenario are formulated to cover other kinds of deviations or uncertainties. For all these scenarios, the multi-barrier system as a whole is designed to allow for the degraded performance of the individual barriers and to reduce the amount of potential releases to below any conceivable harmful level.

Posiva also has to analyse the significance for safety of the lines of evolution that are judged unlikely, but still possible:

"Disturbance scenarios shall be constructed for the analysis of unlikely events impairing long-term safety." (Appendix 1 of YVL Guide D.5)

In the case of such unlikely future scenarios, Posiva has to show that the risks to which they give rise are acceptable according to the safety regulations. In practice this means that the expectation (probability-weighted) value of the consequences has to be less than the limits given for deterministically assessed consequences.

The formulation and assessment of scenarios leading to radionuclide release are collectively termed safety assessment. In general, performance assessment and safety assessment provide feedback and guidance to the system design concerning:

- indications of the need for improved engineered solutions to increase robustness and confidence in the safety case; and
- specifications of the uncertainties and deviations that can be tolerated such that a performance target/target property is still achieved.

The iteration between the design, performance assessment and safety assessment ensures, as far as possible:

- mutual compatibility of the engineered barriers with each other and with the bedrock, taking into account their respective safety functions;
- resistance of the engineered barriers to the main thermal, hydraulic, mechanical and chemical loads to which they will be subjected during evolution of the system; and
- robustness with respect to slow processes and unlikely events that may occur over the regulatory compliance period, and
- a safety case that properly takes into account uncertainties in the implementation of the design (i.e. initial state uncertainties).

5.2 Introduction to the design basis

This Design Basis report covers all requirements presented in Posiva’s requirements management system, VAHA, except the design specifications in VAHA Level 5. The legal and regulatory requirements that guide repository research, design and develop-
ment have been described in Chapter 2 of this report, and the safety concept and safety functions are introduced for each barrier and host rock. Presentation of the rationale justifying these requirements is a key aspect of the report. The evaluation of whether these requirements for the barriers have been achieved is the goal of the *Performance Assessment* report. The *Performance Assessment* assumes that the components of the system have been manufactured and installed as designed, i.e. the KBS-3V system meets its design requirements.

The main basis for the design of the disposal of spent nuclear fuel is to ensure that the spent nuclear fuel is disposed of in a safe manner without causing an unacceptable radiological burden to the coming generations. The safety is based on the long-term durability of the engineered barrier system components and on favourable host rock characteristics. The key processes affecting the long-term safety have been identified during the extensive research programmes of Posiva, SKB and other nuclear waste management companies, e.g. Nagra and Andra. Work on the KBS-3 method has been ongoing since 1970s. The issues requiring further studies are identified and plans to resolve them are presented in the periodic research programmes, the most recent ones are the TKS-2009 and YJH-2012 of Posiva (Posiva 2009b and Posiva 2012a) and RD&D 2010 of SKB (SKB 2010c).

The requirements are presented in this report according to their location in the structure in VAHA's hierarchy. The requirements at the highest levels in VAHA are of a general nature and the requirements become more detailed at the subsystem and design requirement levels (levels 3 and 4). The structuring in this report follows the same principles. The VAHA requirements are presented in *italics*, and then the rationale for each requirement is provided. The subsystem requirements (level 3) and the design requirements (level 4) are discussed in the following Chapters with the aim of giving justification for the requirements based on the extensive research which has been conducted during the development of the KBS-3 method. The design specification requirements on VAHA level 5 aim at fulfilling the performance targets and target properties on subsystem and design requirement levels, and thus are not part of the design basis and are beyond the scope of this report. The design specification requirements are presented in the *Production Line* reports. The discussion is organised in the following sections:

- **Rationale of the requirement**: this section describes why the requirement is needed and how it contributes to the safety and the fulfilment of the safety functions;
- **Loads to be taken into account**: this section discusses the most important processes and sources of loads that affect each requirement and therefore are to be taken into account in the design work;
- **Related requirements**: the dependencies identified between different requirements in VAHA are presented here.

The current solutions to satisfying these requirements for each EBS component are described detail in the *Production Line* reports and other design reports. The fulfilment of these requirements during the assessment period is discussed in the *Performance Assessment* report.
6 HOST ROCK AND UNDERGROUND OPENINGS

By definition, the host rock is the rock surrounding the deposition holes and other excavated rooms that shall provide sufficiently favourable and predictable conditions so that the EBS can fulfill its functions of containment and isolation and ensure that the transport of radionuclides is limited in the case of release. It is required that the host rock shall with high likelihood retain its favourable properties up to at least several hundred thousand years.

The safety functions of the host rock, which are isolation of spent nuclear fuel, providing favourable conditions for the EBS and providing a transport barrier, see discussion in Section 5.1.2, have been used to define target properties for the host rock instead of performance targets. The reasoning is that once the site as a whole has been considered as suitable according to the site-scale criteria, the performance targets as such cannot be set for the smaller scales since the host rock's properties are predefined at any given geological location. The properties can only be affected by selecting the repository depth and suitable locations for the deposition tunnels and holes such that the surrounding rock is likely to provide favourable conditions in the long term, e.g. by selecting locations where the groundwater flow is limited, geochemical conditions are suitable and the rock is sparsely fractured. The target properties are presented in Section 6.3.

The target properties are used to define the rock suitability classification (RSC) criteria, see Posiva (2012b), which are applied to selecting and approving the locations of repository, deposition tunnels and holes. Further, the methods and materials used in construction of the repository shall be selected in a way that the disturbance to the host rock is limited to the extent possible. During construction, the properties of the host rock can be changed temporarily by e.g. grouting of water-conducting fractures, but such changes are not permanent by nature and therefore the long-term safety of disposal cannot be based on such measures. Further, these measures may have adverse effects on the rock properties e.g. by increasing the pH of the groundwater. The design requirements for the underground openings presented in Section 6.4 cover both the RSC criteria and other requirements related to minimising the detrimental effects of construction. The simplified general structure of the host rock requirements is shown in Figure 6-1.
6.1 Definition and objectives

Host rock is the rock surrounding the deposition holes and other excavated rooms that shall provide such favourable and predictable conditions that the EBS can fulfill its functions of containment and isolation and ensure that the transport of radionuclides is limited in the case of release.

and

Host rock shall, with the exception of incidental deviations, retain its favourable properties over hundreds of thousands of years.

6.2 General requirements

6.2.1 Repository depth

The repository shall be located at minimum depth of 400 m.

Rationale of the requirement

This requirement arises from the safety concept of long-term isolation (see Figure 5-1) and from regulations, e.g. Government Decree 736/2008, Section 12 and YVL D.5, paragraph 412, which state that long-term safety has to be a guiding principle in repository design. The range of acceptable repository depths has been defined in the Decision-in-Principle of 21.12.2000 according to Posiva’s application. The repository depth shall be located at a depth between 400 m and 700 m. In general, the deeper the repository is located in the bedrock, the better is the repository de-coupled from processes and events on the surface. In particular, the isolation capacity against future climate effects, human intrusion, and other man-made changes improves with increasing depth, but at the same time various loads on the repository structures may also increase. Usually the rock
stresses become larger, complicating the construction activities and also affecting the near-field properties of the repository tunnels and deposition holes. At Olkiluoto the geochemical conditions will also become more adverse in relation to buffer and backfill performance, and, finally, the faulting sets limit to what are the optimal repository volumes at Olkiluoto. The properties of the host rock are described in detail in the Site Description.

At a depth of approximately 400 metres the host rock properties are in general considered to be favourable for the long-term isolation of the spent nuclear fuel in accordance with the safety concept based on the research and information available during the site investigation programme presented by Äikäs et al. (2000). The Olkiluoto site was determined to be suitable for disposal from the long-term safety point of view by Vieno & Nordman (1999). The initial estimates of site suitability have been verified during the site research programme, see e.g. Hellä et al. (2009).

**Loads to be taken into account**

The repository depth shall be chosen taking into account several competing factors; in general, the deeper the repository is located the more limited is the groundwater flow due to sparser network of flowing fractures and the longer it takes for any possible radionuclide release to reach the biosphere. However, while the density of flowing fractures are low at below -400 m at Olkiluoto, it is not evident that this frequency will be even lower at much greater depths. The groundwater chemistry at Olkiluoto is favourable for a KBS-3 type repository at depths below -300 m due to negligible flux of oxygen from the surface and low sulphate concentration, but as the depth increases, the salinity of the groundwater also increases. The swelling pressure and other properties of the buffer are negatively affected by too high salinities, which limit the deepest suitable repository depth. The groundwater chemistry has been discussed briefly in Chapter 4, see references therein and detailed discussion in Site Description (Posiva 2011a). With increasing depth the rock stresses also increase, such that at some point, they become a challenge to the mechanical integrity of the excavated openings. This may then disturb the rock by producing new fracturing and opening pathways for groundwater flow, see Site Description, Section 11.2.3. The requirement of isolation and also the permafrost depth during glacial periods set limits for the minimum depth, because the associated freezing and thawing may harm some of the repository components.

**Related requirements**

The depth of the repository needs to be selected taking into account the geological conditions and groundwater chemistry, and the compatibility of the chosen barrier materials with the properties of the site at repository depth, which are addressed through the target properties (section 6.3). Canister corrosion also depends on the site hydrology.
6.3 Target properties

6.3.1 Chemical composition of groundwater - canister corrosion

6.3.1.1 Reducing conditions

To avoid canister corrosion, groundwater at the repository level shall be anoxic except during the initial period until the time when the oxygen entrapped in the near-field has been consumed.

Therefore, no dissolved oxygen shall be present after the initially entrapped oxygen in the near-field has been consumed.

Rationale of the requirement

Oxidising conditions at the repository level would lead to increased copper corrosion rates (King et al. 2011), which would then endanger the containment safety function of the copper canister. Therefore the repository level shall be chosen to be at a depth at which the geochemical conditions are reducing and are likely to remain reducing i.e. deep enough and away from highly water conductive features.

Loads to be taken into account

The groundwaters at repository depth in baseline conditions are reducing (Pitkänen et al. 2004). Possible sources of oxygen are oxygen in the infiltrating groundwater and oxygen present in the tunnels. Oxygen is also found in the buffer and backfill. Once the repository is closed and the saturation phase ends, no more oxygen is fed into the groundwaters at repository depth. Oxygen in the infiltrating water is consumed mainly in aerobic oxidation of organic carbon in the overburden and shallow groundwaters and in anaerobic methane oxidation in deep groundwaters, see Pitkänen et al. (2004) and Luukkonen et al. (2004). These reactions are mediated by microbes. The rest of the infiltrating oxygen is used in oxidising mineral sulphides and ferrous iron in silicates in near surface weathering (Pitkänen et al. 1999, 2004). Similar reactions are able to consume the oxygen possibly diffusing into the groundwater from the tunnels. Oxygen within the backfill and buffer is consumed mainly by pyrite oxidation, in reactions with siderite and by microbial degradation reactions. The intrusion of oxygen-rich groundwaters into the rock during deglaciations is an issue discussed in the Features, Events and Processes report.

Related requirements

This requirement is closely related to the requirements to withstand corrosion set for the canister, see Section 7.1.3.1.

6.3.1.2 Groundwater conditions to prevent chloride corrosion

Groundwater at the repository level shall have high enough pH and a low enough chloride concentration to avoid chloride corrosion of the canisters.

Therefore, pH shall be higher than 4 and chloride concentration [Cl-] < 2M.
Rationale of the requirement
The material of the disposal canisters has been originally selected to be compatible with the anticipated chemical conditions in the deep crystalline bedrock. In reducing conditions, chloride corrosion is possible if simultaneously low pH and high chloride concentration are present. Corrosion processes are discussed in detail in Features, Events and Processes report and in King et al. (2011).

Loads to be taken into account
According to Pitkänen et al. (2007b) and Site Description, the salinity at the repository level is on average 10-12 g/L. The baseline pH of the waters at repository depth at Olkiluoto is between 7 and 8 (Pitkänen et al. 2004). Salinity may rise due to upconing due to the disturbance caused by repository construction or during a glaciation, if an ice margin is located close to the site. Based on the results by Löfman et al. (2010), the bounding waters for Olkiluoto have been defined. The maximum Cl− content is 43 g/L corresponding to 1.2 M. If the decay heat of a canister is too high, water evaporation might possibly lead to concentration of salts in the near-field during the saturation phase. The pH may decrease in case the infiltrating waters consume the buffering capacity in the host rock. However, this is not expected as there is abundant calcite buffering in the host rock. Infiltration of meteoric waters and related processes in the geosphere have been studied by Pitkänen et al. (1999), who report the lowest pH to be approximately 5.5.

Related requirements
This requirement is related to the requirements to withstand corrosion set for the canister. The swelling pressure of the bentonite buffer also depends on the salinity of the groundwater. Low pH affects also the solubility and sorption of radionuclides.

6.3.1.3 Limited concentration of solutes with detrimental effect on EBS performance and on radionuclide transport
Concentrations of canister-corroding agents (HS−, NO2−, NO3− and NH4+, acetate) shall be limited in the groundwater at the repository level.

and

Groundwater at the repository level shall have low organic matter, H2 and Stot and methane contents to limit microbial activity, especially that of sulphate reducing bacteria.

Rationale of the requirement
In addition to oxygen, groundwater can contain other canister corroding agents and these can be produced by microbial processes. Of these processes special interest are sulphide produced by sulphate-reducing bacteria (SRB). Therefore the concentrations of nutrients for the sulphate reducing bacteria need to be low. Nutrients include sulphate, hydrogen gas and organics. Colloids and organics are harmful because they can enhance radionuclide transport. To keep the risk of stress corrosion cracking low in the initial period of residual oxygen present, the amounts of nitrogen-containing and other oxidising compounds introduced by excavation should be kept under control.
Loads to be taken into account

The design shall be based on the composition of the current groundwaters and estimated concentrations during site evolution at repository depth. The repository shall be located in such a depth that in harmful substances are not found in high concentrations in the groundwater above or below the repository to prevent them from being introduced into the repository due to hydrological processes during the expected evolution. The baseline conditions have been reported by Pitkänen et al. (2004). The expected waters for the long-term can be found in *Site Description* (Posiva 2011a). Loads from excavation and operation as well as from the EBS system also need to be taken into account. See also the discussion of foreign materials reported in Karvonen (2011).

Related requirements

The requirement is directly related to the safety function of the copper canister, i.e. containment. Other related requirements are the requirements on corrosion resistance of the canister and EBS compatibility requirements for all of the EBS components (Canister: Section 7.1.5, buffer: Section 8.1.2.1, backfill: Section 9.1.3.3, closure: Section 10.1.6).

6.3.2 Chemical composition of the groundwater - buffer and backfill performance

6.3.2.1 Sufficiently high ionic strength

*Groundwater at the repository level shall initially have sufficiently high ionic strength to reduce the likelihood of chemical erosion of the buffer or backfill.*

*Therefore, total charge equivalent of cations, $\Sigma q[Mq+]$, shall initially be higher than 4 mM.*

* $[Mq+] = \text{molar concentration of cations}, q = \text{charge number of ion}.$

Rationale of the requirement

A requirement needs to be set for the lower limit of the ionic strength of the groundwater due to a possibility of chemical erosion of bentonite and formation of colloids when bentonite is in contact with a groundwater having a low ionic strength (Section 6.5.4.2 in Posiva 2009b, referring to SKB 2005 and Pusch 1983, and Neretnieks et al. 2009). According to recent studies (see e.g. SKB 2010b, Section 3.5.11 and Figure 3-29, and Birgersson et al. 2009) the local pore water cation concentration and the ratio between the monovalent and divalent ions in the montmorillonite at the bentonite/groundwater interface has an impact on the colloid formation. These show that the minimum cation concentration should be at least 4 mM to avoid colloid formation.

Loads to be taken into account

Low ionic strengths are not seen naturally in the bedrock of Olkiluoto at repository depth. This process is mainly relevant at the time of retreat of ice sheets when there is a potential for dilute glacial melt water to intrude to the repository depth. However, it cannot be totally ruled out that diluted water would be at least locally present at the repository depth also during a prolonged temperate phase after some thousands of years.
Further, as repository construction draws in surface waters, it is possible that dilute waters may be present for a limited time during the operational phase.

The ionic strengths of the current groundwaters at repository depth are in the order of 0.5 M (Pitkänen et al. 2007b, Posiva 2010a). An estimate of glacial water composition is presented in Pitkänen et al. (2004); see also Posiva (2010a), Table 6-3 and Table 6-7. The composition of the meltwaters presented in Table 6-7 are below 4 mM.

The final stage of the Weichselian deglaciation started about 11,500 years ago (see e.g. Figure 7-1 in Posiva 2009a), and soon after that Olkiluoto emerged from the cover of ice (about 11,000 years ago), but remained below the surface of the mildly saline Yoldia Sea, which had a depth of about 100 m. Glacial meltwater close to the retreating ice margin was able to infiltrate the bedrock under a considerable pressure gradient. The exact penetration depth and the quality of the infiltrated water is still unknown, but depths of 200 to 300 m seem likely, according to groundwater stable isotopic data (Pitkänen et al. 2004, Luukkonen et al. 2005, and Andersson et al. 2007).

The occurrence of glaciations during the next 120 ka is estimated in Pimenoff et al. (2012). They conclude that the present interglacial will last for at least the next 30,000 years. Further, the future simulations showed that the insolation minima in the Northern Hemisphere 50,000–60,000 and 90,000–120,000 years after the present have a potential for inducing the onset of the next glaciation, depending on the degree to which long-term effects of anthropogenically induced greenhouse warming persists. Therefore the effects of glaciations need to be taken into account when assessing the long-term safety of disposal of spent nuclear fuel.

The infiltration of meteoric groundwaters has been discussed in Site Description (Posiva 2011a).

The drawdown of meteoric waters during repository construction shall be limited by available means, such as grouting of fractures with suitable materials, and by limiting the amount of open tunnels in the repository.

**Related requirements**
This requirement is related to the safety functions of the buffer.

### 6.3.2.2 Limited salinity

*Groundwater at the repository level shall have limited salinity so that the buffer and backfill will maintain a high enough swelling pressure.*

*Therefore, in the future expected conditions the groundwater salinity (TDS, total dissolved solids) at the repository level shall be less than 35 g/L TDS. During the initial transient caused by the construction activities salinities up to 70 g/L TDS can be accepted.*
Rationale of the requirement
Highly saline water can have adverse impacts on the stability of the buffer and backfill as the swelling pressure is decreased by exposure to such waters. See SKB (2010b), Section 3.4.1 for discussion of buffer swelling as a function of groundwater salinity. The decrease in swelling pressure under saline conditions is more a problem for the backfill as it has lower density and consists of lower-grade materials and lower amounts of swelling minerals such as montmorillonite. Laboratory tests reported by Martikainen & Schatz (2011) have shown that with optimal backfill and buffer materials the required swelling pressures can be achieved in salinities of up to 70 g/L provided that the density of the material is high enough.

Loads to be taken into account
The baseline composition of the groundwaters at Olkiluoto has been reported in Pitkänen et al. (2007b). The interpretation of the past hydrogeological evolution of Olkiluoto has been presented in Andersson et al. (2007). Löfman et al. (2010) used the Olkiluoto site model 2008 (Posiva 2009a and the layout by Saanio et al. 2009) to study the upconing of saline water during the first 2000 years after repository closure. According to the results by Löfman et al. (2010), the average salinity in the reference volume including the repository and reaching ±50 m above and below the repository, remains unchanged or slightly lowered from the initial value of 12 g/L. The maximum salinity in the reference volume occurs at the deepest depths (~470 m) and ranges from 41 - 80 g/L depending on model parameters used (see Figures 5-16 and 5-17 in Löfman et al. 2010).

The increase in salinity depends on the inflow to open tunnels, i.e. the flow needs to be considered also as “a load” affecting the requirement. Salinity may arise also during glaciation, if an ice margin is located close to the repository site for an extended period of time. Estimates by Löfman & Karvonen (2012) show that salinities under such conditions can reach up to 35 g/L, see also Performance Assessment report.

Related requirements
The requirement on limitation of salinity is closely related to the requirements related to the density of the buffer (Sections 8.1.3.1 and 8.1.3.2) and backfill (Sections 9.2.2.1, 9.1.3.1, 9.1.4.1). It is also related to the requirements restricting inflows, especially avoiding intersections of transmissive zones, Section 6.4.4.1.

6.3.2.3 Groundwater conditions to prevent montmorillonite dissolution
The pH of the groundwater at the repository level shall be within a range where the buffer and backfill remain stable (no montmorillonite dissolution).

Therefore, the pH shall be in the range of 5–10, but initially a higher pH (up to 11) is allowed locally. The acceptable level also depends on silica and calcium concentrations.

Rationale of the requirement
The chemical degradation of cementitious material may produce a highly alkaline leachate (see Features, Events and Processes). If this fluid comes into contact with bentonite, chemical instability of montmorillonite will inherently result and montmorillo-
nite can begin dissolving (see *Features, Events and Processes*, and Karmland & Birges-
son 2006). The effect of hyperalkaline solution on a compacted mixture of argillite and
MX-80 bentonite, investigated experimentally by Cuisinier et al. (2008), was mani-
fested as microstructural changes in the material, which could be attributed to mineral
dissolution and were likely to change its hydraulic and mechanical properties over time.
Short periods of initially high pH, up to 11, in groundwater can be accepted if the
amount of high pH water interacting with the buffer is so limited, and the exposure time
so brief, that it cannot endanger the performance of the buffer.

**Loads to be taken into account**

The pH of the natural Olkiluoto groundwaters at repository level is approximately 7-8.
Concrete plugs are used at the entrances to deposition tunnels. When concrete made
from ordinary portland cement dissolves, the leachate can have a pH of above 12, see
*Features, Events and Processes*, and Lehikoinen 2009. Low pH cements in which port-
land cement and silica are mixed to produce calcium silica hydrates of optimal composi-
tion have been developed and tested, see a summary of the work in Heikola (2008),
Chapter 4. The leachate pH values of these low-pH cements reduce quite rapidly. The
amount of OH\(^-\) that can be generated by the concrete at pH>10 is small compared to the
amount of buffer/backfill that can be degraded.

As the change of the pH of the groundwater depends on the minerals and other chemical
substances used in the construction of the repository, such materials shall be selected
which do not result in a large increase of pH. When low pH cements and grouts are
used, the pH of the groundwater will stay within an acceptable range.

**Related requirements**

Montmorillonite dissolution affects the performance of the buffer. Therefore most of the
buffer requirements are closely related to this requirement. See also backfill require-
ments on the deposition tunnel plug (Section 9.1.3.3) and the pH requirement to avoid
localised corrosion (Section 6.3.1.2).

**6.3.2.4 Limited concentration of detrimental solutes**

Concentration of solutes that can have a detrimental effect on the stability of buffer and
backfill (K\(^+\), Fe\(_{\text{tot}}\)) shall be limited in the groundwater at the repository level.

**Rationale of the requirement**

K\(^+\) and Fe\(_{\text{tot}}\) have a detrimental effect on the buffer and backfill performance. The reaction
of Ca- and Na-montmorillonite with potassium produces illite and silica, see Laine
& Karttunen (2010), Section 3.2.1. Illitisation results in a loss of swelling pressure on
the clay materials, see *Features, Events and Processes*, FEP 5.2.6. Illitisation requires
elevated temperatures of above 100 °C (Wersin et al. 2007b).

Iron(II) in solution may be present in the bentonite porewater due to corrosion of iron
components, such as the iron insert in a failed canister or originally present as impurities
in the buffer or iron from the groundwater in contact with the buffer. Clay materials in
contact with zero-valent iron are reactive and may affect the corrosion process. Thus,
the clay may act as sink for corroded iron. This has been shown in several laboratory
tests (e.g. Kumpulainen et al. 2010; Carlson et al. 2006; Milodowski et al. 2009). The
details of these interactions are still not resolved, but there are indications that the prop-
erties swelling clays may be affected by reduction of structural iron (Lantenois et al.
2005) or cementation by precipitation of iron oxyhydroxides (e.g. Kumpulainen et al.
2010). Moreover, transformation of montmorillonite to a non-swelling iron-rich
phyllosilicate, such as berthierine cannot be excluded, although this process should be
very slow at low temperatures, i.e. below 100 °C (e.g. Mosser-Ruck et al. 2010; Wilson
et al. 2006a & 2006b).

Loads to be taken into account
The groundwater chemistry needs to be taken into account. The effects of illitisation
shall be taken into account in the buffer and backfill design. Introduction of sources of
these harmful materials into the repository shall be limited. Steel is needed in construc-
tion of e.g. the deposition tunnel plugs and it is used e.g. in reinforcing the host rock for
operational safety reasons. The amount of steel used shall be controlled. See also the
discussion of foreign materials reported in Karvonen (2011).

Related requirements
This requirement is limited to buffer and backfill requirements which require the swell-
ing pressure, such as mitigation of rock shear damage provided by buffer (Section
8.1.2.6), limitation of mass flows from and onto the canister (Section 8.1.2.7), support
to deposition holes (Section 8.1.3.1), keeping canisters in position (Section 8.1.3.2),
buffer's self-sealing (Section 8.2.2.1), backfill requirements to limit advective flow
(Section 9.1.3.1), ability to keep the buffer in place and support deposition tunnels (Sec-
tion 9.1.4.1), prevention of canister uplift (Section 9.1.4.3), backfill's self-sealing and
self-healing (Section 9.2.2.1) and also similar requirements for clay-based closure mate-
rials.

6.3.3 Chemical composition of the groundwater - radionuclide release
and transport

6.3.3.1 Reducing groundwater conditions

Groundwater conditions shall be reducing in order to have a stable fuel matrix and low
solubility of the radionuclides.

