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

Initial state of the repository, PSAR version

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Keywords: Post-closure safety, SFR, Final repository, Low- and intermediate-level radioactive waste, Forsmark, Safety assessment, Initial state, Operational waste, Decommissioning waste, Radionuclide inventory, Material inventory, Waste vault, Design, Dimensions, Variables.

Summary

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

The initial state is defined as the expected state of the repository and its environs immediately after closure. The initial state of the repository is based on verified and documented properties of the wastes and repository components plus an assessment of changes in these properties up to the time of closure. The estimated year of closure is 2075.

This report describes the following, which define an initial state of SFR:

- Waste acceptance criteria.
- Waste types.
- Handling of waste.
- Waste packaging.
- Origin of waste.
- Design considerations and safety features of each waste vault.
- Waste packages in each waste vault.
- Material quantities in each waste vault.
- Radionuclide inventories in each waste vault.
- Main dimensions of the waste vaults.
- Inspection and control processes.

An overview of proposed measures for plugging and closure of SFR is also given. Overall, the report provides input to the assessment of the post-closure safety of the SFR repository system.

Finally, the expected properties and condition of each system component and uncertainties at repository closure are described following prescribed lists of variables (parameters), see Tables 12-1, 12-3 and 12-4.

Sammanfattning

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

Initialtillståndet är definierat som det förväntade tillståndet för förvaret och dess omgivning direkt efter förslutning. Initialtillståndet för förvaret bygger på kontrollerade och dokumenterade egenskaper hos avfall och förvarskomponenter samt bedömning av förändrade egenskaper under tiden fram till och med förslutning. Tidpunkten för förslutning uppskattas till år 2075.

För att definiera och säkerställa ett ändamålsenligt initialtillstånd för SFR beskrivs följande i rapporten:

- Acceptanskriterier för avfall.
- Avfallstyper.
- Avfallshantering.
- Avfallsemballage.
- Avfallets ursprung.
- Förvarsdelarnas design.
- Fördelning av avfall mellan förvarsdelarna.
- Materialmängder.
- Radionuklidinventarium.
- Förvarsdelarnas dimensioner.
- Inspektions- och kontrollprocesser.

En översikt över föreslagna åtgärder för pluggning och förslutning av SFR ges också. Sammantaget utgör den här rapporten underlag för analysen av säkerheten efter förslutning av SFR:s förvarssystem.

Slutligen beskrivs de förväntade egenskaperna vid förslutning för varje systemkomponent i förvaret samt deras tillstånd med hjälp av föreskrivna listor med variabler (parametrar), se Tabell 12-1, 12-3 och 12-4.

Contents

1 Introduction

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

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

1.1 Background

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

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

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

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

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

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

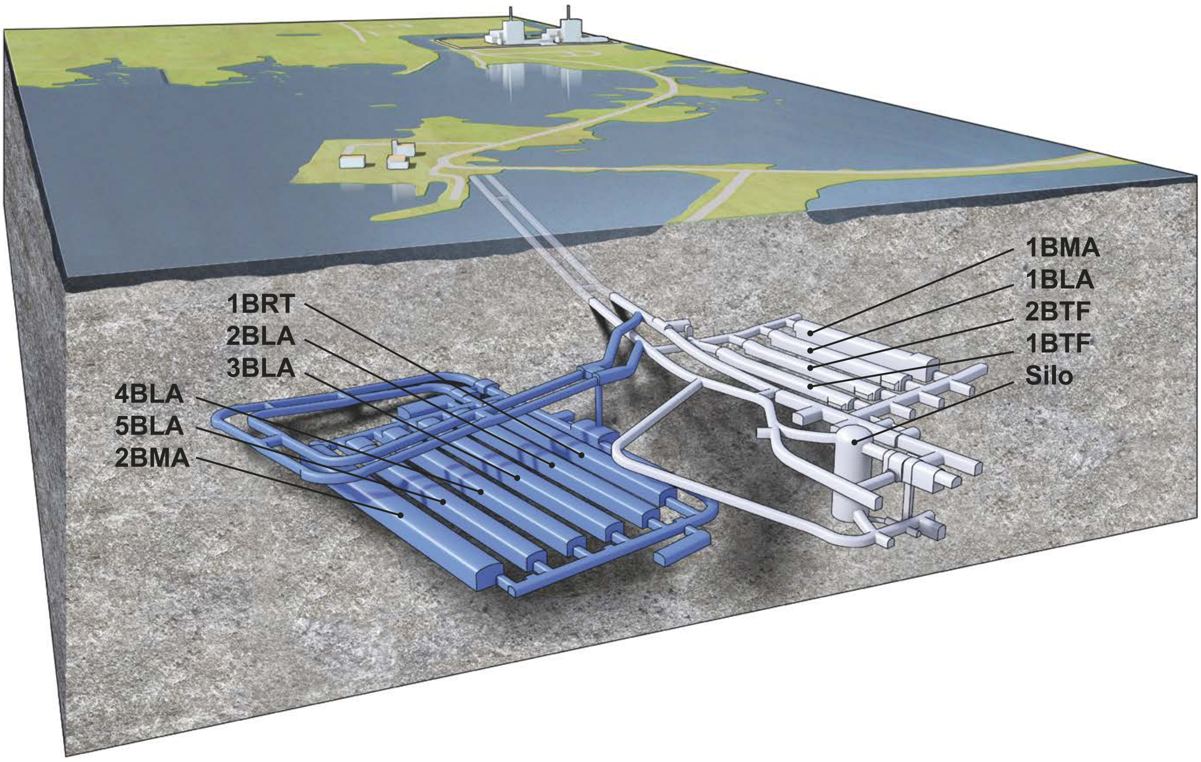

Figure 1-1. *Schematic illustration of SFR. The grey part is the existing repository (SFR1) and the blue part is the extension (SFR3). The waste vaults in the figure are the silo for intermediate-level waste, 1–2BMA vaults for intermediate-level waste, 1BRT vault for reactor pressure vessels, 1–2BTF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

1.2 Post-closure safety assessment

1.2.1 Overview

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

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

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

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

1.2.2 Report hierarchy

The **Post-closure safety report** and main references for the post-closure safety assessment are listed and briefly described in Table 1-1, also including the abbreviated titles (in bold) by which they are identified in the text. Furthermore, there are numerous additional references that include documents compiled either by SKB or other organisations, or that are available in the scientific literature, as indicated in Figure 1-2.

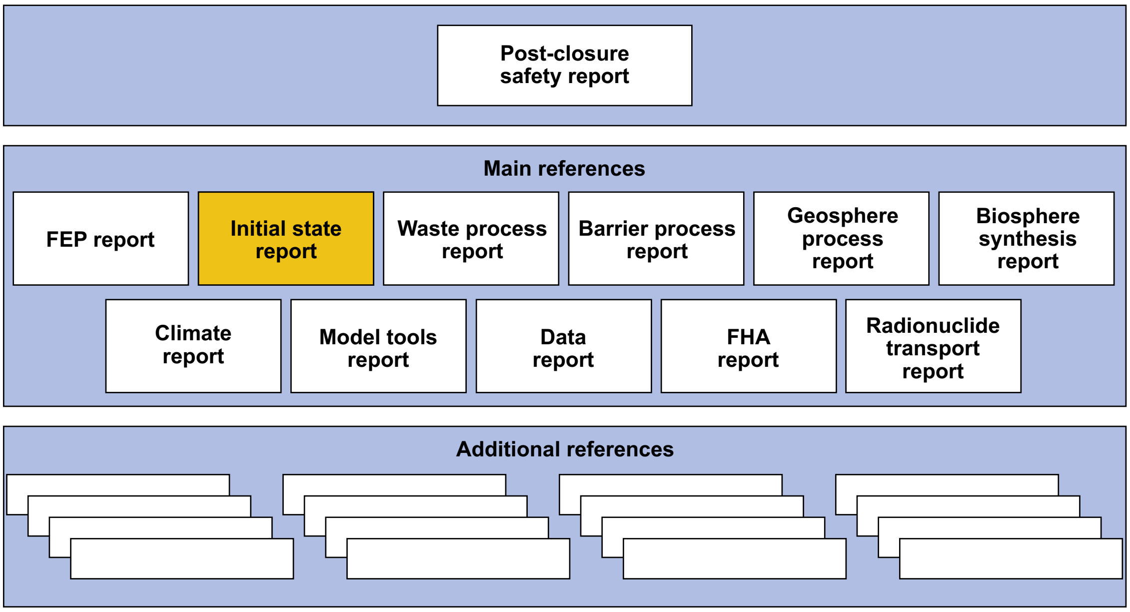

Figure 1-2. *The hierarchy of the Post-closure safety report, main references and additional references in the post-closure safety assessment.*

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

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

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

1.3 This report

A ten steps methodology is applied to assess post-closure safety for SFR, see Chapter 2 in the **Post-closure safety report**. The steps are carried out partly concurrently and partly consecutively. This report belongs to Step 2: Description of initial state.

1.3.1 Purpose

The initial state is defined as the expected state of the repository and its environs at closure of the repository. The initial state is fundamental to the safety assessment and requires thorough substantiation.

This report describes the initial state of the waste and the repository features.

The initial state of the repository part that is currently in operation is based on verified and documented properties of the wastes and the repository and an assessment of how these will change up to the time of closure, whereas the initial state of the extension is mainly based on the reference design and present waste forecasts.

The initial state of the repository environs is assumed to be similar to present-day conditions, as described in Chapter 4 in the **Post-closure safety report** and in the site descriptive model, SDM-PSU (SKB TR-11-04) and the **Biosphere synthesis report**.

Information in this report is used in several of the subsequent steps in the methodology e.g. Step 4 – Description of processes through the process reports for the waste (**Waste process report**) and the engineered barriers (**Barriers process report**) respectively and Step 9 – Analysis of selected scenarios.

The report is an update of the Initial state report for the safety assessment SR-PSU (SKB TR-14-02). The extent of the update is described in subsection 1.3.2.

1.3.2 Main developments since the SR-PSU

This report builds on the initial state report for the SR-PSU. The update comprises e.g. updated radionuclide and material inventories in the waste because more knowledge has been gained from the production of waste packages in the years since the last inventory compilations. The waste production outcome is now used to replace previous forecasts for the relevant time-period. The forecasted waste production up to the closure of SFR has moreover been improved due to further experience from additional years of operation. The distribution of waste packages between the different waste vaults has also been altered, to optimise the disposal strategy further.

This report is furthermore updated as a result of the changes in the reference design described in Section 2.2. Consequently, variables given in Chapter 12 that e.g. are used in near-field hydrological calculations have been updated (**Radionuclide transport report**). Uncertainty discussions have also been added in the report since the SR-PSU version.

1.3.3 Contributing experts

Project leader for the PSAR safety assessment has been Jenny Brandefelt (SKB). A number of people from various fields of expertise have been involved in the description of the initial state. The most involved in preparation of this report are listed below in alphabetical order:

Name	Affiliation	Contribution to this report
Katrin Ahlford	SKB	waste properties, co-author, editor
Miranda Keith-Roach	Kemakta Konsult AB	co-author
Klas Källström	SKB	co-author
Maria Lindgren	Kemakta Konsult AB	repository dimensions, co-author
Ola Wessely	SKB	repository design and variables, co-author

This report has been significantly improved at different stages by adjustments in accordance with comments provided by informal and factual reviewers. Informal reviewers have been: Svante Hedström (SKB), Per Mårtensson (SKB), Ola Wessely (SKB), Georg Lindgren (SKB) and Maria Lindgren (Kemakta Konsult AB). Factual reviewers have been: Mike Thorne (Mike Thorne and Associates Ltd.) and Jordi Bruno (Amphos 21 Consulting).

1.4 Structure of this report

This report comprises twelve chapters and an appendix. Following is a brief description of the contents:

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

Chapter 2 – General considerations. This chapter introduces the waste and the reference design for SFR, defines the repository system and its subcomponents and discusses general uncertainties that are associated with the initial state.

Chapter 3 – Waste. Waste acceptance criteria, descriptions of waste types and packaging, the distribution of waste packages in the waste vaults, and material quantities and radionuclide inventories in each vault are given in this chapter.

Chapters 4 to 10 – Waste vaults. The waste vaults are the silo for intermediate-level waste, 1–2BMA vaults for intermediate-level waste, the 1BRT vault for reactor pressure vessels, 1-2BTF vaults for concrete tanks and 1-5BLA vaults for low-level waste. In these chapters the design and design considerations for each waste vaults are described. The main dimensions are given in tables.

Chapter 11 – Plugs and other closure components. An overview of proposed measures for plugging and closure of SFR is given in this chapter.

Chapter 12 – Variables at initial state for the system components. The expected conditions of the different system components at repository closure are defined by going through the lists of variables (parameters) that are required to describe the properties and condition of each system component.

Appendix A – Estimated material and void + pore volumes in the waste vaults. For each waste vault, the volumes and pore volumes of the materials present are given in a table together with the void volumes. These data are based on the dimensions given in Chapters 4–10.

1.5 Terms and abbreviations – Initial state report

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

Table 1-2. Terms and acronyms used is the PSAR post-closure safety assessment.

Name	Description
1–2BTF	Vaults for concrete tanks in SFR1.
1BLA	Vault for low-level waste in SFR1.
1BMA	Vault for intermediate-level waste in SFR1.
1BRT	Vault for reactor pressure vessels in SFR3.
1BST	Waste vault tunnel in SFR1.
1SBT	Silo bottom tunnel.
1SDT	Silo drainage tunnel.
1ST	Silo tunnel.
1STT	Silo roof tunnel.
1TT	Transverse tunnel in SFR1.
2–5BLA	Vaults for low-level waste in SFR3.

Name	Description
2BMA	Vault for intermediate-level waste in SFR3.
2BST	Waste vault tunnel in SFR3.
2TT	Transverse tunnel in SFR3.
3D	Three-dimensional.
3FS	A vertical shaft in SFR3.
Barrier	In the safety assessment context, a barrier is a physical feature, engineered or natural, which in one or several ways contributes to the containment and retention or prevention of dispersion of radioactive substances, either directly or indirectly by protecting other barriers.
Bedrock	In the safety assessment context, the solid rock beneath the regolith also including the groundwater in the rock.
Best estimate	A single value for a parameter, describing a property or a process, used in deterministic calculations. Best estimates are typically derived from site and/or literature data and often correspond to mean values of the underpinning datasets.
BT	Construction tunnel (one of two access tunnels).
BWR	Boiling water reactor.
Bulk density	The bulk density of a porous medium is defined as the mass of the solid particles that make up the medium divided by the total volume they occupy. The total volume includes particle volume, inter-particle void volume and internal pore volume.
Calculation case	Used for the quantitative assessment of the scenarios selected in the safety assessment, typically by calculating doses.
Clab	Central interim storage facility for spent nuclear fuel in Simpevarp, Sweden.
Clink	Facility comprising the central interim storage (currently Clab) and the planned encapsulation plant.
Conditioning	Those operations that produce a waste package suitable for handling, transport, storage and/or disposal.
Connecting tunnel	General term used for tunnels outside waste vaults, for example BST.
Crushed rock	Mechanically crushed rock material with varying grain size distribution and hydraulic properties. The selected grain size distribution is dependent on the required properties. See also macadam.
CT	Central tunnel in SFR.
Data uncertainty	Uncertainties concerning all quantitative input data, that is parameter values, used in the assessment.
DT	Operational tunnel (one of two access tunnels).
DTPA	Diethylenetriaminepentaacetic acid, a complexing agent.
EDTA	Ethylenediaminetetraacetic acid, a complexing agent.
FEP	Features, events and processes.
GEKO/QI	Product name of bentonite used in the silo.
HCP	Hydrated cement paste.
IAEA	International Atomic Energy Agency.
Initial state	The expected state of the repository and its environs at closure of the repository.
Intermediate-level waste	Radioactive waste that requires final disposal in a geological repository and shielding during handling. Cooling of the waste is not required.
ISA	Isosaccharinate, a complexing agent that is a cellulose degradation product.
ISO	International Organization for Standardization.
Layout 2020	Layout for SFR3 from 2020, used in the post-closure safety assessment (PSAR SFR).
Layout 2021	Final layout for SFR3 used in the PSAR SFR application.
Long-lived radionuclide	In the safety assessment context, radionuclides with a half-life exceeding 31 years.
Low-level waste	Radioactive waste that requires final disposal in a geological repository. Shielding during handling and cooling are not required.
Macadam	Crushed rock sieved in fractions 2–65 mm. Macadam has no or very little fine material (grain size < 2 mm). The fraction is given as intervals, for example “Macadam 16–32” is crushed rock comprising the fraction 16–32 mm.
NBT	Lower construction tunnel.
Near-field	Typically used for the model domain representing the repository, which may contain part of the nearby bedrock to obtain boundary conditions.
NSP	Lower silo plug.
NTA	Nitrilotriacetic acid, a complexing agent.

Name	Description
Packaging	The outer container, such as a mould, drum or ISO-container, protecting the waste form (synonymous with Waste packaging).
PDF	Probability density function.
Pessimistic	Indicates an expected overestimate of annual effective dose that follows from assumptions made, or models and parameter values selected, beyond the reasonably expected range of possibilities.
PSAR	Preliminary Safety Analysis Report.
PSU	Programme SFR extension.
PVC	Polyvinyl chloride.
PWR	Pressurised water reactor.
Repository	The disposed waste packages, the engineered barriers and other repository structures.
Repository system	The repository, the bedrock and the biosphere surrounding the repository. Synonymous with repository and its environs.
Risk	Refers in the post-closure safety assessment to the radiological risk, defined as the product of the probability of receiving a radiation dose and the harmful effects of that radiation dose.
RNT	Radionuclide transport.
Safety analysis	In the context of the present safety assessment, the distinction is generally not viewed as important and therefore safety analysis and safety assessment are used interchangeably. However, if the distinction is important, safety analysis should be used as a documented process for the study of safety and safety assessment should be used as a documented process for the evaluation of safety.
Safety assessment	The safety assessment is the systematic process periodically carried out throughout the lifetime of the repository to ensure that all the relevant safety requirements are met and entails evaluating the performance of the repository system and quantifying its potential radiological impact on human health and the environment. The safety assessment corresponds to the term safety analysis in the Swedish Radiation Safety Authority's regulations.
SAR	Safety Analysis Report.
Scenario	A description of a potential evolution of the repository and its environs, given an initial state and specified external conditions and their development and how the protective capability of the repository is affected.
SDM-PSU	Site descriptive model for the SFR area.
SFL	Final repository for long-lived radioactive waste.
SFR	Final repository for short-lived radioactive waste at Forsmark.
SFR1	The existing part of SFR.
SFR3	The extension part of SFR.
Silo	Cylindrical vault for intermediate-level waste (part of SFR1).
SKB	Swedish Nuclear Fuel and Waste Management Company.
SKBdoc	Internal document management system at SKB.
SR-PSU	Post-closure safety assessment that was a reference to the F-PSAR for the extended SFR, reported to the regulatory authority in 2014.
SSM	Swedish Radiation Safety Authority.
SSMFS	Regulations of the Swedish Radiation Safety Authority.
System component	A physical component of the repository system; a sub-system.
Transition material	Component in earth dam plug e.g. 30/70 mixture bentonite and crushed rock. The role of the transition material is to hinder bentonite transport from the hydraulically tight section, to take up the load from bentonite swelling and transfer it to the backfill material.
Waste domain	Part of waste vaults where waste is placed (inside the engineered barriers).
Waste form	Waste in its physical and chemical form after treatment and/or conditioning.
Waste package	The waste (form) and its packaging.
Waste packaging	The outer container, such as a mould, drum or ISO-container, protecting the waste form (synonymous with Packaging).
Waste stream	The pathway of a specific waste, from its origin through to its disposal in a defined waste type.
Waste type	SKB's systematic classification of wastes according to a developed code system.
Waste type description	Safety report for a waste type. The waste type description contains, among other things, information about the waste, waste packaging, treatment of the waste and where the waste is to be disposed.
Waste vault	Part of repository where waste is disposed.
ÖSP	Upper silo plug.

2 General considerations

This chapter introduces the waste and the reference design for SFR, defines the repository system and its subcomponents and discusses general uncertainties that are associated with the initial state.

2.1 Waste

The initial state description for the waste in both the existing part (SFR1) and the extension (SFR3) is based on estimated material quantities in the repository and the calculated radionuclide inventory. Future waste quantities are based on forecasts.

SKB plans to extend SFR to enable the disposal of decommissioning waste and additional operational waste resulting from the planned prolonged operation of the nuclear power plants. The extension of SFR is therefore being designed to receive additional short-lived low- and intermediate-level operational waste and all short-lived decommissioning waste expected to result from the dismantling of today's nuclear power plants, including waste from the old power plant at Ågesta and the Studsvik reactor, and decommissioning waste from the interim storage facility for spent fuel and the planned adjacent encapsulation plant (Clink). Also, the decommissioning waste from AB SVAFO, Studsvik Nuclear AB and Cyclife Sweden AB is included.

The nuclear facilities that generate waste are responsible for ensuring that the waste is conditioned, that waste packages are produced and for the interim storage of the waste. SKB is responsible for the transport to SFR and disposal of the waste. Nevertheless, the waste producers remain accountable for their waste until final closure of the repository in which the waste is disposed.

The tools used to ensure that the waste is properly managed and emplaced in the correct waste vault in SFR are the waste handling manual (Canderyd 2022), waste type descriptions, waste audits and a waste register. Waste acceptance criteria are given in the safety analysis report (SAR) for the repository. The waste type descriptions contain information on how the acceptance criteria, relevant for the specific waste type, will be fulfilled and verified.

2.2 Reference design

One part of the repository (SFR1) exists today, whereas the extension (SFR3) is at the planning stage. Therefore, the description of the initial state of SFR1 can be given more accurately, based on measurements and observations. However, additional reinforced concrete walls will be erected outside the existing concrete structure in 1BMA before closure, and the initial state of 1BMA includes the proposed design of these walls. The initial state of the extension is based on the proposed design for SFR3.

The design of the repository will evolve over time from the initial drawings to the final *as built* design. Therefore, a *reference design* is used during technical development, design improvement and for post-closure safety assessments.

The reference design for SFR1 is mainly based on system descriptions and technical drawings. The reference design for SFR3, except for that used in the post-closure safety assessment, is based on the design here called Layout 2021. The post-closure safety assessment for SFR in the PSAR, including this report, is instead based on the repository extension design from an earlier layout, here called Layout 2020. Since the preparation of a licence application is an iterative and relatively long process, the model of hydrogeological conditions for the PSAR is based on an even earlier design than that given in this report (Abarca et al. 2020, Öhman and Odén 2018). All other parts of the post-closure safety assessment are however based on the Layout 2020 design. The main design features that are changed since the previous safety assessment, SR-PSU, are:

- Additional reinforced external concrete walls in 1BMA, see Table 5-1.

- Height and width of the excavated rock vault and the caissons are increased in 2BMA, see Table 6-1.
- One fewer caisson in 2BMA.
- The reactor pressure vessels are segmented and embedded in concrete in steel packaging.
- 1BRT contains a concrete structure with compartments for the waste packages.
- All dimensions of the excavated 1BRT rock vault are increased, see Table 7-1.
- The height of the excavated 2–5BLA rock vault is somewhat reduced, see Table 10-1.

In the description of the extension of SFR given in this report, all figures are according to Layout 2021 and dimensions are given in tables for both layouts.

The existing waste vaults of SFR1 are located approximately 60 m below the floor of the Baltic Sea in the bedrock. The extension SFR3 is planned to be built at a depth of approximately 120 m (where the highest point in SFR3 is approximately level with the bottom of the silo in the existing SFR1), see Figure 2-1. The six new waste vaults of SFR3 will directly connect to the existing SFR1 through two tunnels.

When waste disposal in SFR is completed, the operational period will end and the sealing and closure of vaults and tunnels will begin. After sealing and closure is completed by 2075, no further actions will be needed to support the function of the passive underground repository. An overview of the repository after the planned sealing and closure measures described in the closure plan for SFR (Mårtensson et al. 2022) is shown in Figure 2-2. The planned closure measures and the technical solutions that will be used at closure have however not yet been finalised.

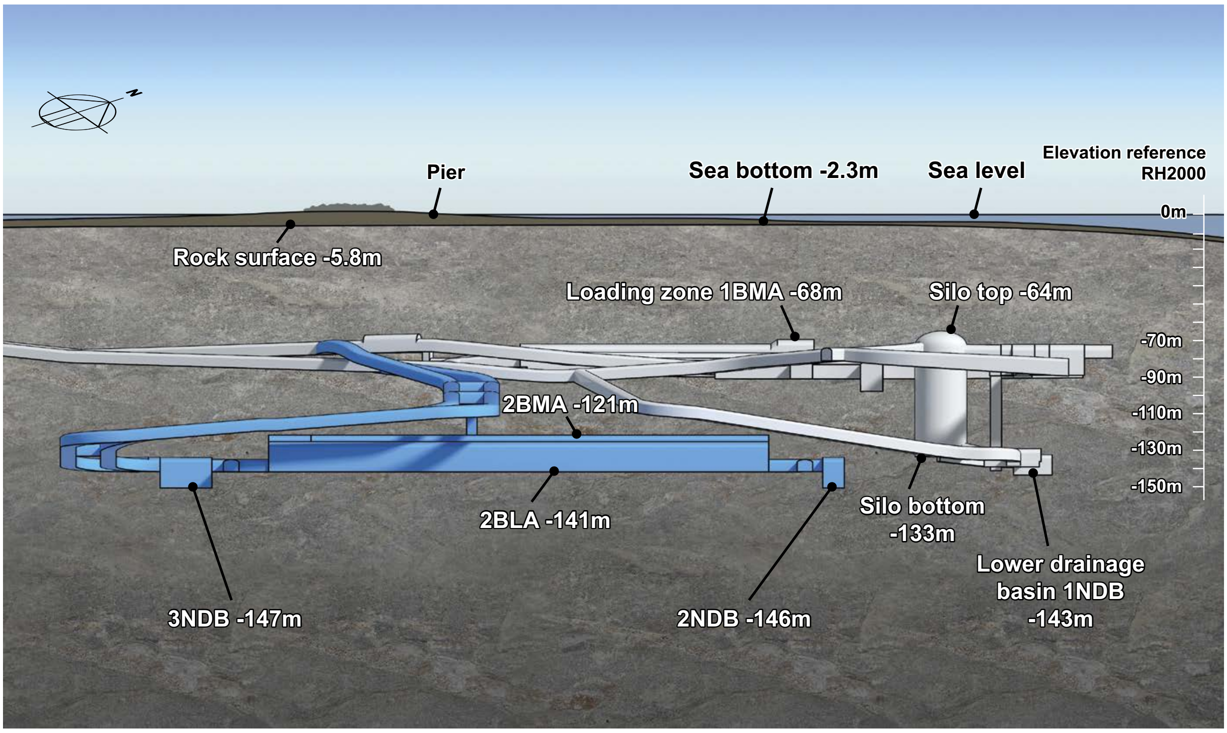

Figure 2-1. View of SFR with designated levels in RHB 2000 (RHB 2000 is the Swedish geographical height system). View is towards the NW, approximately perpendicular to the waste vaults. Note that stipulated elevations for the top surface of the rock and the sea floor are to be regarded as approximate since they are point data and vary in the plane above SFR. The grey part is SFR1 and the blue part is SFR3.

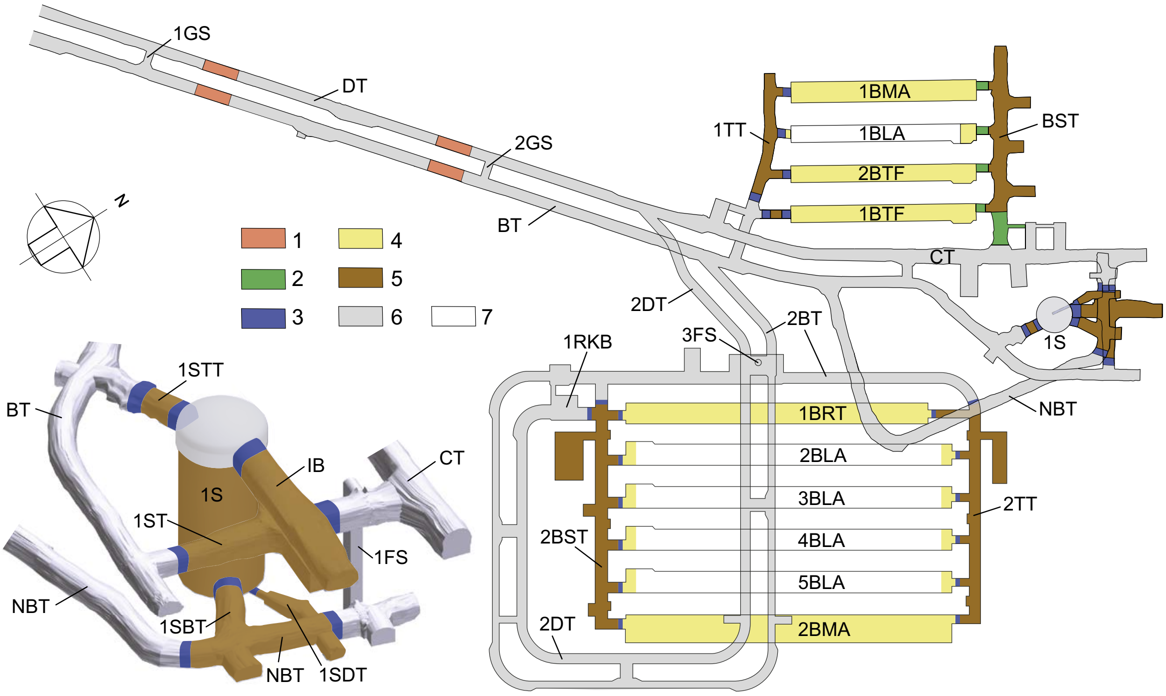

Figure 2-2. *Overview of SFR after closure with a detailed view of the silo. Key to numbered colours: 1) Plugs in access tunnels 2) Transition material 3) Concrete mechanical constraint 4) Backfill material of macadam 5) Hydraulically tight section of bentonite 6) Backfill material in silo top, access tunnels and tunnel system 7) Non-backfilled openings.*

2.3 Laws and regulations

SFR shall conform to the requirements of relevant laws and regulations.

The international treaties and national laws and regulations relevant for the design of a final repository for low- and intermediate-level radioactive waste are the following.

International treaty:

- Joint convention on the safety of spent fuel management and on the safety of radioactive waste (IAEA 2006).

National laws:

- Act on Nuclear Activities, KTL (SFS 1984:3).
- Radiation Protection Act, SSL (SFS 2018:396).

Regulations:

- Regulations concerning safety in nuclear facilities (SSMFS 2008:1).
- Regulations concerning physical protection of nuclear facilities (SSMFS 2008:12).
- Regulations concerning safety in connection with the disposal of nuclear material and nuclear waste (SSMFS 2008:21).
- Regulations on the protection of human health and the environment in connection with the final management of spent nuclear fuel and nuclear waste (SSMFS 2008:37).

In addition, the following laws must be followed during design, construction and operation of the repository:

- The Swedish Environmental Code, MB (SFS 1998:808).
- The Planning and Building Act, PBL (SFS 2010:900).
- The Work Environment Act, AML (SFS 1977:1160).

In addition, stakeholder demands are expressed in SKB's guiding principles. These are that safety, efficiency and responsiveness shall be considered in the design.

2.4 Repository system

The repository system is broadly defined as the disposed radioactive waste, the waste packaging, the engineered barriers surrounding the waste packages, the host rock and the biosphere surrounding the repository.

According to the **FEP** (Features, Events and Processes) **report**, the repository can be divided into system components. A system component is a physical component of the repository. This report follows the definition given in the **FEP report**, but many other definitions of SFR system components are used elsewhere.

The waste packages are divided into two system components:

- Waste form, i.e. waste including conditioning material.
- Waste packaging, e.g. drums, moulds (concrete and steel), concrete tanks, and containers.

The main system components for disposal of waste packages are:

- SFR1
- Silo
- 1BMA
- 1BTF and 2BTF
- 1BLA
- SFR3
- 2BMA
- 1BRT
- 2BLA, 3BLA, 4BLA and 5BLA.

Each of these main system components consist of several other system components. For example, 1BMA consists of the existing concrete structures, additional reinforced cement walls and lids and macadam.

Other system components in the repository are:

- Plugs and other closure components (including investigation boreholes).

In addition, the rock surrounding the repository and the surface environment in the repository area are defined as system components in the **FEP report**. The barriers and their function are described in the **Post-closure safety report** Chapter 4.

2.5 Inspection and control

SKB has a quality management system that includes procedures for project management and safety audit. These procedures have served as a basis for framing the control documents, or quality assurance systems, that have governed the work relating to both SFR1 and SFR3. The quality management system meets the requirements in ISO 9001, 45001 and 14001.

Controls performed during the construction, inspection and measurement of conditions in the existing facility SFR1 are documented. The existing control programme comprises e.g. measurements of groundwater inflows and groundwater chemistry, and inspection of the physical condition of the waste vaults. The purpose of the programme is to examine ongoing changes in the system such as settlement of the silo and the future impacts of blasting during construction of SFR3. A special control programme is defined for the silo (Section 4.3), which has the most effective engineered barrier system.

Methods for testing and inspecting SFR3 during its construction (tunnels and waste vaults) will be developed and defined during the detailed design phase for the extension. It is foreseen that a special control programme will be defined for 2BMA, due to its new design with unreinforced caissons, see Section 6.3.

2.6 Uncertainties

The initial state is in this report described in terms of a reference waste inventory and a repository reference design. This initial state may be subject to uncertainties, some of which are important to consider in the subsequent analysis. Uncertainties in the reference waste inventory arise, for instance, due to the necessity to forecast the amount and activity of wastes that have not yet been generated. In order to account for uncertainties, a Monte Carlo simulation was carried out as described in SKB (R-18-07). The result is reported in Section 3.8 as the 95th-percentile of activity in each vault at repository closure in 2075. For some radionuclides (e.g. Cl-36) there is not sufficient information available to quantify the probability density function used in the MC-simulation. In such cases a single pessimistic value has been used instead.

Complexing agents that can have an impact on radionuclide transport in relatively small amounts are also handled stochastically to manage relevant uncertainties. The amounts are in most cases not specified among the materials in Section 3.7, but are accounted for in Keith-Roach et al. (2021). In the report it is described how the uncertainty associated with the estimated masses of complexing agents in the waste is assessed. For instance, the uncertainties associated with the mass of cellulose, that can degrade to the complexing agent isosaccharinate (ISA), were assessed using a Monte Carlo approach.

The condition of the waste packaging at closure also contributes to the uncertainties, see Section 12.2.1.

Uncertainties in the repository reference design, and in particular the initial state of the barriers, is a central aspect of the safety assessment. The uncertainties are described where applicable for the different waste vaults in Sections 4.4 (Silo), 5.4 (1BMA), 6.4 (2BMA), 7.4 (1BRT) and 8.4 (1–2BTF) respectively. This assessment focuses on uncertainties related to the initial state of 1BMA and the planned measures to repair and strengthen the existing concrete construction (Elfwing et al. 2018), see Section 5.4. During the repairs in 1BMA and construction of the vaults in the extension of SFR, controls and inspections will be undertaken during the construction to ensure that requirements are met and to ensure an adequate knowledge of the achieved initial state of the waste vaults, which reduces uncertainties.

The scenario analysis includes a less probable scenario with an alternative concrete evolution, which assesses the robustness of the concrete barrier by including a deviating initial state that represents a limiting case of the initial state uncertainty range. For the other waste vault materials, a pessimistic strategy has been applied with respect to the hydraulic conductivities of the different components to handle data uncertainties.

The variables for the system components are listed in Chapter 12. Many of the parameters connected to the variables are not listed in this report, but are documented in the **Data report**. The handling of the data uncertainty in relation to these variables is therefore also described in the **Data report**.

3 Waste

3.1 Waste acceptance criteria

Waste acceptance criteria can be defined as quantitative or qualitative requirements that must be fulfilled in order for the waste to be accepted for final disposal.

Waste acceptance criteria are required according to the updated SSMFS 2008:1 regulation (Chapter 6 Sections 11–12 (there is no official translation available of the updated version of 2008:1 including these sections)):

Acceptance criteria

Section 11: For facilities that handle nuclear material that is no longer intended for use or nuclear waste from other facilities, there must be documented requirements (acceptance criteria) regarding the properties of materials that may be received for storage, final disposal or other handling. Acceptance criteria shall, as far as reasonable and possible, take into account the safety and radiation protection in every step of the further management. Acceptance criteria shall be included in the safety analysis report in accordance with Chapter 4, Section 2.

Section 12: In order to receive materials for storage, final disposal or other handling, written instructions are required to control how the received material has been handled earlier in the chain of custody and showing that it meets the acceptance criteria. There should also be documented procedures for handling materials that do not meet the acceptance criteria, either returning them to the sender or correcting the deviations.

These paragraphs were added to SSMFS 2008:1 and have been applied since November 2012. The waste acceptance criteria are summarised in the following subsection.

3.1.1 The SFR waste acceptance criteria

The waste acceptance criteria concern general, radiological, chemical and physical as well as mechanical requirements. Waste acceptance criteria are continuously updated as a result of further investigations but also due to iterations with post-closure safety analyses. The latest waste acceptance criteria for operational waste in SFR1 were stipulated in 2021.[4] A previous version of the waste acceptance criteria for operational waste in SFR1 was current as the data freeze for this report was set.[5] Preliminary waste acceptance criteria have been defined for SFR3 (Eriksson Örtengren and Eriksson 2014) and these have since been updated for waste allocated to 1BRT,[6] 2BMA[7] and 2–5BLA[8]. A summary of the waste acceptance criteria is given below, with focus on the criteria that are of importance for post-closure safety. The summary is based on the previous waste acceptance criteria for operational waste in SFR1[5] and major differences between these and the preliminary criteria for SFR3 are pointed out.

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[4] Södergren K, Snis K, Reitti M, 2021. Acceptanskriterier för avfall i SFR1. SKBdoc 1336074 ver 5.0, Svensk Kärnbränslehantering AB. (In Swedish.) (Internal document).

[5] Lihnell M, Södergren K, 2018. Acceptanskriterier för avfall i SFR1. SKBdoc 1336074 ver 3.0, Svensk Kärnbränslehantering AB. (In Swedish.) (Internal document).

[6] Södergren K, 2019. Preliminär acceptanskriterier för avfall till BRT i utbyggt SFR. SKBdoc 1705745 ver 1.0, Svensk Kärnbränslehantering AB. (In Swedish.) (Internal document).

[7] Snis K, 2019. Preliminära acceptanskriterier för avfall till 2BMA i utbyggt SFR. SKBdoc 1881601 ver 1.0, Svensk Kärnbränslehantering AB. (In Swedish.) (Internal document).

[8] Calderon M, 2021. Preliminär acceptanskriterier för avfall till 2–5BLA i utbyggt SFR. SKBdoc 1677507 ver 2.0, Svensk Kärnbränslehantering AB. (In Swedish.) (Internal document).

General requirements

The general requirements concern the geometry, dimensions, weight, labelling and conditioning of waste packages. These requirements are related to the handling and documentation of the waste.

Radiological requirements

The radiological requirements concern the radionuclide inventory, surface dose rate, dose rate at a certain distance, surface contamination, and radiation effects on the waste.

Radionuclide inventory

The radionuclide inventory should be known and documented in a register. The inventory of radionuclides should be obtained by direct or indirect radionuclide-specific measurements and/or calculations.

Up to the point of the data freeze for this report, SFR1 was licensed to hold a total activity of 10^{16} Bq. However, there are also activity limits relating to the disposal of specific radionuclides in each waste vault, see Table 3-1. The overall activity limits set by the license relate to the sum of the activity across all waste packages in a waste vault, which should be within the limit for that waste vault.

The PSAR contains an updated inventory for both SFR1 and SFR3. This forms the basis for defining the waste acceptance criteria and will be fully implemented after SSM's approval of the SAR. The best estimate inventory is given in Section 3.7 and the best estimate including uncertainties (95 percentile) is given in Section 3.8.

Table 3-1. Limits for activities in the different waste vaults in SFR1 (Bq).

Radionuclide	Silo	1BMA	1–2BTF	1BLA
H-3	1.3×10^{14}	-	-	-
C-14org*	6.8×10^{11}	2.9×10^{10}	1.3×10^{10}	2.6×10^{8}
C-14inorg*	6.1×10^{12}	2.6×10^{11}	1.2×10^{11}	2.3×10^{9}
Fe-55	7.1×10^{14}	1.0×10^{14}	1.7×10^{13}	2.3×10^{12}
Ni-59	6.8×10^{12}	1.0×10^{12}	1.5×10^{11}	2.3×10^{10}
Co-60	1.8×10^{15}	2.6×10^{14}	4.0×10^{13}	5.8×10^{12}
Ni-63	6.3×10^{14}	8.8×10^{13}	1.5×10^{13}	1.9×10^{12}
Sr-90	2.5×10^{14}	6.5×10^{12}	2.7×10^{12}	7.1×10^{10}
Nb-94	6.8×10^{9}	1.0×10^{9}	1.5×10^{8}	2.3×10^{7}
Tc-99	3.3×10^{11}	8.8×10^{9}	3.6×10^{9}	1.1×10^{8}
Ru-106	6.1×10^{12}	1.7×10^{11}	6.2×10^{10}	2.1×10^{9}
I-129	1.9×10^{9}	4.7×10^{7}	2.2×10^{7}	6.4×10^{5}
Cs-134	8.1×10^{14}	2.2×10^{12}	1.1×10^{13}	2.6×10^{11}
Cs-135	1.9×10^{10}	5.3×10^{8}	2.2×10^{8}	6.4×10^{6}
Cs-137	4.9×10^{15}	1.3×10^{14}	5.3×10^{13}	1.4×10^{12}
Pu-238	1.2×10^{12}	3.1×10^{10}	1.7×10^{10}	4.7×10^{8}
Pu-239	3.8×10^{11}	1.2×10^{10}	6.9×10^{9}	1.9×10^{8}
Pu-240	7.8×10^{11}	1.9×10^{10}	1.1×10^{10}	2.9×10^{8}
Pu-241	4.2×10^{13}	9.4×10^{11}	5.4×10^{11}	1.5×10^{10}
Am-241	1.0×10^{12}	2.4×10^{10}	1.3×10^{10}	3.8×10^{8}
Cm-244	1.2×10^{11}	2.8×10^{9}	1.5×10^{9}	4.4×10^{8}

* C-14 has been divided into organic and inorganic activity.

Surface dose rate

The maximum surface dose rates allowed according to the waste acceptance criteria for waste packages in the different waste vaults are given in Table 3-2 (implemented for SFR1 and preliminary for SFR3.[6, 7, 8] However, transport and handling prior to disposal may in some cases put further limitations on the dose rates close to the waste packages.

Surface contamination

The surface contamination should not exceed 40 kBq/m^2 for beta- and gamma-emitters and 4 kBq/m^2 for alpha-emitters. These are the same as the limits applied in the regulations for clearance of materials (SSMFS 2018:3). There are additional requirements for the waste packages and transport containers relating to transport.

Table 3-2. Maximum surface dose rates for waste packages in the different waste vaults (mSv/h) (implemented for SFR1 and preliminary for SFR3.[6, 7, 8]

Waste vault	Surface dose rate limit (mSv/h)
1BMA	100 (< 30 for 80 %, > 30 for 20 %)
2BMA	100
1BTF	2 for drums and 10 for other waste packages (however the current transport system limits the dose rate to 8 for concrete tanks and 2 for drums)
2BTF	10
Silo	500
1BLA	2. The maximum surface dose rate of components that are placed in containers is also 2.
2–5BLA	2. The maximum surface dose rate of components that are placed in containers is also 2.
1BRT	60

Radiation effects

The integrated dose received by waste packages in 1–2BMA and the silo that contain organic material should not exceed 10^5 Gy.

Chemical and physical requirements

The chemical and physical requirements concern composition, structure, liquids, fire resistance, chemical reactivity (complexing agent contents) and environmentally hazardous substances.

Composition and structure

The chemical composition and structure of the waste form and waste packaging must be known and the amounts of specified materials must be reported per waste package. These materials are aluminium/zinc, bitumen, cellulose, ion exchange resins, iron/steel, sludge, other organic material, concentrates and polyacrylonitrile filter aids.

Liquids

The content of the waste package is not allowed to be liquid. Specifically, the waste shall not contain free or contained liquid.

Fire resistance

Explosive and strongly oxidising substances are not allowed in the waste packages. The design of the packaging shall prevent the spread of fire. The containers disposed in 1–5BLA shall not show rusting or physical damage that could lead to the formation of holes during disposal. Inner packaging for inflammable material shall also be sealed and without visible damage. To avoid self-ignition of BLA waste:

- Oil-saturated porous material shall be contained in tight steel drums.
- Metal cuttings that are contaminated with oil-like products shall be contained in tight steel drums.
- Batteries and equipment with inbuilt batteries shall be enclosed in inner packaging. The inner packaging shall be protected from short-circuiting and packed in robust outer packaging. Equipment does not require the outer packaging if it in itself fulfils the above requirements.
- Active carbon products shall be contained in packaging that cannot burn.
- Compactable combustible waste shall be baled.
- If the above measures are judged to be inadequate to prevent self-ignition, the waste shall be stabilised and then placed in a container.