Rationale of the requirement
Radionuclide solubility depends on the redox conditions of the groundwater. The major-
ity of fission products and higher actinides in the nuclear fuel are present as solid solu-
tions in the UO₂ matrix. Upon contact with groundwater, the nuclear fuel matrix will
start to dissolve or otherwise alter. This results in the release of uranium and other ra-
dionuclides contained in the nuclear fuel matrix. This process is controlled by the
chemical environment in the fuel/cladding gap, and the fuel composition and structure.
The redox conditions at the fuel surface are the most important factor affecting the dis-
solution mechanism (see Features, Events and Processes).
** Loads to be taken into account **

The conditions in the near field shall be reducing. This can only be achieved by locating the repository at sufficient depth in an anoxic environment. Residual oxygen introduced during the operational period or possibly the presence of oxidising glacial meltwater during the long-term evolution will also act as oxidising loads on the local groundwater conditions. Under current conditions the oxygen of infiltrating waters is consumed in the overburden and shallow bedrock as discussed in Section 6.3.1.1.

** Related requirements **

The reducing conditions require anoxic groundwaters, which are found at depth in the Olkiluoto bedrock. This requirement is related to the requirement on repository depth (Section 6.2.1) and reducing conditions (Section 6.3.1.1).

6.3.3.2 pH for sorption

To ascertain the data for sorption parameters, the pH shall be in the range of 6−10 after the initial period when a higher pH of up to 11 is allowed.

Rationale of the requirement

Sorption of radionuclides depends both on the pH and on the ionic strength of the groundwater, and on the redox conditions, see *Features, Events and Processes*. The pH dependency of sorption behaviour is different for each element. The behaviour of the important nuclides needs to be known for the expected pH range.

Loads to be taken into account

The pH range during the expected evolution varies from the baseline pH, around 7-8, to the alkaline waters which are leached from concrete structures used in the repository, which produce waters with a pH of approximately 10 if they are made from low-pH cement. Glacial meltwaters may have a pH of approximately 6; see e.g. Pitkänen et al. (2004, p. 13). These conditions need to be considered when selecting sorption parameters for modelling.

Related requirements

Several requirements define the acceptable pH range in the repository system and are thus indirectly related to each other. These include chloride corrosion resistance (Section 6.3.1.2), limitation of detrimental solutes (Section 6.3.1.3), prevention of montmorillonite dissolution (Section 6.3.2.3), limitation of use of foreign materials (Section 6.4.2.4), canisters chemical resistance (Section 7.1.3), backfill’s EBS compatibility (Section 9.1.3.3) and requirements related to structures used in closure (Section 10).

6.3.3.3 Low colloid and organic content

In the vicinity of the deposition holes, natural groundwater shall have a low colloid and organic content to limit radionuclide transport.

Rationale of the requirement

Colloids and organic materials may enhance transport of radionuclides both in the near field and in the geosphere (see *Features, Events and Processes*). Colloids are microscopic particles that are transported in groundwater and may have sorption sites avail-
able for radionuclides. If a radionuclide is sorbed on a colloid, its transport properties are not determined by its own chemistry but by the transport properties and stability of the colloid. The reversibility of sorption also affects the colloidal transport.

**Loads to be taken into account**
The natural colloid concentrations in the groundwater depend on the hydrogeochemical conditions of the repository site and cannot be adjusted by engineering methods. The amounts of organic materials in the repository shall be limited to the greatest extent possible.

**Related requirements**
The requirement is related to the limitation of harmful substances in the buffer, backfill and materials used for closure (Sections 8.1.2.1, 9.1.3.3, 9.2.5.1 and 10.1.6)

### 6.3.4 Groundwater flow and solute transport

#### 6.3.4.1 Low flow rate around the deposition holes

*Under saturated conditions the groundwater flow in any fracture in the vicinity of a deposition hole shall be low to limit mass transfer to and from EBS.*

*Therefore, the flow rate in such a fracture shall be in the order of one litre of flow per one meter of intercepting fracture width in a year (l/(m*year)) at the most. In case of more than one fracture, the sum of flow rates is applied.*

**Rationale of the requirement**
The requirement is set to ensure the performance of the buffer and canister. High groundwater flow in a fracture intersecting a deposition hole may increase the mass transfer between the fracture and the buffer. As a consequence there is a risk of erosion and increased risk of exchange of solutes e.g. corroding agents.

**Loads to be taken into account**
Spatially and to some extent also temporally varying groundwater flow rates exist in the fractures. Low flow rate is related, although not in an unambiguous way, to the inflow in the open deposition hole. Avoiding the identified hydrogeological zones and leaving a respect distance to them, and to fractures intersecting the deposition tunnels, as well as not using deposition holes with high inflow both contribute to fulfillment of this requirement. Therefore the groundwater flows to each deposition hole needs to be ascertained during excavation to ensure that this requirement is met. However, for evaluation of acceptable flow rates in saturated conditions the flow rates to open deposition holes must be scaled down according to the expected gradients in the conditions after the repository closure. The deposition hole locations need to fulfil the rock suitability criteria i.e. no large fractures nor high inflows are allowed in the deposition holes.

**Related requirements**
The low flow requirement is indirectly related to the requirements on buffer density and to the safety functions of the buffer. Formation of an excavation damaged zone (EDZ) and occurrence of thermal spalling is also related to this requirement, as well as the transport resistance requirement (Section 6.3.4.2). Practical limit for inflow into a deposition hole is given in Section 6.4.5.1.
6.3.4.2  **Sufficient transport resistance**

*Flow conditions in the host rock shall contribute to high transport resistance.*

*Therefore, migration paths in the vicinity of the deposition hole, shall have a transport resistance (WL/Q) higher than 10,000 years/m for most of the deposition holes and at least a few thousand years/m.*

**Rationale of the requirement**

The transport resistance WL/Q describes the flow-dependent transport properties of a migration path, see Figure 5-11 of, and detailed discussion in Sections 5.2.2 and 6.3.1 in Posiva (2010a) and Sections 11.5 and 11.6 in Vieno & Nordman (1999), see also Poteri (2007). Geosphere retention is able to reduce the releases to the biosphere in the following cases:

- For all nuclides in reducing the activity release rate due to sudden releases from the IRF (e.g. Cs-135, I-129)
- For all nuclides in reducing the release rates from the other parts of the fuel assembly that have faster release rates compared to the fuel matrix (e.g. C-14, Cl-36)
- For highly sorbing nuclides to reduce the activity release rate due to long-term release from the fuel matrix over time scales of tens of thousands to hundreds of thousands of years (e.g. Cs-135, Pu-239)

In case of anions, which are non-sorbing, geosphere retention has little effect on the activity release rates in the long term, as specifically applies in the case of releases from the fuel matrix.

The transport resistance WL/Q practically determines geosphere retention for the non-sorbing nuclides. In the case of sorbing nuclides, high WL/Q contributes significantly to geosphere retention, but especially in the case of radionuclides with long half-lives higher $K_d$ values are needed to significantly reduce the activity releases from the geosphere to the biosphere.

Therefore a sufficiently high transport resistance is needed to limit the consequences of a possible radionuclide release. This requirement is directly linked to the safety function of the rock to limit transport and retard the migration of harmful substances to the biosphere.

**Loads to be taken into account**

The transport resistance depends on the existence and dimensions of a flow path and the flow rate in it. The transport resistance is estimated based on measured fracture properties and groundwater flow modelling using DFN models, see Posiva (2010a). High transport resistance is achieved by avoiding highly conductive fractures and hydraulically conductive zones and their respect distances.

**Related requirements**

This requirement is related to the requirements on low flow rate around the deposition holes (Section 6.3.4.1), on limited flow to protect the backfill (Section 6.3.4.3), on limi-
tation of inflow to open repository rooms (Section 6.4.2.5), on avoiding intersections with layout determining features (Section 6.4.4.1), on limitation of inflow to deposition tunnels (Section 6.4.4.2), on limitation of inflow to deposition holes (Section 6.4.5.1) and on avoidance of respect volumes of layout determining features (Section 6.4.5.7).

6.3.4.3  Limited flow to protect backfill

Inflow of groundwater to deposition tunnels shall be limited to ensure the performance of the backfill.

Rationale of the requirement
Restrictions on inflow to deposition tunnels are needed for the successful installation of the backfill and to support the performance of the backfill in the early phases e.g. to avoid piping and erosion. The performance of the backfill supports also the performance of the buffer.

Loads to be taken into account
The groundwater flows into a deposition tunnel mostly from fractures in the host rock. Avoiding the hydrogeological zones and leaving a respect distance to them contributes to fulfillment of this requirement. The groundwater flows to each deposition tunnel need to be considered during planning and ascertained during excavation to ensure that inflows stay at a level that the backfill can tolerate. The tightness of the plugs at the ends of deposition tunnels will also affect the total flow through the backfilled tunnels. Measures to control the inflowing water, such as grouting, may need to be taken in cases where local inflows are potentially high.

Related requirements
The low flow requirement is related to the safety functions and requirements of the backfill, and indirectly related to the safety functions of the buffer and to the requirements on buffer density.

6.3.4.4  Favourable retention properties

The properties of the host rock shall be favourable for matrix diffusion and sorption.

Rationale of the requirement
Limiting transport and retarding the migration of harmful substances to the biosphere is one of the safety functions of the host rock. The retention properties of the near-field rock affect the transport of radionuclides in case of a release. The higher the sorption on the rock, the more a radionuclide release is retarded. The retention-related properties (solubility, speciation, sorption, porosity and diffusivity) of many radionuclides are affected by the chemical environment, including salinity, pH, dissolved carbonate content and redox conditions. The rock types and rock properties, e.g. alteration also affect sorption. A summary of the contributing factors can be found in Appendix 1 in Hagros (2006).

Loads to be taken into account
The retention depends on e.g. the chemical conditions (pH, salinity, speciation) and mineralogy and properties, e.g. alteration, of the host rock and fracture surfaces (Hagros (2006)).
The properties need to be favourable both in current conditions and in expected future repository conditions.

The sorption-related retention parameters for the Olkiluoto repository have been estimated by Hakanen (2011). Porosity and diffusivity are discussed in the Site Description (Posiva 2011a). The typical minerals in the host rock and on fracture surfaces are able to retard a release of sorbing radionuclides in the expected hydrogeological conditions.

Note also that although there are differences between the retention properties of the different fracture and rock types, the degree of variation is such that it is not meaningful to consider this characteristic further in the criteria adopted in locating the deposition holes. In general, more significant for geosphere retention is transport resistance WL/Q, see Section 6.3.4.2.

**Related requirements**

Retardation is linked to several groundwater chemistry requirements (Sections 6.3.1.1 Reducing conditions, 6.3.2.2 Limited salinity, 6.3.3.1 Reducing groundwater conditions, 6.3.3.2 pH for sorption and 6.3.3.3 Low colloid and organic content) and to the transport resistance requirement (Section 6.3.4.2).

### 6.3.5 Mechanical stability

*The location of the deposition holes shall be selected so as to minimise the likelihood of rock shear movements large enough to break the canister.*

*Therefore, the likelihood of a shear displacement exceeding 5 cm shall be low.*

**Rationale of the requirement**

The limit set on rock shear movement is based on the need to protect the canister to ensure that its containment safety function can be met. Shear displacement occurring in fractures intersecting a deposition hole within the canister height range is considered to be one of the potential canister failure modes.

The deposition holes will be located outside significant fault zones to avoid rock shear, but the possibility of single fractures intersecting the deposition holes cannot be completely excluded. According to current thinking, the maximum sizes of the fracture shear movements are correlated with the dimensions of the fractures, and, therefore, by setting limits to the size of the fractures that are allowed to intersect the deposition hole, the maximum rock displacement that can potentially occur will be limited in these fractures.

The damage caused by a shear movement depends on the displacement, shear rate and shear plane orientation in respect to canister, and on the properties of the buffer and canister. Seismicity increases and rock shears are most likely to happen after deglaciations when the isostatic pressure decreases and land uplift begins (Hutri 2007; Bödvars-son et al. 2006).
On the basis of the structural integrity calculations for the canister-buffer system, the criteria for the dimensions of the fractures that are allowed to intersect the deposition holes is set in a way that the likelihood of rock displacements bigger than 5 cm in the deposition holes is made as small as possible. See Raiko et al. (2010) for a summary of canister's design analyses.

Load to be taken into account

The seismic events recorded in the Olkiluoto area, and in a wider view in southern Finland and Estonia, are related to the Åland-Paldis-Pskov seismic belt. All significant earthquakes (\(M \geq 3.5\)) in the region of the Gulf of Finland and in the Åland archipelago are related to this zone (Saari 2008). Two seismically active shear zones cross the Bothnian Sea. The Arlanda shear zone in the northern part of the Bothnian Sea runs in the Pori area about 35 km away from Olkiluoto. The Haseela shear zone is part of the Åland-Paldis-Pskov seismic belt. At the closest point this shear zone is about 70 km SW of Olkiluoto. The registered earthquakes of the Olkiluoto area are small (\(M \leq 3.1\)) and their recurrence periods are long. The magnitudes of earthquakes can be higher during deglaciations due to the relief from higher loads.

Large enough shear movements to damage the canisters can occur only in deformation zones hosting earthquakes or in large fractures undergoing secondary displacements. The probability of such shear movements can be decreased by positioning the deposition holes outside the deformation zones and their influence zones as well as positioning the canisters in such a way that they are not intersected by large fractures. A modelling study carried out by Fälth & Hökmark (2011) shows that seismically-induced fracture shear displacements would be very modest at the Olkiluoto site and, for 75 m radius fractures that do not intersect the deformation zones which have earthquake potential, exceed about 5 mm only by way of exception even at fault distances as small as 100 m. See Fälth & Hökmark (2011) for a more thorough discussion.

Related requirements

Requirements on the mechanical stability of the canister (Sections 7.1.4 Mechanical resistance, 7.2.2.2 Mechanical resistance, 7.2.4.2 Mechanical strength of insert) and buffer requirements to mitigate the effects of rock shear on the canister (Sections 8.1.2.6 Mitigation of rock shear damage on canister, 8.2.2.3 Mechanical protection) are directly related to the rock shear limit requirement on the host rock. Mechanical protection is provided by low enough buffer swelling pressure, defined by its density.

6.4 Design requirements for the underground openings

6.4.1 Definitions

Access routes in this context means the access tunnel and shafts including, personnel shaft, canister shaft and ventilation shafts.

All subsurface rooms in this context means the access routes, technical rooms, central tunnels, deposition tunnels, deposition holes and demonstration tunnels.
Layout determining features (LDFs) are large deformation zones that form the main groundwater flow routes or that can transmit movements of earthquakes large enough to induce canister-breaking secondary displacements, and are thus of significance for long-term safety.

6.4.2 Performance - All subsurface rooms

6.4.2.1 Limitation of damage to rock

The layout and dimensions of the repository shall be designed and the repository shall be constructed in such a way that thermally and mechanically induced damage to the host rock is kept sufficiently low.

Rationale of the requirement
Mechanical damage is caused to the rock during excavation, see Section 6.4.2.6. Thermal damage to the host rock can be caused by the decay heat of the spent nuclear fuel. Heating, along with the stress state of the host rock, may result in spalling (Hakala et al. 2008), which may increase the groundwater flow, increase mass transfers and reduce the transport resistance near underground openings.

Loads to be taken into account
Stress changes due to construction that are dependent, e.g., on the tunnel orientation, are an issue, as is formation of the EDZ, which can be affected by the drill and blast method used. The drill and blast method shall be optimised appropriately to limit rock damage.

The spent nuclear fuel in the canister is the only heat source in the repository. The highest decay heat power is 1830 W for an OL3-PWR canister (Raiko 2011), see also Sections 3.1 and 7.2.2.5. The maximum temperature of the repository is adjusted by spacing of the canisters and deposition tunnels (Ikonen & Raiko 2012).

Thermal effects on the host rock shall be limited through canister positioning by thermal dimensioning, see Ikonen & Raiko (2012). Formation of an EDZ shall be limited by optimisation of excavation techniques, see Mustonen et al. (2010), Chapter 3. Thermal and mechanical damage can also be limited by locating the deposition tunnels optimally with respect to the stress field. The Excavation Damaged Zone (EDZ) is discussed in Section 6.4.2.6.

Related requirements
Thermally induced damage is related to canister decay heat limits (Section 7.2.2.5). Mechanically induced damage is related to limitation of the EDZ (Sections 6.4.2.6 and 7.2.2.5). Backfill can help reduce the effects of thermal damage to the host rock by supporting it (Section 9.1.4.1).

6.4.2.2 Avoidance of layout determining features

Intersections with the LDFs and their respect volumes shall be avoided as far as possible when locating any sub-surface rooms.
Rationale of the requirement
The Guide YVL D.5, paragraph 511 requires that the structures of the host rock of importance in terms of groundwater flow, rock movements or other factors relevant to long-term safety, shall be defined and classified. Accordingly, relevant structures called layout determining features need to be defined together with a respect volume surrounding each feature so that an adequate distance remains between the relevant structure and the deposition holes.

Layout determining features are large deformation zones that form the main groundwater flow routes or that can become unstable due to future loadings related to post-glacial faulting, and are thus of significance for long-term safety. As they are main groundwater flow routes they are of importance for transport of solutes and chemical stability at the site. The rock properties in layout determining features and their respect volumes do not meet the performance targets set with respect to long-term safety. The layout determining features along with other rock suitability criteria are defined in the Posiva (2012b). Between these features the host rock properties are such that it is suitable for hosting deposition holes with local exceptions (Posiva 2012b).

Loads to be taken into account
Respect distances to layout determining features shall be complied with when the repository layout is planned. The respect distances have been identified and rock volumes suitable for the repository described in Posiva (2012b). The repository layout of Kirkkomäki (2012) takes into account the respect distances.

Related requirements
Respect distances defined for LDFs shall be complied with in the repository layout for any tunnel, shaft, drill hole (Section 6.4.2.3) and access tunnel (Section 6.4.3.2).

6.4.2.3 Avoidance of drillholes

When designing the underground openings, intersection with existing drillholes (except for pilot holes) should be avoided by applying a respect distance to such holes. Deposition tunnels must not be intersected by existing drillholes connecting them to the surface or LDFs.

Rationale of the requirement
The investigation drillholes have been used to map the layout determining features and the properties of the host rock. They need to be avoided in repository construction, because they can form pathways to ground surface and to water-conducting fractures. Intersecting drillholes during construction would increase inflows into the repository. The drillholes are closed and sealed during repository closure, but any unnecessary connection to the ground surface shall be avoided.

Loads to be taken into account
The drillholes form flowpaths to the surface when not closed and sealed, thus increasing water inflows to tunnels if they are intersected during excavation. Drillhole locations are
thus to be avoided in the layout design. Intersected drillholes could also be unfavourable for long-term safety.

**Related requirements**
The requirement is related to the limitation of the groundwater flow in the vicinity of the tunnel (Section 6.4.4.2) and deposition holes (Section 6.4.5.1) and also to the requirement on transport resistance (Section 6.3.4.2).

### 6.4.2.4 Limitation of use of foreign materials

*Use of foreign materials in underground openings shall be controlled and regulated.*

**Rationale of the requirement**
Foreign materials are materials that are not naturally found in the host rock, with the exception of the main materials used in the canister, buffer and backfill. The impurities in the aforementioned materials, such as accessory minerals in the clay materials are, however, considered to be foreign materials. Such foreign materials or substances may have a negative effect on EBS components, see Section 6.3.1.3. The most important foreign substances to be avoided or at least limited include sulphur, organic materials, nitrogen compounds and cement. Their use during repository construction and operations shall be controlled and regulated.

**Loads to be taken into account**
Iron, sulphur, nitrogen and carbon are the most important substances that may have an adverse effect on the long-term safety of disposal. Iron may be present in swelling clays both in ferric and ferrous forms and is present in steel which is needed e.g. in construction of plugs and as rock bolts. Sulphur, as sulphide, is one of the most important minor components in bentonites. The pH of grouts used in grouting, shotcreting, plug construction and installation of rock bolts can be high, and the allowed pH range has to be taken into account (see Sections 6.3.1.2 and 6.3.2.3). Organic materials are found in cement superplasticisers and as impurities in buffer and backfill. Nitrogen compounds are used in excavation and may be introduced by human activities. See Section 6.3.1.3 for a list of detrimental solutes.

The use of foreign materials has been controlled by Posiva since the beginning of construction of ONKALO. The allowed materials are identified in Posiva's Material Handbook, described in Kasa (2010, p. 4), and their amounts estimated in Karvonen (2011).

**Related requirements**
This requirement is an EBS compatibility requirement and is related to all components (Canister: Section 7.1.5, buffer: Section 8.1.2.1, backfill: Section 9.1.3.3, closure: Section 10.1.6).

### 6.4.2.5 Limitation of inflow to open repository rooms

*Total inflow to the open sub-surface rooms shall be limited.*
Rationale of the requirement
Inflow of groundwater into the open sub-surface rooms shall be controlled, because installation of backfill and buffer materials is difficult in wet conditions, see further details in Chapter 9. Inflow shall also be limited because of the risk of upconing, intrusion of near surface waters to the repository and the general mixing of the groundwater system.

Loads to be taken into account
Seepage of inflow water is discussed in Posiva (2009a) and the Site Description 2011.

Related requirements
Inflow into the open repository is related to the inflow requirements on deposition tunnels (Section 6.4.4.2) and deposition holes (Section 6.4.5.1).

6.4.2.6 Limitation of formation of EDZ
The excavation/boring shall be carried out in a controlled way to limit the EDZ of the walls of tunnels and shafts and floor of the tunnels, in particular, to limit the formation of connected flow pathways along the tunnel length.

Rationale of the requirement
Excavation of and operations within the repository will cause changes in host rock properties. Drilling and blasting causes fracturing of a limited layer of host rock at deposition tunnel walls, which is called the Excavation Damaged Zone (EDZ). A continuous EDZ along a tunnel may create a preferential transport pathway. Radionuclide retardation along a pathway in such an EDZ may be less than retardation in buffer or backfill. The rock in the EDZ might on the other hand have a higher density of available sorption sites for radionuclides than undisturbed host rock due to higher specific surface area as a result of fracturing. Furthermore, experiences both from ONKALO (Mustonen et al. 2010) and Sweden (SKB 2011a, Section 10.2.2) suggest that the blasting damage may not form a connected network.

Loads to be taken into account
The blasting shall be designed taking into account the excavation recommendations given by Mustonen et al. (2010) in order to minimise the formation of an EDZ.

Related requirements
Formation of an EDZ is closely related to spalling and several requirements of the host rock (Sections 6.3.4.1 Low flow rate around deposition holes, 6.3.4.2 Sufficient transport resistance and 6.3.4.4 Favourable retention properties).

6.4.3 Performance - Access routes

6.4.3.1 Avoidance of head differences in access routes
The entrances of the access routes should be located at the same level to avoid groundwater flow caused by head differences.
Rationale of the requirement
Water always flows from a higher pressure towards a lower pressure. Immediately after closure or in the long term, due to degradation of closure and backfill components, the hydraulic conductivities of the access routes to the repository level might be somewhat higher than the conductivity of the host rock. If there is a height difference between the access routes, the pressure gradient may drive water to the repository level from one access route and discharge it from another one located at a lower height.

 Loads to be taken into account
The head difference does not exist if the access routes are located at the same level. The hydraulic conductivities of the unsaturated and saturated backfill and host rock affect the phenomenon.

Related requirements
This requirement is related to all groundwater flow-related requirements.

6.4.3.2 Avoidance of potential deposition tunnel locations in access route construction
Construction of access routes in such a way that they would be located above or near the potential location of the deposition tunnels should be avoided.

Rationale of the requirement
The requirement was originally given in STUK letters Y811/35 and Y811/37. The construction of access routes causes disturbances in the host rock and its hydrogeology. The access routes are open for the longest period of time and have more pronounced effects than other underground openings. Therefore, proximity of the access routes to deposition tunnels shall be avoided.

 Loads to be taken into account
Open tunnels cause disturbances to the groundwater flows. Respect distances shall be kept to the access routes in the layout design. Blasting of new tunnels may cause short-term increase in hydraulic pressure in fractures in the nearby deposition areas.

Related requirements
This requirement is related to requirements that limit hydraulic disturbances (e.g. Section 6.4.2.5).

6.4.4 Performance - Deposition tunnels

6.4.4.1 Avoidance of intersections with LDFs
Intersections with the LDFs and their respect volumes shall be avoided when locating the deposition tunnels.

Rationale of the requirement
The areas within respect distances to layout determining features shall not be used for deposition tunnels for the reasons stated in Section 6.4.2.2.

**Loads to be taken into account**
See Section 6.4.2.2.

**Related requirements**
Avoiding LDFs is related to limitations on inflow for deposition tunnels (Section 6.4.2.2) and deposition holes (Section 6.4.5.1) and rock shear limitation requirements (Section 6.4.5.3).

### 6.4.4.2 Limitation of inflow to deposition tunnels

*Inflow to deposition tunnels shall be limited to ensure the installation of the backfill, and to limit piping and erosion.*

**Rationale of the requirement**
The backfill is sensitive to inflows during the installation period up to the time when a deposition tunnel plug has been constructed. Excessively high localised inflow would result in partial swelling in the backfill and as a result the backfill blocks might start cracking, see Chapter 6 in Keto et al. (2009). Flow paths may then form in the backfill, which can cause local erosion of the backfill and result in material loss.

**Loads to be taken into account**
Based on the experiments and discussion by Dixon et al. (2008 a,b,c) and Hansen et al. (2010), the backfill can withstand localised flows up to 0.1…0.5 L/min. Fractures with inflows larger than that shall have to be sealed. An inflow limit for a deposition tunnel is set in the host rock’s design specifications.

**Related requirements**
The deposition tunnel inflow limitation is related to all of the backfill requirements, see Section 9.