To reduce the risk of self-ignition in 1–5BLA further, containers allocated to 1–5BLA are stored for three months prior to disposal.

Chemical reactivity (complexing agents)

Acceptance criteria for chemical reactivity apply to waste that is allocated to the silo, BMA and BTF, but not BLA. Substances that are classified as strong complexing agents shall not be disposed in the silo, BMA and BTF. These are:

- N-carboxylated diamines, e.g. EDTA (ethylenediaminetetraacetic acid).
- N-carboxylated triamines, e.g. DTPA (diethylenetriaminepentaacetic acid).
- N-carboxylated amino acids, e.g. NTA (nitrilotriacetic acid).
- α-hydroxy-carboxylic acids, e.g. gluconic acid.
- Fuel extraction liquids, e.g. tributyl phosphate (TBP)

Esters of these strong organic complexing agents shall not be disposed in the silo, BMA and BTF.

The concentration of dicarboxylic acids, e.g. oxalic acid, may not exceed 10^{-2} M in each waste package. The concentration of tricarboxylic acids, e.g. citric acid, may not exceed 10^{-3} M in each waste package. Esters of carboxylic acids shall not exceed the concentration given for the corresponding carboxylic acid.

The waste shall not contain more cellulose or cellulose-derivate than can lead to an isosaccharinate concentration of 10^{-4} M over time.

SKB should be consulted for advice before introducing a new product that will accumulate in the waste and may give rise to radionuclide complexation.

Environmentally hazardous substances

Disposal of cadmium, mercury, cyanide, PCB (polychlorinated biphenyl) and pesticides is forbidden in SFR. If the waste contains other environmentally hazardous substances, they must be reported and registered. The amounts of environmentally hazardous substances shall be kept as low as possible. Asbestos shall be placed in double plastic bags or another sealed packaging.

Asbestos-containing waste allocated to 1BRT shall be placed in sealed packaging.

Mechanical requirements

The mechanical requirements concern the robustness against external influences, internal stability and corrosion resistance.

Robustness against external influences

Waste packages allocated to the silo shall withstand stacking of 42 moulds or 56 drums grouted with concrete until closure. Waste packages allocated to 1–2BMA shall withstand stacking of 6 moulds or 8 drums. Waste packages allocated to 1–2BTF shall withstand stacking of two concrete tanks together, which together with an overload from other structural elements totals a load of approximately 25 tonnes, or 10 drums lying on their sides, which is equivalent to a load of 3.6 tonnes. Waste packages allocated to 1–5BLA shall be of ISO-standard according to SS-ISO1496-1. Waste packages allocated to 1BRT shall withstand stacking of 4 moulds/double moulds until closure.

There are additional requirements for the waste packages and transport containers relating to handling and transport. These requirements are different between different waste types depending on differences in their handling and transport from the producers to final disposal. The requirements are given in the Waste type description together with references to supporting studies.

Internal stability

The void volume available in waste packages must be sufficient to compensate for potential swelling of the waste or conditioning materials. For waste packages containing cement-conditioned ion exchange resins, the water:cement ratio should be between 0.38 – 0.42 (excluding gel water).

Corrosion resistance

The waste packaging shall have a corrosion resistance so that the packaging is intact at the time for concrete grouting or closure of repository.

3.1.2 Waste handling manual

The waste handling manual for low- and intermediate-level waste is the steering document for administrative handling of low- and intermediate-level waste that will be disposed in SFR.

The waste handling manual provides guidance about what information that should be included in the waste type description. The code system adopted is given in the manual, see Section 3.2.1.

3.2 Waste types and waste type descriptions

3.2.1 Waste types

In order to systematically classify the wastes, different waste types have been defined and a code system developed. The code system is available in the waste handling manual. The code system is used, for example, when transferring data between the waste producers and SFR. The code system consists of one letter that denominates the producer of the waste package, and two digits giving information on the kind of raw waste, treatment method, geometry and in which part of SFR the waste should be deposited. A complementary number (given after a colon) can also be used to give information about a feature that differentiates this waste from others of the same code.

For example the code R.01:9 means ion-exchange resins from the Ringhals nuclear power plant solidified in cement in a 1.2 × 1.2 × 1.2 m concrete mould. The waste is meant for disposal in the vault for intermediate-level waste (BMA). The ':9' means that it was produced before 1988. The meaning of the complimentary numbers is defined for each waste type, e.g. for B.05:2 the ':2' means that the drums are in a bad condition and have been placed in an extra steel box. The only complementary number with a SFR-wide definition is ':9' which means that the package was made before the operation of SFR started 1988.

Table 3-3 and Table 3-4 explain the different abbreviations used for the different waste types.

Table 3-3. Abbreviations in the code system for the nuclear facilities in Sweden.

Abbreviation	Nuclear facility
B	Barsebäck nuclear power plant
C	Clab (central interim storage for spent fuel) in the future Clink (Clab and encapsulation plant)
E	Cyclife Sweden AB
F	Forsmark nuclear power plant
O	Oskarshamn nuclear power plant
R	Ringhals nuclear power plant
S	Studsvik Nuclear AB
V	AB SVAFO
Å[1]	Ågesta

[1] Based on SKB R-18-07. It has however been changed to "G" since this reference was published.

Table 3-4. Abbreviations for the operational waste in the code system for treatment etc.

Abbreviation	Disposal in	Raw waste	Package	Treatment
01	BMA	Ion-exchange resin	Concrete mould	Cement-solidified
02	Silo	Ion-exchange resin	Concrete mould	Cement-solidified
04	Silo	Ion-exchange resin	Steel drum	Cement-solidified
05	BMA	Ion-exchange resin	Steel drum	Bitumen-solidified
06	Silo	Ion-exchange resin	Steel drum	Bitumen-solidified
07	BTF	Low-level ion-exchange resin	Concrete tank	Dewatered
09	BMA	Sludge	Steel drum	Cement-solidified
10	BMA	Sludge	Concrete mould	Cement-solidified
11	Silo	Sludge and ion-exchange resin	Steel mould	Cement-solidified
12	BLA	Trash and scrap metal	ISO-container	None
13	BTF	Ashes	Steel drum	Concrete-embedded
14	BLA	Trash and scrap metal	Steel drums in ISO-container	Concrete-embedded in drums
15	BMA	Ion-exchange resin	Steel mould	Cement-solidified
16	Silo	Ion-exchange resin	Steel mould	Cement-solidified
17	BMA	Ion-exchange resin	Steel mould	Bitumen-solidified
18	Silo	Ion-exchange resin	Steel mould	Bitumen-solidified
20	BLA	Ion-exchange resins	Steel drums in ISO-container	Bitumen-solidified in drums
21	BMA	Trash and scrap metal	Steel drum	Concrete-embedded
22	Silo	Trash and scrap metal	Steel drum	-
23	BMA	Trash and scrap metal	Concrete/Steel mould	Concrete-embedded
24	Silo	Trash and scrap metal	Concrete/Steel mould	Concrete-embedded
25	BMA	Ashes	Steel drum	Concrete-embedded
28	BLA	Evaporator concentrate	Steel drum in ISO-container	-
29	BMA	Evaporator concentrate	Concrete mould	Cement-solidified
99	All waste vaults	Odd waste	Differs	Differs

To facilitate the compilation of all present and future waste, SKB (R-18-07) provides a provisional system in the forecast of decommissioning waste, see Table 3-5. To easily distinguish between operational and decommissioning waste, the letter D (*D* for *Decommissioning*) has been added after the number in the code for the decommissioning waste types. An additional letter is added to distinguish between the main waste fractions *(C* for *Concrete, R* for *Reactor pressure vessel, M* for *Miscellaneous* and *S* for *Sand*). The system has been further developed since SKB (R-18-07) but due to data freeze reasons, it has not been updated in the present report.

For more detailed information about the different packages and the treatment methods, see Section 3.5 and the inventory report (SKB R-18-07).

Table 3-5. Abbreviations for provisional codes for decommissioning waste (SKB R-18-07).

Abbreviation	Disposal in	Raw waste	Package	Treatment
04:D	Silo	Ion-exchange resin	Steel mould	Cement-solidified
12:D	BLA	Trash and scrap metal	ISO-container[1]	None
12C:D	BLA	Concrete	ISO-container	None
12S:D	BLA	Sand/Soil	ISO-container	None
12M:D	BLA	Miscellaneous decommissioning waste	ISO-container	None
16:D	Silo	Ion-exchange resin	Steel mould	Cement-solidified
18:D	Silo	Ion-exchange resin	Steel mould	Bitumen-solidified
21:D	2BMA	Sludge	Steel drum	None
23:D	2BMA	Trash and scrap metal	Concrete/steel/double mould or steel drum[2]	Concrete-embedded
23C:D	2BMA	Concrete	Steel/double mould	Concrete-embedded
23S:D	2BMA	Sand	Steel/double mould	Concrete-embedded
23R:D	1BRT	Reactor pressure vessel	Double mould	Concrete-embedded

[1] In the decommissioning waste from SNAB, some waste fractions are placed in drums.

[2] Double mould is a future waste packaging and is not yet in use.

3.2.2 Waste type descriptions

Every waste type that is to be disposed in SFR must have an approved waste type description that describes the whole handling sequence from production to final disposal of the waste, before production of that waste type starts. Waste type descriptions have been used since the late 1980s with the purpose of documenting the waste disposed in SFR. Waste type descriptions are also used in the safety assessment for both SFR during operation and the nuclear facilities.

Together with the overview of the handling sequence, the waste type descriptions include detailed descriptions of the waste properties and characteristics, including the waste category, type of packaging and treatment methods etc. In addition, the waste type description explains how the waste meets the waste acceptance criteria in all steps of the handling sequence and what controls need to be performed regarding packaging, waste form and waste package.

Production and review of the waste type descriptions is an iterative process between the waste producers and SKB. The safety review that is conducted by the waste producers focuses on the production and further handling until transport to the final disposal site. SKB's safety review focuses on transport and disposal as well as the post-closure safety for the final repository. Before waste packages of a specific type are disposed, SSM must approve the waste type description and give their approval to allow transport and disposal.

3.3 Handling and control of waste

The handling of the waste comprises the following steps:

Production of the waste package

The production of the waste package is performed according to the waste type description. The waste type description also includes other instructions such as the prescription for stabilisation or how wastes are sorted according to their dose rate. Information about the waste package is registered in the database GADD (gemensam avfallsdriftdatabas), where it is confirmed that the data characterising the waste complies with the waste acceptance criteria.

Interim storage

The waste type descriptions give details of the interim storage plans. They may also give instructions on, for example, transport to the interim storage site.

Transport

Before transport, a transport message (TRAM) is produced and information about the transport is registered in the database GADD. SFR reviews the waste data to ensure that the acceptance criteria are fulfilled and that the specified waste codes are approved for disposal.

Disposal and registration

When the waste package is lifted out of the transport packaging at SFR, the ID-number is checked against the number given in the transport message (TRAM) and in the waste register. At or after disposal, the exact disposal position of the waste package is registered in the waste register. All information about the waste package, transport and handling is registered in GADD.

3.3.1 Handling and control at the waste producer

The waste producer is responsible for:

- Waste conditioning and producing waste packages.
- Documenting production data.
- Measuring the activity of waste and measuring the dose rate of the waste package.
- Assigning a unique identity to the waste package and marking the number on the waste packaging.
- Shipping documentation.

The waste type descriptions include details on the quality control procedures for the packaging, waste form and waste package. The waste producers are required to ensure that the producer of the packaging has a satisfactory programme for quality control. The quality of the waste form is primarily controlled by the surveillance of production, including both technical and administrative routines that influence the properties of the waste form. The producer must ensure that the activity content and dose rates of the final waste package are measured and are within the specified limits.

3.3.2 Waste audits

SKB performs a quality audit of the waste handling at each nuclear facility every third year. Every nuclear facility is required to have routines and instructions for the sorting and emplacement of waste. It must be clear which waste will be placed in which packaging. There are prescribed processes for stabilisation treatments that should be followed.

The aims of the audits are to judge whether:

- Valid waste type descriptions are used.
- The producers follow their own routines and instructions for assessing whether the acceptance criteria are fulfilled.
- The producer is in control of the steering, management and documentation of the waste process, including routines for safety review.

The audit is performed in accordance with an audit plan and results in an audit report that includes any deviations or observations. The audited facility returns the audit report, together with an action plan in the case of deviations, to SKB. If anything else is prescribed the audit result is followed-up at the next ordinary audit.

3.3.3 Handling and control in the SFR facility

The activity content of a waste package is a crucial factor when determining the optimal position for the package in SFR. Also, as the activity content influences the surface dose rate, it affects the routines needed for handling the package.

All waste packages are transported in special transport packaging, except ISO-containers for 1–5BLA and drums allocated to 1BTF. Packages are transported at the facility using a terminal vehicle.

The receiving control/inspection of the waste at SFR comprises:

- Determination of identity and inspection of the shipping document.
- Measurement of surface dose rate.
- Measurement/control of surface contamination.
- Evaluation of mechanical damage.

When underground, the waste packages are transported to the respective waste vault for which they are destined. The waste packages are placed in the loading zone of the respective waste vault. When the transport packaging is discharged, it is monitored for surface contamination inside and out. If there is no contamination, the waste packages can be prepared to be disposed. If the packaging is contaminated, it is cleaned. The loading zone is also checked for contamination after each disposal campaign and cleaned if necessary.

The waste packages in the silo and 1BMA are emplaced using remote control, and this is monitored by surveillance cameras. Waste packages in 2BMA and 1BRT will also be emplaced using remote control.

The underground disposal facility also uses forklift trucks. Waste packages in 1–5BLA and 1–2BTF are emplaced manually by the forklift truck driver.

After disposal the register in the GADD database is updated.

3.3.4 Waste register

After disposal, the exact disposal position of the waste package is registered in the GADD database. The information from the waste data file from the waste producers is also stored in the waste register. Table 3-6 shows the type of information that is stored in GADD.

Table 3-6. Information stored in GADD.

Information
Waste producer and waste package producer
Waste package ID
Waste type
Package type code
Waste category code
Conditioning method/materials
Package and waste weight
Date of production
Material content (according to a code system described in Canderyd (2022))
Radionuclide content (measureable radionuclides) and total gamma activity
Surface dose rate
Dose rate at 1 metre
Measuring date
Special information from the producer
Disposal date
Position in SFR after disposal

3.4 Future waste

The tools used to ensure that the waste is emplaced in the correct packaging and in the correct waste vault in SFR are the waste handling manual, waste type descriptions, waste audits and the waste register GADD.

The waste handling manual, material codes and waste codes, is a document that is continuously updated so that it always remains valid. The document is updated gradually and when necessary expanded with new waste codes for operational waste and decommissioning waste, as well as new acceptance criteria for waste that will be disposed in SFR3.

The existing waste type descriptions will be used and updated as far as possible and new waste type descriptions will be produced for the new waste types.

The waste audits at the waste producers are planned to continue as before.

The waste register will continue to be used by the waste producers and SKB.

3.5 Waste packaging

The main types of waste packaging used or intended to be used in SFR are briefly described in this section. More detailed information can be found in the inventory report (SKB R-18-07). The types of waste packaging are illustrated in Figure 3-1 and consist of:

- Concrete moulds.
- Steel moulds.
- Steel drums.
- Concrete tanks.
- ISO-containers.
- Double moulds of steel (intended to be used for decommissioning waste, but may also be used for operational waste).
- Other packaging.

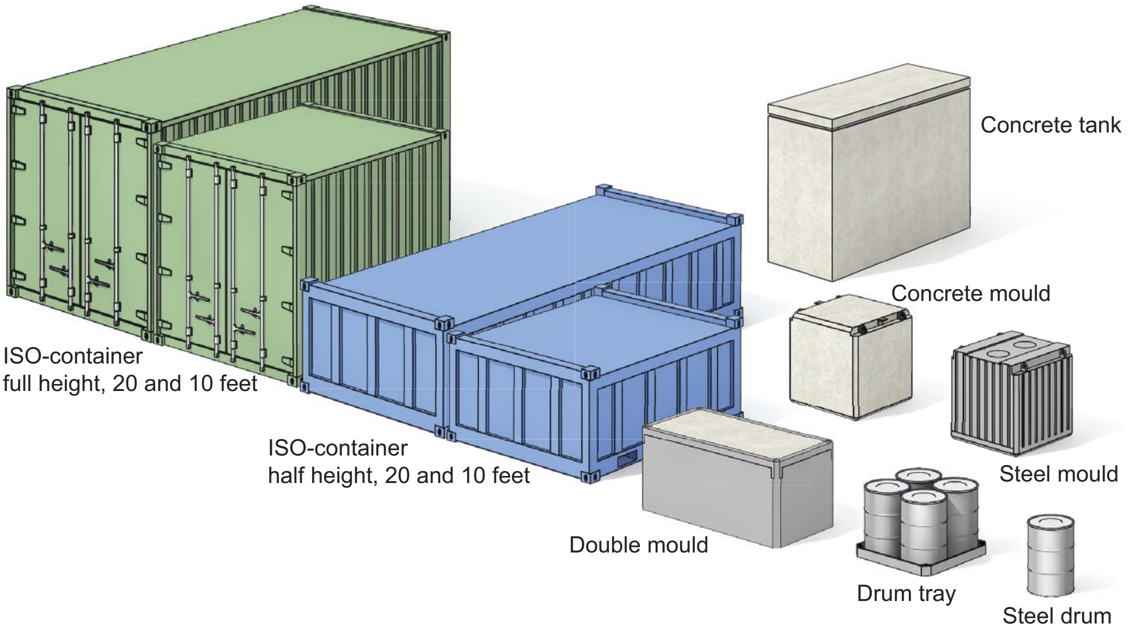

Figure 3-1. *Schematic illustration of waste packaging used or intended to be used in SFR.*

3.5.1 Concrete moulds

The concrete moulds are cubic boxes made of reinforced concrete. The dimensions of the moulds are 1.2 × 1.2 × 1.2 m^3, resulting in a disposal volume of 1.73 m^3. The walls are normally 10 cm thick but can in some cases be thicker. Normally, the inner volume is about 1 m^3 and the lid is made by casting at least 10 cm thick concrete on the top of the mould. The concrete weight is 1 840 kg and the reinforcement weight is 274 kg, with a metal surface of 11.8 m^2.

The concrete moulds are mainly used as packaging for ion-exchange resins, solidified with cement. In addition, concrete moulds are used for solid waste embedded in concrete.

For waste solidified with cement, a stirrer made of carbon steel is included in the waste package. It weighs 16 kg and has an estimated surface area of 1 m^2. To avoid cracking of the 10-cm thick moulds, due to expansion of the concrete matrix, a lining of compactable material (e.g. polyethene) is placed inside each mould. The lining has a thickness of 20 mm and a total weight of 10 kg. A plate made of steel is placed on top of the waste to prevent splashing during stirring. This cover plate is left in the mould.

Solid waste is either packaged directly in the mould or in a steel drum, which is then placed in the mould. The waste is embedded in concrete and the steel drums are grouted. In some cases, a drum basket is used to centre the waste inside the drums.

The inventory report (SKB R-18-07) shows details on how the concrete moulds differ depending on waste type.

3.5.2 Steel moulds

Steel moulds are cubes with the same outer dimensions as the concrete moulds, but with 5 or 6 mm thick walls, resulting in the same disposal volume of 1.73 m^3 but an inner volume of 1.7 m^3. Typically, the steel weight of the packaging is around 500 kg, whereas the metal surface is around 15 m^2. The weight of the empty steel moulds can differ significantly due to differences in the amount of reinforcement and corrugation. This allows the stability of the mould to be optimised for the weight of the waste.

The steel moulds are used for waste solidified with cement or bitumen. In addition, steel moulds are used for solid waste embedded in concrete.

For waste solidified with cement, a stirrer made of carbon steel is included in the waste package. It weighs 25 kg and has an estimated surface area of 3 m^2. A plate made of steel is placed on top of the waste to prevent splashing during stirring. This cover plate is left in the mould. The lid is either made of steel or, for most waste types, concrete cast directly on top of the waste.

Stirrers and cover plates are not required for waste solidified in bitumen, since the mixing of waste and bitumen is performed before filling the steel moulds. The lid for waste solidified in bitumen is made of steel.

Solid waste is often compacted using a steel plate that is left in the mould. The lid is either made of steel or concrete cast directly on top of the waste.

The inventory report (SKB R-18-07) shows details on how the steel moulds differ depending on waste type.

3.5.3 Steel drums

The steel drums are standard 200-litre drums. The dimensions differ slightly, but the drums are approximately 90 cm high and have a diameter of 60 cm, resulting in an inner volume of 0.24 m^3 and a disposal volume of 0.32 m^3. Typically, the steel weight of the packaging is around 25 kg whereas the metal surface is around 4 m^2. There are also packages that consist of waste in a 100-litre drum which is placed inside a 200-litre drum and embedded in concrete.

For waste solidified with cement, a stirrer made of carbon steel is included in the waste package. It weighs 10 kg and has an estimated surface area of 0.5 m^2.

The drums in the silo and 1BMA are mostly stored on steel trays with four drums on each, but some are stored in steel boxes. Drums containing bituminised waste will expand in the future and, to avoid damage to the concrete structure of the silo, expansion boxes are placed in the middle of the four drums on a tray. The drums in 1BTF are not stored on trays or in boxes but stacked horizontally.

The inventory report (SKB R-18-07) shows details on how the steel drums differ depending on waste type.

3.5.4 Concrete tanks

The concrete tanks have a length of 3.3 m, width of 1.3 m and height of 2.3 m. The walls are 15 cm thick, resulting in an inner volume of 6 m^3 and a disposal volume of about 10 m^3. The concrete weight of the packaging is 10070 kg and the reinforcement weight is 647 kg, with a metal surface area of 40 m^2. The tanks are lined with 2 mm thick butyl rubber on the inside. The lining weighs 50 kg. The concrete tanks have a drainage system. Steel lids are placed on the opening in the top of the concrete tanks. The steel weight of the lid is 321 kg, with a metal surface area of 9 m^2.

The variations between packages are small. However, the inventory report (SKB R-18-07) shows details on how the concrete tanks differ depending on waste type.