### 6.4.5 Performance - Deposition holes

#### 6.4.5.1 Limitation of inflow to deposition holes

*Inflow to deposition holes shall be limited to provide favourable conditions for the EBS and radionuclide retention.*

**Rationale of the requirement**
Restrictions on inflow to deposition holes are needed for the successful installation of the buffer and to support the performance of the buffer in the early phases e.g. to avoid piping and erosion of the buffer. The buffer shall not begin to swell significantly before the canister has been emplaced (Juvankoski 2009, p. 33). Low inflow is also an indication, although not an unambiguous one, for a low flow rate around the deposition hole in saturated conditions thus limiting the transport of corrosive agents and providing a high transport resistance in the vicinity of the deposition hole.
**Loads to be taken into account**  
Water inflow into a deposition hole can be monitored. The rock suitability criteria states that the inflow into a deposition hole shall be below 0.1 L/min.

**Related requirements**  
As an EBS compatibility requirement this requirement is related to all other EBS compatibility requirements (Canister: Section 7.1.5, buffer: Section 8.1.2.1, backfill: Section 9.1.3.3, closure: Section 10.1.6). It is also related to requirements limiting inflow in the repository, and avoidance of respect volumes of LDFs.

### 6.4.5.2 Avoidance of hydrogeological zones

Deposition holes shall not intersect the respect volumes of hydrogeological zones.

**Rationale of the requirement**  
Respect volumes are rock volumes around the faults or hydrogeological zones that are most influenced by deformations and are considered as a weak or transmissive part of the host rock. The respect volumes are defined following geological, hydrogeological or geophysical measurements of pilot holes. Respect volumes are discussed in detail in the Posiva (2012b). The deposition holes shall avoid hydrogeological zones since they are pathways of water to and from the buffer, and rock shear movements may take place along such zones, see Sections 7.1.4, 7.2.2.2 and 7.2.4.2.

**Loads to be taken into account**  
The respect volumes shall be avoided in design. Specific loads are not applicable in relation to this requirement.

**Related requirements**  
This requirement is related to all requirements on rock shear (Section 6.3.5), limited groundwater flow (Sections 6.4.4.2 and 6.4.5.1) and high transport resistance in the vicinity of the deposition holes (Section 6.3.4.2).

### 6.4.5.3 Avoidance of shear fractures

Fractures that may undergo shear movements with potential to break the canister are not allowed to intersect the canister.

**Rationale of the requirement**  
See Section 6.3.5.

**Loads to be taken into account**  
See Section 6.3.5. Furthermore, the canister is not designed to withstand large shear movements (more than 5 cm) across the canister. By avoiding placing the canister such that it would be intersected by a fracture with the potential for large shear movement this risk is mitigated. As discussed previously only large fractures have the potential to experience such shear movements in the case of a future earthquake.

**Related requirements**  
See Section 6.3.5.
6.4.5.4 Avoidance of brittle deformation zones

Deposition holes shall not intersect the respect volumes of brittle deformation zones.

Rationale of the requirement
Shear movements are more likely in the brittle deformation zones and on fractures within the respect volume. Also brittle deformation zones may form flow paths.

Loads to be taken into account
See Section 6.3.5 Mechanical stability, Section 6.4.2.2 Avoidance of layout determining features, Section 6.4.4.1 Avoidance of intersections with LDFs and Section 6.4.5.2 Avoidance of respect volumes.

Related requirements
See Section 6.3.5 Mechanical stability, Section 6.4.2.2 Avoidance of layout determining features, Section 6.4.4.1 Avoidance of intersections with LDFs and Section 6.4.5.2 Avoidance of respect volumes.

6.4.5.5 Straightness of deposition holes

Deposition holes should be straight enough to allow installation of the buffer and the canister and to ensure sufficient density of the buffer.

Rationale of the requirement
The tolerances between the host rock, buffer and canister are small. A lack of straightness, i.e. both straightness relative to the centre point and relative to the inclination of the hole, cause difficulties in buffer and canister installation, and can result in an asymmetric load on the canister, which may be temporary or permanent. Permanent asymmetric loads may occur due to an uneven buffer density distribution after water saturation in combination with lack of straightness of the deposition hole (Raiko et al. 2010).

Loads to be taken into account
The dimensions of the canister and buffer components and their tolerances are the limiting factors which determine the requirement for hole straightness. Tolerances must be such that the drainage system of the deposition hole can be installed and removed. The dimensions and tolerances can be found in the Canister and Buffer Production Line reports.

Related requirements
This requirement is related to Section 6.4.5.6 Allow installation of buffer and canister.

6.4.5.6 Allowance of installation of buffer and canister

The dimensions and the quality of wall and bottom of each deposition hole shall allow installation of the buffer and the canister in a planned way to ensure sufficient density of the buffer.

Rationale of the requirement
In addition to the needed straightness of the deposition hole (Section 6.4.5.5), the walls and bottom of the hole need to be smooth and level enough to ensure that the density of
the buffer is sufficient after saturation. Large unevenness in the deposition hole surfaces may lead to non-uniform swelling pressure and cause unnecessary load on the canister. If the deposition hole wall is largely damaged due to spalling, the buffer density limits may not be met.

**Loads to be taken into account**
Direct loads cannot be defined. The deposition hole shall fulfill its design specifications regarding its tolerances. See also Section 6.4.5.5.

**Related requirements**
This requirement is related to Section 6.4.5.5 Ensure straightness of deposition hole.

**6.4.5.7 Avoidance of respect volumes of LDFs**

Deposition holes shall not intersect the respect volumes of the LDFs.

**Rationale of the requirement**
See Section 6.4.2.2.

**Loads to be taken into account**
Layout determining features are large deformation zones that form the main groundwater flow routes or that can become unstable due to future loadings related post-glacial faulting, and are thus of significance for long-term safety.

**Related requirements**
This requirement is related to requirements in the following sections: 6.3.5 Mechanical stability, 6.4.2.2 Avoidance of layout determining features, 6.4.4.1 Avoidance of intersections with LDFs and 6.4.5.2 Avoidance of respect volumes.

**6.4.5.8 Limitation of temperature in repository**

Taking into account the thermal properties of the host rock and the heat generation of the waste canisters, the minimum spacing between deposition tunnels and deposition holes should be defined such that no high temperatures that could cause damage to the EBS are reached.

**Rationale of the requirement**
The disposed canisters produce residual heat due to radioactive decay of radioactive elements. The decay heat is conducted to surrounding rock mass. The temperature outside the canister is highest at the interface between the canister and buffer, and is required to stay below 100 °C; this can be achieved by selecting appropriate canister spacing in each deposition tunnel, and by selecting appropriate deposition tunnel spacing.

**Loads to be taken into account**
The thermal dimensioning shall be performed taking into account the decay heat of the canisters and the thermal conductivity of the buffer and the thermal diffusivity and specific heat of the host rock. The thermal properties of the EBS are presented in Ikonen & Raiko (2012), whereas the thermal properties of the host rock are presented in the Site Description (Posiva 2011a).
Related requirements
The temperature limit is related to canister requirements (Sections 7.2.2.5 Limitation of heat generation and 7.2.2.6 Thermal conductivity), and to a buffer requirement (Section 8.1.2.3 Heat transfer).

6.4.6 Performance - Demonstration tunnels

The requirements set for the deposition tunnels and deposition holes shall apply for demonstration tunnels, however some exceptions are allowed as defined at level 5.

Rationale of the requirement
The ultimate goal of an underground research and characterisation facility is to allow testing and demonstration of the disposal system as designed. To fulfill this goal, the excavation work shall be performed as it will be in the repository in order to be certain that the demonstrations represent the repository as-built. The feasibility of the entire chain of activities related to the disposal procedure, i.e. characterisation and modelling of the site, design and construction of the disposal facility (including deposition tunnels and deposition holes), emplacement of the canister and the engineered barriers and closure of the repository can be tested and proven. The outcome of the studies in the test and demonstration facilities will provide feedback to the design and operation of the repository.
7 CANISTER

The canister consists of an insert and an overpack. The canister shall contain the spent nuclear fuel for hundreds of thousands of years except for incidental deviations in the expected repository conditions. The simplified general structure of the VAHA requirements for the canister is shown in Figure 7-1.

![Figure 7-1. The general structure of the canister requirements.](image)

7.1 Performance targets for the canister

The sub-system requirements set for the canister fall into seven categories: containment, chemical resistance, mechanical resistance, compatibility with the EBS and host rock performance, subcriticality, handling before disposal and retrievability.

7.1.1 Definition

**Canister is a container with a water-tight and gas-tight shell and a mechanical load-bearing insert in which the spent nuclear fuel is placed for final disposal in the repository. The canister shall contain the spent fuel and prevent, and in the case of a leak, limit the dispersal of radioactive substances into the environment.**

7.1.2 Containment

7.1.2.1 Canister intactness

*The canister shall initially be intact when leaving the encapsulation plant for disposal except for incidental deviations.*

**Rationale of the requirement**
The origin of the requirement is the containment function in the overall safety concept. The requirement means that the canister shall be constructed, welded, inspected and
handled in the encapsulation plant in such a way that there are initially no penetrating defects in the canister. However, it is recognised that a very limited number of canisters may have small, non-penetrating or penetrating, defects that are not possible to be detected using realistic non-destructive testing methods (Canister Production Line report, Section 7 and Holmberg & Kuusela 2011).

**Loads to be taken into account**
The fulfillment of the requirement relies on three main aspects: the canister materials shall be selected and the canister manufactured so that material inspections are possible; the canister and the weld shall be manufactured so that they have no penetrating defects that would mean the loss of containment function of the canister and that the canister is handled carefully in the encapsulation plant in a way that no unacceptable defects (e.g. scratches, dents) are induced.

**Related requirements**
Most requirements in VAHA are related to this requirement, in particular those related to the chemical resistance and mechanical resistance of the canister. The requirement on handling of the canister is also related to this requirement (Section 7.1.7).

### 7.1.2.2 Canister's service lifetime

In the expected repository conditions the canister shall remain intact for hundreds of thousands of years except for incidental deviations.

**Rationale of the requirement**
The life-time requirement for the canister is based on the radioactivity of the spent nuclear fuel. The activity inventories of the fuel have been estimated by Anttila (2005b), see Figure 7-2. The activity in the figure has been calculated for a discharge burnup of 50 MWd/kgU, but the design value for maximum average burnup is 60 MWd/kgU, also reported in Anttila (2005b). The inventories used in the RNT-2008 analysis were for a discharge burnup of 40 MWd/kgU, see Posiva (2008a, Section 5.1.1). The currently allowed maximum average discharge burnup is 50 MWd/kgU for the Olkiluoto power plant and 57 MWd/kgU for the Loviisa power plant. TVO has plans to increase the maximum average discharge burnup in near future (Posiva 2012a).

On the basis of the radioactivity inventory, it has been shown that in a few hundred thousand years the radiotoxicity of the spent nuclear fuel is similar to the toxicity of the natural uranium it was originally made from (SKB 2011a, p. 15). When the design lifetime of the canister is set at hundreds of thousands of years and the design requirements for the other engineered barriers are set in a way that they support this life-time requirement, the containment function of the EBS as a whole will be sufficient to keep the radiation doses and releases from the repository below the safety limits given by the radiation safety authorities.
Figure 7-2. Spent nuclear fuel types from the three different reactors and their activity over time after unloading from the reactor. The enrichment for each fuel type is 4.0%. The burn-up was 40 MWd/tU for each type apart from the fourth (yellow curve) EPR 60 MWd/kgU which shows the impact of the higher burn-up for the EPR fuel (data from Anttila 2005b) (from Complementary Considerations report).

**Loads to be taken into account**

The processes that determine the lifetime of a canister are corrosion and mechanical failure due to the buffer swelling pressure together with isostatic and shear loads during and after glaciations. The processes are discussed in Sections 7.1.3 and 7.1.4 and in the design requirements in Section 7.2.

**Related requirements**

Most requirements in VAHA are related to this requirement, in particular those related to the chemical resistance and mechanical resistance of the canister. The requirements on canister encapsulation and handling are also related to this requirement. The requirements on buffer performance also affect the lifetime of the canister. The swelling pressure of the bentonite buffer is a major component on the load exerted on the canister. The requirement regarding limiting rock shear and groundwater flow rates and chemistry also affect the canister service lifetime.

### 7.1.3 Chemical resistance

#### 7.1.3.1 Ability to withstand corrosion

The canister shall withstand corrosion in the expected repository conditions.
Rationale of the requirement
The expected repository conditions arise from the expected evolution of the repository, taking into account climate and landscape change, and changes in the chemistry and groundwater flow in the near field.

The chemical resistance requirement can be directly derived from the containment requirement of the canister. The canister material shall be chosen keeping in mind the present and future chemical conditions at repository depth. The baseline conditions, which are the conditions before the excavation of ONKALO began and thus represent the natural state of the groundwaters at Olkiluoto, have been reported by Pitkänen et al. (2004). Current conditions are reported e.g. in Posiva (2009a) and Site Description (Posiva 2011a). The future evolution of the groundwater conditions is discussed in the Performance Assessment and Formulation of Radionuclide Release Scenarios reports.

Loads to be taken into account
The different corrosion mechanisms need to be taken into account, see Features, Events and Processes and King et al. (2011) for discussion of the corrosion mechanisms relevant for a copper canister. These include general corrosion under oxic and anoxic conditions, localised corrosion (pitting), microbially influenced corrosion and stress corrosion cracking. Microbial effects are limited to the reduction of SO$_4^{2-}$, which is present in seeping water in the buffer and backfill, to HS-. See also Raiko (2011), Section 8.6.

The most important corrosion agents are oxygen and sulphide. Oxygen is introduced into the repository during operation and via the amount trapped in the buffer and the backfill. Sulphide is present in groundwater and can be produced via microbial activity in the seeping groundwater and buffer and backfill. Methane and H$_2$ are of importance because they support microbial activity. Corrosion is also affected by pH, chloride ions and stress corrosion (SCC) enhancing agents, such as nitrogen-containing compounds and acetates, see Features, Events and Processes. The potential for stress corrosion cracking as well as corrosion due to O$_2$ intrusion with glacial meltwater have been assessed in the Performance Assessment report and determined to be negligible and therefore SCC and oxic corrosion due to glacial meltwater are not design basis chemical loads. Some controversy has arisen since Szakálos et al. (2007) published their results regarding copper corrosion in pure water. King (2010) carried out a critical review of the literature and concluded that the scientific evidence for this mechanism is still weak and that, even if it were to happen, it would be a self-limiting process because the repository can be considered an almost completely closed system in which hydrogen is able to build up and suppress corrosion (King 2010, Section 3.6). Hence, this process is not taken into account in the design of the canister. Experiments are under way to study the process.

Related requirements
Related requirements are the design requirements for corrosion resistance and the target properties concerning groundwater composition (Section 6.3.1.1 Reducing conditions, Section 6.3.1.2 Groundwater conditions to prevent chloride corrosion, Section 6.3.1.3 Limited concentration of solutes with detrimental effects on EBS). Buffer and backfill also have some requirements related to the chemical resistance requirement (Section 8.1.2.5 Chemical protection (to limit microbial activity), Section 8.1.2.7 Limitation of
mass flows from and onto the canister, Section 8.1.2.1 Limitation of amounts of sub-
stances harmful to other components, Section 9.1.2.1 Maintainance of favourable condi-
tions, Section 9.2.5.1 Limited content of harmful substances).

7.1.4 Mechanical resistance

The canister shall withstand the expected mechanical loads in the repository.

Rationale of the requirement

The requirement can be directly derived from the containment requirement for the can-
istor. The canister shall be designed taking into account the mechanical loads during the
expected evolution.

Loads to be taken into account

The mechanical loads that need to be taken into account arise from several distinct
sources: an isostatic load of 4.1 MPa is exerted on the canister by the hydrostatic pres-
sure. An additional pressure of 25 MPa from a possible ice-sheet shall also be taken into
account. The swelling pressure of the bentonite buffer, up to 15 MPa, also affects the
canister. The swelling pressure of the buffer may initially not be distributed evenly on
the canister, so it is required that uneven swelling pressure shall not damage the canis-
ter.

During different phases of glacial periods the bedrock is under strain, and the strain is
released in fractured rock in movements in the fracture zones. If a fracture intersects a
deposition hole, rock movement in the fracture results in a shear load on the canister.
The maximum design load is a shear movement of 5 cm (see discussion in Section 6.3.5
and references therein). Shear velocities of up to 1 m/s have been taken into account in
the design of the canister (Raiko et al. 2010).

Related requirements

The requirements on the bedrock are closely related to the requirements of mechanical
strength. The rock suitability criteria shall be set in such a way that shear loads larger
than the design values for the canister are very unlikely. The effect of the rock shear
depends also on the stiffness of the buffer (i.e. the density should not be too high). The
requirements about the straightness of the deposition hole and on the dimensions and
the quality of the wall of the deposition hole are aimed at avoiding an uneven swelling
pressure of the buffer onto the canister.

The requirements on the bentonite are also closely related. The swelling pressure of the
bentonite buffer shall not be excessive (i.e. design specification on buffer density, see
Buffer Production Line report, and requirement on mitigation of rock shear damage on
canister). The swelling of the bentonite depends on the availability of water, further
linking the mechanical resistance requirement of the canister to the requirements on the
rock.

7.1.5 Compatibility with other barriers and host rock performance

The canister shall not impair the safety functions of other barriers.
**Rationale of the requirement**
The requirement itself is self-evident; all of the EBS components shall be manufactured from materials which are compatible with each other. If any component could significantly impair the safety functions of any other component, the whole disposal concept would become unacceptable.

**Loads to be taken into account**
The materials of the canister shall be selected such that the corrosion products of the canister materials do not impair the performance of the buffer on relevant timescales. The corrosion of the canister shall not have any significant effect on the swelling pressure or retardation properties of bentonite.

The thermal load caused by the fuel in the canister can have adverse effects both on the bentonite buffer and on host rock. High temperatures will lead to alteration of the bentonite minerals and cause spalling of the host rock. The surface temperature of the canister shall be lower than the boiling point of water at repository depth after buffer saturation in order to prevent salt precipitation on the canister surface and bentonite. It is possible that salinity in the buffer might slightly increase due to groundwater evaporation before the buffer is fully saturated. The decay heat limit on the canister will be taken into account when the fuel is loaded into the canisters. The radiation of spent nuclear fuel inside the canister causes radiolysis, which needs to be taken into account.

**Related requirements**
The thermal load from the canister affects the host rock and the buffer. This requirement is related to the following requirements: canister requirements on limitation of radiation level and heat generation (Sections 7.2.2.4 and 7.2.2.5) and buffer requirement on heat transfer (Section 8.1.2.3).

### 7.1.6 Subcriticality
*The canister shall be subcritical in all postulated operational and repository conditions including intrusion of water through a damaged canister wall.*

**Rationale of the requirement**
Criticality is to be avoided because it could lead to widespread release of radionuclides into the environment. According to STUK-YVL D.3 draft, paragraph 428, the spent nuclear fuel disposal canister must meet the criticality safety criteria in such a way that the effective multiplication factor \( k_{\text{eff}} \) is always less than 0.95 even when the canister is filled with water and may have undergone mechanical changes. The discharge burnup of the fuel bundles can be taken into account in the criticality safety calculations if the burn-up value of each fuel bundle can be verified during the encapsulation process.

**Loads to be taken into account**
The criticality status of the canister depends on the properties of the spent nuclear fuel, its configuration inside the canister and moderator materials. The moderator material to be used in designing the canister is defined as water in the Guide D.3. Therefore the design can only alter the amount of fuel inside a canister and the configuration of the spent nuclear fuel in the canister. The configuration is controlled by the insert, which
keeps the appropriate distances between the fuel elements. Corrosion of the insert induces mechanical and chemical transformations inside the canister that are currently being assessed from the criticality point of view.

**Related requirements**
The subsystem and design requirements on mechanical resistance (Sections 7.1.4 Mechanical resistance and 7.2.2.2 Mechanical resistance) and canister design lifetime (Section 7.1.2.2 Canister’s service lifetime) contribute to ascertain that subcriticality is achieved.

### 7.1.7 Handling before disposal

*The canisters shall be stored, transferred and emplaced in such a way that the copper shell is not damaged.*

**Rationale of the requirement**
The requirement is an extension of the requirements on containment, i.e. the canister shall initially be intact when leaving the encapsulation plant for disposal. The reasoning for this requirement is similar; if the copper shell of the canister was damaged, the canister’s long-term safety function of containment would not be met even before disposal. Thus the main principle of the KBS-3 method, prolonged containment, would not be met.

**Loads to be taken into account**
The loads to be taken into account have been summarised in Raiko et al. (2010), Section 2.1. The machinery used to handle the canister at all stages in the encapsulation plant and during transfers to the repository shall be designed such that the canisters are handled with care at all times. During normal operations the canister is lifted a few times from the lifting shoulder on the copper lid. The design handling loads originate from postulated emergency brakings as a result of lifting malfunctions, see Raiko et al. (2010), Section 2.1. The canister shall also not be damaged during emplacement in the deposition hole.

**Related requirements**
The related requirements are the requirements on containment, and lifting and transfer (Sections 7.1.2 Containment and 7.2.3.2 Lifting and transfer). The reasoning behind both requirements is similar.

### 7.1.8 Retrievability

*The design of the canister shall facilitate the retrievability of spent fuel assemblies from the repository.*

**Rationale of the requirement**
The requirement of retrievability has been set in the Decisions-in-Principle (2000 and 2001) granted to Posiva. The reasoning behind the requirement is that future generations can, if they so wish, retrieve the spent nuclear fuel from the repository. Different motives can be envisaged for retrieving spent nuclear fuel from the repository: progress in
science and technology may allow alternative disposal solutions, or the fuel or other materials in the repository might possibly be considered as a resource in the future.

**Loads to be taken into account**
Retrieval operations will apply mechanical loads onto the canister and these need to be assessed. Retrievability is possible with methods similar to installation as long as the canisters are intact, which mostly depends on the corrosion processes and rate, which depend on the chemical and microbiological conditions near the canister. The cost and safety procedures needed for retrieval increase as the canister integrity is lost.

**Related requirements**
The requirements on containment (Section 7.1.2), chemical and corrosion resistance (Section 7.2.2.1 Chemical resistance and Section 7.2.3.1 Corrosion resistance) relate closely to the requirement on retrievability because the canisters can be retrieved only as long as they are intact. The process of closure has to be designed to allow retrievability (Section 10.1.7) while respecting the containment safety function of the repository. Mechanical strength requirements on the canister are related because of the loads applied onto the canisters during retrieval operations.

### 7.2 Design requirements for the canister

The design requirements at VAHA level 4 are more specific and detailed than the subsystem requirements at level 3. The requirements are divided into three subcategories as follows: performance, copper overpack and cast iron insert.

#### 7.2.1 Definition

*The canister is composed of a leak-tight copper shell and of a load-bearing nodular cast iron insert.*

#### 7.2.2 Performance

##### 7.2.2.1 Chemical resistance

*The copper overpack shall provide the corrosion resistance required in the postulated repository conditions.*

**Rationale of the requirement**
The requirement on chemical resistance can be directly derived from the safety function of the canister, i.e. containment, see Section 7.1.2, and from subsystem requirement on chemical resistance (Section 7.1.3). The time frame for the needed corrosion resistance is given in the life-time requirement of the canister, which is hundreds of thousands of years (Section 7.1.2.2).

The life-time requirement was taken into account when the canister material was selected in the late 1970s and early 1980s by SKB. The aim was to find a material that can fulfill the life-time requirement under the expected conditions when all known corrosion processes are considered. The earliest KBS-3-canister designs from 1983 were already based on copper, which is thermodynamically very stable in the expected anoxic reposi-
tory conditions, and is also found in nature in native form. Other materials, e.g. ceramics, were also initially considered suitable from the point of view of corrosion, but their other properties were not considered as good as the selected canister design's properties.

**Loads to be taken into account**
See Section 7.1.3.1.

**Related requirements**
Corrosion processes are related to the chemistry in the near field. Therefore, all requirements affecting groundwater, buffer and backfill chemical composition as well as mass transport and ground water flow rate are closely related to the corrosion resistance requirement.

**7.2.2.2 Mechanical strength**

*The iron insert shall provide the mechanical strength required.*

**Rationale of the requirement**
The requirement is due to the fact that copper cannot provide the mechanical strength needed for the canister. The interior of the early KBS-3 canister designs in the 1980s was composed of lead, but the need was early recognised to replace the use of molten lead in the encapsulation facility with something less risky to handle. The development work first produced a design of a composite canister with steel canister inside a copper shell, which then later gave way to another type of double canister in which the inner part was replaced by an inner canister of nodular cast iron with prefabricated slots for the spent nuclear fuel elements. The cast iron structure was considered to give a more reliable guarantee for subcriticality than the steel canister with granular material as a backfill of the void space.

**Loads to be taken into account**
The potential mechanical loads that need to be taken into account arise from two distinct sources:

- isostatic load due to combination of the buffer swelling pressure and the hydraulic pressure of the groundwater, possibly augmented by an overlying ice-sheet, and
- shear loads caused by potential displacements of the surrounding rock or by uneven swelling pressure of the bentonite buffer.

An isostatic load is exerted on the canister by the hydrostatic pressure, which at repository depth is approximately 4.1 MPa (Raiko 2011). The swelling pressure of the bentonite buffer is another load to take into account, especially during the early evolution of the buffer when the swelling pressure may be unevenly distributed on the canister surface. Later, during glaciations, the hydrostatic pressure may increase by 25 MPa due to an estimated maximum ice sheet thickness of 2500 m in Olkiluoto (Lambeck & Purcell (2003), Pimenoff et al. (2011)).

The design saturated density for the bentonite buffer approximately 2000 kg/m³, see *Buffer Production Line* report. The resulting swelling pressure is 2-10 MPa, respec-
tively, see e.g. Figure 5-15 in SKB (2011a), Buffer Production Line report and discussion in Karnland et al. (2006). Cation exchange in the bentonite leading to formation of Ca-Na bentonite can increase the swelling pressure up to 15 MPa. The enveloping maximum sum of isostatic pressure load at Olkiluoto site is 44 MPa (Raiko 2011). The Swedish canister design basis pressure is 45 MPa due to formation of potentially thicker ice sheets over the Forsmark site (SKB 2009a). It should be noted that the designs of SKB’s canisters (SKB 2010a) and Posiva’s canisters (Canister Production Line 2012) have no major differences and thus have similar strength.

During different phases of glacial periods, the bedrock experiences varying strain. In fractured rock, the strain is most likely released in slip movements in the fracture zones. If a fracture intersects a deposition hole, rock movement in the fracture results in a shear load on the canister. The design shear movement is a 5 cm fracture slip (Section 6.3.5).

**Related requirements**

Requirements related to mechanical strength of the canister are e.g. the RSC requirements on the bedrock which regulate the locations of the deposition holes and the acceptable respect distance to known fractures, see Section 6.4. The repository depth affects the isostatic pressure (Section 6.2.1).

Furthermore, the groundwater chemistry has an effect on the bentonite swelling pressure. The requirements on acceptable groundwater composition and the density specification on the buffer are directly related to the requirement for a canister's mechanical strength. The backfill requirement to keep the buffer in the deposition hole also affects the swelling pressure of the buffer (Section 9.1.4.1).

**7.2.2.3 Subcriticality**

*To ensure subcriticality, the properties (e.g., enrichment, burnup) of the fuel inside the canisters, as well as the internal geometry of the insert, shall be known precisely enough to provide a high degree of confidence in criticality safety.*

**Rationale of the requirement**

See Section 7.1.6.

**Loads to be taken into account**

A spent nuclear fuel disposal canister must meet the normal criticality safety criteria. The effective multiplication factor (a.k.a. $k_{eff}$) must be less than 0.95 when the canister is in the most reactive credible configuration (optimum moderation and close reflection). Uncertainties in the calculation methods may necessitate the use of an even lower reactivity limit (Anttila 2005a). Criticality depends on the properties of the fuel (amount of fissile material), the distance and materials between the fuel elements, and the moderator material. Even in the worst, yet still credible, case the subcriticality shall be guaranteed with a large margin of safety. When assessing the subcriticality state of the canister, the following pessimistic assumptions have to be made (Anttila 2005a and STUK YVL D.3, 428):

- the fuel and the whole canister have the most reactive credible configuration,
the moderation by water is at its optimum, and
the neutron reflection on all sides of the canister is as effective as credibly possible.

STUK-YVL D.3 also states that burnup credit can be used if the burnup of each fuel element can be verified during the encapsulation.

**Related requirements**
Subcriticality depends on the performance of the canister insert (Section 7.1.4 Mechanical resistance, Section 7.2.2.2 Mechanical resistance and Section 7.2.4 Cast iron insert) and the neutron-reflective capability of the canister materials. The material requirements for the canister components are thus closely related to the subcriticality requirements.

### 7.2.2.4 Limitation of radiation level

*The shielding provided by the canister shall limit the dose rate to minimise radiolysis of water outside the canister.*

and

*The fuel elements for encapsulation shall be selected in a pre-planned, controlled and documented way to limit the radiation dose on the canister surface.*

**Rationale of the requirements**
The requirements on limitation of radiation level are derived from the subsystem requirements of EBS compatibility. High levels of radiation could, in principle, induce changes to the buffer through radiolysis of porewater or moist air surrounding the canister (*Features, Events and Processes*). High levels of radiation could also induce hardening and embrittlement of cast iron, and radiolysis of residual aerated water trapped within the fuel could form nitric acid. It has been verified that if the fuel in the canister meets the decay heat limit requirement, it also fulfils the requirement on the radiation level since radioactive decay and decay heat are related parameters (Raiko 2011).

**Loads to be taken into account**
This is an extension of the requirement on the decay heat for the canister. With a given decay heat limit the radiation level is also met. The radionuclide inventory of the spent nuclear fuel together with the shielding properties of the canister’s internal structure determines the radiation levels outside the copper overpack. The radionuclide inventories for different types of fuel, different enrichment levels and burnup have been reported in Anttila (2005b). When the heat load limits are applied to the fuel encapsulated in the canister, the surface dose rate is well below 1 Gy/h (Raiko 2011). Limitation of radiation level can also be achieved by increasing cooling times.

**Related requirements**
The requirement is closely related to the decay heat limit for the canister (Sections 7.1.5 and 7.2.2.5), EBS compatibility requirements for canister and buffer (Section 7.1.5 Compatibility with the EBS and host rock performance, and Section 8.1.2.1 Limitation of amounts of substances harmful to other components).
7.2.2.5 Limitation of heat generation

The heat generation inside the canister shall be limited in such a way that the performance of the other barriers is not impaired.

and

The fuel elements for encapsulation shall be selected in a pre-planned, controlled and documented way to meet the decay heat limit set for each canister type.

Rationale of the requirement

The heat generation requirements are a direct result of the EBS compatibility requirements of buffer and host rock. Excessive heat loads can result in a loss of performance of some of the EBS components. This can mainly affect the buffer, in which high temperatures may accelerate mineral alteration rates, and the host rock, in which excessive heat input may lead in increased spalling and thereby changes in groundwater flow paths and mass transfers in the vicinity of deposition holes.

Loads to be taken into account

The heat generation depends on the properties of the individual spent nuclear fuel elements in each canister. Heat is generated by the radioactive decay in the fuel pellets and is transported in the fuel and cavity by conduction and thermal radiation to the canister insert and then through the insert material to the canister shell, bentonite buffer and to the near and far field. The heat capacity of the far field rock stores the thermal energy for a few thousands of years after the most intensive heat production in the fuel has ceased.

The discharge burnups of the fuel elements need to be known in order to ensure that the heat production limits for each canister type are not exceeded. The heat production limits are 1370 W for the VVER canister, 1700 W for the BWR canister and 1830 W for the OL3-PWR canister, based on Raiko (2011). These numbers are derived from the reference design by weighting with the respective canister’s cooling surface area. The maximum design temperature at the canister surface is 100 °C; but a 5 degree margin has been reserved due to natural variations in the thermal properties of buffer and rock, and the contact between them. Thus, the target maximum temperature in the dimensioning analyses is set to 95 °C, when using average thermal properties of the system (Ikonen & Raiko 2012).

The temperature of the repository is adjusted by altering the canister spacing in deposition tunnels, and deposition tunnel spacing in the repository. The thermal heat from the canister and thermal conductivity of the host rock together set limits for the minimum distance between canisters and deposition tunnels.

Related requirements

The requirements related to the heat generation limit are the EBS compatibility requirements. The requirement also aims at limiting damage to the host rock. It is also related to the buffer’s heat transport requirement (Section 8.1.2.3). As noted above, the requirement aims at limiting damage to the host rock and it is related to the host-rock requirement to limit temperature at the repository (Section 6.4.5.8).
7.2.2.6 Thermal conductivity

The canister materials shall have a sufficiently high thermal conductivity such that the heat from the spent nuclear fuel is effectively dissipated.

Rationale of the requirement
The heat generation and thermal conductivity requirements are a direct result of the EBS compatibility requirements. The decay heat of the spent nuclear fuel shall be transported out of canister so that the spent nuclear fuel would not overheat. The temperature inside the canister shall be low enough that the fuel elements and the canister's internal structures are not damaged.

Loads to be taken into account
See Section 7.2.2.5 Limitation of heat generation.

Related requirements
The thermal conductivity requirements are a direct result of the EBS compatibility requirements and the requirements on limitation of radiation level and heat generation (Sections 7.2.2.4 and 7.2.2.5).

7.2.2.7 Canister geometry

The copper overpack and insert shall be dimensioned so that the insert can be installed into the copper overpack.

Rationale of the requirement
This requirement is self-evident. The canister must be possible to be assembled.

Loads to be taken into account
The dimensions of the canister components shall be designed and criteria for their manufacturing tolerances set so that the canisters can be assembled. See further in Canister Production Line report.

Related requirements
The fulfilment of this requirement is needed to enable disposal operations. Therefore, it is indirectly related to all other requirements set for the canister.

7.2.3 Copper overpack

The copper overpack is composed of a copper lid and a bottom welded into a copper tube or of a copper lid welded into a copper tube with an integrated bottom.
To ensure the long-term safety of the canisters, the following requirement has been set for the welds:

Properties of the weld shall fulfill the same performance requirements as the rest of the copper shell.
Rationale of the requirement
The requirement on the welds arises from the safety function of the canister, i.e. containment, and from the lifetime requirement of the canister, which is several hundreds of thousands of years. In order to fulfill these requirements, the weld shall fulfill the performance requirements set for the canister.

Loads to be taken into account
The loads to be taken into account are the loads defined in the Sections discussing corrosion resistance (Sections 7.2.2.1 and 7.2.3.1) and mechanical resistance (Sections 7.1.4, 7.2.2.2 and 7.2.4.2).

Related requirements
The requirements related to the performance of the welds are the lifetime requirement of the canister (Section 7.1.2), the requirements on corrosion resistance (Sections 7.2.2.1 and 7.2.3.1) and the requirements on mechanical resistance (Sections 7.1.4 and 7.2.2.2).

7.2.3.1 Corrosion resistance
The design, manufacturing and any further processing and handling of the canister shall aim at limiting the risk of stress corrosion cracking in repository conditions.

Rationale of the requirement
The requirements are derived from the safety function of the canister through the subsystem requirements set for chemical resistance.

Loads to be taken into account
The corrosion loads have been described in Section 7.2.2.1.

The residual stresses have been discussed in Raiko (2011, Section 13.6). The interest in residual stresses in copper shells is primarily related to the possibility of stress corrosion cracking and plastic deformation (creep) that could lead to canister failure. Residual stress appears in the materials due to manufacturing processes such as casting and canister lid welding. The welding method causes distortions leading to residual tensile stresses both in transverse and longitudinal orientations relative to the weld pass. Some preliminary results are reported in Gripenberg & Hänninen (2006) and Gripenberg (2009). The welding method will be selected so that the residual stress level is minimised. Post-manufacturing stresses might be induced to the canister if it is not properly handled, see further discussion about handling before disposal in Sections 7.1.7 and 7.2.3.2.

Related requirements
The related requirements are the requirements on containment (Section 7.1.2), chemical and corrosion resistance (Sections 7.1.3, 7.2.2.1 and 7.2.3.1), and handling before disposal (Sections 7.1.7 and 7.2.3.2).
7.2.3.2  Lifting and transfer

The copper overpack shall be designed to bear the load from canister handling and transfer.

and

Dent marks and scratches on the copper surface shall be minimised during canister handling and transport.

Rationale of the requirement
The lifting and transfer design requirements are derived from the subsystem requirement set for the handling before disposal. The requirements are an extension of the requirements on containment, i.e. the canister shall stay intact during the encapsulation process and all transfers before disposal. The reasoning for this requirement is similar; if the copper shell of the canister was damaged, the canister's long-term safety functions would not be met even before disposal. Thus the main principle of the KBS-3 method, prolonged containment, would not be met.

Loads to be taken into account
The handling and transfer loads have been defined in Raiko et al. (2010), section 2.1.

Related requirements
The related requirements are the requirements on containment (Section 7.1.2), handling before disposal (Section 7.1.7) and mechanical resistance (Sections 7.1.4, 7.2.2.2 and 7.2.4.2).

7.2.3.3  Copper overpack ductility

The canister copper overpack shall be designed to withstand the plastic deformation and creep caused by any postulated mechanical or thermal load.

Rationale of the requirement
The requirement is derived from the subsystem requirement on mechanical resistance and from the containment safety function. See discussion in Sections 7.1.4 and 7.2.2.5.

Loads to be taken into account
The loads have been described in Section 7.1.4 Mechanical resistance and Section 7.2.2.5 Limitation of heat generation.

Related requirements
The related requirements are the requirements on mechanical resistance (Sections 7.1.4, 7.2.2.2 and 7.2.4.2) and limitation of heat generation (Section 7.2.2.5).
7.2.4  Cast iron insert

7.2.4.1  Subcriticality

The insert geometry and acceptance criteria for soundness shall be set so that subcriticality is guaranteed.

Rationale of the requirement
Subcriticality requirements originate from the regulations and STUK’s YVL Guide D.3.

Loads to be taken into account
The loads to be taken into account are discussed in Section 7.2.2.3.

Related requirements
Subcriticality depends on the fissile material present in the canister, as well as on the moderating and neutron reflecting conditions inside the canister. Since the amount and characteristics of spent nuclear fuel are limited by the decay heat limit (Section 7.2.2.4 Limitation of radiation level and Section 7.2.2.5 Limitation of heat generation), those requirements are closely related to the subcriticality requirement. The material, design and manufacturing requirements for the canister components are also closely related to the subcriticality requirements.

7.2.4.2  Mechanical strength

The canister insert shall be designed to bear the hydrostatic pressure from groundwater and from swelling of bentonite.

and

The canister insert shall be designed to bear the hydrostatic load caused by glaciation.

and

The canister insert shall be designed to bear unevenly distributed swelling loads.

and

The canister insert shall be designed to bear the loads from the postulated rock shear displacements in the deposition hole.

Rationale of the requirement
The design requirement can be derived from the subsystem requirements of the canister, mainly from its life-time requirement and requirements on containment and mechanical resistance. The canister shall be designed to withstand the mechanical loads during the expected evolution.

Loads to be taken into account
See Section 7.2.2.2 Mechanical resistance.

Related requirements
The related requirements are the requirements on mechanical resistance of the canister (Sections 7.1.4 and 7.2.2.2) and the canister's service life-time requirement to provide containment (Section 7.1.2).
8 BUFFER

The buffer is the second of the barriers of the KBS-3 method. The safety functions of the buffer are to contribute to mechanical, geochemical and hydrogeological conditions that are predictable and favourable to the canister, and to protect canisters from external processes that could compromise the safety function of complete containment of the spent nuclear fuel and associated radionuclides, and to limit and retard radionuclide releases in the event of canister failure. The general structure of the buffer requirements is presented in Figure 8-1. The requirements can be divided into two categories: requirements related to the performance of the buffer, and requirements related to support to other systems. The performance requirement can be further divided into requirements related to chemical protection, mechanical protection and limitation of mass flows in the near field, and heat transfer, which is needed for EBS compatibility.

![Image: General structure of the buffer requirements.](image)

**Figure 8-1. General structure of the buffer requirements.**

8.1 Performance targets for the buffer

8.1.1 Definition

Buffer is the component that surrounds the canister and fills the void spaces between the canister and the rock. The purpose of the buffer is to protect the canister from detrimental thermal, hydraulic, mechanical and chemical, including microbiological (THMC) processes that could compromise the safety function of complete containment, to maintain favourable conditions for the canister and to slow down the transport of radionuclides if the canister starts leaking.
8.1.2 Performance

8.1.2.1 Limitation of amounts of substances harmful to other components

The amount of substances in the buffer that could adversely affect the canister, backfill or rock shall be limited.

Rationale of the requirement
The requirement itself is self-evident; all of the EBS components shall be manufactured from materials that are compatible with each other. If any component could significantly impair the safety functions of any other component, the whole disposal concept would become unacceptable.

Loads to be taken into account
Because the buffer bentonite is a natural material, there are variations both in its mineralogy and chemical composition. Sulphur and organic carbon are the most important substances which may have an adverse effect on the long-term safety of disposal. Iron can be present in accessory minerals in both ferric and ferrous forms (Kumpulainen & Kiviranta 2010). Iron may have a detrimental effect on bentonite because it may transform montmorillonite into a non-swelling mineral (see Features, Events and Processes report, FEP 5.2.6).

Sulphur is one of the most important minor components in bentonites. Like iron, it is a redox-sensitive element with a special link to biogeochemical processes, which may be disadvantageous to the stability of EBS components. Consequently, sulphur content and redox-speciation of sulphur in bentonite needs to be studied carefully. The vital component of biogeochemical processes is organic carbon. Carbon may be present in various forms in bentonite, ranging from inorganic carbonate to organic molecules of living or dead cells, but often as “suborganic” phases like humic and fulvic acids and other decomposition products of living material. In practice, determination between the carbon forms may be limited to separation between organic and total carbon of bentonite (Ahoenen et al. 2008).

Related requirements
The requirement is directly related to the safety functions of the copper canister, i.e. containment. Other related requirements are the requirements on corrosion resistance of the canister and EBS compatibility requirements for all of the EBS components (Canister: sections 7.1.5, buffer: section 8.1.2.1, backfill: section 9.1.3.3, and closure: section 10.1.6).

8.1.2.2 Preserve required properties in repository conditions

Unless otherwise stated, the buffer shall fulfill the requirements listed below over hundreds of thousands of years in the expected repository conditions except for incidental deviations.

Rationale of the requirement
The longevity requirements of the EBS components are determined on the basis of the needs for radionuclide containment. These, in turn, are governed by the radiotoxicity of
the spent nuclear fuel. According to Government Decree 736/2008, section 11, the safety functions shall effectively prevent releases of radioactive materials for at least several thousands of years. In Guide STUK-YVL D.5, paragraph 408, the timescale is further defined to be at least 10,000 a. Due to the radioactivity inventory and the amount of spent nuclear fuel to be disposed of (see Section 3.1.4), the design life-time of the KBS-3 type repository at Olkiluoto needs to be at least several hundreds of thousands of years.

**Loads to be taken into account**
The current repository conditions are presented in the *Site Description* (Posiva 2011a) and future conditions during the expected evolution in the *Formulation of Radionuclide Release Scenarios* report; current conditions are briefly presented in Chapter 4 of this report. The buffer experiences e.g. temperature variations due to the decay heat of the fuel (maximum design temperature of the canister surface is below 100 °C (Section 7.2.2.5), variable salinities of the groundwater (up to 70 g/L, Section 6.3.2) and variable groundwater flow conditions.

**Related requirements**
The safety functions of the EBS components are all related to the life-time requirement. The timescale of hundreds of thousands of years is the same for all of the components. Also the chemistry and flow related target properties of the host rock contribute to long term performance of the buffer.

**8.1.2.3 Heat transfer**

*The buffer shall transfer the heat from the canister efficiently enough to keep the buffer temperature < 100°C.*

**Rationale of the requirement**
Too high temperature has harmful effects on bentonite; see Juvankoski & Marcos (2009), Section 4.2.2. The main concern is that bentonite can be altered to non-swelling clays if the temperature is too high. Excessively high temperature can also cause thermally induced spalling of the deposition hole surface, and thus have an impact on the buffer-rock interface layer (impact of spalled rock fragments on bentonite). Therefore the buffer shall be able to efficiently transfer the heat from the canister into the host rock.

**Loads to be taken into account**
The thermal loads arising from the canister have been discussed in Section 3.1.2. The thermal evolution at repository depth is discussed in the *Performance Assessment* report. The temperature of the undisturbed host rock is discussed in detail in *Site Description*.

**Related requirements**
The requirement is directly related to the heat generation limits on the canister, Section 7.2.2.5, and the host rock requirement to limit the temperature, Section 6.4.5.8.
8.1.2.4  Gas transfer

The buffer shall allow gases to pass through it without causing damage to the repository system.

**Rationale of the requirement**
Gases will form in the proximity of the canister, mainly because of corrosion. The concern is the buildup of these gases in the near field which may then open flow routes into the buffer possibly resulting in radionuclide transport if a canister is leaking.

**Loads to be taken into account**
In the expected repository conditions, very little gas will be generated if the canister is intact. The only gas generating processes are copper corrosion and radiolysis of moist air or porewater in the buffer (see *Features, Events and Processes*). Available experimental results show that gas can migrate through a highly compacted buffer without jeopardising the continuing function of the buffer. Other gas generation processes in the presence of a breached canister (e.g. insert corrosion, release of He and other gases from the fuel) are analysed in the *Formulation of Radionuclide Release Scenarios* and *Assessment of Radionuclide Release Scenarios for the Repository System* reports.

**Related requirements**
The requirement is indirectly related to canister’s radiation limit requirement (Section 7.2.2.4), because of the potential for gas generation through radiolysis outside the canister. The buffer shall be self-sealing to be able to close any flow route formed (Section 8.2.2.1).

8.1.2.5  Chemical protection

The buffer shall limit microbial activity.

**Rationale of the requirement**
Microbial activity can produce chemical species that may accelerate corrosion of copper (*Features, Events and Processes*). The most important types of microbes are those that produce sulphide. The prerequisites for significant viability of microbes are sufficient availability of free water, nutrients and energy and swelling pressure and pore size of the buffer, which will exert an increasing constraint on the space for living cells with increasing buffer density (King et al. 2011).

**Loads to be taken into account**
Bacteria are not expected to be able to stay active in the specified high density of the buffer. In the SR-Can safety assessment, the clay density limit for microbial sulphide production was set at 1800 kg/m$^3$ (SKB 2006a), which gives a low enough pore space and high enough swelling pressure close to the one reported to suppress microbes by Masurat (2006).

**Related requirements**
The corrosion resistance of copper (Sections 7.2.2.1 and 7.2.3) is directly related to this requirement.
8.1.2.6 Mitigation of rock shear damage on canister

The buffer shall mitigate the impact of rock shear on the canister.

**Rationale of the requirement**

Rock shear movements are possible when the stresses in bedrock are released, see Sections 6.3.5 and 6.4.5.3. The buffer shall act as a plastic material between the host rock and canister. To perform this function the swelling pressure of the buffer must be kept under a specific limit.

**Loads to be taken into account**

The rock suitability criteria state that the probability of a rock shear larger than 5 cm (see Section 6.3.5) shall be low. The system must be designed to withstand this load. The design of the buffer shall be such that it can mitigate the consequences for the canister.

**Related requirements**

The rock shear limits set in the RSC and the mechanical resistance requirements of the canister (Sections 6.3.5, 7.1.4 and 7.2.4.2) are directly related to the requirement of mitigation of rock shear damage on canister set for the buffer.

8.1.2.7 Limitation of mass flows from and onto the canister

The buffer shall be impermeable enough to limit the transport of radionuclides from the canisters into the bedrock.

and

The buffer shall be impermeable enough to limit the transport of corroding substances from the rock onto the canister surface.

and

The buffer shall limit the transport of radiocolloids to the rock.

**Rationale of the requirement**

These three requirements are all related to similar processes and arise from the safety functions of the buffer, which are to contribute to mechanical, geochemical and hydrogeological conditions that are predictable and favourable to the canister, and to protect canisters from processes that could compromise the safety function of complete containment of the spent nuclear fuel and associated radionuclides; and to limit and retard radionuclide releases in the event of canister failure.

**Loads to be taken into account**

The substances of concern in the rock/groundwater are oxygen, Cl⁻, HSO⁻, K⁺, Fe_{tot}, NO_3⁻, NO_2⁻ and NH₄⁺ (see Section 6.3.1), which are either potentially corroding substances for the canister or harmful to the performance of the buffer. Salinities will vary during the expected evolution of the repository due to upconing of saline waters and due
to infiltration of non-saline and possibly oxygen-rich waters, e.g. glacial meltwaters, from the surface.

**Related requirements**
The buffer's requirement on limitation of mass flows is related to the fulfillment of the containment safety function of the KBS-3 type repository. It is directly related to the requirement limiting water inflow to a deposition hole (Sections 6.3.4.1 and 6.4.5.1), because too high inflows might lead to buffer erosion. This requirement is also related to groundwater chemistry.

### 8.1.3 Support of the other systems

#### 8.1.3.1 Support to deposition holes

*The buffer shall provide support to the deposition hole walls to mitigate potential effects of rock damage.*

**Rationale of the requirement**
A contact between the buffer and host rock is needed for several reasons: the deposition hole walls need support during the period of high temperature during the first decades after repository closure in order to mitigate the effects of rock spalling. Also, during the saturation phase and later if hydraulic conditions change during changes in isostatic pressure, groundwater flow may be enhanced and cause piping and erosion in the buffer, thus flow paths are formed.

The host rock may start spalling when the temperature increases after canister has been placed in the deposition hole and the hole has been closed (Hakala et al. 2008), possibly forming flow paths along the deposition hole.

**Loads to be taken into account**
Rock damage (spalling) depends on the stress-state of the host rock and the temperature. The potential for spalling has been evaluated by Hakala et al. (2008) and Siren et al. (2011). If spalling occurs, buffer’s self-sealing and self-healing capability due to swelling should be able to mitigate the effects of spalling damage.

**Related requirements**
The requirements on self-sealing and self-healing of the buffer support the contact requirement; see Section 8.2.2.1. The host rock requirements for the deposition hole (Sections 6.4.5.5 and 6.4.5.6) are related to the contact requirement.

#### 8.1.3.2 Keeping the canister in position

*The buffer shall be able to keep the canister in the correct position (to prevent sinking and tilting).*

**Rationale of the requirement**
The buffer's main role is to reduce the potential negative interactions between the canister and the host rock including the groundwater. If the buffer density is too low, allowing it to deform under the weight of the canister and thus allowing the canister either to
sink or to tilt so that it touches the deposition hole walls or the bottom of the deposition hole, the buffer's safety functions would no longer be effective.

**Loads to be taken into account**
The buffer needs to be able to support the weight of the canister containing the fuel, which is from 18.8 to 29.0 tons (Raiko 2011, Table 6). The swelling pressure and friction between the buffer and the canister and the host rock can be taken into account. The unevenness of the deposition hole may lead to variations in buffer density within the deposition hole, which may then lead to development of non-uniform swelling pressure that could induce movement of the canister.

**Related requirements**
The fulfillment of many of the canister requirements depend on the performance of the buffer and are thus related to this requirement.

### 8.2 Design requirements for the buffer

#### 8.2.1 Definition

*The main component of the buffer material shall consist of natural swelling clays.*

**Rationale of the requirement**
The buffer needs to have a swelling component because the transport of substances needs to be diffusion dominated. The host rock also needs support to mitigate spalling. Swelling is also needed for the buffer to be self-sealing and self-healing because good contact with the host rock needs to be achieved. Only natural swelling clay materials are considered, because smectites, including the montmorillonite in bentonite, are known to be remarkably stable minerals in low temperature environments in spite of their large structural and chemical heterogeneity on the nano-to-micrometre scale. This is evident, for example, by the occurrence of natural bentonites that have been formed many millions of years ago and have retained their smectite content under variable geochemical conditions (e.g. Juvankoski & Marcos 2009, Laine & Karttunen 2010).