3.5.5 ISO-containers

There are four different standard ISO-containers that are used in SFR; 20-foot half-height, 20-foot full-height, 10-foot full-height and 10-foot half-height. Among these, the 20-foot half-height container is most frequently used. It has the dimensions $1.3 \times 2.4 \times 6.1$ m^3 and a wall thickness of 1.5 mm, which results in an inner volume of 15 m^3 and an outer volume of 15.24 m^3. The disposal volume is 20 m^3, the steel weight is 1900 kg and the metal surface area is 103 m^2.

The containers can hold drums, boxes or bales. They can also hold unpackaged scrap metal.

The inventory report (SKB R-18-07) shows details on how the ISO-containers differ depending on waste type.

3.5.6 Double moulds

A double mould is the size of two normal steel moulds and is intended for decommissioning waste, but may also be used for operational waste. The inner, outer and disposal volumes from the inventory report (SKB R-18-07) are given in Table 3-7. The steel weight is around 1100 kg and the metal surface area is about 23 m^2. The double mould has replaced the tetra mould that was introduced in the previous inventory report (SKB R-15-15).

After the publication of the inventory report (2019), it was noted that the inner volume of double moulds was calculated from the smallest distance between the corrugated sides, rather than the average distance. The outer volume of the double moulds was likewise calculated from the longest distance between the corrugated sides. For the current report, the inner volume has been changed to include half the difference between the inner and outer dimensions given in the inventory report, once the volume of the steel packaging had been subtracted. The extra volume inside each double mould results in extra concrete conditioning material, which has been added to the inventory for the relevant vaults, 2BMA and 1BRT.

Table 3-7. Differences in the dimensions applied to double moulds in this report, compared to the inventory report (SKB R-18-07).

	Inner volume (m^3)	Outer volume (m^3)	Disposal volume (m^3)
Inventory report	2.43	3.46	3.46
This report	2.87	3.01	3.46

3.5.7 Other packaging

In addition to the packaging listed above, there are certain other odd packagings and in some cases large items of waste (components) that are emplaced in SFR without packaging. Data for these are available in the inventory report (SKB R-18-07).

3.6 Waste in different parts of the repository

In this section, the waste types, waste volumes and material types allocated to different waste vaults are given.

The information is based on waste produced up until the end of 2016 as well as future prognoses from the inventory report (SKB R-18-07).

Volumes of waste in different vaults

The waste allocated to different waste vaults is shown in Figure 3-2. The amount of miscellaneous decommissioning wastes (wastes that arise during decommissioning, mostly materials that have been brought into a classified area, used, contaminated and discarded) is very uncertain and has therefore been shown separately in red in the figure.

Operational waste

Most of the waste in SFR1 comes from the Swedish nuclear power plants. During nuclear fission in the reactor core fission products, such as Cs-137, and neutrons are produced. The neutrons can cause further fission or transmute the uranium in the fuel. Neutron absorption and subsequent rapid radioactive decay result in the formation of transuranic elements such as plutonium and americium. As with the fission products, these transuranics form in the fuel itself and will only contaminate in the reactor water if the fuel cladding is damaged.

In the reactor water, radionuclides are also formed from activation of substances outside the fuel rods. These substances may already be dissolved or dispersed in the reactor water, as a result of corrosion of material surfaces, but they may also be activated on surfaces near the core and then dissolve in the reactor water.

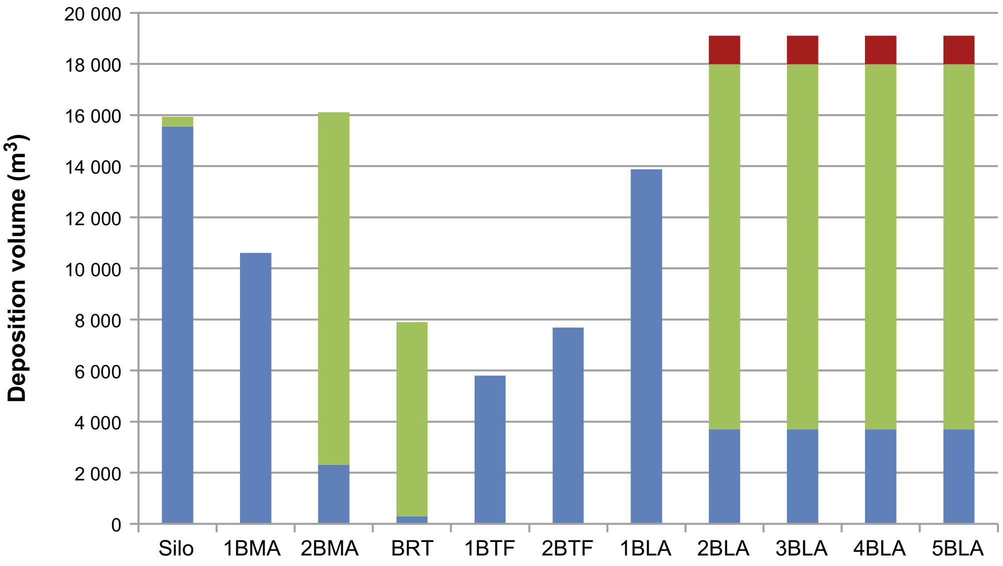

***Figure 3-2.** Volume of waste allocated to different waste vaults. Operational waste is shown in blue, decommissioning waste in green and miscellaneous decommissioning waste (wastes that arise during decommissioning, mostly materials that have been brought into a classified area, used, contaminated and discarded) in red.*

The reactor water in the primary circuit undergoes continuous clean-up to remove radioactive substances. The reactor water is purified in the reactor's clean-up circuits by means of ion-exchange resins that absorb radionuclides that are present as ions in the reactor water. The ion-exchange resins also remove dispersed particles consisting of oxides/hydroxides as a result of the corrosion and dissolution of the engineering materials.

Even though most of the radionuclides that have left the core are isolated in the clean-up system, small amounts spread to other systems. Relatively large volumes of ion-exchange resins and mechanical filter resins are used in the boiling water reactors for clean-up of the water that condenses in the condenser. Due to the fact that small quantities of radioactive substances are carried from the reactor to the turbines, this water and its filter resins become weakly radioactive. Pressurised water reactors have a closed system and hence no radioactivity reaches the turbines (under normal operating conditions), and smaller volumes of ion-exchanges resins are consumed.

Additional waste consisting of ion-exchange resin, mechanical filter resin and sludge arises in the water clean-up system.

Some radioactive substances are also released from the spent fuel stored in the storage pools at the nuclear power plants and at the interim storage Clab. These pools also have clean-up systems with ion-exchange resins that are used in roughly the same way as in the reactor water clean-up systems.

Low- and intermediate-level solid waste is also generated at nuclear facilities. Compared with the wet waste, its activity is often much lower. The solid waste can consist of components of the primary system or other active systems, but mostly consists of material that has been brought into a classified area, used, contaminated and discarded.

Material types

Much of the activity in SFR1 is present in the waste that is categorised as wet at the waste producer. The wet waste consists, for the most part, of bead resin, powder resin, mechanical filter aids and sludge. The ion-exchange resins consist of organic polymers with acidic or basic groups, making them capable of cation or anion exchange.

A large portion of the waste volume in SFR1 consists of metals, predominantly carbon steel and stainless steel. Scrap metal arises mainly from maintenance outages when equipment is discarded, modified or renovated.

The largest volume of raw waste consists of combustible solid waste. However, since a part of this is incinerated at the Studsvik site or disposed locally at the plant, the volume remaining for disposal in SFR1 is reasonably small. The waste consists mainly of cellulose (paper, cotton and wood) and plastics (e.g. polystyrene, PVC, polyethylene, polypropylene, etc).

Other materials occurring in the waste include mineral wool (used for insulation), concrete and brick. Various additional materials are also included in smaller quantities.

In addition, there are similar wastes from other industries, research and medical care.

Decommissioning waste

Large quantities of scrap metal and concrete are generated when nuclear power plants are dismantled. Like operational waste, most of this waste is low- and intermediate-level. Some decommissioning waste from systems close to the core, core components, are classified as long-lived and allocated to the repository for long-lived low- and intermediate-level waste, SFL. Also the biological shields from PWR are planned to be disposed in SFL. The decommissioning waste allocated to SFR will mainly be stored in SFR3. One exception is the ion-exchange resins from system decontamination, which are allocated to the silo of SFR1. The resins will be solidified with cement, except for the resins from FKA where bitumen will be used instead.

The source of the radioactivity in the waste is both nuclear fission and activation. The reactor pressure vessels contain predominantly induced activity. The pressure vessels from the BWR reactors as well as the Ågesta PWR pressure vessel are planned to be segmented and disposed in SFR (1BRT). The pressure vessels from the remaining PWR reactors are also planned to be segmented, where activated parts are allocated to SFL and non-activated, but contaminated parts will be disposed in SFR (1BRT).

During decommissioning, components will be decontaminated. This will generate decontamination solutions that will be treated using ion-exchange resins, which will also be disposed in SFR.

In addition to the reactor systems and building material, miscellaneous decommissioning wastes will be produced that consist mostly of material that has been brought into a classified area, used, contaminated and discarded. These wastes are also planned to be disposed in SFR.

Material types

The decommissioning waste materials mainly arise from the power plant buildings, i.e. metals and concrete. Large volumes of concrete also arise from the biological shield from BWR. In addition, sand is used in sand-bed filters in the gas-treatment systems. Waste containing sand may also arise from blast cleaning during decontamination.

The miscellaneous decommissioning waste consists mainly of cellulose (paper, cotton and wood) and plastics (e.g. polystyrene, PVC, polyethylene, polypropylene, etc) but also includes metals and sludge. There are large uncertainties in the forecast of the volume of miscellaneous decommissioning waste, which partly arises from uncertainties in the extent to which this waste will be combusted.

3.6.1 Distribution of waste packages between SFR vaults

The distribution of waste packages between vaults in SFR is given in the inventory report (SKB R-18-07). Details on the emplacement in each vault is described in the subsequent sections.

Distribution of waste between 1BTF and 2BTF

The distribution of waste packages between 1BTF and 2BTF involves the disposal of drums with ashes, concrete moulds and concrete tanks in 1BTF, and concrete tanks in 2BTF.

Distribution of waste between 1BLA and 2–5BLA

Operational waste intended for BLA will be deposited in 1BLA until it is full, then disposal will continue in 2–5BLA. All decommissioning waste intended for BLA will be deposited in 2–5BLA.

Distribution of waste between 1BMA and 2BMA

In addition to the package-level waste acceptance criteria (e.g. Table 3-2), the distribution of future waste between 1BMA and 2BMA also needs to consider the following aspects:

- Mechanical stability. Two rows of concrete moulds (144 moulds) are required in each large compartment in 1BMA to support the prefabricated cement elements that are placed on top of the waste. Low activity moulds are selected that do not contain cellulose.
- Cellulose. To minimise the effect of the cellulose degradation product ISA on radionuclide sorption, the amount of cellulose in future waste packages is restricted by waste acceptance criteria and should be kept as low as possible in each waste compartment.
- Bitumen. To reduce the risk of barrier cracking due to swelling, the maximum number of waste packages with bitumen-solidified waste in each compartment in 1BMA is 144.
- Microbial activity. Microbial activity will be minimised if the pH is high. To obtain a high pH in compartments with bituminised waste, a certain amount of cementitious materials should be in close proximity to the bitumen-solidified waste. In addition, more concrete reduces the negative effects from sulfate-containing evaporator concentrates on the concrete structure. This is based on the hypothesis that sulfate released from the waste will form ettringite inside the compartments prior to forming ettringite in the concrete structures, see the **Post-closure safety report**, Chapter 6.

3.6.2 Silo

Intermediate-level waste is stored in the silo. The waste contains solidified (bitumen or cement) ion-exchange resins and a small amount of concrete-embedded trash and scrap metal. All waste in the silo is handled in moulds or steel drums (four on each tray). The distribution between wastes, conditioning materials and packaging is shown in Figure 3-3.

Waste emplacement

In the majority of shafts, 42 layers of concrete/steel moulds or 56 layers of drums on trays can be emplaced. Each layer holds four moulds or steel trays with four drums on each. This results in 168 moulds or 896 steel drums per shaft. In the half-size shafts (denoted B, C and D in Figure 4-2), two moulds or steel trays with drums can be emplaced in each layer resulting in 84 moulds or 448 steel drums. The shafts denoted E, F and G in Figure 4-2 may be used for odd waste. In the nine central shafts of the silo, bitumen-solidified waste is emplaced.

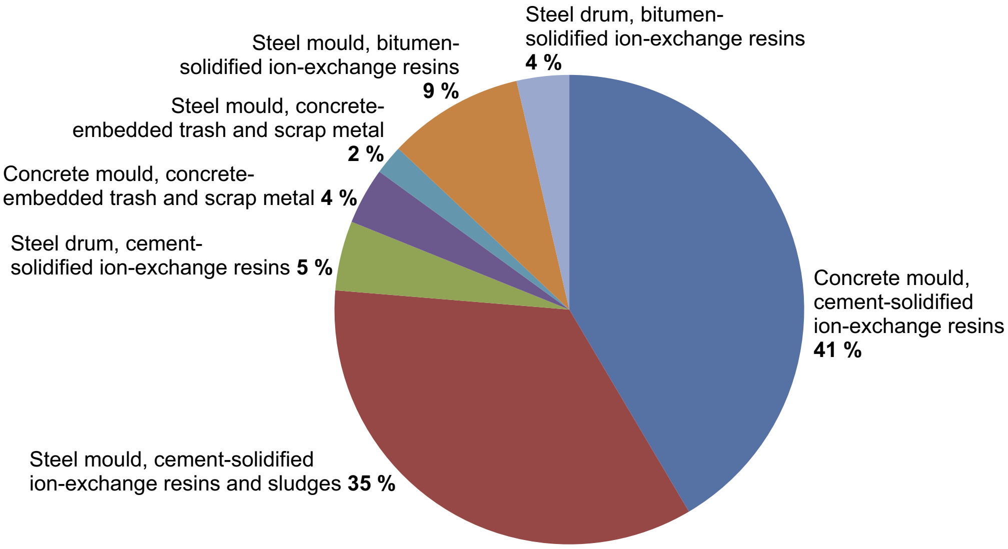

Figure 3-3. *Distribution between wastes, conditioning materials and packaging in the silo (vol %).*

3.6.3 1BMA

1BMA is designed to store intermediate-level waste that has a lower dose rate, or that is not suitable for disposal in the silo. The waste includes solidified (bitumen or cement) ion-exchange resins and concrete-embedded trash and scrap metal. Small amounts of sludges and evaporator concentrates are also stored in 1BMA. All waste in 1BMA is packaged in concrete or steel moulds, or in drums. The drums are either stored on steel trays or in steel boxes. The distribution between wastes, conditioning materials and packaging is shown in Figure 3-4.

Waste emplacement

In the 13 large compartments, it is possible to store twelve moulds in width, six in height and eight in length, which results in a maximum of 576 moulds in each compartment. Two rows of concrete moulds (144 moulds) are required across the middle of each large compartment to support the prefabricated concrete elements. Drums stored on steel trays are positioned on each side of these moulds, three trays in width, eight in height and twelve in length. Since there are four drums on each plate, this results in a maximum of 2 304 drums per large compartment. The maximum number of moulds in the two smaller compartments is 144 (six in width, six in height and four in length) and the maximum number of drums is 768, if stored on steel trays.

The waste emplacement in 1BMA at closure is shown in Table 3-7 as given in the inventory report (SKB R-18-07).

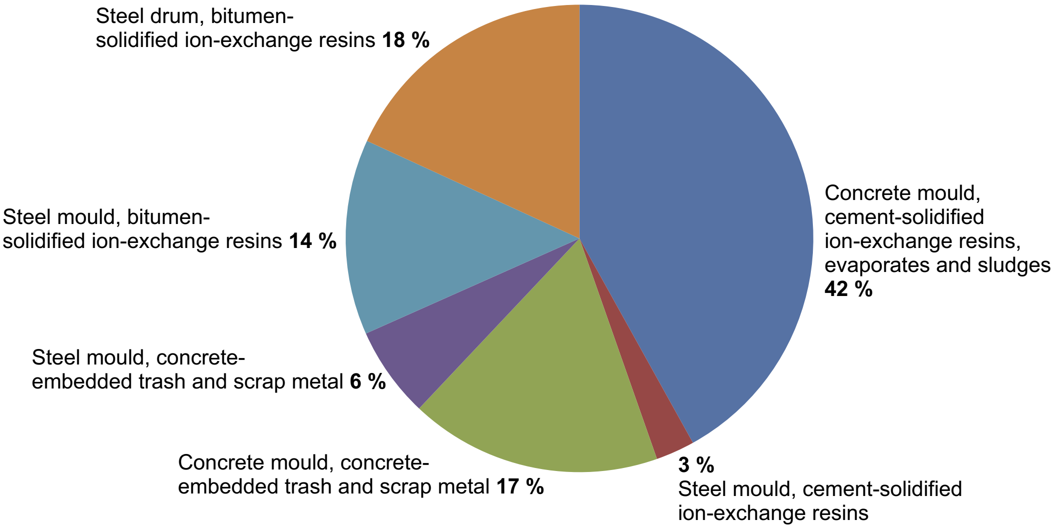

Figure 3-4. *Distribution between wastes, packaging and conditioning materials in 1BMA (vol %).*

3.6.4 2BMA

2BMA is designed to store intermediate-level waste. The distribution of the wastes, packaging and conditioning materials in 2BMA is shown in Figure 3-5.

Waste emplacement

Inner walls will be positioned in a 5 × 5 arrangement within each 2BMA caisson, dividing the caisson into 36 separate inner waste compartments. Each inner waste compartment can hold six layers of four moulds stacked directly on top of each other, i.e. a maximum of 864 moulds in each caisson, or 432 double moulds. Eight layers of steel drums on steel trays can be stacked on top of each other, with four trays per layer in each compartment. This gives a total of 128 drums per compartment or 4 608 drums per caisson. The waste types are anticipated to be distributed equally between the caissons.

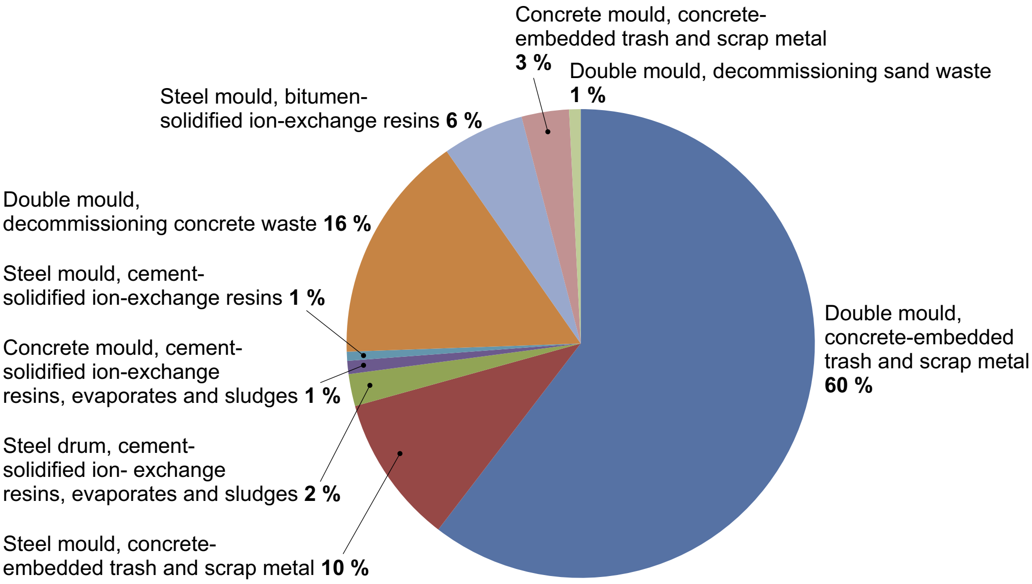

Figure 3-5. *Distribution between, wastes, packaging and conditioning materials in 2BMA (vol %).*

Table 3-7. Forecast of waste in the different compartments in 1BMA at closure (number of packages) (SKB R-18-07). The definitions of the waste types are given in Section 3.2.1. Compartments including bituminised waste are marked with grey.

	Packaging		Number of packages															
Waste type	Code	Type	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Total
B.05:00	205	Steel drum	0	0	0	0	112	192	0	0	0	0	0	0	0	0	0	304
B.05:02	205	Steel drum	0	382	270	0	96	144	0	0	0	0	0	0	0	0	0	892
B.05:09	205	Steel drum	0	0	1168	0	1888	0	0	0	0	0	0	0	0	0	0	3056
B.23:00	32	Concrete mould	0	0	0	0	0	0	0	0	0	0	16	0	0	0	0	16
B.23:00	52	Steel mould	0	0	0	0	0	0	0	0	0	0	32	0	0	0	0	32
C.23:00	20	Concrete mould	0	0	0	0	0	0	0	0	0	15	4	0	0	0	0	19
F.05:01	205	Steel drum	0	1454	0	0	0	0	0	0	0	0	0	0	0	0	0	1454
F.05:02	205	Steel drum	0	258	0	0	0	0	0	0	0	0	0	0	0	0	0	258
F.15:00	50	Steel mould	0	0	0	8	0	3	0	0	0	0	0	0	0	0	0	11
F.17:00	50	Steel mould	0	0	141	0	4	0	0	0	0	0	0	0	0	0	0	145
F.17:00	51	Steel mould	0	0	3	0	4	247	0	0	0	134	8	42	42	86	77	643
F.17:01	50	Steel mould	0	0	0	0	14	6	0	0	0	0	0	0	0	0	0	20
F.17:01	51	Steel mould	0	0	0	0	6	6	0	0	0	0	0	0	0	0	0	12
F.17:02	51	Steel mould	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	10
F.23:00	10	Concrete mould	0	0	0	18	0	0	0	0	0	0	0	0	0	0	0	18
F.23:00	20	Concrete mould	0	0	0	31	0	0	2	4	0	3	0	0	0	0	0	40
F.23:00	50	Steel mould	0	0	0	15	0	0	10	88	0	61	32	0	0	0	0	206
F.99:01	50	Steel mould	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	2
O.01:09	20	Concrete mould	0	0	0	11	0	0	211	10	28	139	0	0	0	0	0	399
O.01:09	30	Concrete mould	0	0	0	20	0	0	10	1	21	9	0	0	0	0	0	61
O.01:09	30	Concrete mould	0	0	0	45	0	0	43	19	156	20	0	0	0	0	0	283
O.23:00	0	Concrete mould	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	2
O.23:00	20	Concrete mould	0	0	0	1	0	0	0	12	30	0	0	0	0	0	0	43
O.23:00	20	Concrete mould	0	0	0	29	0	0	8	83	111	116	99	0	0	0	0	446
O.23:09	0	Concrete mould	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
O.23:09	10	Concrete mould	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
O.23:09	20	Concrete mould	0	0	0	6	0	0	28	51	23	21	0	0	0	0	0	129
R.01:00	30	Concrete mould	351	148	137	96	12	0	0	0	37	0	0	0	0	0	0	781
R.01:09	13	Concrete mould	142	0	0	0	0	0	40	56	16	0	0	0	0	0	0	254
R.01:09	20	Concrete mould	38	0	0	0	1	4	26	25	0	0	0	5	0	0	0	99

Table 3-7. Continued.