#### 8.2.2 Performance

##### 8.2.2.1 Self-sealing

*The buffer shall be designed to be self-sealing after initial installation and self-healing after any hydraulic and mechanical disturbances.*

**Rationale of the requirement**
Buffer mass may be lost due to e.g. piping and erosion during the water saturation phase. The contact between buffer and host rock, and between buffer and canister, are not initially tight along the length of the deposition hole due to spaces needed for installation. The swelling of the buffer during saturation shall be sufficient to self-seal the gaps to prevent preferential flow paths from forming. Different mass loss scenarios and related analysis have been presented by Åkesson et al. (2010).
Hydraulic disturbances, e.g. increased groundwater flow due to increased hydraulic gradients during the repository operating period or caused by an ice sheet may result in local mass loss due to chemical erosion (Features, Events and Processes). The deposition hole may deform in the case of a rock shear, which may lead to local buffer densities that differ from the design specifications. In addition, migration of canister insert corrosion gases from a defect at canister surface through the buffer would create locally at least a temporary hydro-mechanical disturbance. The buffer must be able to self-heal from local density deviations and maintain sufficient density.

**Loads to be taken into account**
The hydraulic and mechanical conditions during the expected evolution and possible release of canister insert corrosion gases shall be taken into account. The erosion processes are related to water inflows, requirements for which have been given in RSC, see also Section 6.4.4.2 Limitation of inflow to deposition tunnels and Section 6.4.5.1 Limitation of inflow to deposition holes.

**Related requirements**
The self-sealing requirement of the buffer is related to its requirements in relation to groundwater flows into deposition hole (Section 6.4.5.1) and gas transfer (Section 8.1.2.4)

### 8.2.2.2 Chemical protection

The buffer shall be so designed that the possibility of corrosion of a canister by sulphide and other corroding agents, including microbially-induced processes, will be limited.

and

The buffer material shall be selected so as to limit the contents of harmful substances (organics, oxidising compounds, sulphur and nitrogen compounds) and microbial activity.

**Rationale of the requirement**
Canister corrosion is caused by several chemical substances that are found in the groundwater and may be introduced into the repository during construction, such as oxygen, sulphur and others, see Section 6.3.1 for details. Therefore, introduction of these harmful substances into the repository shall be limited. Bacterial processes can transform some substances into chemical forms that may be unfavourable for the canister, such as reduction of sulphate to sulphide, see Section 8.1.2.5.

**Loads to be taken into account**
The design of the buffer needs to take into account the amounts of detrimental substances in the materials. Furthermore, selection of the buffer material must be undertaken with a view to avoiding introduction of large amounts of these detrimental substances to the system. The transport of detrimental substances through the buffer shall be limited by sufficient density and sufficiently low transmissivity. The buffer shall also be designed to have a high enough density to suppress bacterial growth, see Section 8.1.2.5 Chemical protection.
**Related requirements**
The corrosion resistance of copper (Sections 7.2.2.1, 7.2.3) is directly related to this requirement. The buffer requirements of limitation of mass transfer (Section 8.1.2.7) and limitation of the amounts of harmful substances (Section 8.1.2.1) are also directly related.

**8.2.2.3 Mechanical protection**

*The buffer shall be so designed that it will mitigate the mechanical impact of the postulated rock shear displacements on the canister to the level that the canister integrity is preserved.*

**Rationale of the requirement**
See Section 8.1.2.6 Mitigation of rock shear damage on canister.

**Loads to be taken into account**
See Section 8.1.2.6 Mitigation of rock shear damage on canister.

**Related requirements**
The rock shear limits set in the RSC and the mechanical resistance requirements of the canister (Section 6.3.5 Mechanical stability, Section 7.1.4 Mechanical resistance and Section 7.2.4.2 Mechanical strength) are directly related to the mechanical protection requirement of the buffer.

**8.2.2.4 Limitation of mass flows to and from canister**

*The buffer shall be designed in such a way as to make diffusion the dominant transport mechanism for solutes.*

and

*The buffer material must be selected in a way that favours the retardation of the transport of radionuclides by sorption (e.g. cation exchange) at the clay and other mineral surfaces.*

and

*The buffer shall have sufficiently fine pore structure so that transport of radiocolloids formed within or around the canister is limited.*

**Rationale of the requirement**
The need for limitation of advective transport in buffer arises firstly from the need to protect the canister from corroding substances in the groundwater, and secondly from the need to retard radionuclide releases in cases where the integrity of a canister has been lost.

Particles with sizes of the order of $10^{-9}$ to $10^{-6}$ m (colloids) could form by dissolution of the fuel and due to oversaturation. Colloids are also formed in the clay-based buffer and
backfill materials. The colloids can have available sorption sites that may result in radionuclide sorption on the colloids and colloid-facilitated faster transport in geosphere.

**Loads to be taken into account**

Mass flows in the near field arise due to several mechanisms: the groundwater flows in the host rock, carrying solutes and colloids. Solutes and colloids move also by diffusion in pore waters of the host rock, buffer and backfill. These flows are affected by e.g. the elevated temperatures during the first few thousand years, and by infiltration of less saline waters from the surface during deglaciations. The salinity of the groundwater in the near field of the repository changes during such processes. Colloid stability is primarily controlled by ionic strength, see Karnland (2005) and Wold & Eriksen (2005).

**Related requirements**

The buffer's requirement on limitation of mass flows is related to the fulfillment of the containment safety function of the KBS-3 type repository and the host rock requirement to limit water inflow into a deposition hole (Section 6.4.5.1).

### 8.2.2.5 Heat transfer

*The gap between the canister and buffer and buffer blocks and rock should be made as narrow as possible without compromising the future performance of the buffer.*

**Rationale of the requirement**

This requirement is a result of the buffer’s subsystem heat transfer requirement (Section 8.1.2.3). Heat transfer from the canister through the buffer into the host rock is achieved sooner after installation, if the gaps are kept small, resulting in less need for the buffer to swell to achieve proper contact.

**Loads to be taken into account**

See Section 8.1.2.3.

**Related requirements**

See Section 8.1.2.3.

### 8.2.3 Support of other system components

*The buffer shall initially provide a good contact with the host rock.*

**Rationale of the requirement**

The surfaces of the deposition hole are prone to spalling especially at elevated temperatures. Spalling is a relatively common mechanism of rock damage and occurs at the surface of a rock when there are shear stresses under the rock surface. These stresses are caused by the in situ state of stress in the rock mass (primary stress state), the excavation-induced stress changes (secondary stress state) and the increase of temperature due to the decay heat production of the spent nuclear fuel. If spalling occurs in a deposition hole, flow paths may form in the rock zone damaged by spalling. The damaged zone may have long-term significance for groundwater flow. The buffer can help mitigate the effects of spalling in a deposition hole, if there is a contact between the buffer and host
rock. The contact is achieved by placing bentonite pellets into the gap between the buffer and the host rock.

** Loads to be taken into account **

The potential for spalling depends on the stress state of the rock mass, the excavation stress and on the effects of elevated temperatures. The potential for spalling has been evaluated by Hakala et al. (2008). Estimates of the combined stress state around the deposition holes due to both the in situ stress and the thermally induced stress indicate that some spalling may occur. The swelling pressure of the bentonite buffer is needed to mitigate this effect.

** Related requirements **

The requirements on self-sealing and self-healing of the buffer support the contact requirement; see Section 8.2.2.1. The host rock requirements for the deposition hole (Sections 6.4.5.5 and 6.4.5.6) are related to the spalling requirement.
9 BACKFILL

The backfill herein refers to the materials used to fill the deposition tunnels and the plug that is needed to keep the deposition tunnel backfill in place during the operating period of the repository. The safety functions of the backfill are to contribute to favourable and predictable mechanical, geochemical and hydrogeological conditions for the buffer and canisters, to limit and retard radionuclide releases in the possible event of canister failure, and to contribute to the mechanical stability of the deposition tunnels. The general structure of the backfill requirements is shown in Figure 9-1. The latest backfill design has been presented in the Backfill Production Line report and summarised in the Description of the Disposal System report.

![Figure 9-1. General structure of backfill requirements.](image)

9.1 Performance targets for deposition tunnel backfill and plugs

9.1.1 Definition

The sealing structures of the deposition tunnels consist of backfill and plugs. Backfill is the material or materials that is/are used for backfilling the deposition tunnels. Plugs will be placed at the mouths of the deposition tunnels. The purpose of the backfill is to keep the buffer in place, maintain favourable and predictable conditions for the buffer and the canister, and also favourable rock mechanical, hydrological and geochemical conditions in the near-field and to retard the transport of radionuclides if the canister starts leaking.

9.1.2 Performance

9.1.2.1 Maintainance of favourable conditions

Unless otherwise stated, the backfill and plugs shall fulfill the performance targets listed below over hundreds of thousands of years in the expected repository conditions except for incidental deviations.

Rationale of the requirement
The longevity requirements of the EBS components are determined on the basis of the needs for radionuclide containment. These, in turn, are governed by the radiotoxicity of the spent nuclear fuel. According to Government Decree 736/2008, section 11, the safety functions shall effectively prevent releases of radioactive substances for at least several thousand years. In Guide STUK-YVL D.5, paragraph 408, the timescale is further defined to be at least 10,000 a. Due to the radionuclide inventory and the amount of spent nuclear fuel to be disposed of (see Section 3.1.4), the design life-time of the KBS-3 type repository at Olkiluoto is hundreds of thousands of years.

The backfill's role in maintaining favourable and predictable conditions for the buffer and canister is to limit water flows in the deposition tunnel and to prevent harmful substances from e.g. the deposition tunnel plug from reaching the deposition hole. The backfill also helps to confine the buffer in its intended volume in the deposition hole and supports the host rock.

** Loads to be taken into account**

The expected repository conditions are presented in the *Performance Assessment* report. The current conditions have been presented in *Site Description*. Both the current and expected conditions are briefly summarised in Chapter 4 of this report. The backfill experiences e.g. variable salinities of the groundwater and variable groundwater flow conditions and changes of groundwater pH due to leachates from grouts and plugs.

**Related requirements**

The safety functions of the EBS components are all related to the life-time requirement. The timescale of hundreds of thousands of years is the same for all of the components. And some of the target properties of the host rock give consideration to providing favourable properties for the backfill (especially limitation of flows).

**9.1.3 Hydraulic and transport properties**

**9.1.3.1 Limitation of advective flow**

The backfill shall limit advective flow along the deposition tunnels.

**Rationale of the requirement**

One of the background assumptions in the development of the KBS-3 method has been that after backfilling and closure of the tunnels and shafts the original hydraulic and chemical conditions in the host rock would gradually be restored. A prerequisite for this is that the repository tunnels should not short-circuit hydraulically important zones and thus create new preferential flowpaths, which could also contribute to changes in the geochemical conditions of the host rock. In addition, the advective flow through the deposition tunnels should be limited to prevent them from becoming preferential transport pathways to or from the deposition holes.

One of the most probable places where preferential flow path(s) could develop is at the interface between the backfill and the rock. Advective flows in the backfill are most likely to form during the installation period and their significance diminishes after the
deposition tunnel has been plugged and once the backfill becomes saturated due to the self-sealing properties of the backfill.

**Loads to be taken into account**

The probability for advective flow along the deposition tunnels is high during the installation period and before backfill saturation and their effect depends on the flow rates. The limits for inflow into deposition tunnel scale are given in the deposition tunnel design specifications. Based on experiments and former experiences presented in Dixon et al. (2008 a,b,c) and Hansen et al. (2010), a limit of maximum local (fracture related) inflow into a deposition tunnel is 0.25 l/min at the time of backfill installation. Fractures with inflows larger than that have to be sealed. Management of water inflows may also be needed.

**Related requirements**

Limiting of advective flow is directly related to the backfill's self-sealing and self-healing requirement (Section 9.2.2.1) and to the host rock requirement to limit inflows (Section 6.3.4.3).

### 9.1.3.2 Hydraulic isolation

*The plugs shall isolate the deposition tunnels hydraulically during the operational phase of the repository.*

**Rationale of the requirement**

Advective flows are possible in the backfill after installation before the deposition tunnel backfill reaches saturation (Keto et al. 2009). Piping and erosion processes can transport buffer and backfill materials and could lead to unacceptable losses of buffer or backfill material before saturation of the backfill if the plug is not hydraulically tight. The plug also needs to be hydraulically tight to provide favourable conditions for the saturation of the backfill and buffer. The hydraulic isolation provided by the deposition tunnel plug is not of major importance after the closure of the repository, because the backfilling of the central tunnels also inhibits groundwater flows.

**Loads to be taken into account**

The inflow rates into the deposition tunnel have to be taken into account. When designing the plug, the hydraulic isolation requirement can be met if the plug has a tight contact with the host rock, and if the hydraulic conductivity of the plug is low. In addition, the plug shall need to withstand the hydraulic pressure at repository depth (from 4.1 MPa at the current designed repository depth of 420 metres, up to 7 MPa in the depth range allowed in the Decision-in-Principle 2000) and the difference between the swelling pressure of the backfill (up to 3 MPa, Hansen et al. 2010, p. 67) on the deposition tunnel side and atmospheric pressure on the central tunnel side. The location of a plug is selected so that no fractures with high flow rates intersect the plug section.

**Related requirements**

The plug shall be hydraulically isolating to enable the self-sealing properties of the backfill to be developed (Section 9.2.2.1). The host rock has a requirement to limit inflow into deposition tunnels (Section 6.3.4.3).
9.1.3.3 EBS compatibility

The chemical composition of the backfill and plugs shall not jeopardise the performance of the buffer, canister or bedrock.

Rationale of the requirement
The requirement itself is self-evident; all of the EBS components shall be manufactured from materials that are compatible with each other. If any component could significantly impair the safety functions of any other component, the whole disposal concept would become unacceptable.

Loads to be taken into account
The backfill consists of natural materials and its chemical composition depends on its source. The chemical composition of natural materials is variable. The backfill material alternatives are mostly swelling clays such as Friedland clay and others; see Keto et al. (2009), Chapter 5 and Backfill Production Line report. The materials need to be analysed for the same compounds as bentonite, e.g. sulphur, iron and organics, see Section 8.1.2.1 Limitation of amounts of substances harmful to other components.

The plug consists of concrete. The major risk for the other EBS components is the high pH leachates from the concrete, which are especially harmful for bentonite (see Section 6.3.2.3 Groundwater conditions to prevent montmorillonite dissolution, Section 6.3.1.3 Limited concentration of solutes with detrimental effect on EBS). Low pH cements have to be used. The detrimental material restrictions apply also for the aggregate material in the concrete and possible additives needed.

Related requirements
Materials potentially increasing the pH of groundwater are used also in the underground facility construction; see Section 6.3.2.3 Groundwater conditions to prevent montmorillonite dissolution. Backfill materials are similar to buffer materials regarding sensitivity to higher pH, see Section 8.1.2.1 Limitation of amounts of substances harmful to other components.

9.1.4 Support of other components of the disposal system

9.1.4.1 Ability to keep buffer in place and support deposition tunnels

The backfill shall keep the buffer in place.

and

The backfill shall contribute to the mechanical stability of the deposition tunnels.

Rationale of the requirement
At the interface between the buffer and the backfill, the buffer exerts a swelling pressure against the backfill and vice versa, depending on the evolution of the saturation process in the buffer and backfill, respectively. Since the difference in swelling pressure may be great, a net pressure arises against the backfill whereby the buffer swells and the backfill is compressed. In this process, the swelling pressure from the buffer decreases as the
density decreases. At the same time, the counterpressure from the backfill increases as it is compressed and its density increases. The swelling of the buffer and compression of the backfill are counteracted to some extent by friction against the rock. When the force of the swelling pressure in the buffer is equal to the sum of the force of the counterpressure in the backfill and the friction against the rock, the process ceases since equilibrium has been established (SKB 2010b, p.90). If the density (and swelling pressure) of the backfill is not large enough, the density of the buffer may decrease below its target range. Therefore, it is required that the backfill shall provide enough support to keep the buffer in the deposition hole.

The host rock in the deposition tunnel faces similar stability issues as the host rock in the deposition hole, i.e. spalling due to secondary stresses and elevated temperature, and due to excavation damage, which mostly happen before the installation of the backfill. The backfill needs to provide support for the rock to prevent blocks from falling and continuous water-conducting pathways from forming at the host rock-backfill interface.

**Loads to be taken into account**

The magnitude of displacement at the buffer-backfill interface depends on various factors such as the initial swelling pressure of the buffer, friction angle between the buffer and the rock, saturation state of the buffer and the backfill and composition of the backfill. Since a backfill consisting of blocks and pellets is initially heterogeneous, the deformation of the backfill is affected not only by the deformation properties of the materials used but also by the geometry of different backfill components. In order to evaluate this, a number of analytical calculations and numerical modelling cases were performed by Johannesson & Nilsson (2006), Johannesson (2008), Börgesson & Hernelind (2009) and Korkiala-Tanttu (2008). The basic assumption made in these studies was that the saturated buffer density should remain above 1950 kg/m³ at the level of the canister lid. See the discussion in Keto et al. (2009), Section 6.3.2.

How swelling of the backfill can prevent block break-outs from the tunnel ceiling and growth of fractures in the EDZ caused by creep as well as thermal and external loads is discussed in Autio et al. (2002). This is recognised and included in the requirements through the need to provide a tight contact between the backfill and the rock in order to prevent the formation of flow paths.

**Related requirements**

Most of the buffer's requirements are related to the backfill requirement of keeping the buffer in the deposition hole.

**9.1.4.2 Ability of plugs to keep backfill in place**

*The plugs shall keep the backfill in place during the operational phase.*

**Rationale of the requirement**

The main function of the deposition tunnel plug is to keep the backfill in place during the operating period of the repository when the central tunnels are still open and to provide support during the swelling of the backfill. If unsupported, the backfill block front would collapse due to water flows and uneven saturation at the pellet front and in the
block backfill, as seen in the experiments reported by Keto et al. (2009, p. 50), which could lead to a decrease of backfill density. When the tunnel is plugged, the deformation of the backfill cannot proceed indefinitely and self-sealing can close possible flow paths (see Section 9.2.2.1).

**Loads to be taken into account**
The backfill material can be transported out of the deposition tunnel if the plug is not hydraulically tight (see Section 9.1.3.2). If the plug is hydraulically tight, the backfill will begin swelling and it exerts a maximum pressure of 3 MPa on the plug (Hansen et al. 2010 p. 67), if high-swelling capacity clay is used as a backfill material. The hydraulic pressure of 4.1 MPa shall also be taken into account.

**Related requirements**
The requirement to keep the backfill in place is directly related to the requirement of hydraulic isolation (Section 9.1.3.2) and the backfill requirement to keep the buffer in place (Section 9.1.4.1).

### 9.1.4.3 Prevention of canister uplift from deposition hole

*The backfill shall contribute to prevent uplifting of the canister in the deposition hole.*

**Rationale of the requirement**
After installation of the canister and buffer the buffer starts swelling and may begin extruding into the deposition tunnel, see Section 9.1.4.1. During this process the canister may also be lifted up into the deposition tunnel. The backfill’s role is to provide a counterpressure to prevent the swelling of the buffer into the deposition tunnel and thus also to prevent canister uplift in the deposition hole.

**Loads to be taken into account**
The backfill shall be able to counter the swelling pressure of the buffer. See discussion in Section 9.1.4.1.

**Related requirements**
See Section 9.1.4.1.
9.2 Design requirements for backfill

9.2.1 Definition

The main component of the backfill material shall consist of natural swelling clays. The plugs shall consist of materials that have a good hydraulic isolation capacity and that will not undergo large volume changes in the long term.

9.2.2 Performance

9.2.2.1 Self-sealing and self-healing

The backfill shall be designed to be self-sealing after initial installation and self-healing after any hydraulic or mechanical disturbances.

Rationale of the requirement

The contact between backfill and rock is not initially tight after installation. The shape of the tunnel limits the cross-section area that can be filled with blocks. The effect is more pronounced due to excavation tolerances and the rate of over-excavation; see Hansen et al. (2010), Chapter 2. According to Hansen et al. (2010), the average block filling degree of the deposition tunnel is 73.5% if the over-excavation rate is 10%. The remaining space will be filled with pellets. The pellet front will initially have void spaces larger than those of the block backfill. Water movement through the backfill is likely to develop as discrete flow channels along the rock-pellet interface before the backfill saturates, resulting in transfer of water and possibly backfill material from the backfilled tunnel towards the deposition tunnel plug. The backfill material shall be such that it can self-seal the pellet front in order to prevent formation of permanent flow paths.

Loads to be taken into account

The backfill shall be self-sealing and self-healing during all expected repository conditions, see the Performance Assessment report. The backfill must be able to self-seal the pellet front and the boundary between pellets and blocks initially to prevent formation of flow paths on the interfaces. Mass loss possibly happening during saturation must be compensated by self-healing. Rock shears happening across the deposition tunnel will disturb the backfill to some extent. The backfill needs to self-heal after such events. The backfill shall also not lose its safety functions in case of a rock shear (Section 6.3.5).

The plugged deposition tunnels may face hydraulic disturbances during the operating period of the repository and during glacial periods, which may affect water inflow into the tunnels and flow through the tunnels under saturated conditions. Possible mechanical disturbances include a rock shear which may happen during the stress changes during glacial periods.

Related requirements

Most of the backfill requirements are related to the self-sealing and -healing requirement. Also, the buffer needs the counterpressure from the backfill to stay in the deposition hole (Section 9.1.4.1).
9.2.3 Hydraulic properties

9.2.3.1 Hydraulic conductivity

The backfill shall be so designed that its hydraulic conductivity over the whole cross-section of the backfilled tunnel will be ≤1·10^{-10} m/s after full saturation.

Rationale of the requirement

The hydraulic conductivity requirement is derived from backfill's subsystem requirement to limit advective flow (Section 9.1.3.1). In order to limit advective flow in the deposition tunnels, the backfill shall, over the entire length and cross-section of the tunnel, have a hydraulic conductivity that is in the same order of magnitude as that of the surrounding rock.

Loads to be taken into account

The backfill materials and manufacturing methods shall be selected so that this requirement is achieved. The hydraulic conductivity in the rock around a deposition tunnel is affected by the EDZ. The hydraulic conductivity of the EDZ in the deposition tunnel can, if it all develops into a continuous volume, be kept below 1·10^{-8} m/s (Bäckblom 2008). Furthermore, by proper blasting design it is likely that no continuous EDZ develops at all (Mustonen et al. 2010, SKB 2011a, p. 160). The average hydraulic conductivity of Olkiluoto host rock at repository level is approximately 1·10^{-10} m/s (Site Description, Chapters 6 and 11).

Related requirements

The hydraulic conductivity requirement is derived from backfill subsystem requirements (Section 9.1.3.1). The hydraulic conductivity requirement is closely related to the self-sealing requirement (Section 9.2.2.1).

9.2.3.2 Service lifetime of plugs

The plugs shall be designed to maintain their hydraulic isolation capacity at least as long as the central tunnels are open

Rationale of the requirement

The plug's main function is to keep the backfill in place. After the central tunnels are backfilled, the deposition tunnel plug has performed most of its tasks. The backfill of the central tunnels is made from swelling clays as in the deposition tunnels, and the swelling pressure of the backfill in the central tunnels helps in keeping the deposition tunnel backfill in place.

 Loads to be taken into account

The operating period of the repository is approximately 100 years, although some of the repository panels may be closed earlier. The design service lifetime of the plugs shall be at least 100 years.

Related requirements

The service lifetime requirement is related to all of the backfill requirements.
9.2.4  Mechanical properties

9.2.4.1  Ability of plugs to withstand swelling and hydrostatic pressure

The plug shall be designed to withstand the sum of the swelling pressure of the backfill and the hydrostatic pressure of the groundwater at the repository depth.

Rationale of the requirement
The plug shall withstand the swelling pressure of backfill and hydrostatic pressure of water in order to support the performance of the backfill during the operating period of the repository. The plug provides a support for the swelling of the backfill by keeping it in place. A loss of this support would result in a loss of backfill swelling pressure in the deposition tunnel, and jeopardise the performance of the backfill and buffer.

 Loads to be taken into account
The maximum swelling pressure of backfill is 3 MPa (Hansen et al. 2010 p. 67), if a high-swelling capacity clay is used as a backfill material. The hydrostatic pressure at repository depth is 4.1 MPa.

Related requirements
Because the main function of the plug is to keep the backfill in place, all of the backfill’s requirements depend on the ability of the plug to provide its safety functions.

9.2.4.2  Ability of plugs to maintain backfilling function

The plugs must be designed to maintain a backfilling function even after their hydraulic isolation capacity has been lost.

Rationale of the requirement
Concrete is a major component of the deposition tunnel plugs. Concrete structures have a finite lifetime in repository conditions due to material dissolution. The service lifetime requirement of the plugs, which has been defined to be only up to approximately 100 years (Section 9.2.3.2), reflects this. When the central tunnels have been backfilled during closure, the plugs start losing their hydraulic isolation capacity slowly. Material loss due to dissolution results finally in cavity formation in the plugs. Backfill from both the central and deposition tunnel can start expanding into the formed open space. The plug must contain some components with long-term stability, which will help keep the backfill densities sufficiently high to maintain the safety functions and performance targets of the backfill.

 Loads to be taken into account
The plug shall be designed in such a way that the mass loss from the backfill is limited to an acceptable level.

Related requirements
If this requirement is not met, the safety functions of the backfill may not be met either. Therefore this requirement is related to all backfill requirements, and also indirectly to the buffer density requirements.
9.2.4.3  Contact with host rock

In the initial state the backfill shall have a good contact with the host rock.

**Rationale of the requirement**
The backfill needs to be designed in such a way that a good contact is achieved with certainty to prevent flow paths from forming and to limit advective flow, see Section 9.1.3.