	Packaging		Number of packages															
Waste type	**Code**	**Type**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**Total**
R.01:09	23	Concrete mould	45	0	7	48	131	138	78	65	35	0	3	3	0	0	0	553
R.01:09	30	Concrete mould	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	2
R.10:00	10	Concrete mould	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
R.10:00	13	Concrete mould	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
R.10:00	20	Concrete mould	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	3
R.10:00	23	Concrete mould	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	10
R.10:00	30	Concrete mould	0	0	0	0	0	0	0	34	35	15	0	0	0	0	0	84
R.15:00	50	Steel mould	0	0	0	124	0	0	0	0	0	0	28	0	0	0	0	152
R.23:00	10	Concrete mould	0	0	0	15	0	0	12	7	11	0	5	0	0	0	0	50
R.23:00	13	Concrete mould	0	0	0	2	0	0	2	0	3	0	0	0	0	0	0	7
R.23:00	20	Concrete mould	0	0	0	88	0	0	23	19	11	0	0	0	0	0	0	141
R.23:00	23	Concrete mould	0	0	0	9	0	0	23	2	3	0	0	1	0	0	0	38
R.23:00	24	Concrete mould	0	0	0	6	0	0	20	5	8	0	11	0	0	0	0	50
R.23:00	29	Concrete mould	0	0	0	3	0	0	12	0	0	0	0	2	0	0	0	17
R.23:00	30	Concrete mould	0	0	0	1	0	0	28	5	16	0	0	1	0	0	0	51
R.23:00	52	Steel mould	0	0	0	0	0	0	0	80	16	0	53	0	0	0	0	149
R.29:00	30	Concrete mould	0	0	0	0	0	0	0	8	0	22	13	0	0	0	0	43
R.99:02	28	Concrete mould	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1

3.6.5 1BRT

The waste in 1BRT includes the ten reactor pressure vessels from Barsebäck (B1, B2), Forsmark (F1, F2, F3), Oskarshamn (O1, O2, O3), Ringhals (R1) and Ågesta. The pressure vessels will be cut into segments, placed in steel double moulds and stabilised with concrete prior to disposal in 1BRT. In addition, the non-activated but contaminated parts from the segmented PWR pressure vessels are also included in the 1BRT waste inventory as well as the extra reactor pressure vessel lids that are currently stored in 1BTF and on the Ringhals site. The waste in 1BRT solely consists of iron/steel. The distribution of the wastes, packaging and conditioning materials in 1BRT is shown in Figure 3-6.

Waste emplacement

The double moulds will be stacked inside compartments of the concrete structure. There are 17 small compartments and one large compartment in the reference design. The space between the double moulds as well as the space between the double moulds and the compartment walls will be grouted.

3.6.6 1BTF

1BTF is primarily designed to contain dewatered ion-exchange resins, but cement-solidified resins and concrete-embedded ashes will also be present. All waste in 1BTF is handled in concrete tanks, moulds or drums. The distribution between wastes, conditioning materials and packaging is shown in Figure 3-7.

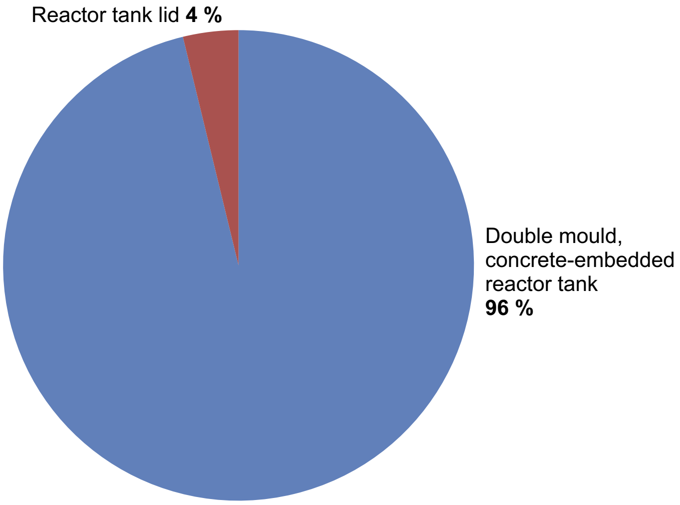

Figure 3-6. *Distribution between wastes, packaging and conditioning materials in 1BRT (vol %).*

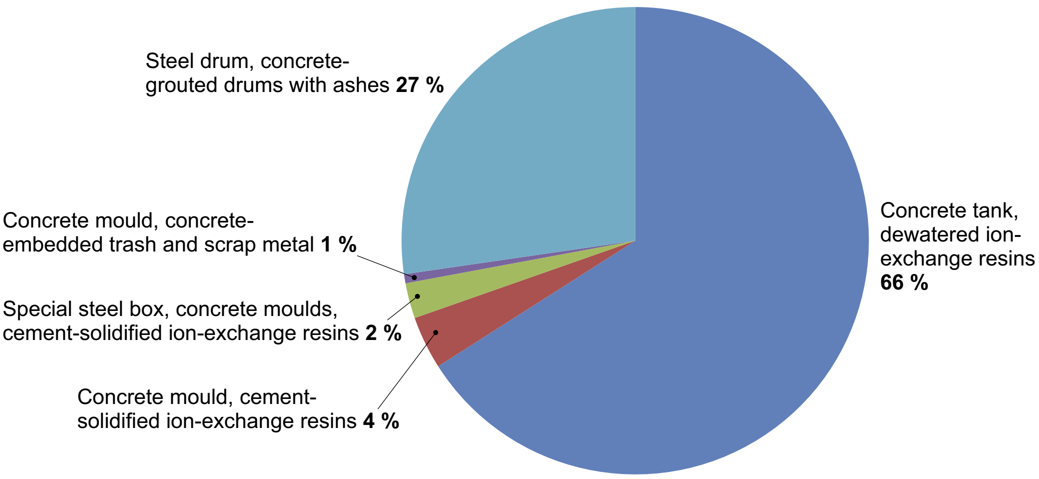

Figure 3-7. *Distribution between wastes, packaging and conditioning materials in 1BTF (vol %).*

Waste emplacement

When drums containing ash are placed in 1BTF, stabilising walls of concrete tanks and moulds are necessary, see Figure 3-8. Concrete tanks are placed alongside the rock walls. The drums are then piled on their sides between the concrete tanks. When six rows of drums have been piled, concrete moulds are placed across the vault. A wall of concrete moulds is made up of nine in width and four in height. A section between two rows of concrete moulds contains 1 110 drums. The walls alongside the rock comprise eight concrete tanks in total per section of drums. The forecast of the number of drums given in the inventory report is 91 (SKB R-18-07).

Concrete tanks, apart from the ones used as walls in the drum section, are stored four in width and two in height, see the upper detail in Figure 8-2.

3.6.7 2BTF

2BTF is primarily designed to contain dewatered ion-exchange resins. Almost all waste in 2BTF is stored in concrete tanks. The distribution between wastes, conditioning materials and packaging is shown in Figure 3-9.

Waste emplacement

Concrete tanks are stored four in width and two in height, see Figure 8-2.

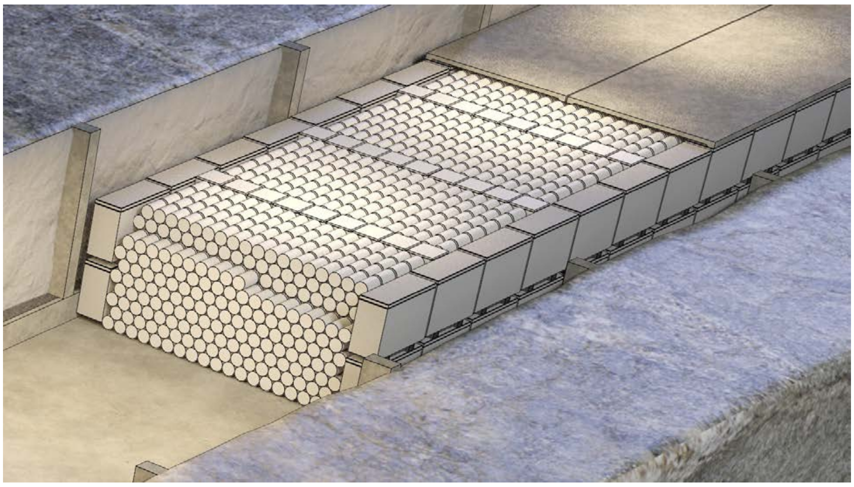

Figure 3-8. *Detail of sections with drums in 1BTF.*

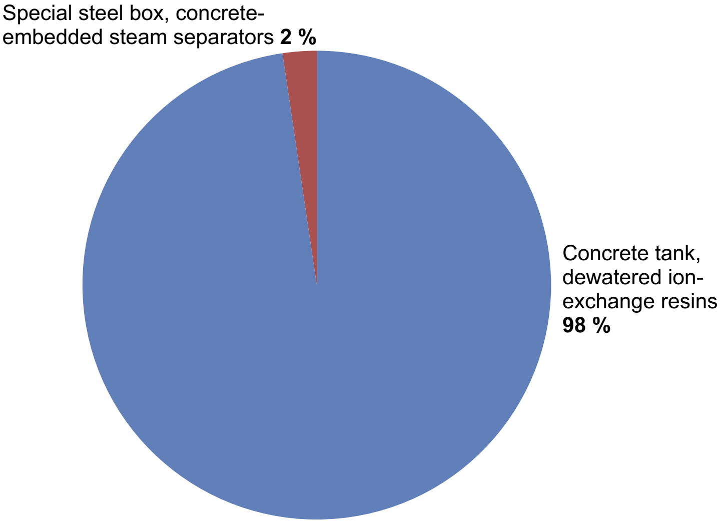

Figure 3-9. *Distribution between wastes, packaging and conditioning materials in 2BTF (vol %).*

3.6.8 1BLA

1BLA is primarily designed to contain low-level trash and scrap metal. All waste in 1BLA is stored in ISO-containers. The containers can hold different smaller packages like drums, boxes and bales. The distribution between wastes, packaging and conditioning materials is shown Figure 3-10.

Waste emplacement

Containers are stored two in width (20-foot) and three in height (full-height) or accordingly for 10-foot containers and half-height containers.

3.6.9 2–5BLA

2–5BLA are primarily designed to contain low-level decommissioning waste. All waste in 2–5BLA is planned to be stored in ISO-containers. The containers can hold smaller packages such as drums, boxes and bales. The distribution between wastes is shown in Figure 3-11. None of the waste in 2–5BLA is conditioned.

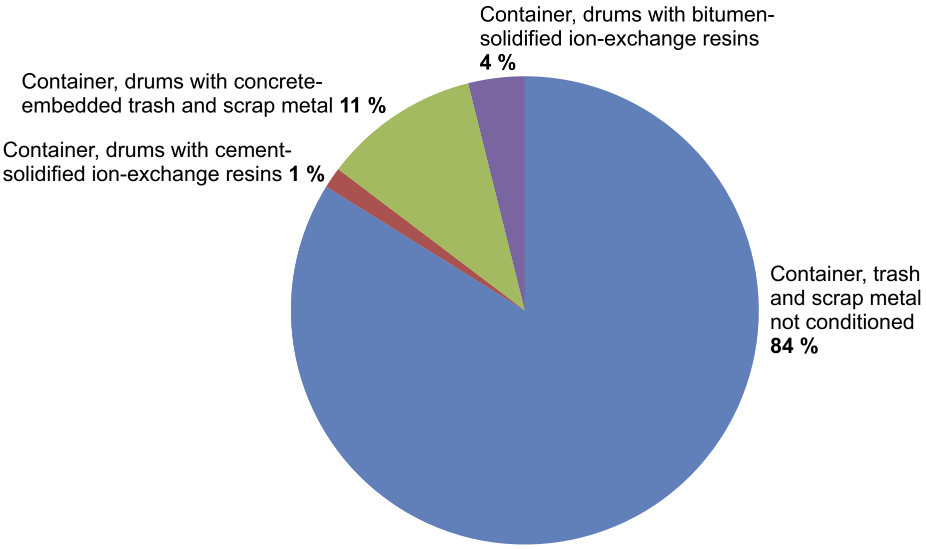

Figure 3-10. *Distribution between wastes, packaging and conditioning materials in 1BLA (vol %).*

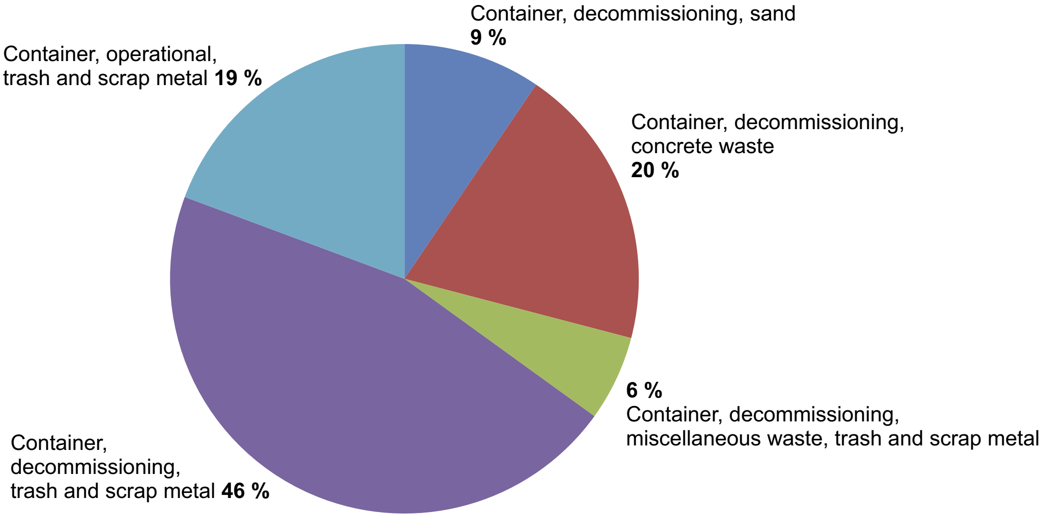

Figure 3-11. *Distribution between wastes in 2–5BLA (vol %). None of the waste in 2–5BLA is conditioned.*

Waste emplacement

Containers (20-foot half-height) will be stored two in width and six in height. In total, 90 rows of containers can be stored in each of the 2–5BLA vaults. This corresponds to a total of 1 080 containers (20-foot half-height) in each vault.

3.7 Material quantities and radioactivity

A summary of the material quantities in the waste packages in the different waste vaults is given in Table 3-8.

Material quantities are specified for materials that are frequently occurring or are known to have an impact on safety. Other materials are accounted for within the categories *other organic* or *other inorganic* where the specific material composition is considered to be of negligible importance to the safety. Complexing agents and other substances that can have an impact on safety in relatively small amounts are not specified among the materials, but are accounted for in Keith-Roach et al. (2021).

SSMFS 2008:37 regulates only the health and environmental risks arising from ionizing radiation. Therefore, the risks associated with the presence of chemotoxic materials are excluded from post-closure safety assessment for a final repository for nuclear waste.

The calculated reference radionuclide inventory at closure of SFR (2075) is given in Table 3-9 for each waste vault.

3.8 Uncertainties

The radionuclide inventory uncertainties have been calculated using Monte-Carlo simulations where parameter values are drawn from the corresponding probability density function (PDF). The establishment of each PDF from analysis of the variance and its distribution is described in detail in SKB (R-18-07). For each realisation, the parameters drawn from the corresponding PDF include:

- each radionuclide activity measured directly on every existing waste package,
- the amount of ion-exchange resins in each waste package,
- total non-packaged-bound data (i.e. data not measured on each waste package) for each producer, radionuclide and waste stream,
- scaling factor for each radionuclide and waste package,
- estimated radionuclide activity for each radionuclide and waste package for future (non-existing) waste types.

The estimated inventory including uncertainties (95th percentile) at closure of SFR (2075) from 10 000 realisations is given for each waste vault in Table 3-10. One thousand of these realisations are propagated in the radionuclide transport calculations. Other possible uncertainties that correspond to changes in operational conditions are not accounted for in the present methodology. They could e.g. include longer reactor life-times, material changes of core components and changed fuel damage frequencies. Instead, these operational changes have been analysed separately as residual scenarios to evaluate the robustness of the SFR repository. The input data for these calculation cases are described in the **Data report,** Chapter 4.

Table 3-8. Materials, corrosion surface areas, voids and pore volumes (in waste packages) along with disposal- and outer volume for the different waste vaults in SFR (SKB R-18-07).

	Waste vault								
	Silo	**1BMA**	**2BMA**	**1BRT**	**1BTF**	**2BTF**	**1BLA**	**2–5BLA**	**SFR**
Waste material/tonnes									
Aluminium	6.0	0.5	15	0	4.9	0	55	173	254
Zinc	0	0.5	0.2	0	0.009	0	8.5	3.4	13
Ashes	0	0.03	30	0	337	0	0	358	725
Cellulose	6.5	22	9.2	0	0.09	0	302	276	616
Filter aid	552	213	40	0	132	383	0	0	1 321
Evaporation concentrate	0	206	193	0	0	0	0.8	0	399
Ion exchange resin	4 737	2 252	350	0	1 584	2 747	93	0	11 764
Iron/Steel	523	265	7 530	6 051	55	59	2 147	26 920	43 550
Sludge	53	85	105	0	2.3	0	13	2.4	260
Plastic/Rubber	26	153	48	0	0.8	0.2	698	424	1 350
Other inorganics	242	198	127	0	9.9	19	783	4 887	6 265
Other organics	62	1.4	15	0	1.4	2.2	260	817	1 158
Sand/Soil	0	0	108	0	0	0	0	6 127	6 235
Concrete	0	0	2 587	0	68	0	107	14 066	16 827
Matrix material/tonnes									
Concrete	2 963	2 658	12 662	7 122	1 412	216	242	0	27 276
Bitumen	1 107	1 333	411	0	0	0	94	0	2 946
Cement	8 888	2 271	326	0	135	0	56	0	11 676
Iron/Steel	1.2	42	13	0	0.1	0	0	0	56
Packaging material/tonnes									
Zinc	9.7	3.6	2.0	0	0	0	10	12	38
Cellulose	0	0	0	0	0	0	34	25	59
Iron/Steel	2 508	1 564	4 991	2 541	609	909	1 391	6 511	21 024
Plastic/Rubber	2.2	3.7	0.3	0.04	22	43	0	0	71
Other inorganics	0	0	0	0	230	450	0	0	680
Other organics	0	0	0	0	0	0	8.7	6.2	15
Concrete	6 469	5 745	937	0	4 066	7 553	7.2	4.2	24 780
Corrosion surface waste/m^2									
Aluminium	884	104	5 034	0	491	0	5 127	25 397	37 038
Zinc	0	262	49	0	11	0	407	275	1 004
Iron/Steel	26 609	12 723	344 784	14 769	13 522	3 024	99 393	2 395 164	2 909 988
Corrosion surface matrix/m^2									
Iron/Steel	55	1 441	375	0	5	0	0	0	1 877
Corrosion surface packaging/m^2									
Zinc	33 117	13 292	7 304	0	0	0	56 426	67 962	178 101
Iron/Steel	124 166	90 311	116 898	51 047	42 284	44 939	90 552	386 250	946 446
Volume/m^3									
Void	587	896	2 665	1 334	422	657	9 956	41 780	58 296
Pore volume	2 418	1 143	948	297	661	870	385	3 911	10 633
Disposal volume	15 930	10 611	16 105	7 896	5 806	7 680	13 880	76 441	154 350
Outer volume	15 640	10 229	16 018	7 641	5 218	7 578	13 652	75 271	151 246

Table 3-9. Calculated reference radionuclide inventory (Bq) for each waste vault in SFR at closure in 2075 (SKB R-18-07).

	Activity reference case (2075-12-31)/Bq							
Radionuclide	**Silo**	**1BMA**	**2BMA**	**1BRT**	**1BTF**	**2BTF**	**1BLA**	**2–5BLA**
H-3	1.35E+10	3.34E+08	2.99E+12	1.04E+09	1.66E+08	4.88E+07	3.34E+06	1.82E+11
Be-10	1.30E+06	1.95E+05	4.15E+04	2.83E+02	1.28E+04	2.52E+04	8.18E+02	2.11E+03
C-14 (inorg)	1.52E+12	1.51E+12	6.57E+11	1.33E+08	2.50E+11	4.25E+11	8.47E+09	9.39E+08
C-14 (org)	5.47E+11	1.97E+11	2.06E+10	5.72E+07	1.28E+10	8.05E+09	1.52E+08	2.25E+08
C-14 (ind)	0.00E+00	0.00E+00	1.99E+10	1.33E+10	0.00E+00	0.00E+00	0.00E+00	1.23E+09
Cl-36	5.32E+08	2.28E+08	2.64E+08	7.38E+06	9.64E+06	9.27E+06	1.86E+07	4.86E+07
Ca-41	0.00E+00	0.00E+00	1.98E+10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.14E+09
Fe-55	2.69E+12	1.43E+07	2.16E+11	1.45E+10	1.11E+09	3.16E+05	2.47E+05	5.12E+08
Co-60	1.47E+13	1.95E+10	4.10E+12	1.89E+11	8.51E+10	1.78E+09	3.35E+08	3.17E+10
Ni-59	8.38E+12	1.14E+12	1.53E+12	1.78E+11	1.47E+10	2.47E+10	3.11E+09	1.28E+10
Ni-63	7.00E+14	7.73E+13	1.50E+14	1.52E+13	9.83E+11	1.47E+12	2.25E+11	1.19E+12
Se-79	1.54E+09	1.98E+08	6.37E+07	0.00E+00	2.84E+07	1.96E+07	5.77E+05	6.17E+06
Sr-90	1.98E+12	1.56E+11	5.49E+11	2.24E+10	2.13E+10	2.71E+10	3.29E+08	2.21E+10
Zr-93	4.94E+09	3.25E+08	1.74E+09	2.44E+08	2.14E+07	4.20E+07	1.36E+06	3.06E+07
Nb-93m	1.03E+13	9.30E+09	1.64E+13	1.07E+12	2.93E+09	1.36E+09	7.78E+07	1.27E+11
Nb-94	1.08E+11	4.08E+09	1.08E+11	9.27E+09	2.14E+08	4.19E+08	3.64E+07	1.08E+09
Mo-93	1.47E+10	6.43E+08	5.62E+09	3.10E+09	8.50E+07	1.37E+08	9.22E+06	1.40E+08
Tc-99	2.05E+10	3.25E+09	3.49E+09	4.82E+08	3.10E+08	3.52E+08	6.95E+07	1.05E+09
Pd-107	3.98E+08	4.95E+07	2.57E+09	0.00E+00	7.10E+06	4.91E+06	1.44E+05	2.23E+06
Ag-108m	2.60E+11	1.70E+10	6.60E+10	4.81E+09	1.19E+09	2.22E+09	2.39E+08	1.55E+09
Cd-113m	1.73E+10	4.85E+08	1.17E+09	0.00E+00	4.42E+08	3.34E+07	2.86E+06	3.15E+07
In-115	0.00E+00	0.00E+00	3.10E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sn-126	2.67E+08	2.47E+07	2.80E+07	8.17E+05	3.55E+06	2.45E+06	7.22E+04	1.01E+07
Sb-125	2.70E+11	1.66E+06	1.65E+10	2.15E+07	1.21E+08	4.13E+04	1.22E+04	4.41E+06
I-129	5.16E+08	7.60E+07	8.18E+07	0.00E+00	7.44E+06	4.35E+06	2.43E+05	2.81E+06
Cs-134	1.59E+11	9.18E+03	2.55E+10	0.00E+00	1.60E+06	1.31E+01	1.14E+02	1.42E+06
Cs-135	2.95E+09	6.52E+08	7.49E+08	0.00E+00	1.94E+07	5.77E+06	2.00E+06	1.84E+08
Cs-137	1.02E+14	6.77E+12	5.74E+12	0.00E+00	2.36E+12	5.89E+11	2.79E+10	4.85E+11
Ba-133	9.18E+08	1.61E+07	1.38E+08	5.62E+04	1.11E+07	2.31E+06	1.81E+05	1.23E+07
Pm-147	2.66E+11	1.10E+06	4.21E+10	1.37E+06	2.20E+08	1.91E+03	9.92E+03	3.78E+06
Sm-151	7.21E+11	7.57E+10	6.93E+10	3.57E+08	1.46E+10	7.22E+09	2.48E+08	6.05E+09
Eu-152	1.86E+09	4.82E+07	1.47E+11	4.84E+05	6.21E+07	3.25E+06	9.16E+07	1.72E+10
Eu-154	8.18E+11	7.81E+09	7.17E+10	8.09E+07	1.96E+10	3.48E+08	6.56E+07	3.58E+08
Eu-155	9.63E+10	8.47E+07	1.24E+10	2.10E+06	1.11E+09	1.09E+06	8.43E+05	1.88E+07
Ho-166m	8.40E+09	1.24E+09	6.41E+08	8.50E+06	8.32E+07	1.60E+08	5.24E+06	9.58E+07
U-232	4.56E+05	5.24E+04	9.89E+05	7.18E+03	5.71E+03	4.87E+03	1.60E+02	2.51E+04
U-234	3.77E+07	4.66E+06	7.47E+07	1.87E+06	3.80E+05	3.86E+05	1.17E+04	3.55E+07
U-235	6.92E+06	9.83E+05	6.92E+06	3.80E+04	1.84E+07	1.01E+05	2.18E+08	6.34E+08
U-236	1.22E+07	1.73E+06	2.28E+07	4.30E+05	1.77E+05	2.70E+05	3.05E+03	4.99E+05
U-238	1.88E+07	2.12E+06	1.80E+07	4.89E+05	3.46E+05	5.03E+05	7.16E+08	1.48E+08
Np-237	6.44E+07	7.91E+06	3.40E+07	5.24E+05	4.64E+05	1.48E+06	1.03E+04	4.65E+05
Pu-238	4.07E+10	2.82E+09	1.23E+11	2.86E+09	5.11E+08	2.54E+08	1.48E+07	2.10E+09
Pu-239	1.70E+10	2.65E+09	5.92E+10	4.75E+08	2.02E+08	2.01E+08	6.62E+06	3.83E+08
Pu-240	1.37E+10	1.63E+09	1.16E+10	6.58E+08	1.65E+08	1.65E+08	4.70E+06	4.01E+08
Pu-241	2.39E+11	7.50E+09	5.64E+11	8.23E+09	2.29E+09	8.09E+08	3.91E+07	9.23E+09
Pu-242	7.48E+07	8.91E+06	2.14E+08	3.38E+06	8.92E+05	8.08E+05	2.53E+04	2.34E+06
Am-241	1.06E+11	1.68E+10	2.32E+11	2.29E+09	1.78E+09	1.22E+09	6.24E+07	2.82E+09
Am-242m	2.61E+08	2.94E+07	6.12E+08	1.36E+07	2.44E+06	2.19E+06	7.45E+04	6.50E+06
Am-243	1.20E+09	2.09E+08	2.36E+09	4.71E+07	1.31E+07	1.38E+07	1.61E+06	2.56E+07
Cm-243	1.62E+08	1.08E+07	3.77E+08	6.15E+06	1.26E+06	8.12E+05	3.67E+04	4.87E+06
Cm-244	1.26E+10	5.83E+08	2.69E+10	6.38E+08	7.28E+07	2.06E+07	2.55E+06	4.06E+08
Cm-245	1.78E+07	2.47E+06	2.78E+07	7.55E+05	1.13E+05	1.06E+05	4.97E+03	2.82E+05
Cm-246	4.86E+06	5.64E+05	8.30E+06	2.49E+05	3.36E+04	3.43E+04	1.23E+03	8.32E+04

Table 3-10. Estimated radionuclide inventory including uncertainties (Bq) (95th percentile) for each waste vault in SFR at closure in 2075 (SKB R-18-07).

	Activity 95-percentile (2075-12-31)/Bq							
Radionuclide	**Silo**	**1BMA**	**2BMA**	**1BRT**	**1BTF**	**2BTF**	**1BLA**	**2–5BLA**
H-3	2.92E+10	5.73E+08	3.48E+12	1.70E+09	4.55E+08	9.76E+07	8.22E+06	2.79E+11
Be-10	2.44E+06	2.81E+05	9.28E+04	6.64E+02	3.31E+04	4.74E+04	1.96E+03	4.08E+03
C-14 (inorg)	2.58E+12	3.38E+12	1.80E+12	2.42E+08	4.03E+11	6.70E+11	2.20E+10	1.37E+09
C-14 (org)	1.07E+12	3.80E+11	4.28E+10	1.03E+08	2.20E+10	1.36E+10	3.88E+08	3.79E+08
C-14 (ind)	0.00E+00	0.00E+00	2.13E+10	1.55E+10	0.00E+00	0.00E+00	0.00E+00	2.03E+09
Cl-36	5.85E+08	2.43E+08	2.87E+08	8.27E+06	1.04E+07	1.32E+07	2.02E+07	7.68E+07
Ca-41	0.00E+00	0.00E+00	2.17E+10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.84E+09
Fe-55	4.48E+12	2.20E+07	3.92E+11	1.65E+10	2.10E+09	3.89E+05	4.69E+05	6.28E+08
Co-60	1.57E+13	2.15E+10	4.39E+12	2.07E+11	1.01E+11	1.84E+09	4.40E+08	3.84E+10
Ni-59	9.30E+12	1.36E+12	1.59E+12	1.94E+11	1.71E+10	2.93E+10	4.87E+09	1.58E+10
Ni-63	7.76E+14	9.23E+13	1.56E+14	1.66E+13	1.13E+12	1.63E+12	3.64E+11	1.49E+12
Se-79	2.08E+09	2.07E+08	8.27E+07	0.00E+00	3.66E+07	2.24E+07	8.32E+05	1.03E+07
Sr-90	2.21E+12	1.81E+11	6.33E+11	2.51E+10	2.55E+10	3.02E+10	4.17E+08	3.42E+10
Zr-93	6.91E+09	4.66E+08	1.86E+09	2.80E+08	5.76E+07	8.07E+07	3.21E+06	3.87E+07
Nb-93m	1.17E+13	1.28E+10	1.72E+13	1.19E+12	6.78E+09	2.06E+09	1.74E+08	1.58E+11
Nb-94	1.21E+11	4.82E+09	1.13E+11	1.04E+10	3.01E+08	4.94E+08	4.68E+07	1.30E+09
Mo-93	1.58E+10	7.12E+08	5.86E+09	3.44E+09	1.03E+08	1.60E+08	1.18E+07	1.80E+08
Tc-99	2.29E+10	3.91E+09	3.95E+09	5.34E+08	3.78E+08	4.14E+08	1.04E+08	1.59E+09
Pd-107	7.95E+08	7.49E+07	3.19E+09	0.00E+00	1.97E+07	1.08E+07	3.97E+05	3.10E+06
Ag-108m	3.71E+11	2.42E+10	7.14E+10	5.68E+09	3.12E+09	4.25E+09	4.06E+08	2.12E+09
Cd-113m	3.95E+10	8.62E+08	2.80E+09	0.00E+00	1.29E+09	7.50E+07	8.49E+06	5.07E+07
In-115	0.00E+00	0.00E+00	3.93E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sn-126	4.54E+08	3.88E+07	3.79E+07	9.13E+05	9.80E+06	5.59E+06	2.01E+05	1.41E+07
Sb-125	5.50E+11	3.22E+06	4.10E+10	2.44E+07	2.87E+08	5.83E+04	3.51E+04	5.38E+06
I-129	5.66E+08	8.71E+07	9.26E+07	0.00E+00	1.07E+07	6.18E+06	3.37E+05	4.13E+06
Cs-134	2.17E+11	1.12E+04	3.71E+10	0.00E+00	1.78E+06	1.60E+01	1.97E+02	1.81E+06
Cs-135	3.64E+09	8.47E+08	8.55E+08	0.00E+00	2.53E+07	8.27E+06	3.21E+06	3.01E+08
Cs-137	1.32E+14	7.05E+12	6.57E+12	0.00E+00	2.85E+12	6.19E+11	3.46E+10	7.73E+11
Ba-133	9.96E+08	1.76E+07	1.52E+08	9.34E+04	1.36E+07	2.50E+06	2.51E+05	1.80E+07
Pm-147	3.48E+11	1.39E+06	5.84E+10	1.55E+06	3.39E+08	2.25E+03	1.53E+04	4.83E+06
Sm-151	9.69E+11	7.93E+10	7.88E+10	3.99E+08	1.88E+10	8.25E+09	3.47E+08	1.00E+10
Eu-152	2.38E+09	5.31E+07	1.63E+11	5.45E+05	7.54E+07	3.63E+06	1.07E+08	2.63E+10
Eu-154	9.97E+11	9.07E+09	8.10E+10	9.13E+07	2.57E+10	3.87E+08	9.39E+07	4.68E+08
Eu-155	1.14E+11	1.05E+08	1.55E+10	2.39E+06	1.55E+09	1.21E+06	1.27E+06	2.44E+07
Ho-166m	9.15E+09	1.27E+09	7.04E+08	1.47E+07	9.84E+07	1.71E+08	6.53E+06	1.61E+08
U-232	5.19E+05	6.28E+04	2.02E+06	8.04E+03	6.53E+03	5.67E+03	1.84E+02	4.06E+04
U-234	4.67E+07	6.80E+06	1.11E+08	2.10E+06	4.51E+05	4.89E+05	1.36E+04	7.80E+07
U-235	7.58E+06	1.07E+06	1.19E+07	4.25E+04	2.03E+07	1.11E+05	2.43E+08	8.10E+08
U-236	1.45E+07	2.27E+06	4.21E+07	4.82E+05	2.05E+05	3.08E+05	3.55E+03	7.99E+05
U-238	2.10E+07	2.61E+06	2.55E+07	5.48E+05	4.20E+05	6.02E+05	9.60E+08	1.89E+08
Np-237	7.04E+07	8.82E+06	6.04E+07	5.84E+05	5.28E+05	1.62E+06	1.37E+04	6.51E+05
Pu-238	4.40E+10	3.22E+09	1.81E+11	3.21E+09	5.47E+08	2.85E+08	1.69E+07	2.77E+09
Pu-239	1.86E+10	3.06E+09	1.02E+11	5.32E+08	2.24E+08	2.26E+08	7.71E+06	5.18E+08
Pu-240	1.68E+10	2.37E+09	1.22E+10	7.36E+08	1.91E+08	2.02E+08	5.41E+06	5.41E+08
Pu-241	3.15E+11	1.09E+10	1.01E+12	9.26E+09	2.94E+09	9.93E+08	4.67E+07	1.15E+10
Pu-242	9.21E+07	1.30E+07	4.06E+08	3.78E+06	1.02E+06	1.00E+06	2.93E+04	3.16E+06
Am-241	1.34E+11	2.37E+10	4.54E+11	2.49E+09	1.97E+09	1.50E+09	7.13E+07	3.77E+09
Am-242m	3.21E+08	4.17E+07	1.09E+09	1.53E+07	2.83E+06	2.69E+06	8.78E+04	8.57E+06
Am-243	1.46E+09	2.76E+08	4.19E+09	5.28E+07	1.49E+07	1.62E+07	2.27E+06	3.37E+07
Cm-243	2.06E+08	1.56E+07	7.00E+08	6.91E+06	1.54E+06	1.01E+06	4.37E+04	6.29E+06
Cm-244	1.82E+10	9.52E+08	3.82E+10	7.15E+08	9.96E+07	3.03E+07	3.11E+06	5.04E+08
Cm-245	2.30E+07	3.71E+06	4.64E+07	8.48E+05	1.30E+05	1.29E+05	5.98E+03	3.65E+05
Cm-246	5.96E+06	8.34E+05	1.35E+07	2.82E+05	3.92E+04	4.20E+04	1.46E+03	1.06E+05

4 Silo

4.1 Design

The silo consists of a cylindrical vault in which a freestanding reinforced concrete cylinder has been erected. The concrete cylinder is constructed of in situ cast concrete and is founded on a layer of 90 % sand and 10 % bentonite by weight. The space between the reinforced concrete walls and the surrounding rock is filled with bentonite. The bentonite is a sodium montmorillonite with the product name GEKO/QI. The rock itself is covered with shotcrete and there is a rock drainage system for groundwater between the rock and the bentonite. The drainage system goes from the top to the bottom of the silo and is installed to limit the water uptake in the bentonite and the risk for development of non-uniform swelling pressures.

The interior of the cylindrical concrete structure is divided into vertical shafts by concrete walls. Intermediate-level waste conditioned in concrete or bitumen is packaged in concrete and steel moulds as well as in steel drums (on a drum tray or in a steel box). The waste packages are placed in the shafts and the voids between the packages are gradually grouted with concrete for stabilisation, see Figure 4-1 and Figure 4-2. A permeable grout is used to allow gas produced inside the shafts to escape. During operation, each shaft is provided with a radiation-shielding lid that is removed at closure. The dimensions of the silo are given in Table 4-1 and in Figure 4-3. Half-size, quarter-size and small shafts (Figure 4-2) are currently unfilled and the final state of these is not yet defined.

Figure 4-1. *Illustration of the silo during the operational period.*

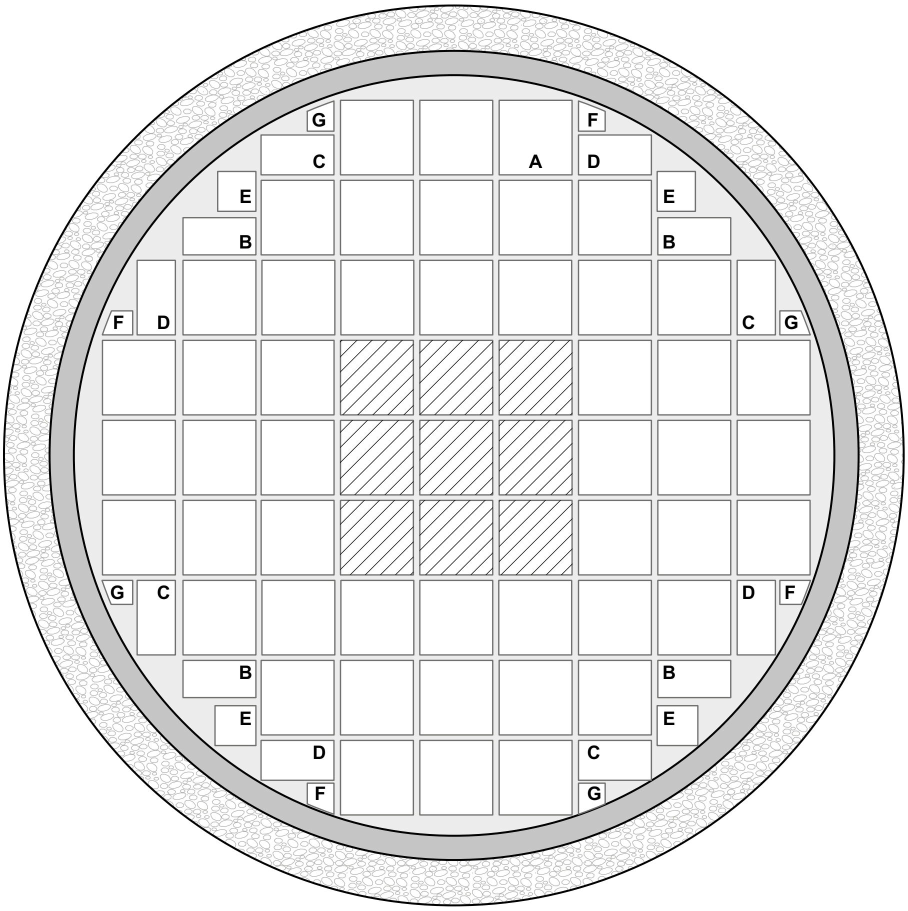

Figure 4-2. Schematic illustration from above of the division of the silo into shafts, indicating the location of the bituminised wastes in the central shafts. A denotes full-size shafts; B, C and D half-size shafts; E quarter-size shafts; F and G small shafts. There are also small shafts in the periphery that are planned to be grouted and hence they are not shown in the figure.

The demolition and dismantling of existing systems, for example the ventilation and electricity, will be adapted to the closure sequence. The closure plan for SFR describes measures for the sealing and closure of the silo (Mårtensson et al. 2022). In an initial step, the shafts are overcast with grout up to the top rim of the cylindrical concrete structure. This provides a radiation shield on top of the cylindrical concrete structure, which simplifies the work of reinforcing and casting a concrete lid. The reinforced concrete lid is cast on a thin layer of sand. Sand-filled gas evacuation channels are installed in the lid to allow the escape of gas that is generated inside the cylindrical concrete structure, see Figure 4-4. The top bentonite layer in the gap between rock and cylindrical concrete structure may have been affected during the operational period and is to be replaced with new bentonite.

The top of the silo, above the concrete lid, is to be backfilled with different layers of backfill material. A mixture of sand and bentonite is placed on top of a thin layer of sand and protected by a thin unreinforced concrete slab. The remaining void above the sand bentonite mixture is backfilled with packed friction material e.g. macadam and, at the very top, with cement-stabilised sand, see Figure 4-4. Finally, the tunnels at the top and bottom of the silo are planned to be sealed off using three plugs, see Section 11.1, Figure 11-1 and 11-2.

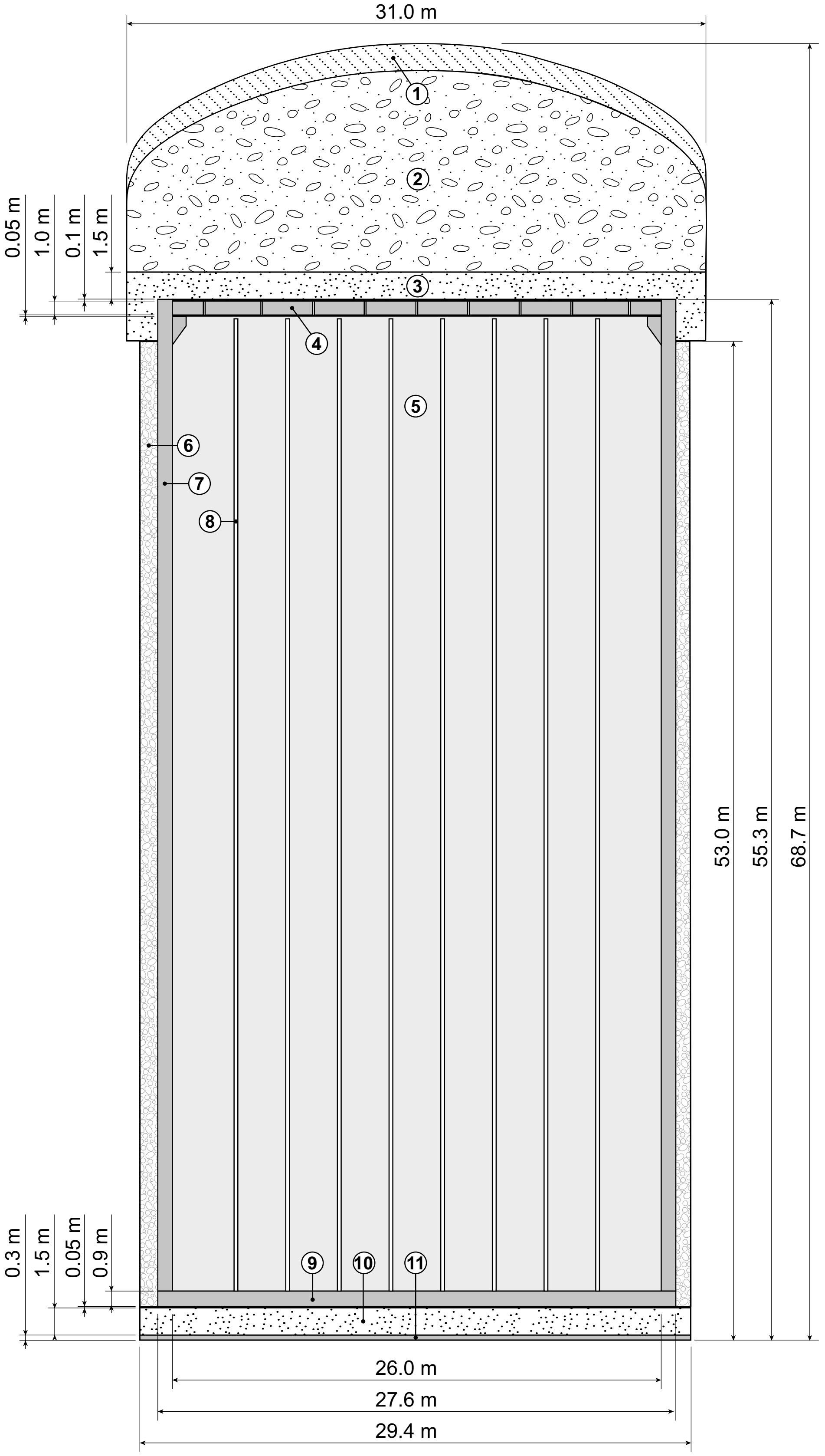

Figure 4-3. *Schematic vertical cross-section of the silo at closure. The waste packages are surrounded by grout in this waste vault. The dimensions of the silo are given in detail in Table 4-1. Key to numbering 1) Cement-stabilised sand 2) Crushed rock backfill 3) Compacted fill with a mixture of 10 % bentonite and 90 % sand 4) Reinforced concrete slab with sand layer and gas evacuation channels 5) Waste 6) Side bentonite layer 7) Outer concrete wall 8) Inner (shaft) walls of concrete 9) Concrete slab 10) Bottom sand-bentonite layer 11) Bottom drainage system.*

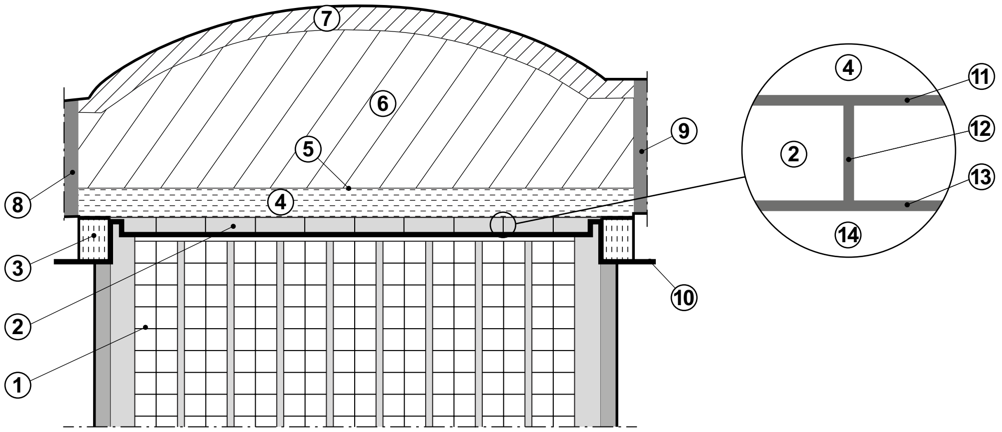

Figure 4-4. Schematic cross-section of silo top after closure. Key to numbering: 1) Waste 2) Reinforced concrete slab with sand layer and gas evacuation channels 3) Compacted fill of 30/70 bentonite/sand mixture 4) Compacted fill of 10/90 bentonite/sand mixture 5) Unreinforced concrete slab 6) Compacted fill of friction material 7) Cement-stabilised sand 8) Constraining wall of concrete against the silo roof tunnel (1STT) 9) Constraining wall of concrete against loading-in building (IB) 10) Boundary between works associated with grouting and backfilling 11)) Sand layer 100 mm 12) Gas evacuation channels ∅ 0.1 m 13) Sand layer 50 mm 14) Grout (permeable).