**Loads to be taken into account**
See Section 9.1.3. The excavation tolerances of the deposition tunnel shall be taken into account.

**Related requirements**
The contact with host rock is not initially tight but is achieved through self-sealing during saturation (Section 9.2.2.1).

9.2.5  Chemical properties

9.2.5.1  Limited content of harmful substances

*Backfill and plug materials shall be selected so as to limit the contents of harmful substances (organics, oxidising compounds, sulphur and nitrogen compounds) and microbial activity.*

**Rationale of the requirement**
Harmful substances may arise from several sources: the backfill, deposition tunnel plug and from cement groutings, see Section 9.1.3.3. The backfill shall be designed to limit the transport of harmful substances from these sources to the buffer.

**Loads to be taken into account**
See Section 9.1.3.3.

**Related requirements**
The backfill shall limit the transport of any harmful substance that may be present in the EBS components, thus this requirement is related to all EBS compatibility requirements. This requirement complements the retardation function of the backfill.

9.2.6  Support other systems

*To keep the buffer in place, the design of the backfill has to take into account, on the one hand, the compressibility and structural stiffness of the backfill, and, on the other hand, the buffer swelling pressure and the friction of buffer against the deposition hole walls.*

**Rationale of the requirement**
The swelling pressure of the buffer is higher than the swelling pressure of the backfill, and saturation of the buffer may happen before saturation of the backfill. As buffer be-
gins swelling, it can extrude out of the deposition hole and begin compressing the backfill, resulting in a lower buffer density. The backfill must have such properties that buffer extrusion does not result in too low a buffer density. Backfill-buffer interactions have been discussed in Keto et al. (2009), Section 6.3 and Korkiala-Tanttu (2008).

**Loads to be taken into account**
The swelling pressure of the buffer may be up to 15 MPa due to formation of Ca-Na-bentonite. The friction between host rock and buffer shall also be taken into account.

**Related requirements**
The requirement of backfill compressibility may affect all of the buffer requirements if it is not met. Also, this requirement is related to the backfill requirement to keep the canister in place (Section 9.1.4.3).
10 CLOSURE

The closure of the disposal facility covers all backfilling and plugs outside the deposition tunnels. The safety functions of the closure materials and structures complement those of the EBS and the host rock. The main function of closure is to prevent the disposal facility openings from compromising the long-term isolation of the repository from the surface environment. The closure shall contribute to favourable and predictable geochemical and hydrogeological conditions for the engineered barriers by preventing the formation of significant water conductive flow paths through the openings. The closure shall also contribute to help restoring natural host rock conditions in the repository system as well as limiting and retarding releases of harmful substances from the repository. The general structure of the closure requirements is shown in Figure 10-1.

![Figure 10-1. General structure of closure requirements.](image)

10.1 Performance targets for closure

10.1.1 Definition

_Closure of the disposal facility includes backfill and plugs in access and central tunnels, shafts, miscellaneous excavations, and investigation holes. Different types of closure components may be used in different parts of the repository volumes. Closure shall complete the isolation of the spent fuel and support the safety function of the other barriers._
10.1.2  Fulfillment of requirements for hundreds of thousands of years

*Unless otherwise stated, the closure materials and structures shall fulfill the performance targets listed below over hundreds of thousands of years in the expected repository conditions except for incidental deviations.*

**Rationale of the requirement**
The life-time requirement for the materials and structures used in closure is based on the need to contain the spent nuclear fuel. See discussion in Section 7.1.2.2.

**Loads to be taken into account**
The structures and materials used in the closure shall fulfill their performance requirements in the expected repository conditions during the expected evolution, except for incidental deviations. The expected evolution is described in the *Performance Assessment* report.

**Related requirements**
The service lifetime requirement of closure is related to the similar requirements set for canister, buffer and backfill.

10.1.3  Prevent intrusion

*Closure shall complete the isolation of the spent nuclear fuel by reducing the likelihood of unintentional human intrusion through the closed volumes.*

**Rationale of the requirement**
Government Decree 736/2008, section 12, states that the intrusion of humans to the repository shall be made difficult. The depth of the repository is such that most human actions do not reach the repository, with the exception of possible site investigation drillings undertaken by far future populations (STUK-YVL D.5, paragraph 315). The most probable intrusion scenario is through the openings made during excavation and operation of the disposal facility, if knowledge about the contents of the repository is lost from societal memory and the repository is "found" again. The closure structures for the access tunnel and shafts need to be designed to discourage intrusion in such cases.

**Loads to be taken into account**
Only the likelihood of inadvertent intrusion can be reduced. The sealing structures shall be designed such that deliberate actions are needed to re-enter the repository even after long periods of time.

**Related requirements**
This requirement is related to closure requirement to restore natural conditions (Section 10.1.4).
10.1.4 Restoration of natural conditions

 Closure shall restore the favourable, natural conditions of the bedrock as well as possible.

Rationale of the requirement

One of the background assumptions in the development of the KBS-3 method has been that after backfilling and closure of the tunnels and shafts the original hydraulic and chemical conditions in the host rock would gradually be restored. A prerequisite for this is that the tunnels and shafts of the disposal facility should not short-circuit hydraulically important zones and thus create new preferential flowpaths, which could also contribute to changes in the geochemical conditions of the host rock. In addition, the advective flow through the deposition tunnels should be limited to prevent them from becoming preferential transport pathways to or from the deposition holes.

One of the most probable places where preferential flow path(s) could develop is at the interface between the backfill materials and the rock. Advective flows in the backfill are most likely to form during the installation period and their significance diminishes after the disposal facility has been closed and once the swelling backfill materials become saturated.

Loads to be taken into account

The hydraulic conductivity of the materials and structures used in closure shall be close to those of the host rock at the same depths. The materials used shall not contain harmful substances that might further disturb the groundwater chemistry. The formation of preferential flowpaths needs to be prevented. The closure of the upper parts of access routes also needs to withstand the effects of permafrost and glacial periods without compromising the safety of the repository.

The shafts and access tunnel intersect with some major hydraulically conducting fractures. The sealing of the access routes at these zones needs special consideration.

Related requirements

The requirement is related to the EBS compatibility requirements of canister, buffer and backfill (Sections 7.1.5, 8.1.2.1, and 9.1.3.3).

10.1.5 Transport properties

 Closure shall prevent the formation of preferential flow paths and transport routes between the ground surface and deposition tunnels/deposition holes.

Rationale of the requirement

When tunnels, shafts and drillholes are drilled or excavated, flow paths are created. These flow paths have to be sealed during closure to restore isolation. The radionuclide transport analyses have not taken directly into account transport in the underground openings because shorter transport paths have been found (Posiva 2008a, 2010a, p. 217). If the openings are not backfilled and sealed properly, groundwater flow rates can increase in deposition tunnels (Posiva 2010a, p. 217).
**Loads to be taken into account**

In order to prevent formation of preferential flow paths and transport routes, the hydraulic conductivity of backfill in different facility sections needs to be sufficiently low to allow the natural host rock hydraulic conditions to be restored after closure. Fracture zones such as HZ19 and HZ20 need to be considered carefully due to their high transmissivities, which may increase erosion in the backfill and plugs and contribute to formation of flow routes in the closed excavations.

Permafrost in the upper parts of the host rock is expected during the repository evolution, see *Performance Assessment* report. The materials used to close the access routes down to the estimated permafrost depth need to be selected such that they withstand freezing and thawing without compromising the safety of the repository.

**Related requirements**

Closure supports the isolation requirements of host rock (Sections 6.3.4) and the buffer (Section 8.1.2).

**10.1.6 EBS compatibility**

_Closure shall not endanger the favourable conditions for the other parts of the EBS and the host rock._

**Rationale of the requirement**

The EBS must be able to function as a whole, and its different components must act together. Closure contributes to the fulfilment of the protection of the EBS by limiting groundwater flow and transport of harmful substances. The closure components shall also not harmfully affect the EBS components of the host rock.

**Loads to be taken into account**

The backfill consists of natural materials and its chemical composition depends on its source. The chemical composition of the natural materials used in closure structures is variable. The backfill material alternatives possibly used in closure may be similar to those of backfill, i.e. lower quality swelling clays; see Keto et al. (2009), Chapter 5 and Section 9.1.3.3. The materials need to be analysed for the same compounds as bentonite, e.g. sulphur, iron and organics, see Section 8.1.2.1.

The plugs consist of concrete. The major risk for the EBS components is the high pH leachates from the concrete, which are especially harmful for bentonite (see Sections 6.3.2.3, 6.3.1.3). Low pH cements have to be used close to the repository level where harmful high pH leachates could have detrimental interactions with the backfill and buffer (*Closure Production Line* report).

**Related requirements**

This requirement is closely related to the closure requirement to prevent formation of flow paths, see Section 10.1.5. See also Section 10.2.2.5.
10.1.7 Retrievability

Retrieval of the spent nuclear fuel canisters shall be technically feasible in spite of repository tunnel and closure structures.

Rationale of the requirement
The requirement of retrievability has been set in the Decisions-in-Principle given to Posiva. The reasoning behind the requirement is that future generations can, if they so wish, retrieve the spent nuclear fuel from the repository. Different motivations can be envisaged for retrieving the spent nuclear fuel.

Loads to be taken into account
Retrievability is possible as long as the canisters are intact, which mostly depends on the corrosion processes and rates, which depend on the chemical and microbiological conditions near the canister. The structures and materials used in closure need to be designed in a way that retrievability is possible, however keeping in mind that inadvertent human intrusion shall be prevented as far as possible (see Section 10.1.3).

Related requirements
The canister requirements on containment (Section 7.1.2), chemical and corrosion resistance (Sections 7.2.2.1 and 7.2.3.1) relate closely to the requirement on retrievability because the canisters can be safely retrieved only as long as they are intact.

10.2 Design requirements for closure

10.2.1 Definitions

Backfill in the context of closure refers to the materials utilised to backfill investigation holes and excavated rock openings other than deposition tunnels.

Plugs in the context of closure refer to structures utilized for one of the following purposes: 1) for isolation of different facility sections during the operational phase, 2) for avoiding the formation of transport routes through the tunnels and other excavated openings over the long-term, 3) for obstructing inadvertent human intrusion into the repository through existing tunnels and shafts after closure over the long-term, and 4) for stabilising sections of investigation holes that intersect water-bearing fracture zones.

10.2.2 Performance

10.2.2.1 Prevention of human intrusion

The ground surface of the disposal area shall be landscaped to resemble its natural surroundings.

and
Structures and materials that considerably obstruct unintentional intrusion shall be utilized in the closure of the uppermost parts of the facility and investigation holes extending to the ground surface.

**Rationale of the requirement**
These requirements contribute to the requirement for the obstruction of inadvertent human intrusion. The landscape in the repository area shall not draw attention to itself after closure, and access routes to the repository shall be sealed so that they are not easily found, and if found, are not easily accessible.

**Loads to be taken into account**
Not applicable.

**Related requirements**
These requirements are derived from the subsystem requirement on preventing inadvertent human intrusion, see Section 10.1.3.

10.2.2.2 Ability to withstand conditions during expected evolution

Structures and materials of the closure components shall be selected in such a way that the isolation functions of closure can be provided despite possible loadings related to glacial cycles, such as permafrost or changing groundwater chemical conditions.

and

Rock materials shall be used increasingly as backfill when moving from the disposal depth up to the ground surface due to the increasing risk of clay erosion.

**Rationale of the requirement**
The isolation functions of closure shall not be lost in events and processes taking place during the expected evolution, which will introduce permafrost at least in closure components close to surface. Changing chemical conditions are expected during the evolution of the repository and the site. Glaciations are expected to take place during the evolution of the repository, see Performance Assessment report. During periods of cold climates the permafrost is expected to reach depths down to nearly 300 m at most (Hartikainen 2012). The permafrost depth is variable throughout the site evolution, and the structures used in the closure of upper parts of the disposal facility will thus freeze and thaw several times. The performance of the plugs and backfill at these levels shall not be completely lost as a consequence in order to preserve isolation of the repository.

The risk of backfill erosion becomes higher when moving from the deposition depth towards the ground surface because environmental loadings become stronger as one approaches the ground surface. Erosion might result in advective water flow in places where it would not naturally occur and hence the use of an erosion-resistant material such as rock is necessary especially near the ground surface. Materials less prone to being adversely affected by freezing and thawing shall be used in the zone where such processes are expected.
Loads to be taken into account
The permafrost analysis done by Hartikainen (2012) suggests that permafrost may affect at its maximum the uppermost 300 metres of the bedrock. See also discussion in the Performance Assessment report. Glacial erosion has to be taken into account in the top-most parts of the disposal facility closure components.

Related requirements
None identified.

10.2.2.3 Transport properties

Closure as a whole shall be so designed that the hydraulic connections from the disposal depth to the surface environment through the closed tunnels, shafts, and investigation holes are not better than through existing natural fractures and fracture zones.

and

Sections in the underground openings intersected by highly transmissive zones such as the HZ20 structure shall be hydraulically isolated from other facility sections.

and

The closure as a whole shall be so designed that short-cuts from the deposition tunnels/deposition holes to existing significant groundwater flowpaths are prevented.

Rationale of the requirement
This requirement has been discussed in Section 10.1.5.

Loads to be taken into account
This requirement has been discussed in Section 10.1.5.

Related requirements
This requirement has been discussed in Section 10.1.5.

10.2.2.4 Ability to keep backfill in place

The closure components shall keep the backfill and plugs of the deposition tunnels in place.

Rationale of the requirement
The deposition tunnel plugs are designed to be able to withstand the swelling pressure of the backfill during the operational period, i.e. up to approximately 100 years. After that the backfilling of the closure shall provide support in the central tunnels and help keep the deposition tunnel backfill in place so that its safety functions can be met for the design lifetime of the repository.

Loads to be taken into account
The swelling pressure of the backfill is 3 MPa at most (Hansen et al. 2010, p. 67). In addition to that, the hydraulic pressure at repository depth is 4.1 MPa. The expected
changes in the hydrogeochemistry shall be taken into account, because they may cause changes in the swelling pressures on clay-based materials.

**Related requirements**
This requirement is related to the performance requirements set for the backfill.

**10.2.2.5 Chemical properties**
The amount of chemical species harmful for canister/buffer/deposition tunnel backfill/host rock in closure components shall be limited.

**Rationale of the requirement**
All of the closure and other EBS components shall be manufactured from materials that are compatible with each other. If any component could significantly impair the safety functions of any other component, the safety functions (isolation and containment) will not be met.

**Loads to be taken into account**
The backfill consists of natural materials and its chemical composition depends on its source. The chemical composition of natural materials is variable. The backfill material alternatives possibly used in closure of the lower levels of the disposal facility may be similar to those of deposition tunnel backfill, i.e. lower quality clays; see *Closure Production Line* report, Keto et al. (2009), Chapter 5, and Section 9.1.3.3 of this report. Materials used near the ground surface do not need to have swelling components and more focus is on the ability to withstand meteoric waters and freezing and thawing. The materials need to be analysed for the same compounds as bentonite, e.g. sulphur, iron and organics, see Sections 6.3.1.3 and 6.3.2.3.

The plugs consist of concrete. The major risk for the other EBS components is the high pH leachates from the concrete, which are especially harmful for bentonite and backfill materials (see Sections 6.3.2.3 and 6.3.1.3). Low pH cements have to be used at repository depth, see also Section 9.1.3.3. Iron used in the concrete structures has a detrimental effect on swelling clays as the iron is released via the corrosion process. Iron may react with the clay fraction in either backfill or buffer by sorption (e.g. Géhin et al. 2007) and by altering the montmorillonite structure (Lantenois et al. 2005). The precipitation of iron corrosion products as well as the Fe-smectite interaction process may lead to cementation effects at the Fe source/bentonite interface. However, there are situations where these interactions may be allowed in the closure structures, for example in the plug structures whose performance is not jeopardised by the clay alteration.

**Loads to be taken into account**
Materials that are harmful for the buffer and backfill shall not be used in the design of the plug. The materials shall be selected according to Posiva's Material Handbook. The use of foreign materials is discussed in Kasa (2010).

**Related requirements**
The EBS compatibility requirements for all of the EBS components are similar to this.
11 REFERENCES

TURVA-2012 Portfolio MAIN reports

Assessment of Radionuclide Release Scenarios for the Repository System

Biosphere Assessment

Biosphere Data Basis

Biosphere Radionuclide Transport and Dose Assessment Modelling

Complementary Considerations

Description of the Disposal System

Design Basis

Dose Assessment for the Plants and Animals

Features, Events and Processes

Formulation of Radionuclide Release Scenarios
Safety case for the disposal of spent nuclear fuel at Olkiluoto - Formulation of Radionu-

Models and Data for the Repository System

Performance Assessment

Surface and near-surface hydrological modelling

Synthesis

Terrain and Ecosystem Development Modelling

TURVA-2012 Portfolio SUPPORTING reports

Backfill Production Line report

Biosphere Description

Buffer Production Line report

Canister Production Line report

Closure Production Line report
Site Description

Underground Openings Production Line report

Design Reports


Other reports


Bäckblom, G. 2008. Excavation damage and disturbance in crystalline rock – results from experiments and analyses. SKB TR-08-08.


SKB 2011a. Long-term safety for the final repository for spent nuclear fuel at Forsmark Main report of the SR-Site project. SKB TR-11-01.


## Appendix A. Requirement tables

*Table A-1. VAHA Level 1 - Stakeholder requirements.*

<table>
<thead>
<tr>
<th>ID</th>
<th>Level 1 - Stakeholder Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1-STH-1</td>
<td>General principles of the use of nuclear energy</td>
</tr>
<tr>
<td>L1-STH-2</td>
<td>The use of nuclear energy must be safe; it shall not cause injury to people, or damage to the environment or property.</td>
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<tr>
<td>L1-STH-3</td>
<td>The use of nuclear energy without the licence provided by this Act is prohibited.</td>
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<tr>
<td>L1-STH-4</td>
<td>It shall be the licensee's obligation to assure safe use of nuclear energy.</td>
</tr>
<tr>
<td>L1-STH-5</td>
<td><strong>Requirements concerning the safety of disposal of spent fuel</strong></td>
</tr>
<tr>
<td></td>
<td>L1-STH-6 The safety of nuclear energy use shall be maintained at as high a level as practically possible.</td>
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<td></td>
<td>L1-STH-7 The safety of a nuclear facility shall be ensured by means of successive levels of protection independent of each other (safety principle of defence-in-depth). This principle shall extend to the operational and structural safety of the plant.</td>
</tr>
<tr>
<td></td>
<td>L1-STH-8 The long-term safety of disposal shall be based on safety functions achieved through mutually complementary barriers so that a deficiency of an individual safety function or a predictable geological change will not jeopardise the long-term safety.</td>
</tr>
<tr>
<td></td>
<td>L1-STH-9 Targets based on high quality scientific knowledge and expert judgement shall be specified for the performance of each safety function. In doing so, the potential changes and events affecting the disposal conditions during each assessment period shall be taken into account. In an assessment period extending up to several thousands of years, one can assume that the bedrock of the site remains in its current state, taking however account of the changes due to predictable processes, such as land uplift and those due to excavations and disposed waste.</td>
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<td>L1-STH-10 Safety functions shall effectively prevent releases of disposed radioactive materials into the bedrock for a certain period, the length of which depends on the duration of the radioactivity in waste. For short-lived waste, this period shall be at least several hundreds of years, and for long-lived waste, at least several thousands of years.</td>
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<td>L1-STH-11 The safety approach for disposal of spent fuel shall be that the safety functions provided by the engineered barriers will limit effectively the release of radioactive substances into bedrock for at least 10,000 years. Respectively, the length of effective containment provided by the engineered barriers shall be at least 500 years for short-lived waste.</td>
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<td>L1-STH-12 Performance targets for the safety functions of engineered barriers shall be specified taking account of the activity level of waste and the half-lives of dominating radionuclides.</td>
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<td>L1-STH-13 For the further development of safety, measures shall be implemented that can be considered justified considering operating experience and safety research and advances in science and technology.</td>
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<td>L1-STH-14 Compliance with the requirements concerning long-term radiation safety, and the suitability of the disposal method and disposal site, shall be proven through a safety case that must analyse both expected evolution scenarios and unlikely events impairing long-term safety.</td>
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<tr>
<td></td>
<td>L1-STH-15 Unlikely events induced by natural phenomenon to be considered shall include at least rock movements jeopardizing the integrity of disposal canisters.</td>
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<td>Level 1 - Stakeholder Requirements</td>
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<tr>
<td>L1-STH-16</td>
<td><strong>Radiation safety</strong></td>
</tr>
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</table>
| L1-STH-17 | Disposal of nuclear waste shall be planned so that in any assessment period, during which the radiation exposure of humans can be assessed with sufficient reliability, and which shall extend at a minimum over several millennia, radiation impacts arising as a consequence of expected evolution scenarios will not exceed the following constraints:  
1) the annual dose to the most exposed people shall remain below the value of 0.1 mSv; and  
2) the average annual doses to other people shall remain insignificantly low. |
| L1-STH-18 | During assessment periods after the period referred to in subsection 2 of section 4 in the Government Decree 736/2008, average quantities of radioactive materials over long time periods, released into the living environment from the disposed nuclear waste, shall remain below the maximum values specified separately for each radionuclide by the Radiation and Nuclear Safety Authority (STUK). |
| L1-STH-19 | The nuclide specific constraints for the radioactive releases to the environment (average release of radioactive substances per annum) referred to above are as follows:  
- 0.03 GBq/a for the long-lived, alpha emitting radium, thorium, protactinium, plutonium, americium and curium isotopes  
- 0.1 GBq/a for the nuclides Se-79, Nb-94, I-129 and Np-237  
- 0.3 GBq/a for the nuclides C-14, Cl-36 and Cs-135 and for the long-lived uranium isotopes  
- 1 GBq/a for the nuclide Sn-126  
- 3 GBq/a for the nuclide Tc-99  
- 10 GBq/a for the nuclide Zr-93  
- 30 GBq/a for the nuclide Ni-59  
- 100 GBq/a for the nuclide Pd-107. |
<p>| L1-STH-20 | These constraints given by STUK (Guide YVL D.5, section 312) apply to activity releases which arise from expected evolution scenarios and which may enter the environment earliest after several thousands of years. These activity releases can be averaged over 1000 years at the most. The sum of the ratios between the nuclide specific activity releases and the respective constraints shall be less than one. |
| L1-STH-21 | Releases of radioactive materials caused by the use of nuclear energy shall be limited in compliance with the principle laid down in paragraph 2, section 2 of the Radiation Act (592/1991) (principle of optimization, ALARA principle). |
| L1-STH-24 | <strong>Disposal site</strong> |
| L1-STH-25 | Emplacement rooms are not allowed to be build beneath such areas where new nuclear power plant units are planned to be built in the future. |
| L1-STH-26 | The geological characteristics of the disposal site shall, as a whole, be favourable to the isolation of the radioactive substances from the environment. |
| L1-STH-27 | For the purposes of disposal facility design and acquiring data required for safety assessments, the geological characteristics of the host rock at the site shall be characterized through investigations at the intended disposal depth, in addition to surface based investigations. |
| L1-STH-28 | The layout, excavation, construction and closure of underground facilities shall be implemented so that the characteristics of the host rock deemed important in terms of long-term safety are retained, as far as possible. |
| L1-STH-29 | The characteristics of the host rock shall be favourable regarding the long-term performance of engineered barriers. Such conditions in the bedrock as are of importance to long-term safety, shall be stable or predictable up to at least several thousands of years. The range of geological changes which occur thereafter, particu- |</p>
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<td>larly due to the large scale climate changes, shall be estimable and be considered in specifying the performance targets for the safety functions.</td>
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</table>
| L1-STH-30 | The construction, operation and closure of the waste emplacement rooms and other underground openings shall aim at maintaining the rock characteristics important to long-term safety. For this purpose, particularly in case of the implementation of spent fuel disposal,  
- such rock construction methods shall be used that limit the excavation disturbances in rock around waste emplacement rooms  
- reinforcement and injection of host rock shall be done so that no significant amounts of substances detrimental to the performance of barriers enter the waste emplacement rooms  
- introduction of organic and oxidising substances to the waste emplacement rooms shall be minimised  
- waste emplacement rooms shall be backfilled and closed as soon as expedient with regard to the disposal activities and related monitoring activities. |
| L1-STH-31 | Any area with a feature that is substantially adverse to long-term safety shall not be selected as the disposal site. |
| L1-STH-32 | The planned final disposal site shall contain sufficiently large, intact rock volumes that facilitate the construction of the waste emplacement rooms. |
| L1-STH-33 | The depth of the waste emplacement rooms shall be selected appropriately as regards the waste type and local geological conditions. The goal related to disposal depth shall be that any impacts on the long-term safety of above-ground events, activities and environmental changes will remain minor and that intrusion into the waste emplacement rooms will be difficult. |
| L1-STH-34 | The bedrock of the disposal site shall be such that it adequately acts as a natural barrier, as specified in Guide YVL D.5, paragraph 406. Factors indicating unsuitability of a disposal site may include at least  
- proximity of exploitable natural resources  
- abnormally high rock stresses with regard to the strength of the rock  
- predictable anomalously high seismic or tectonic activity  
- exceptionally adverse groundwater characteristics, such as lack of reducing buffering capacity and high concentrations of substances which might substantially impair the safety functions. |
<p>| L1-STH-35 | Such structures and other characteristics of rock surrounding the waste emplacement rooms which may have importance regarding groundwater flow, rock movements or other factors affecting long-term safety, shall be defined and classified. Modifications of the layout of the underground openings shall be provided for in case that the quality of rock surrounding the designed excavations proves to be significantly inferior to the design basis. |
| L1-STH-36 | The location of the repository shall be favourable with respect to the groundwater flow regime at the disposal site. The disposal depth shall be selected giving priority to long-term safety, taking into account the geological structures of the bedrock as well as the trends with depth in hydraulic conductivity, groundwater chemistry and rock stress - strength ratio. |
| L1-STH-37 | Design of the disposal facility and practices |
| L1-STH-38 | The design of a nuclear waste facility shall take account of any impacts caused by potential natural phenomena and other events external to the facility. |
| L1-STH-39 | The disposal of nuclear waste in a manner intended as permanent shall be planned giving priority to safety and so that ensuring long-term safety does not require the surveillance of the final disposal site. |
| L1-STH-40 | The planning of the construction, operation and closure of a disposal facility shall take account of reduction of the activity of nuclear waste through interim storage, the utilisation of high-quality technology and scientific data and the need to ensure long-term safety via investigations and monitoring. |
| L1-STH-42 | Ensuring the long-term safety requires that the disposal canisters fulfil high quality requirements. |</p>
<table>
<thead>
<tr>
<th>ID</th>
<th>Level 1 - Stakeholder Requirements</th>
</tr>
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</table>
| L1-STH-43 | Acceptance criteria shall be drawn up for the characteristics of the disposal canister of importance to the safety of disposal and only canisters meeting these criteria shall be transferred to the disposal facility. In order to verify the consistence with the acceptance criteria, the licensee shall  
  - prepare the construction plan for each canister type in accordance with Guide YVL 4.2 (YVL E.2)  
  - qualify the manufacturing methods and organisations of the canister components in accordance with Guide YVL 1.14 (YVL E.3)  
  - control the manufacture of the canister components in adequate extent  
  - perform a reception inspection for the canister components transferred to the encapsulation facility including review of the quality control records and verifying tests  
  - perform a final inspection after sealing of the canister including verification of the acceptability of welding and confirmation that the canister has not damaged during encapsulation. |
| L1-STH-44 | Natural phenomena to be considered in the design of the disposal facility include at least lightning, earthquake and flood. Potential internal events to be considered, besides those discussed above (handling failure, fire and explosion), include at least tunnel collapse and flooding due to pumping failure of leak waters. |
| L1-STH-45 | The design of the safety functions shall aim to provide a disposal concept that is not sensitive to changes in the bedrock. Another design objective shall be that the characteristics of waste packages or the disposal environment will not evolve with time in a way that may affect adversely the safety functions. |
| L1-STH-46 | Systems, structures and components of a disposal facility shall be classified according to their functional and structural importance to safety. The classification shall be based besides the operational safety, also the long-term safety of disposal. The safety class shall be considered in setting requirements for the design, fabrication, installation, testing and inspection of a system, structure or component. Structures and components shall also be classified on the basis of resistance to environmental conditions. The classifications related to the operation of the disposal facility shall comply with Guide YVL 2.1 (YVL B.2) as applicable. |
| L1-STH-47 | The prevention of fires and explosions shall be primarily based on the layout and design of fire compartments. The materials to be used shall be predominantly incombustible and heat resistant. No materials or equipment that could increase the fire load or cause the risk of fire ignition or explosion, shall be placed within fire compartments important to safety or in their immediate vicinity. |
| L1-STH-48 | The layout of the disposal facility shall be designed so that the waste emplacement activities are appropriately separated from the transfers of excavated rock, backfill materials and heavy machinery. Excavation induced rock collapses or displacements in openings where waste canister emplacement is underway or completed, shall be prevented by careful excavation, rock support, and by keeping these openings at sufficient distance from the excavation activities. |
| L1-STH-49 | Operation of the disposal facility |
| L1-STH-50 | In handling of spent nuclear fuel, any damage to the fuel shall be prevented to a high degree of certainty. |
| L1-STH-51 | The emplacement activities shall be separated from the excavation and construction work of the disposal facility in such a manner as to ensure that excavation and construction work cannot have any harmful impact on the operational safety of the facility or the long-term safety of disposed waste. |
| L1-STH-52 | During the construction and operation of the disposal facility, an investigation, testing and monitoring program shall be executed to ensure the suitability for disposal of the rock to be excavated, to determine safety relevant characteristics of the host rock and to ensure long-term performance of barriers. This program shall include at least  
  - characterization of the rock volumes intended to be excavated  
  - monitoring of rock stresses, movements and deformations in rock surrounding the waste emplacement rooms  
  - hydrogeological monitoring of rock surrounding the waste emplacement rooms  
  - monitoring of groundwater chemistry at the disposal site |
<table>
<thead>
<tr>
<th>ID</th>
<th>Level 1 - Stakeholder Requirements</th>
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<tbody>
<tr>
<td></td>
<td>• monitoring of the behaviour of engineered barriers.</td>
</tr>
<tr>
<td>L1-STH-53</td>
<td>Transfer into the disposal position of a spent fuel canister or other waste package with long-term durability requirements, alongside the installation of buffer and backfill materials, shall be performed so that no damages compromising the performance of the engineered barriers will occur.</td>
</tr>
<tr>
<td>L1-STH-54</td>
<td><strong>Prevention of incidents and accidents</strong></td>
</tr>
<tr>
<td>L1-STH-55</td>
<td>The disposal package containing spent nuclear fuel shall be designed so that no self-sustaining chain reaction of fissions can occur, even in the disposal conditions.</td>
</tr>
<tr>
<td>L1-STH-56</td>
<td>In handling of spent nuclear fuel, occurrence of a self-sustaining chain reaction of fissions shall be prevented to a high degree of certainty.</td>
</tr>
<tr>
<td>L1-STH-57</td>
<td>The formation of such spent fuel configurations that would cause an uncontrolled chain reaction of fission shall be prevented by means of structural design of systems and components.</td>
</tr>
<tr>
<td>L1-STH-58</td>
<td>The repository for spent fuel shall be located at the depth of several hundreds of meters in order to mitigate adequately the impacts from aboveground natural phenomena, such as glaciation, and human actions.</td>
</tr>
<tr>
<td>L1-STH-59</td>
<td><strong>Retrievability</strong></td>
</tr>
<tr>
<td>L1-STH-60</td>
<td>The final disposal shall be designed in such a manner that the repository can be opened, if advanced technology renders it appropriate. Retrievability means that even in the post-closure phase, it is possible to retrieve the spent fuel canisters from the repository for a sufficiently long time.</td>
</tr>
<tr>
<td>L1-STH-61</td>
<td>Facilitation of retrievability shall not impair the long-term safety.</td>
</tr>
</tbody>
</table>
### Table A-2. VAHA Level 2 - System requirements.