4.2 Design considerations

Safety features considered for the surrounding rock

The depth of the silo (~ 60 to 130 m) results in favourable conditions with respect to mechanical stability of the rock, low groundwater flow and anoxic redox conditions.

Safety features considered for the system components in the silo

The silo has the most extensive barriers of the SFR vaults.

Level of radioactivity – The silo contains most of the radioactivity in SFR, see Section 3.7. Even though the level of radioactivity is greater than in the other waste vaults, limiting the amount of radioactivity in the waste packages is an important factor for radiological safety. The waste is solidified with cement/bitumen or embedded with concrete to limit the release of radionuclides from the waste packages. The acceptance criteria for the waste packages are given in Section 3.1.

Limited advective transport – The bentonite buffer surrounding the cylindrical concrete structure has a low hydraulic conductivity and will limit advective flow in the shafts of the concrete structure and through the waste packages. In addition, the shaft walls and grout surrounding the waste packages will limit the potential flow through the waste packages.

The inflow of water to the top and the bottom of the silo from connecting tunnels will be limited by a number of plugs in connecting tunnels, see Section 11.1.

Mechanical stability – The post-closure stability of the cylindrical concrete structure is enhanced by the grout around waste packages and the bentonite buffer. The concrete structure is designed to withstand a swelling pressure from the surrounding bentonite of 500 kPa (Pusch 2003). The backfilling of the cupola will limit the effect of potential rock fallout from the silo ceiling. The gas transport properties of the selected grout and the gas evacuation channels in the lid ensure that gas can be released.

Limited dissolution – The dissolution of radionuclides from the bitumen-solidified waste is determined by the limited rate of water uptake in the bitumen. The concentration of some radionuclides, such as Ni-63 and Ni-59, will be within the range of their solubility limits. The release of radionuclides present as induced activity in metal will be determined by the corrosion rate of the metal.

Sorption – The vast majority of radionuclides released from cement-solidified waste or concrete-embedded waste will be retarded by sorption on these cementitious materials. In addition, the radionuclide release from all waste matrices, including bitumen, will be limited by sorption in the concrete moulds, the grout surrounding waste packages, the concrete walls and the bentonite outside the concrete structures.

Favourable water chemistry – The water chemistry in the silo is influenced by the large amounts of cementitious materials in the waste packages, the cylindrical concrete structure and grout. The resulting alkaline environment will limit the rates of corrosion and microbial degradation. In addition, reducing conditions in the disposal shafts due to steel corrosion will favour the sorption of many radionuclides e.g. technetium and some actinides.

4.3 Inspection and control of the silo

The inspection and control of the silo can be divided into the following steps.

- Inspection and control of the concrete structures in the silo during construction.
- Inspection and control of the bentonite material surrounding the concrete walls and bottom during construction.
- Inspection and control of the silo during the emplacement of waste. Measurements are made regularly (e.g. measurements of the settlement of the cylindrical concrete structure, top subsidence and swelling pressures in the surrounding buffer).
- Inspection and control of the continuous grouting that is performed in campaigns during operation.
- Final inspection of the top of the cylindrical concrete structure before backfilling with friction material e.g. macadam.

Construction

The cylindrical concrete structure was constructed using a slip form. The concrete structure rests on a bed of a mixture of 10 % finely ground GEKO/QI bentonite and 90 % sand. The bed material was applied in several layers and compacted to get the required density. Pure GEKO/QI bentonite granulate with a grain size ranging between 0.1 and 20 mm was used to fill the gap between the silo concrete walls and the rock. The filling material was not compacted. Frequent measurements and tests were made of the bentonite material properties of the installed materials (Pusch 2003).

Settlement of the cylindrical concrete structure

Settlement has been measured regularly in the silo since its construction in 1987. Annual data gathered up to 1999 and model predictions suggested that the settlement process was so slow and predictable that its progress could be checked and reported on every three years. However, since 2002 the measurements have been made on yearly basis (SKB TR-14-02).

The settlement of the cylindrical concrete structure is small and is not judged to deviate from the original expectation of about five centimetres by year 2040. The settlement is steady and is now slower than in the first few years after construction. The accuracy in the measurements is judged to be in the order of ± 0.3 mm (Pusch 2003).

Vertical movements of the bentonite top filling

Reference bolts were anchored in the shotcreted rock early after the construction of the silo and corresponding bolts were cast in the cylindrical concrete structure so that its vertical movements can be measured by precision levelling. The measurements indicate limited movement in the top filling of the side bentonite layer. The small movements show that no significant wetting of the side bentonite layer has occurred, which in turn suggests that the wall drainage is functioning as intended (Pusch 2003, Malmberg and Kristensson 2015).

Pressure build up in the bentonite

A number of pressure cells are installed to measure the swelling pressure in the bentonite surrounding the cylindrical concrete structure, to ensure that the swelling pressure is below the tolerable level for the design. Pressure gauges are installed at slab level, mid-height level (25 m above the slab) and at the top level of the cylindrical concrete structure (50 m above the slab). The most recent values are from 2021 and are roughly the same as earlier measurements. The pressure at the top of the cylindrical concrete structure is well below the tolerable level for the design. At mid-height and the bottom of the cylindrical concrete structure, the pressures are considerably lower than the tolerable level (SKB TR-14-02). This indicates more effective dewatering of the surface rock and drainage than had been assumed at the design stage.

4.4 Uncertainties

The silo concrete barrier is with regard to cracks anticipated to be intact and in accordance with the proposed initial state at closure of the repository. Due to the bentonite barrier outside the concrete barrier in the silo, continuous inspections on the concrete barrier are difficult to perform and inspections have therefore only been done during the construction. The condition of this barrier at closure is thus somewhat uncertain, which is why it is handled in a pessimistic manner in the main scenario assuming the silo to be in a more degraded state compared to the anticipated initial state.

4.5 Silo dimensions and material quantities

The main dimensions of the silo are given in Table 4-1. The cylindrical concrete structure is divided in 57 full-size shafts, 12 half-size shafts and a number of smaller shafts denoted E to G in Figure 4-2. In addition, there are several even smaller shafts that are planned to be grouted. The excavated volume of the cylindrical vault is 45 900 m^3 and the estimated volumes of different materials in the silo after closure are given in Table A-1 in Appendix A. The total void in the vault including void and porosities in the materials are also given in Table A-1 in Appendix A.

Table 4-1. Silo dimensions.

Silo property	Value	Comment*
Excavated rock cavity		
Maximum height (m)	68.7	Calculated from values (435.7 – 367) given in drawing 1411-10020610
Diameter silo cupola (m) (above cylindrical part)	31	Value given in drawing 1411-10020610
Diameter cylindrical part (m) (outside concrete cylinder)	29.4	Value given in drawing 1411-10020610
Height silo cupola (m)	15.7	Calculated from values (435.7 – 420) given in drawing 1411-10020610
Height of cylindrical part (m) (silo bottom to cupola)	53	Calculated from values (420 – 367) given in drawing 1411-10020610
Excavated volume (m^3)	45 900	Estimated in SKB TR-14-02
Bottom		
Cast coarse concrete for drainage system (m)	0.1	Calculated from values given in drawings 1411-10020610 and 1-1010008, Periphery (367.1 – 367.1) and Centre (367.1 – 367.0), i.e 0 – 0.1 m
Concrete plate with drainage system (m)	0.2	Value given in drawing 1-1010008
Sand-bentonite (90/10) thickness (m)	1.5	Value given in drawing 1-1010008
Sand-bentonite (90/10) diameter (m)	28.6	Value radius 14.300 m given in drawing 1-1010012
Thin concrete layer	0.05	Value given in drawing 1-1010008
Thickness reinforced slab (m)	0.9	Value given in drawing 1-1010008

Table 4-1. Continued.

Silo property	Value	Comment*
Concrete structure		
Diameter outer (m)	27.6	Value radius 13.800 m given in drawings 1-1010006, 1-1010021
Height outer walls (m) (standing on slab)	52.6	Calculated from values (422.3 – 369.75) given in drawing 1-1010008
Thickness cylindrical wall (m)	0.8	Value given in drawing 1-1010006
Height shaft walls (m)	51.3	Calculated from values (421.05 – 369.75) given in drawing 1-1010008
Thickness shaft walls (m)	0.2	Value given in drawings 1-1010021
57 Shafts full-size (m) x (m) – A	2.55 × 2.55	Values given in drawings 1-1010021. Type of shafts in drawing 3-1057070 and 42-1057063
12 Shafts half-size (m) x (m) – B, C, D	2.55 × 1.35	Values given in drawings 1-1010021. Type of shafts in drawing 3-1057070 and 42-1057063
4 Shafts quarter-size (m) x (m) – E	1.3 × 1.3	Values given in drawings 1-1010021. Type of shafts in drawing 3-1057070 and 42-1057063
8 Small shafts (m) x (m) – F, G	0.75 × (0.64 – 0.91)	Values given in drawings 1-1010021. Type of shafts in drawing 3-1057070 and 42-1057063
Bentonite buffer surrounding concrete cylinder		
Bentonite thickness (m)	0.9	Calculated from values ((29.400 – (2 × 13.800)) / 2) given in drawings 1411-10020610 and 1-1010006
Bentonite height (m)	51.2	Calculated from values (420 – 368.85 + 0.05) from 1-1010008, 1411-10020610
Silo top		
Top lid – Sand layer above concrete grout thickness (m)	0.05	Value given in closure plan for SFR (Mårtensson et al. 2022)
Top lid – Reinforced lid with gas evacuation channels thickness (m)	1	Value given in closure plan for SFR (Mårtensson et al. 2022)
Top lid – Gas evacuation channels, diameter (m)	0.1	57 channels (one per full-size shaft) with a diameter of 0.1 m
Top lid – Sand above concrete lid thickness (m)	0.1	Value given in closure plan for SFR (Mårtensson et al. 2022)
Sand – bentonite (90/10) thickness (m)	1.5	Value given in closure plan for SFR (Mårtensson et al. 2022)
Concrete not reinforced (m)	thin	Value given in closure plan for SFR (Mårtensson et al. 2022)
Friction material thickness (m)	up to about 1 m from top	Estimate from closure plan for SFR (Mårtensson et al. 2022)
Cement-stabilised sand thickness (m)	1	Estimate from closure plan for SFR (Mårtensson et al. 2022)

* Drawing numbers in column "Comment" refer to SKB's internal documents.

5 1BMA

5.1 Design

The waste vault for intermediate-level waste, 1BMA, currently houses an approximately 140 m long reinforced concrete structure divided into 13 large compartments and two smaller compartments, see Figure 5-1. The construction is in effect a large concrete box with inner walls that create the compartments. Conventional techniques were used to build the existing structure, and reinforcement bars and other steel construction components (e.g. tie rods, grid plates, grouting pipes) are present in the concrete slab and walls. Tie rods were used to keep the formwork in place while casting the concrete walls and to prevent the concrete from collapsing or shifting. The concrete in the PSAR is considered to have a higher porosity than in previous safety assessments (Elfwing et al. 2015).

The concrete structure rests on concrete joists that are positioned directly on the solid rock bottom of the vault. The areas between the joists and between the joists and the vault walls are covered with crushed rock. The slab of the concrete structure rests on this layer of crushed rock.

The waste in 1BMA is conditioned in cement, bitumen or concrete. The waste packages (concrete and steel moulds, and steel drums on a tray or in a steel box) are positioned in the compartments using a remote-controlled overhead crane that runs along the top edge of the walls of the concrete structure, see Figure 5-1. The moulds are stacked six high and drums eight high. Each compartment will contain at least two rows of concrete moulds across its width that act as a support for prefabricated reinforced concrete elements. The elements are put in position as soon as a compartment is filled. Before the waterproofing membrane was installed in 1BMA, a thin concrete layer was cast on top of the lid in order to prevent water intrusion during the operational period. Note that the 1BMA compartments will not be grouted to avoid problems associated with the swelling of bitumen-stabilised wastes post-closure.

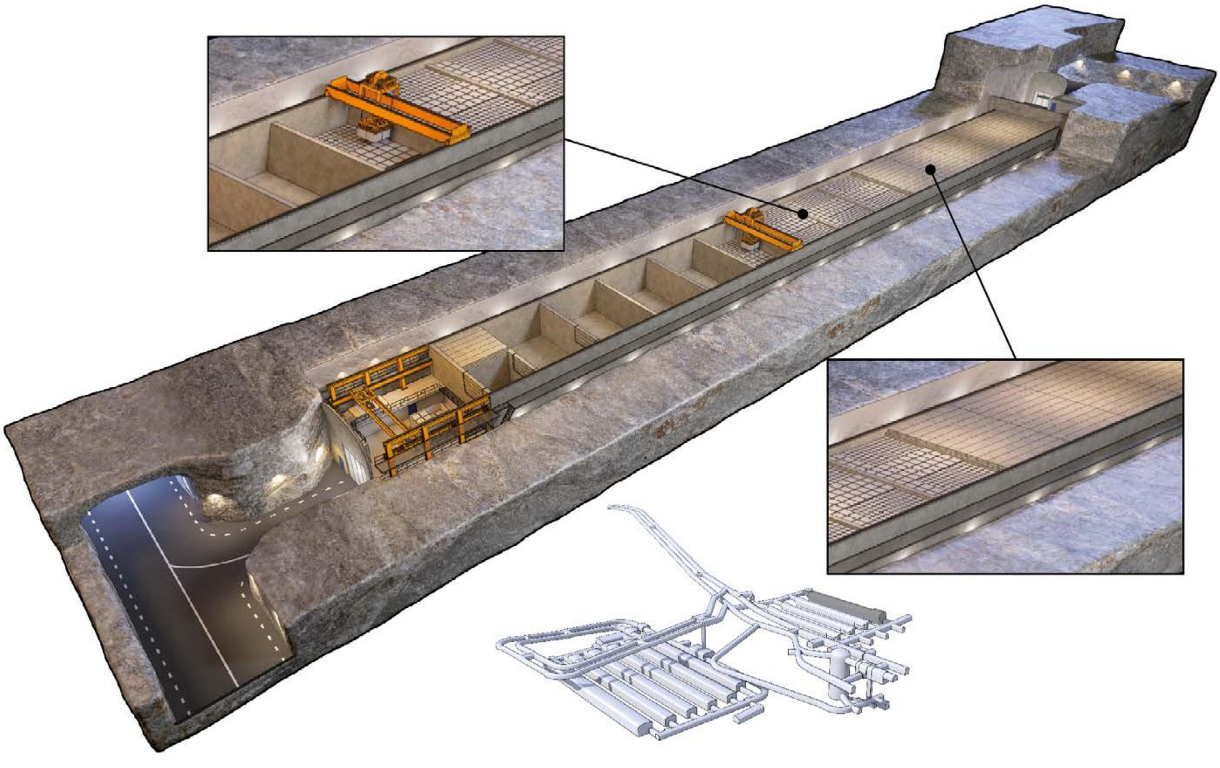

Figure 5-1. *Illustration of 1BMA during the operational period. The upper detail shows the emplacement of waste packages, the lower detail shows the concrete lid. In addition there is a view of SFR with the position of 1BMA highlighted.*

When the operational period is complete, new reinforced concrete walls will be erected on the outside of the existing ones, see Figure 5-2. This will limit groundwater flow through the waste, and will compensate for the cracking that has been observed in the existing structure. The external concrete walls will replace the existing ones as the main hydraulic barrier of the concrete structure and ensure that the desired initial state is obtained. On top of the prefabricated concrete elements, which provide radiation shielding during the operational period, a thick reinforced concrete lid that can carry the load of the backfill material will be cast, Figure 5-2. It should be noted that the slab in 1BMA will not be further repaired by injecting cement into cracks or by introducing an additional external repair. The slab is thus considered to be transmissible in this assessment.

The new outer walls will be cast with a minimal amount of surface reinforcement, and without form rods. The rationale for these measures is described in more detail for 2BMA in Chapter 6.

The demolition and dismantling of existing systems, for example the ventilation and electricity, will be adapted to the closure sequence for 1BMA described in the SFR closure plan (Mårtensson et al. 2022). The empty space around the concrete barrier is planned to be backfilled with macadam up to 1 m (or less if possible) below the ceiling of the rock vault, see Figure 5-2. Macadam is crushed crystalline rock that contains no or very little fine material, see the definition in Section 1.5. A concrete mechanical constraint will be installed at the end of the vault that connects to the transverse tunnel (1TT), as part of the plug. It is not possible to install a concrete mechanical constraint in the entrance to the waste vault tunnel (BST); instead, a section in the waste vault will be filled with transition material and backfill material as a mechanical constraint for the bentonite.

The walls and roof of the vault are lined with shotcrete to stabilise the rock during the operational period. The dimensions of the waste vault are given in Table 5-1 and Figure 5-2.

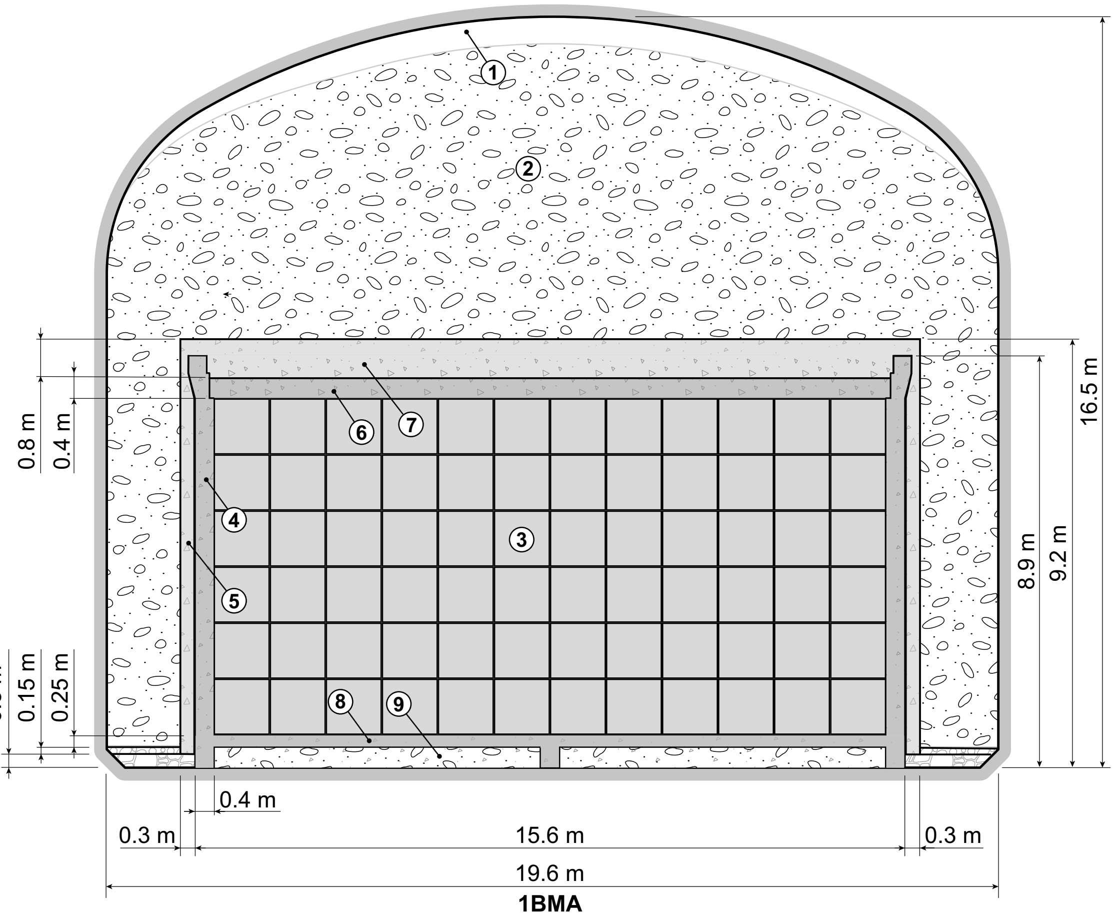

Figure 5-2. *Schematic cross-section of 1BMA after closure. The dimensions of 1BMA are given in detail in Table 5-1. Key to numbering: 1) Void 2) Macadam backfill 3) Waste domain 4) Existing outer wall 5) New outer wall 6) Pre-fabricated concrete element 7) New concrete lid 8) Slab 9) Crushed rock.*

5.2 Design considerations

The 1BMA design presented in this report is technically feasible. However, the sealing and closure design for 1BMA is expected to be developed and optimised further before the closure of SFR.