<table>
<thead>
<tr>
<th>ID</th>
<th>Level 2 - System requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>L2-SYS-1</td>
<td>The spent fuel elements shall be disposed of in a repository located deep in the Olkiluoto bedrock. The release of radionuclides shall be prevented with a multi-barrier disposal system consisting of a system of engineered barriers (EBS) and host rock such that the system effectively isolates the radionuclides from the living environment.</td>
</tr>
</tbody>
</table>
| L2-SYS-3 | The engineered barrier system shall consist of  
a) the canister to contain the radionuclides as long as these could cause significant harm to the environment  
b) the buffer between the canisters and the host rock to protect the canisters as long as containment of radionuclides is needed  
c) the deposition tunnel backfill and plugs to keep the buffer in place and to help in restoring the natural conditions in the host rock  
d) the closure, i.e. the backfill and sealing structures to decouple the repository from the surface environment |
| L2-SYS-4 | The host rock and depth of the repository shall be selected in such a way as to make it possible for the EBS to fulfill the functions of containment and isolation described above. |
| L2-SYS-5 | Should any of the canisters start leaking, the repository system as a whole shall hinder or retard the releases of radionuclides to the biosphere to the level required by the long-term safety criteria. |
| L2-SYS-6 | The total amount of spent nuclear fuel to be disposed is at most 9000 tons of uranium. |
### Table A-3. VAHA Level 3 - Subsystem requirements for canister.

<table>
<thead>
<tr>
<th>ID</th>
<th>Level 3 - Subsystem requirements for the canister</th>
<th>Section in this report</th>
</tr>
</thead>
<tbody>
<tr>
<td>L3-CAN-1</td>
<td>1 DEFINITION</td>
<td></td>
</tr>
<tr>
<td>L3-CAN-2</td>
<td>Canister is a container with a water-tight and gas-tight shell and a mechanical loadbearing insert in which the spent nuclear fuel is placed for final disposal in the repository. The canister shall contain the spent fuel and prevent, and in the case of a leak, limit the dispersal of radioactive substances into the environment.</td>
<td>7.1.1</td>
</tr>
<tr>
<td>L3-CAN-3</td>
<td>2 CONTAINMENT</td>
<td></td>
</tr>
<tr>
<td>L3-CAN-4</td>
<td>The canister shall initially be intact when leaving the encapsulation plant for disposal except for incidental deviations.</td>
<td>7.1.2.1</td>
</tr>
<tr>
<td>L3-CAN-5</td>
<td>In the expected repository conditions the canister shall remain intact for hundreds of thousands of years except for incidental deviations.</td>
<td>7.1.2.2</td>
</tr>
<tr>
<td>L3-CAN-6</td>
<td>3 CHEMICAL RESISTANCE</td>
<td></td>
</tr>
<tr>
<td>L3-CAN-7</td>
<td>The canister shall withstand corrosion in the expected repository conditions.</td>
<td>7.1.3.1</td>
</tr>
<tr>
<td>L3-CAN-8</td>
<td>4 MECHANICAL RESISTANCE</td>
<td></td>
</tr>
<tr>
<td>L3-CAN-9</td>
<td>The canister shall withstand the expected mechanical loads in the repository.</td>
<td>7.1.4</td>
</tr>
<tr>
<td>L3-CAN-10</td>
<td>5 COMPATIBILITY WITH THE EBS AND HOST-ROCK PERFORMANCE</td>
<td></td>
</tr>
<tr>
<td>L3-CAN-11</td>
<td>The canister shall not impair the safety functions of other barriers.</td>
<td>7.1.5</td>
</tr>
<tr>
<td>L3-CAN-13</td>
<td>6 SUBCRITICALITY</td>
<td></td>
</tr>
<tr>
<td>L3-CAN-14</td>
<td>The canister shall be subcritical in all postulated operational and repository conditions including intrusion of water through a damaged canister wall.</td>
<td>7.1.6</td>
</tr>
<tr>
<td>L3-CAN-15</td>
<td>7 HANDLING BEFORE DISPOSAL</td>
<td></td>
</tr>
<tr>
<td>L3-CAN-16</td>
<td>The canisters shall be stored, transferred and emplaced in such a way that the copper shell is not damaged.</td>
<td>7.1.7</td>
</tr>
<tr>
<td>L3-CAN-17</td>
<td>8 RETRIEVABILITY</td>
<td></td>
</tr>
<tr>
<td>L3-CAN-18</td>
<td>The design of the canister shall facilitate the retrievability of spent fuel assemblies from the repository.</td>
<td>7.1.8</td>
</tr>
</tbody>
</table>
Table A-4. VAHA Level 3 - Subsystem requirements for the buffer.

<table>
<thead>
<tr>
<th>ID</th>
<th>Level 3 – Subsystem requirements for the buffer</th>
<th>Section in this report</th>
</tr>
</thead>
<tbody>
<tr>
<td>L3-BUF-1</td>
<td><strong>1 DEFINITION</strong></td>
<td>8.1.1</td>
</tr>
<tr>
<td></td>
<td>Buffer is the component that surrounds the canister and fills the void spaces between the canister and the rock. The purpose of the buffer is to protect the canister from detrimental thermal, hydraulic, mechanical and chemical, including microbiological (THMC) processes that could compromise the safety function of complete containment, to maintain favourable conditions for the canister and to slow down the transport of radionuclides if the canister starts leaking.</td>
<td></td>
</tr>
<tr>
<td>L3-BUF-2</td>
<td><strong>2 PERFORMANCE</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>The amount of substances in the buffer that could adversely affect the canister, backfill or rock shall be limited.</td>
<td>8.1.2.1</td>
</tr>
<tr>
<td>L3-BUF-4</td>
<td>Unless otherwise stated, the buffer shall fulfill the requirements listed below over hundreds of thousands of years in the expected repository conditions except for incidental deviations.</td>
<td>8.1.2.2</td>
</tr>
<tr>
<td>L3-BUF-5</td>
<td><strong>2.1 HEAT TRANSFER</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>The buffer shall transfer the heat from the canister efficiently enough to keep the buffer temperature &lt; 100°C.</td>
<td>8.1.2.3</td>
</tr>
<tr>
<td>L3-BUF-6</td>
<td><strong>2.2 GAS TRANSFER</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>The buffer shall allow gases to pass through it without causing damage to the repository system.</td>
<td>8.1.2.4</td>
</tr>
<tr>
<td>L3-BUF-7</td>
<td><strong>2.3 CHEMICAL PROTECTION</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>The buffer shall limit microbial activity.</td>
<td>8.1.2.5</td>
</tr>
<tr>
<td>L3-BUF-8</td>
<td><strong>2.4 MECHANICAL PROTECTION</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>The buffer shall mitigate the impact of rock shear on the canister.</td>
<td>8.1.2.6</td>
</tr>
<tr>
<td>L3-BUF-9</td>
<td><strong>2.5 LIMITATION OF MASS FLOWS FROM AND ONTO THE CANISTER</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>The buffer shall be impermeable enough to limit the transport of radionuclides from the canisters into the bedrock.</td>
<td>8.1.2.7</td>
</tr>
<tr>
<td>L3-BUF-10</td>
<td>The buffer shall be impermeable enough to limit the transport of corroding substances from the rock onto the canister surface.</td>
<td>8.1.2.7</td>
</tr>
<tr>
<td>L3-BUF-11</td>
<td>The buffer shall limit the transport of radiocolloids to the rock.</td>
<td>8.1.2.7</td>
</tr>
<tr>
<td>L3-BUF-12</td>
<td><strong>3 SUPPORT OF OTHER SYSTEM COMPONENTS</strong></td>
<td></td>
</tr>
<tr>
<td>ID</td>
<td>Level 3 – Subsystem requirements for the buffer</td>
<td>Section in this report</td>
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</tr>
<tr>
<td>L3-BUF-16</td>
<td>The buffer shall provide support to the deposition hole walls to mitigate potential effects of rock damage.</td>
<td>8.1.3.1</td>
</tr>
<tr>
<td>L3-BUF-17</td>
<td>The buffer shall be able to keep the canister in the correct position (to prevent sinking and tilting).</td>
<td>8.1.3.2</td>
</tr>
</tbody>
</table>
Table A-5. VAHA Level 3 - Subsystem requirements for deposition tunnel backfill and plug.

<table>
<thead>
<tr>
<th>ID</th>
<th>Level 3 – Subsystem requirements for deposition tunnel backfill and plug</th>
<th>Section in this report</th>
</tr>
</thead>
<tbody>
<tr>
<td>L3-BAC-1</td>
<td><strong>1 DEFINITION</strong></td>
<td></td>
</tr>
<tr>
<td>L3-BAC-2</td>
<td>The sealing structures of the deposition tunnels consist of backfill and plugs. Backfill is the material or materials that is/are used for backfilling the deposition tunnels. Plugs will be placed at the mouths of the deposition tunnels. The purpose of the backfill is to keep the buffer in place, maintain favourable and predictable conditions for the buffer and the canister, and also favourable rock mechanical, hydrological and geochemical conditions in the near-field and to retard the transport of radionuclides if the canister starts leaking.</td>
<td>9.1.1</td>
</tr>
<tr>
<td>L3-BAC-3</td>
<td><strong>2 PERFORMANCE</strong></td>
<td></td>
</tr>
<tr>
<td>L3-BAC-5</td>
<td>Unless otherwise stated, the backfill and plugs shall fulfill the performance targets listed below over hundreds of thousands of years in the expected repository conditions except for incidental deviations.</td>
<td>9.1.2.1</td>
</tr>
<tr>
<td>L3-BAC-7</td>
<td><strong>2.1 HYDRAULIC AND TRANSPORT PROPERTIES</strong></td>
<td></td>
</tr>
<tr>
<td>L3-BAC-8</td>
<td>The backfill shall limit advective flow along the deposition tunnels.</td>
<td>9.1.3.1</td>
</tr>
<tr>
<td>L3-BAC-9</td>
<td>The plugs shall isolate the deposition tunnels hydraulically during the operational phase of the repository.</td>
<td>9.1.3.2</td>
</tr>
<tr>
<td>L3-BAC-12</td>
<td><strong>2.2 CHEMICAL PROPERTIES</strong></td>
<td></td>
</tr>
<tr>
<td>L3-BAC-13</td>
<td>The chemical composition of the backfill and plugs shall not jeopardise the performance of the buffer, canister or bedrock.</td>
<td>9.1.3.3</td>
</tr>
<tr>
<td>L3-BAC-15</td>
<td><strong>3 SUPPORT OF OTHER COMPONENTS OF THE DISPOSAL SYSTEM</strong></td>
<td></td>
</tr>
<tr>
<td>L3-BAC-16</td>
<td>The backfill shall keep the buffer in place.</td>
<td>9.1.4.1</td>
</tr>
<tr>
<td>L3-BAC-17</td>
<td>The backfill shall contribute to the mechanical stability of the deposition tunnels.</td>
<td>9.1.4.1</td>
</tr>
<tr>
<td>L3-BAC-18</td>
<td>The plugs shall keep the backfill in place during the operational phase.</td>
<td>9.1.4.2</td>
</tr>
<tr>
<td>L3-BAC-19</td>
<td>The backfill shall contribute to prevent uplifting of the canister in the deposition hole.</td>
<td>9.1.4.3</td>
</tr>
</tbody>
</table>
Table A-6. VAHA Level 3 - Subsystem requirements for closure.

<table>
<thead>
<tr>
<th>ID</th>
<th>Level 3 – Subsystem requirements for closure</th>
<th>Section in this report</th>
</tr>
</thead>
<tbody>
<tr>
<td>L3-CLO-1</td>
<td>1 DEFINITIONS</td>
<td></td>
</tr>
<tr>
<td>L3-CLO-2</td>
<td>Closure of the disposal facility includes backfill and plugs in access and central tunnels, shafts, miscellaneous excavations, and investigation holes. Different types of closure components may be used in different parts of the repository volumes. Closure shall complete the isolation of the spent fuel and support the safety function of the other barriers.</td>
<td>10.1.1</td>
</tr>
<tr>
<td>L3-CLO-4</td>
<td>2 PERFORMANCE</td>
<td></td>
</tr>
<tr>
<td>L3-CLO-13</td>
<td>Unless otherwise stated, the closure materials and structures shall fulfill the performance targets listed below over hundreds of thousands of years in the expected repository conditions except for incidental deviations.</td>
<td>10.1.2</td>
</tr>
<tr>
<td>L3-CLO-5</td>
<td>Closure shall complete the isolation of the spent nuclear fuel by reducing the likelihood of unintentional human intrusion through the closed volumes.</td>
<td>10.1.3</td>
</tr>
<tr>
<td>L3-CLO-6</td>
<td>Closure shall restore the favourable, natural conditions of the bedrock as well as possible.</td>
<td>10.1.4</td>
</tr>
<tr>
<td>L3-CLO-7</td>
<td>Closure shall prevent the formation of preferential flow paths and transport routes between the ground surface and deposition tunnels/deposition holes.</td>
<td>10.1.5</td>
</tr>
<tr>
<td>L3-CLO-8</td>
<td>Closure shall not endanger the favourable conditions for the other parts of the EBS and the host rock.</td>
<td>10.1.6</td>
</tr>
<tr>
<td>L3-CLO-10</td>
<td>3 OTHER REQUIREMENTS</td>
<td></td>
</tr>
<tr>
<td>L3-CLO-11</td>
<td>Retrieval of the spent nuclear fuel canisters shall be technically feasible in spite of repository tunnel and closure structures.</td>
<td>10.1.7</td>
</tr>
</tbody>
</table>
### Table A-7. VAHA Level 3 - Subsystem requirements for host rock.

<table>
<thead>
<tr>
<th>ID</th>
<th>Level 3 – Subsystem requirements for host rock</th>
<th>Section in this report</th>
</tr>
</thead>
<tbody>
<tr>
<td>L3-ROC-1</td>
<td>1 DEFINITION AND OBJECTIVES</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Host rock is the rock surrounding the deposition holes and other excavated rooms that shall provide such favourable and predictable conditions that the EBS can fulfill its functions of containment and isolation and ensure that the transport of radionuclides is limited in the case of release.</td>
<td>6.1</td>
</tr>
<tr>
<td>L3-ROC-3</td>
<td>Host rock shall, with the exception of incidental deviations, retain its favourable properties over hundreds of thousands of years.</td>
<td>6.1</td>
</tr>
<tr>
<td>L3-ROC-4</td>
<td>2 GENERAL REQUIREMENTS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>The reservoir shall be located at minimum depth of 400 m.</td>
<td>6.2.1</td>
</tr>
<tr>
<td>L3-ROC-8</td>
<td>3 TARGET PROPERTIES</td>
<td></td>
</tr>
<tr>
<td>L3-ROC-9</td>
<td>3.1 CHEMICAL COMPOSITION OF THE GROUNDWATER</td>
<td></td>
</tr>
<tr>
<td>L3-ROC-10</td>
<td>To avoid canister corrosion, groundwater at the repository level shall be anoxic except during the initial period until the time when the oxygen entrapped in the near-field has been consumed.</td>
<td>6.3.1.1</td>
</tr>
<tr>
<td></td>
<td>Therefore, no dissolved oxygen shall be present after the initially entrapped oxygen in the near-field has been consumed.</td>
<td></td>
</tr>
<tr>
<td>L3-ROC-11</td>
<td>Groundwater at the repository level shall have high enough pH and low enough chloride concentration to avoid chloride corrosion of the canisters.</td>
<td>6.3.1.2</td>
</tr>
<tr>
<td></td>
<td>Therefore, pH shall be higher than 4 and chloride concentration $[Cl^-] &lt; 2M$.</td>
<td></td>
</tr>
<tr>
<td>L3-ROC-12</td>
<td>Concentrations of canister-corroding agents (HS⁻, NO₂⁻, NO₃⁻ and NH₄⁺, acetate) shall be limited in the groundwater at the repository level.</td>
<td>6.3.1.3</td>
</tr>
<tr>
<td>L3-ROC-13</td>
<td>Groundwater at the repository level shall have low organic matter, H₂ and $S_{ox}$ and methane contents to limit microbial activity, especially that of sulphate reducing bacteria.</td>
<td>6.3.1.3</td>
</tr>
<tr>
<td>L3-ROC-28</td>
<td>3.1.2 BUFFER AND BACKFILL PERFORMANCE</td>
<td></td>
</tr>
<tr>
<td>L3-ROC-14</td>
<td>Groundwater at the repository level shall initially have sufficiently high ionic strength to reduce the likelihood of chemical erosion of</td>
<td>6.3.2.1</td>
</tr>
<tr>
<td>ID</td>
<td>Level 3 – Subsystem requirements for host rock</td>
<td>Section in this report</td>
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<tr>
<td></td>
<td>the buffer or backfill. Therefore, total charge equivalent of cations, $\Sigma q[M^{q+}]^*$, shall initially be higher than 4 mM.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$* [M^{q+}]$ = molar concentration of cations, $q$ = charge number of ion</td>
<td>6.3.2.2</td>
</tr>
<tr>
<td>L3-ROC-15</td>
<td>Groundwater at the repository level shall have limited salinity so that the buffer and backfill will maintain a high enough swelling pressure.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Therefore, in the future expected conditions the groundwater salinity (TDS, total dissolved solids) at the repository level shall be less than 35 g/l TDS. During the initial transient caused by the construction activities salinities up to 70 g/l TDS can be accepted.</td>
<td>6.3.2.2</td>
</tr>
<tr>
<td>L3-ROC-16</td>
<td>The pH of the groundwater at the repository level shall be within a range where the buffer and backfill remain stable (no montmorillonite dissolution).</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Therefore, the pH shall be in the range of 5–10, but initially a higher pH (up to 11) is allowed locally. The acceptable level also depends on silica and calcium concentrations.</td>
<td>6.3.2.3</td>
</tr>
<tr>
<td>L3-ROC-17</td>
<td>Concentration of solutes that can have a detrimental effect on the stability of buffer and backfill ($K^+$, $Fe_{tot}$) shall be limited in the groundwater at the repository level.</td>
<td>6.3.2.4</td>
</tr>
<tr>
<td>L3-ROC-27</td>
<td><strong>3.1.3 RADIONUCLIDE RELEASE AND TRANSPORT</strong></td>
<td></td>
</tr>
<tr>
<td>L3-ROC-29</td>
<td>Groundwater conditions shall be reducing in order to have a stable fuel matrix and low solubility of the radionuclides.</td>
<td>6.3.3.1</td>
</tr>
<tr>
<td>L3-ROC-30</td>
<td>To ascertain the data for sorption parameters, the pH shall be in the range of 6–10 after the initial period when a higher pH of up to 11 is allowed.</td>
<td>6.3.3.2</td>
</tr>
<tr>
<td>L3-ROC-31</td>
<td>In the vicinity of the deposition holes, natural groundwater shall have a low colloid and organic content to limit radionuclide transport.</td>
<td>6.3.3.3</td>
</tr>
<tr>
<td>L3-ROC-18</td>
<td><strong>3.2 GROUNDWATER FLOW AND SOLUTE TRANSPORT</strong></td>
<td></td>
</tr>
<tr>
<td>L3-ROC-19</td>
<td>Under saturated conditions the groundwater flow in any fracture in the vicinity of a deposition hole shall be low to limit mass transfer to and from EBS.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Therefore, the flow rate in such a fracture shall be in the order of one litre of flow per one meter of intercepting fracture width in a year ($l/(m*year)$) at the most. In case of more than one fracture, the sum of flow rates is applied.</td>
<td>6.3.4.1</td>
</tr>
<tr>
<td>L3-ROC-20</td>
<td>Flow conditions in the host rock shall contribute to high transport resistance.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Therefore, migration paths in the vicinity of the deposition hole, shall have a transport resistance (WL/Q) higher than 10,000 years/m for most of the deposition holes and at least a few thousand years/m.</td>
<td>6.3.4.2</td>
</tr>
<tr>
<td>L3-ROC-21</td>
<td>Inflow of groundwater to deposition tunnels shall be limited to ensure the performance of the backfill.</td>
<td>6.3.4.3</td>
</tr>
<tr>
<td>ID</td>
<td>Level 3 – Subsystem requirements for host rock</td>
<td>Section in this report</td>
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</tr>
<tr>
<td>L3-ROC-33</td>
<td>The properties of the host rock shall be favourable for matrix diffusion and sorption.</td>
<td>6.3.4.4</td>
</tr>
<tr>
<td>L3-ROC-22</td>
<td><strong>3.3 MECHANICAL STABILITY</strong></td>
<td></td>
</tr>
<tr>
<td>L3-ROC-23</td>
<td>The location of the deposition holes shall be selected so as to minimise the likelihood of rock shear movements large enough to break the canister.</td>
<td>6.3.5</td>
</tr>
<tr>
<td></td>
<td>Therefore, the likelihood of a shear displacement exceeding 5 cm shall be low.</td>
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### Table A-8. VAHA Level 4 - Design requirements for canister.

<table>
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<tbody>
<tr>
<td>L4-CAN-1</td>
<td><strong>1 DEFINITION</strong></td>
<td></td>
</tr>
<tr>
<td>L4-CAN-2</td>
<td>The canister is composed of a leak-tight copper shell and of a load-bearing nodular cast iron insert.</td>
<td>7.2.1</td>
</tr>
<tr>
<td>L4-CAN-3</td>
<td><strong>2 PERFORMANCE</strong></td>
<td></td>
</tr>
<tr>
<td>L4-CAN-4</td>
<td><strong>2.1 CHEMICAL RESISTANCE</strong></td>
<td></td>
</tr>
<tr>
<td>L4-CAN-5</td>
<td>The copper overpack shall provide the corrosion resistance required in the postulated repository conditions.</td>
<td>7.2.2.1</td>
</tr>
<tr>
<td>L4-CAN-6</td>
<td><strong>2.2 MECHANICAL STRENGTH</strong></td>
<td></td>
</tr>
<tr>
<td>L4-CAN-7</td>
<td>The iron insert shall provide the mechanical strength required.</td>
<td>7.2.2.2</td>
</tr>
<tr>
<td>L4-CAN-8</td>
<td><strong>2.3 SUBCRITICALITY</strong></td>
<td></td>
</tr>
<tr>
<td>L4-CAN-9</td>
<td>To ensure subcriticality, the properties (e.g., enrichment, burnup) of the fuel inside the canisters, as well as the internal geometry of the insert, shall be known precisely enough to provide a high degree of confidence in criticality safety.</td>
<td>7.2.2.3</td>
</tr>
<tr>
<td>L4-CAN-10</td>
<td><strong>2.4 LIMITATION OF RADIATION LEVEL</strong></td>
<td></td>
</tr>
<tr>
<td>L4-CAN-11</td>
<td>The shielding provided by the canister shall limit the dose rate to minimise radiolysis of water outside the canister.</td>
<td>7.2.2.4</td>
</tr>
<tr>
<td>L4-CAN-43</td>
<td>The fuel elements for encapsulation shall be selected in a pre-planned, controlled and documented way to limit the radiation dose on the canister surface.</td>
<td>7.2.2.4</td>
</tr>
<tr>
<td>L4-CAN-13</td>
<td><strong>2.5 LIMITATION OF HEAT GENERATION</strong></td>
<td></td>
</tr>
<tr>
<td>L4-CAN-14</td>
<td>The heat generation inside the canister shall be limited in such a way that the performance of the other barriers is not impaired.</td>
<td>7.2.2.5</td>
</tr>
<tr>
<td>L4-CAN-15</td>
<td>The fuel elements for encapsulation shall be selected in a pre-planned, controlled and documented way to meet the decay heat limit set for each canister type.</td>
<td>7.2.2.5</td>
</tr>
<tr>
<td>L4-CAN-16</td>
<td><strong>2.6 THERMAL CONDUCTIVITY</strong></td>
<td></td>
</tr>
<tr>
<td>L4-CAN-17</td>
<td>The canister materials shall have a sufficiently high thermal conductivity such that the heat from the spent nuclear fuel is effectively dissipated.</td>
<td>7.2.2.6</td>
</tr>
<tr>
<td>ID</td>
<td>Level 4 – Design requirements for canister</td>
<td>Section in this report</td>
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<tr>
<td>L4-CAN-41</td>
<td><strong>2.7 CANISTER GEOMETRY</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>The copper overpack and insert shall be dimensioned so that the insert can be installed into the copper overpack.</td>
<td>7.2.2.7</td>
</tr>
<tr>
<td>L4-CAN-18</td>
<td><strong>3 COPPER OVERPACK</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>The copper overpack is composed of a copper lid and a bottom welded into a copper tube or of a copper lid welded into a copper tube with an integrated bottom.</td>
<td>7.2.3</td>
</tr>
<tr>
<td>L4-CAN-19</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Properties of the weld shall fulfill the same performance requirements as the rest of the copper shell.</td>
<td>7.2.3</td>
</tr>
<tr>
<td>L4-CAN-20</td>
<td><strong>3.1 CORROSION RESISTANCE</strong></td>
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</tr>
<tr>
<td>L4-CAN-21</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>The design, manufacturing and any further processing and handling of the canister shall aim at limiting the risk of stress corrosion cracking in repository conditions.</td>
<td>7.2.3.1</td>
</tr>
<tr>
<td>L4-CAN-23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L4-CAN-24</td>
<td><strong>3.2 LIFTING AND TRANSFER</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>The copper overpack shall be designed to bear the load from canister handling and transfer.</td>
<td>7.2.3.2</td>
</tr>
<tr>
<td>L4-CAN-25</td>
<td></td>
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<tr>
<td></td>
<td>Dent marks and scratches on the copper surface shall be minimised during canister handling and transport.</td>
<td>7.2.3.2</td>
</tr>
<tr>
<td>L4-CAN-26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L4-CAN-27</td>
<td><strong>3.3 COPPER OVERPACK DUCTILITY</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>The canister copper overpack shall be designed to withstand the plastic deformation and creep caused by any postulated mechanical or thermal load.</td>
<td>7.2.3.3</td>
</tr>
<tr>
<td>L4-CAN-28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L4-CAN-29</td>
<td></td>
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</tr>
<tr>
<td>L4-CAN-30</td>
<td><strong>4 CAST IRON INSERT</strong></td>
<td></td>
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<tr>
<td>L4-CAN-31</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>The insert geometry and acceptance criteria for soundness shall be set so that sub-criticality is guaranteed.</td>
<td>7.2.4.1</td>
</tr>
<tr>
<td>L4-CAN-32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L4-CAN-33</td>
<td><strong>4.1 SUB-CRITICALITY</strong></td>
<td></td>
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<tr>
<td></td>
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<td></td>
</tr>
<tr>
<td>L4-CAN-34</td>
<td><strong>4.2 MECHANICAL STRENGTH</strong></td>
<td></td>
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<tr>
<td></td>
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<td></td>
</tr>
<tr>
<td>L4-CAN-35</td>
<td>The canister insert shall be designed to bear the hydrostatic pressure from groundwater and from swelling of bentonite.</td>
<td>7.2.4.2</td>
</tr>
<tr>
<td>L4-CAN-36</td>
<td>The canister insert shall be designed to bear the hydrostatic load caused by glaciation.</td>
<td>7.2.4.2</td>
</tr>
<tr>
<td>L4-CAN-37</td>
<td>The canister insert shall be designed to bear unevenly distributed swelling loads.</td>
<td>7.2.4.2</td>
</tr>
<tr>
<td>L4-CAN-38</td>
<td>The canister insert shall be designed to bear the loads from the postulated rock shear displacements in the deposition hole.</td>
<td>7.2.4.2</td>
</tr>
<tr>
<td>ID</td>
<td>Level 4 – Design requirements for canister</td>
<td>Section in this report</td>
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</tr>
<tr>
<td>L4-CAN-39</td>
<td>5 QUALITY CONTROL</td>
<td></td>
</tr>
<tr>
<td>L4-CAN-40</td>
<td>Material and dimensions of the canister components shall allow non-destructive testing.</td>
<td></td>
</tr>
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</table>
Table A-9. VAHA Level 4 - Design requirements for buffer.

<table>
<thead>
<tr>
<th>ID</th>
<th>Level 4 – Design requirements for buffer</th>
<th>Section in this report</th>
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<tbody>
<tr>
<td>L4-BUF-1</td>
<td>1 DEFINITION</td>
<td></td>
</tr>
<tr>
<td>L4-BUF-2</td>
<td>The main component of the buffer material shall consist of natural swelling clays.</td>
<td>8.2.1</td>
</tr>
<tr>
<td>L4-BUF-3</td>
<td>2 PERFORMANCE</td>
<td></td>
</tr>
<tr>
<td>L4-BUF-16</td>
<td>The buffer shall be designed to be self-sealing after initial installation and self-healing after any hydraulic and mechanical disturbances.</td>
<td>8.2.2.1</td>
</tr>
<tr>
<td>L4-BUF-4</td>
<td>2.1 CHEMICAL PROTECTION</td>
<td></td>
</tr>
<tr>
<td>L4-BUF-5</td>
<td>The buffer shall be so designed that the possibility of corrosion of a canister by sulphide and other corrodants including microbially-induced processes will be limited.</td>
<td>8.2.2.2</td>
</tr>
<tr>
<td>L4-BUF-19</td>
<td>The buffer material shall be selected so as to limit the contents of harmful substances (organics, oxidising compounds, sulphur and nitrogen compounds) and microbial activity.</td>
<td>8.2.2.2</td>
</tr>
<tr>
<td>L4-BUF-6</td>
<td>2.2 MECHANICAL PROTECTION</td>
<td></td>
</tr>
<tr>
<td>L4-BUF-7</td>
<td>The buffer shall be so designed that it will mitigate the mechanical impact of the postulated rock shear displacements on the canister to the level that the canister integrity is preserved.</td>
<td>8.2.2.3</td>
</tr>
<tr>
<td>L4-BUF-8</td>
<td>2.3 LIMITATION OF MASS FLOWS TO AND FROM THE CANISTER</td>
<td></td>
</tr>
<tr>
<td>L4-BUF-9</td>
<td>The buffer shall be designed in such a way as to make diffusion the dominant transport mechanism for solutes.</td>
<td>8.2.2.4</td>
</tr>
<tr>
<td>L4-BUF-10</td>
<td>The buffer material must be selected in a way that favours the retardation of the transport of radionuclides by sorption (e.g. cation exchange) at the clay and other mineral surfaces.</td>
<td>8.2.2.4</td>
</tr>
<tr>
<td>L4-BUF-18</td>
<td>The buffer shall have sufficiently fine pore structure so that transport of radiocolloids formed within or around the canister is limited.</td>
<td>8.2.2.4</td>
</tr>
<tr>
<td>L4-BUF-20</td>
<td>2.4 HEAT TRANSFER</td>
<td></td>
</tr>
<tr>
<td>L4-BUF-21</td>
<td>The gap between the canister and buffer and buffer blocks and rock should be made as narrow as possible without compromising the future performance of the buffer.</td>
<td>8.2.2.5</td>
</tr>
<tr>
<td>L4-BUF-11</td>
<td>3 SUPPORT OF OTHER SYSTEM COMPONENTS</td>
<td></td>
</tr>
<tr>
<td>L4-BUF-12</td>
<td>The buffer shall initially provide a good contact with the host rock.</td>
<td>8.2.3</td>
</tr>
</tbody>
</table>
### Table A-10. VAHA Level 4 - Design requirements for deposition tunnel backfill and plug.

<table>
<thead>
<tr>
<th>ID</th>
<th>Level 4 – Design requirements for deposition tunnel backfill and plug</th>
<th>Section in this report</th>
</tr>
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<tbody>
<tr>
<td>L4-BAC-1</td>
<td><strong>1 DEFINITION</strong></td>
<td></td>
</tr>
<tr>
<td>L4-BAC-2</td>
<td>The main component of the backfill material shall consist of natural swelling clays. The plugs shall consist of materials that have a good hydraulic isolation capacity and that will not undergo large volume changes in the long term.</td>
<td>9.2.1</td>
</tr>
<tr>
<td>L4-BAC-3</td>
<td><strong>2 PERFORMANCE</strong></td>
<td></td>
</tr>
<tr>
<td>L4-BAC-28</td>
<td>The backfill shall be designed to be self-sealing after initial installation and self-healing after any hydraulic or mechanical disturbances.</td>
<td>9.2.2.1</td>
</tr>
<tr>
<td>L4-BAC-4</td>
<td><strong>2.1 HYDRAULIC PROPERTIES</strong></td>
<td></td>
</tr>
<tr>
<td>L4-BAC-5</td>
<td>The backfill shall be so designed that its hydraulic conductivity over the whole cross-section of the backfilled tunnel will be ( \leq 1 \times 10^{-10} ) m/s after full saturation.</td>
<td>9.2.3.1</td>
</tr>
<tr>
<td>L4-BAC-6</td>
<td>The plugs shall be designed to maintain their hydraulic isolation capacity at least as long as the central tunnels are open.</td>
<td>9.2.3.2</td>
</tr>
<tr>
<td>L4-BAC-12</td>
<td><strong>2.2 MECHANICAL PROPERTIES</strong></td>
<td></td>
</tr>
<tr>
<td>L4-BAC-13</td>
<td>The plug shall be designed to withstand the sum of the swelling pressure of the backfill and the hydrostatic pressure of the groundwater at the repository depth.</td>
<td>9.2.4.1</td>
</tr>
<tr>
<td>L4-BAC-14</td>
<td>The plugs must be designed to maintain a backfilling function even after their hydraulic isolation capacity has been lost.</td>
<td>9.2.4.2</td>
</tr>
<tr>
<td>L4-BAC-29</td>
<td>In the initial state the backfill shall have a good contact with the host rock.</td>
<td>9.2.4.3</td>
</tr>
<tr>
<td>L4-BAC-17</td>
<td><strong>2.3 CHEMICAL PROPERTIES</strong></td>
<td></td>
</tr>
<tr>
<td>L4-BAC-18</td>
<td>Backfill and plug materials shall be selected so as to limit the contents of harmful substances (organics, oxidising compounds, sulphur and nitrogen compounds) and microbial activity.</td>
<td>9.2.5.1</td>
</tr>
<tr>
<td>L4-BAC-19</td>
<td><strong>3 SUPPORT OF OTHER SYSTEM COMPONENTS</strong></td>
<td></td>
</tr>
<tr>
<td>L4-BAC-30</td>
<td>To keep the buffer in place, the design of the backfill has to take into account, on the one hand, the compressibility and structural stiffness of the backfill, and, on the other hand, the buffer swelling pressure and the friction of buffer against the deposition hole walls.</td>
<td>9.2.6</td>
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</table>
Table A-11. VAHA Level 4 - Design requirements for closure.

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<th>ID</th>
<th>Level 4 – Design requirements for closure</th>
<th>Section in this report</th>
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<tbody>
<tr>
<td>L4-CLO-1</td>
<td><strong>1 DEFINITIONS</strong></td>
<td></td>
</tr>
<tr>
<td>L4-CLO-2</td>
<td>Backfill in the context of closure refers to the materials utilised to backfill investigation holes and excavated rock openings other than deposition tunnels.</td>
<td>10.2.1</td>
</tr>
<tr>
<td>L4-CLO-4</td>
<td>Plugs in the context of closure refer to structures utilized for one of the following purposes: 1) for isolation of different facility sections during the operational phase, 2) for avoiding the formation of transport routes through the tunnels and other excavated openings over the long-term, 3) for obstructing inadvertent human intrusion into the repository through existing tunnels and shafts after closure over the long-term, and 4) for stabilising sections of investigation holes that intersect water-bearing fracture zones.</td>
<td>10.2.1</td>
</tr>
<tr>
<td>L4-CLO-5</td>
<td><strong>2 PERFORMANCE</strong></td>
<td></td>
</tr>
<tr>
<td>L4-CLO-6</td>
<td>The ground surface of the disposal area shall be landscaped to resemble its natural surroundings.</td>
<td>10.2.2.1</td>
</tr>
<tr>
<td>L4-CLO-7</td>
<td>Structures and materials that considerably obstruct unintentional intrusion shall be utilized in the closure of the uppermost parts of the facility and investigation holes extending to the ground surface.</td>
<td>10.2.2.1</td>
</tr>
<tr>
<td>L4-CLO-8</td>
<td>Structures and materials of the closure components shall be selected in such a way that the isolation functions of closure can be provided despite possible loadings related to glacial cycles, such as permafrost or changing groundwater chemical conditions.</td>
<td>10.2.2.2</td>
</tr>
<tr>
<td>L4-CLO-9</td>
<td>Rock materials shall be used increasingly as backfill when moving from the disposal depth up to the ground surface due to the increasing risk of clay erosion.</td>
<td>10.2.2.2</td>
</tr>
<tr>
<td>L4-CLO-10</td>
<td>Closure as a whole shall be so designed that the hydraulic connections from the disposal depth to the surface environment through the closed tunnels, shafts, and investigation holes are not better than through existing natural fractures and fracture zones.</td>
<td>10.2.2.3</td>
</tr>
<tr>
<td>L4-CLO-11</td>
<td>Sections in the underground openings intersected by highly transmissive zones such as the HZ20 structure shall be hydraulically isolated from other facility sections.</td>
<td>10.2.2.3</td>
</tr>
<tr>
<td>L4-CLO-12</td>
<td>The closure as a whole shall be so designed that short-cuts from the deposition tunnels/deposition holes to existing significant groundwater flowpaths are prevented.</td>
<td>10.2.2.3</td>
</tr>
<tr>
<td>L4-CLO-21</td>
<td>The closure components shall keep the backfill and plugs of the deposition tunnels in place.</td>
<td>10.2.2.4</td>
</tr>
<tr>
<td>L4-CLO-22</td>
<td>The amount of chemical species harmful for canister/buffer/deposition tunnel backfill/host rock in closure components shall be limited.</td>
<td>10.2.2.5</td>
</tr>
<tr>
<td>L4-CLO-17</td>
<td><strong>3 OTHER REQUIREMENTS</strong></td>
<td></td>
</tr>
</tbody>
</table>
Table A-12. VAHA Level 4 - Design requirements for host rock.

<table>
<thead>
<tr>
<th>ID</th>
<th>Level 4 – Design requirements for host rock</th>
<th>Section in this report</th>
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<tbody>
<tr>
<td>L4-ROC-1</td>
<td><strong>1 DEFINITIONS</strong></td>
<td></td>
</tr>
<tr>
<td>L4-ROC-2</td>
<td>Access routes in this context means the access tunnel and shafts including, personnel shaft, canister shaft and ventilation shafts.</td>
<td>6.4.1</td>
</tr>
<tr>
<td>L4-ROC-53</td>
<td>All subsurface rooms in this context means the access routes, technical rooms, central tunnels, deposition tunnels, deposition holes and demonstration tunnels.</td>
<td></td>
</tr>
<tr>
<td>L4-ROC-3</td>
<td>Layout determining features (LDFs) are large deformation zones that form the main groundwater flow routes or that can transmit movements of earthquakes large enough to induce canister-breaking secondary displacements, and are thus of significance for long-term safety.</td>
<td>6.4.1</td>
</tr>
<tr>
<td>L4-ROC-39</td>
<td><strong>2 PERFORMANCE</strong></td>
<td></td>
</tr>
<tr>
<td>L4-ROC-40</td>
<td><strong>2.1 ALL SUB-SURFACE ROOMS</strong></td>
<td></td>
</tr>
<tr>
<td>L4-ROC-41</td>
<td>The layout and dimensions of the repository shall be designed and the repository shall be constructed in such a way that thermally and mechanically induced damage to the host rock is kept sufficiently low.</td>
<td>6.4.2.1</td>
</tr>
<tr>
<td>L4-ROC-42</td>
<td>Intersections with the LDFs and their respect volumes shall be avoided as far as possible when locating any sub-surface rooms.</td>
<td>6.4.2.2</td>
</tr>
<tr>
<td>L4-ROC-43</td>
<td>When designing the underground openings, intersection with existing drillholes (except for pilot holes) should be avoided by applying a respect distance to such holes. Deposition tunnels must not be intersected by existing drillholes connecting them to the surface or LDFs.</td>
<td>6.4.2.3</td>
</tr>
<tr>
<td>L4-ROC-44</td>
<td>Use of foreign materials in underground openings shall be controlled and regulated.</td>
<td>6.4.2.4</td>
</tr>
<tr>
<td>L4-ROC-45</td>
<td>Total inflow to the open sub-surface rooms shall be limited.</td>
<td>6.4.2.5</td>
</tr>
<tr>
<td>L4-ROC-46</td>
<td>The excavation/boring shall be carried out in a controlled way to limit the EDZ of the walls of tunnels and shafts and floor of the tunnels, in particular, to limit the formation of connected flow pathways along the tunnel length.</td>
<td>6.4.2.6</td>
</tr>
<tr>
<td>L4-ROC-48</td>
<td><strong>2.2 ACCESS ROUTES</strong></td>
<td></td>
</tr>
<tr>
<td>L4-ROC-49</td>
<td>The entrances of the access routes should be located at the same level to avoid groundwater flow caused by head differences.</td>
<td>6.4.3.1</td>
</tr>
<tr>
<td>L4-ROC-50</td>
<td>Construction of access routes in such a way that they would be located above or near the potential location of the deposition tunnels should be avoided.</td>
<td>6.4.3.2</td>
</tr>
<tr>
<td>L4-ROC-7</td>
<td><strong>2.3 DEPOSITION TUNNELS</strong></td>
<td></td>
</tr>
<tr>
<td>L4-ROC-8</td>
<td>Intersections with the LDFs and their respect volumes shall be avoided when locating the deposition tunnels.</td>
<td>6.4.4.1</td>
</tr>
<tr>
<td>ID</td>
<td>Level 4 – Design requirements for host rock</td>
<td>Section in this report</td>
</tr>
<tr>
<td>------</td>
<td>----------------------------------------------------------------------------------------------------------------</td>
<td>------------------------</td>
</tr>
<tr>
<td>L4-ROC-9</td>
<td>Inflow to deposition tunnels shall be limited to ensure the installation of the backfill, and to limit piping and erosion.</td>
<td>6.4.4.2</td>
</tr>
<tr>
<td>L4-ROC-12</td>
<td><strong>2.4 DEPOSITION HOLES</strong></td>
<td></td>
</tr>
<tr>
<td>L4-ROC-13</td>
<td>Inflow to deposition holes shall be limited to provide favourable conditions for the EBS and radionuclide retention.</td>
<td>6.4.5.1</td>
</tr>
<tr>
<td>L4-ROC-14</td>
<td>Deposition holes shall not intersect the respect volumes of hydrogeological zones.</td>
<td>6.4.5.2</td>
</tr>
<tr>
<td>L4-ROC-15</td>
<td>Fractures that may undergo shear movements with potential to break the canister are not allowed to intersect the canister.</td>
<td>6.4.5.3</td>
</tr>
<tr>
<td>L4-ROC-16</td>
<td>Deposition holes shall not intersect the respect volumes of brittle deformation zones.</td>
<td>6.4.5.4</td>
</tr>
<tr>
<td>L4-ROC-17</td>
<td>Deposition holes should be straight enough to allow installation of the buffer and the canister and to ensure sufficient density of the buffer.</td>
<td>6.4.5.5</td>
</tr>
<tr>
<td>L4-ROC-18</td>
<td>The dimensions and the quality of wall and bottom of each deposition hole shall allow installation of the buffer and the canister in a planned way to ensure sufficient density of the buffer.</td>
<td>6.4.5.6</td>
</tr>
<tr>
<td>L4-ROC-19</td>
<td>Deposition holes shall not intersect the respect volumes of the LDFs.</td>
<td>6.4.5.7</td>
</tr>
<tr>
<td>L4-ROC-20</td>
<td>Taking into account the thermal properties of the host rock and the heat generation of the waste canisters, the minimum spacing between deposition tunnels and deposition holes should be defined such that no high temperatures that could cause damage to the EBS are reached.</td>
<td>6.4.5.8</td>
</tr>
<tr>
<td>L4-ROC-21</td>
<td><strong>2.5 DEMONSTRATION TUNNELS</strong></td>
<td></td>
</tr>
<tr>
<td>L4-ROC-22</td>
<td>The requirements set for the deposition tunnels and deposition holes shall apply for demonstration tunnels, however some exceptions are allowed as defined at level 5.</td>
<td>6.4.6</td>
</tr>
</tbody>
</table>
**LIST OF REPORTS**


**POSIVA-REPORTS 2012**

<table>
<thead>
<tr>
<th>POSIVA 2012-01</th>
<th>Monitoring at Olkiluoto – a Programme for the Period Before Repository Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Posiva Oy</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>POSIVA 2012-02</th>
<th>Microstructure, Porosity and Mineralogy Around Fractures in Olkiluoto Bedrock</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><em>Jukka Kuva (ed.), Markko Myllys, Jussi Timonen,</em></td>
</tr>
<tr>
<td></td>
<td>University of Jyväskylä</td>
</tr>
<tr>
<td></td>
<td><em>Maarit Kelokaski, Marja Siitari-Kauppi, Jussi Ikonen,</em></td>
</tr>
<tr>
<td></td>
<td>University of Helsinki</td>
</tr>
<tr>
<td></td>
<td><em>Antero Lindberg,</em> Geological Survey of Finland</td>
</tr>
<tr>
<td></td>
<td><em>Ismo Aaltonen,</em> Posiva Oy</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>POSIVA 2012-03</th>
<th>Safety Case for the Disposal of Spent Nuclear Fuel at Olkiluoto - Design Basis 2012</th>
</tr>
</thead>
</table>