Safety features considered for the surrounding rock

The depth of 1BMA (~70 m) creates favourable conditions with respect to mechanical stability of the rock, low groundwater flow and anoxic redox conditions.

Safety features considered for the system components in 1BMA

Level of radioactivity – The most important radiological safety principle for 1BMA is the limited level of radioactivity in the waste packages. The waste consists mainly of ion-exchange resins solidified with cement/bitumen and some concrete-embedded solid waste, see Section 3.6.3. The acceptance criteria for the waste packages are given in Section 3.1.

The criteria relating to the level of radioactivity and waste package design, together with the design of the system components in 1BMA, will provide radiation protection during the operational period and enhance post-closure safety.

Limited advective transport – Water flow in the interior of the compartments and through the waste packages will be limited. In 1BMA, the hydraulic contrast between the permeable macadam backfill surrounding the concrete structure and the less permeable concrete structure enclosing the waste will divert water flow away from the compartments to the more permeable surrounding materials. In addition, water flow inside the compartments will occur preferentially in the void space, limiting flow through the waste packages.

The inflow of water to 1BMA from connecting tunnels will be limited by the plugs in the ends of the waste vault and the bentonite backfilled sections in the connecting tunnels, see Section 11.1.

Mechanical stability – The post-closure stability of the waste vault, the concrete structure (for example the stability against rock fallout) is enhanced by backfilling the waste vault with macadam. Each compartment will have at least two rows of concrete moulds that support the prefabricated concrete elements. The thickness of the new outer walls and lid and the amount of reinforcement will be sufficient to withstand the load from the macadam backfill and the groundwater pressure during the saturation.

Limited dissolution – The dissolution of radionuclides from the bitumen-solidified waste is determined by the limited rate of water uptake in bitumen. The concentration of some radionuclides, such as Ni-63 and Ni-59, will be within the range of their solubility limits. The release of radionuclides present as induced activity in metal will be determined by the corrosion rate of the metal.

Sorption – The vast majority of radionuclides released from cement-solidified waste or concrete-embedded waste will be retarded by sorption to these cementitious materials. In addition, the radionuclides released from all waste matrices, including bitumen, will be limited by sorption to the concrete moulds and structural elements of the vault as well as the macadam backfill outside the 1BMA barriers.

Favourable water chemistry – The water chemistry in the waste vault will be influenced by the chemical composition of intruding groundwater and the large amounts of cementitious material in the waste packages, concrete structures and barrier. Geochemically reducing conditions will also be established soon after closure of the vault due to metal corrosion and microbial degradation processes. Overall, the alkaline, anoxic environment that will be created is favourable for the sorption of many long-lived radionuclides e.g. technetium and some actinides, and will limit the rates of corrosion and microbial degradation processes.

5.3 Inspection and control of 1BMA

An extensive investigation of the existing 1BMA concrete structure revealed the presence of cracks that would compromise its hydraulic and mechanical properties as a barrier after closure. The 1BMA design presented in this report includes repair measures and the introduction of additional reinforced external concrete walls to achieve the desired properties at closure (Elfwing et al. 2018).

The closure plan for SFR (Mårtensson et al. 2022) describes the planned measures for closure of 1BMA.

The inspection and control of 1BMA can be divided into the following three steps.

- Control and inspection of concrete structures in the waste vault during construction, including repair operations.
- Control and inspection of conditions in the waste vault during the emplacement of waste – the operational period.
- Final inspection of the waste vault and concrete structures before backfilling with macadam and closure with plugs.

5.4 Uncertainties

Steel reinforcement (rebar) in the original concrete structure will corrode during the operational period and this assessment therefore focuses on uncertainties related to the initial state of 1BMA and the planned measures to repair the structural concrete (Elfwing et al. 2018). Inspections show that the original concrete structure is cracked to an extent that will significantly affect the hydraulic conductivity (Hejll et al. 2012). The inspections have been performed in empty compartments in 1BMA, corresponding to one quarter of the entire concrete structure. Extrapolating the results from the mapping of cracks to the entire concrete structure, introduces further uncertainties. A new outer hydraulic barrier will therefore be built outside the walls and roof of the existing structural concrete. The situation is similar for the 1BMA slab, where extrapolating the cracking profile from inspected compartments to the rest of the concrete foundation also is uncertain. The 1BMA slab will however remain unrepaired. In this assessment, it is anticipated that the concrete foundation has penetrating cracks and therefore is hydraulically transmissible.

For the 1BMA repairs, controls and inspections are undertaken during the construction to ensure requirements are met. The inspections and controls are to ensure an adequate knowledge of the achieved initial state of the waste vaults, which reduces uncertainties.

A recent compilation of available information for the existing 1BMA concrete structure has identified additional contributions to uncertainties in the initial state properties of the concrete structure (Elfwing et al. 2015).

5.5 1BMA dimensions and material quantities

The main dimensions of the waste vault 1BMA are given in Table 5-1. The dimensions of the original structure and the additional reinforced external concrete walls are given separately. The excavated volume is 48 000 m^3. The estimated volumes of different materials and the pore and void volumes in the waste vault after closure are given in Table A-2 in Appendix A. Table A-3 in Appendix A gives these volumes if the planned repair measures were not implemented.

Table 5-1. 1BMA dimensions.

1BMA property	Value	Comment*
Excavated rock cavity		
Total length (m)	160	Calculated from values (120 + 40) given in drawing 1411−100200800
Width (m)	19.6	Value given in drawing 1411−10020810
Height (max) (m)	16.5	Value given in drawing 1411−10020810
Height average (m)	15.3	Calculated 300/19.6
Vertical cross-sectional area (m^2)	300	Value given in closure plan for SFR (Mårtensson et al. 2022)
Excavated volume (m^3)	48000	Calculated 160 × 300
Shotcrete thickness (m)	0.05	From Carlsson and Christiansson (2007), Table 6-2
		Unreinforced 1 or 2 layers: 0.03 or 0.05 m
		Fibre reinforced: 0.05 or 0.08 m
Inner zone (at tunnel TT)		
Length (m) (outside concrete wall)	4.65 (2.1 + 2.55)	Dimensions adapted from those given in drawings 1470-10097060 and 1411-10020800. 2.1 m with full cross-sectional area and 2.55 m with smaller cross-sectional area, but within the total length of 160 m. The original dimensions were 2.4 m with full cross-sectional area and 2.55 m with smaller cross-sectional area, within the total length of 160 m. The thickness of the new outer walls (0.3 m) has been subtracted from the 2.4 m length with a full cross-sectional area.
Waste disposal area		
Original concrete structure		
Length outer (m)	139.85	Calculated from values (174.650 + 0.400 − 35.200) given in drawings 1-1009702, 1-1009703
Width outer (m)	15.62	Calculated from values given in drawing 1-1009703 (0.4 + 0.4 + 14.82 ± 0.03 m)
Height outer wall (m) (above slab)	8.2	Standing on slab. Calculated from values given in Figure 5-2 (8.9 − 0.25 − 0.15 − 0.3)
Prefabricated concrete element (reinforced) (m)	0.4	Value given in drawing 1BMA_ny_04-03_TR1402_13okt-01
Outer concrete lid (m)	0.5	Based on the difference between the height of the inner and outer walls (above slab) (8.2 − 7.3)
Thickness outer walls (reinforced) (m)	0.4	Value given in drawings 1-1009702 and 1-1009703
Thickness outer wall facing inner zone at tunnel TT (reinforced) (m)	0.4	Value given in drawing 1-1009702
Thickness outer wall facing reloading zone at tunnel BST (reinforced) (m)	0.6	Value given in drawing 1-1009703
Concrete slab (reinforced) (m)	0.25	Value given in drawing 1-1009727, 1-1009728. The slab also has beams below the walls and in the middle, the height of the beams below the outer side walls increases with the depth of the ditches of the vault. The other beams are 0.15 m.
Additional reinforced external concrete walls		
Length outer (m)	140.45	Length of the concrete structure plus the thickness of the barrier (139.85 + 2 × 0.3)
Width outer (m)	16.22	Width of the concrete structure plus the additional barrier (15.62 + 2 × 0.3)
Height (m)	8.9	Based on the dimensions in Figure 4-3, 9.2 − 0.3 m
Thickness wall (m)	0.3	Shown in Figure 5-2. Based on Elfwing et al. (2018)
Thickness of concrete over the prefabricated and outer lids** (m)	0.3	Shown in Figure 5-2. Based on Elfwing et al. (2018)

Table 5-1. Continued.

1BMA property	Value	Comment*
13 large storage compartments		
Length inner (m)	9.9	Value given in drawings 1-1009702 and 1-1009703 (9.90 ± 0.03 m)
Width inner (m)	14.82	Value given in drawings 1-1009702 and 1-1009703 (14.82 ± 0.03 m)
Height inner walls (m)	7.3	Calculated from values given in drawing 1-1009706 (422.32−415.02)
Thickness inner walls (reinforced) (m)	0.4	Value given in drawings 1-1009702 and 1-1009703
2 small storage compartments		
Length inner (m)	4.95	Value given in drawing 1-1009703 (4.95 ± 0.03 m)
Width inner (m)	7.21	Value 7.210 given in drawing 1-1009703 (thickness inner wall 0.4 m)
Height inner (m)	7.3	Calculated from values given in drawing 1-1009706 (422.32−415.02)
Bottom		
Macadam thickness (m)	0.15	Value given in drawing 1-1009727, 1-1009728
Rock fill thickness (m)	0.3	Min value given in drawing 1-1009727
Coarse concrete below beams height (m)	0.3	Typical value, given in drawings 1-1009727, 1-1009728
Reloading zone (at tunnel BST)		
Length (m) (outside concrete wall)	14.9	Calculated from the values above (160 − 2.1 − 2.55 − 139.85 − 2 × 0.3)

* Drawing numbers in column “Comment” refer to SKB’s internal documents.

** In reality, the outer lid assigned to the existing 1BMA structure and the concrete of the new barrier over the outer lid is one thickness of concrete that will be cast at one time, 0.8 m thick.

6 2BMA

6.1 Design

The 2BMA vault will be built for the disposal of intermediate-level waste, conditioned in concrete or cement, as part of the planned extension of SFR, see Figure 6-1. A new design and construction method has been developed for the new vault, in response to experience with the existing vault for intermediate-level waste, 1BMA (Elfwing et al. 2017). The main features are as follows:

- 13 free-standing, unreinforced concrete caissons with a base of 18.12 × 18.12 m and a height of 9 m are to be built in the waste vault.
- The vault will be constructed as a hydraulic cage and therefore a 1 m thick layer of macadam will be placed on the vault floor.
- A concrete slab will be cast on top of the macadam, and this will be nearly as long as the vault itself. The concrete slab will not have any other external supporting structures.
- A concrete base for the overhead crane system will be built on each side of the concrete slab.
- Prefabricated inner walls will be placed inside each caisson (Figure 6-2).
- In order to reduce the risk of crack formation, the empty space between waste packages in the caissons will not be grouted. The outer and inner walls of the caissons will provide mechanical strength, limit advective flow and provide a large amount of hydrated cement for the sorption of radionuclides and for maintaining a high pH environment.
- The compartments will be covered with a 0.5 m thick concrete radiation shield once they have been filled with waste. Corrugated steel (0.04 m high) will then be placed on the radiation shield and a concrete lid will be cast. The corrugated steel will create unfilled horizontal channels between the radiation shield and the lid to allow gas to escape from the caissons. Six vertical channels 0.20 m wide, 0.25 m long and 0.64 m deep (Mårtensson et al. 2022) will also be created between an outer wall and the cast lid so that they connect with the horizontal gas release channels. The vertical channels will be filled to a certain depth with a porous grout, identical to the grout used in the silo. The depth and the hydraulic conductivity of the grout is chosen in a way that gas is released once a sufficient gas pressure has built up inside the caisson.

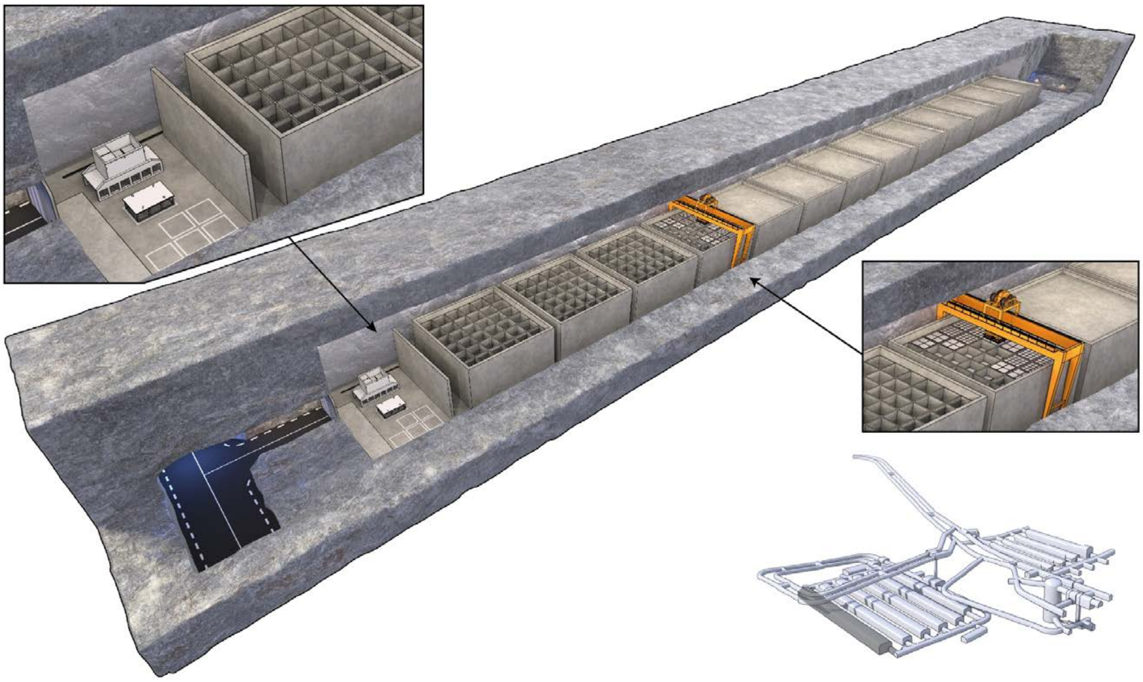

Figure 6-1. Illustration of 2BMA during the operational period. The lower detail show the emplacement and a view of SFR with the position of 2BMA in SFR highlighted.

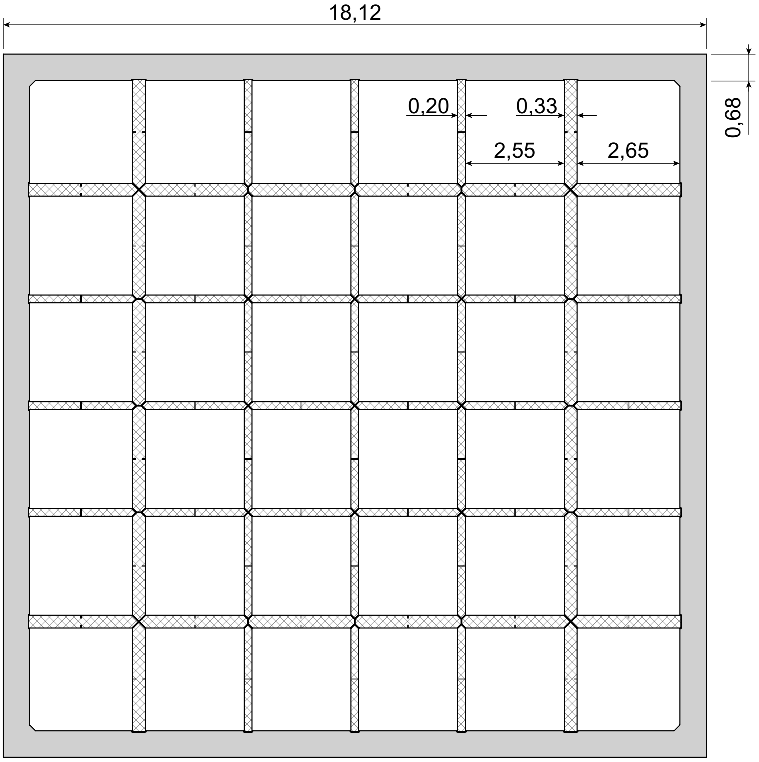

***Figure 6-2.** Illustration of the inner walls in the 2BMA caissons, as seen from above. Layout 2021.*

The walls and roof of the vault will be lined with shotcrete. The waste packages (mainly steel moulds and steel double moulds) will be emplaced using an overhead crane. The dimensions of the waste vault are given in Table 6-1, Figure 6-4 and Figure 6-5.

The closure plan for SFR describes measures for the sealing and closure of 2BMA (Mårtensson et al. 2022). The demolition and dismantling of existing systems, for example the ventilation and electricity, will comply with the closure sequence. The concrete lid will be cast to allow gas release, see Figure 6-3. The gas venting system consists of:

1. Horizontal (empty) discharge channels running along the border between the radiation shielding prefabricated concrete elements and the more compact overcast.
2. Vertical gas discharge channels filled with porous cement mortar emplaced along an outer wall (and which penetrate the cast lid). In the present design, six vertical gas discharge channels for each caisson are to be built, each with a cross section of 0.20 m × 0.25 m. The gas venting system is designed so that the structural integrity of the concrete structure is not affected.

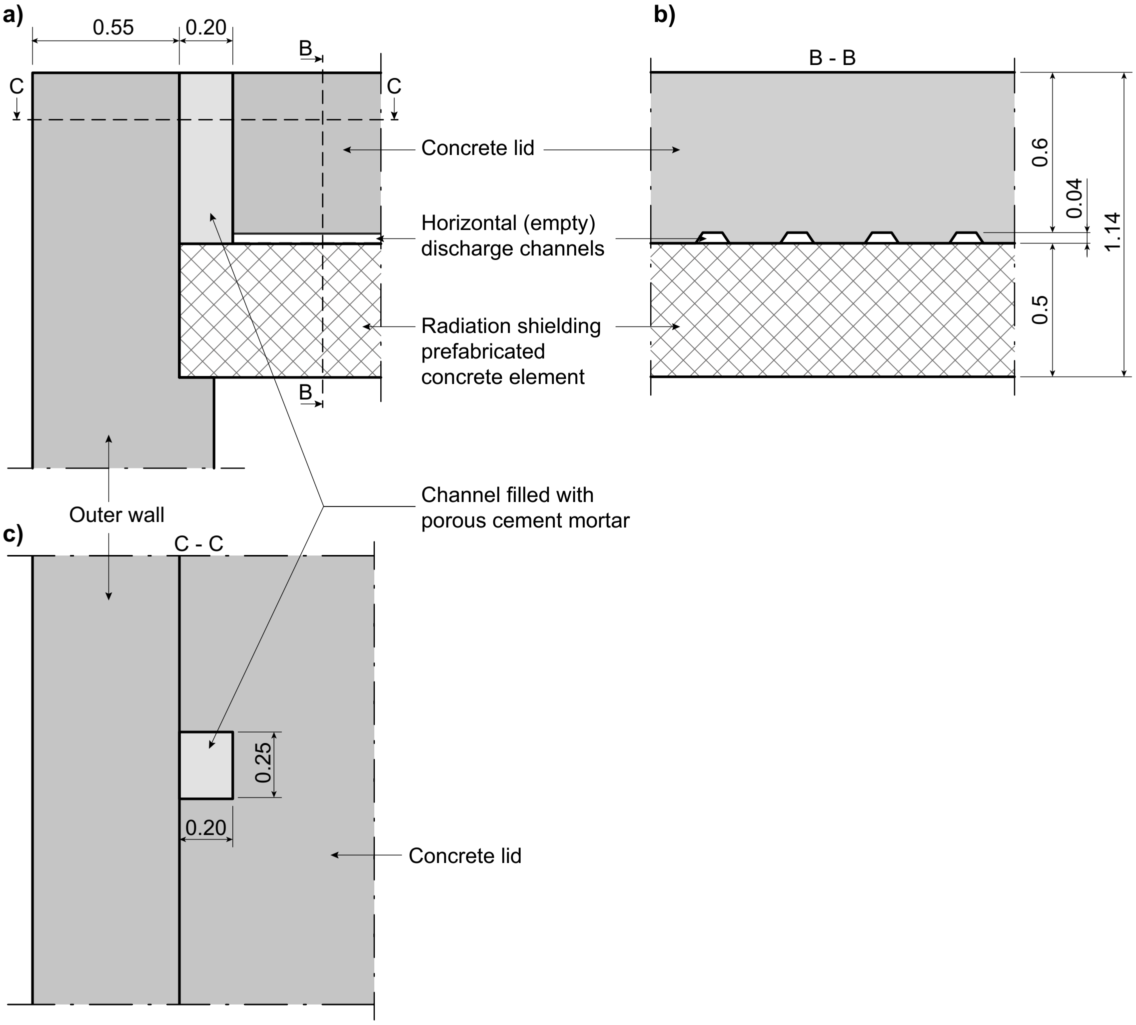

***Figure 6-3.** Schematic illustration of the planned gas venting system in 2BMA (units in m). a) Cross section of the whole system. b) Cross section showing horizontal (empty) discharge channels. c) Vertical discharge channels filled with porous cement mortar, seen from above.*

Equipment and installations in the waste vault are removed and the space between caissons, as well as between caissons and the rock wall, is backfilled with macadam. The geometry of the waste vault is such that concrete plugs can be installed at both ends of the waste vault as mechanical constraints for the bentonite in connecting tunnels.

The empty space in the 2BMA vault will be backfilled with macadam to 1 m (or less if possible) below the ceiling of the vault, see Figure 6-4. Concrete mechanical constraints will be installed at both ends of the waste vault, as part of the plugs. Although it is not specified in the closure plan, the concrete structures used in the reloading zone during the operational period are expected to be demolished during closure and left in the vault. The base of the overhead crane system is also expected to be left in the vault.

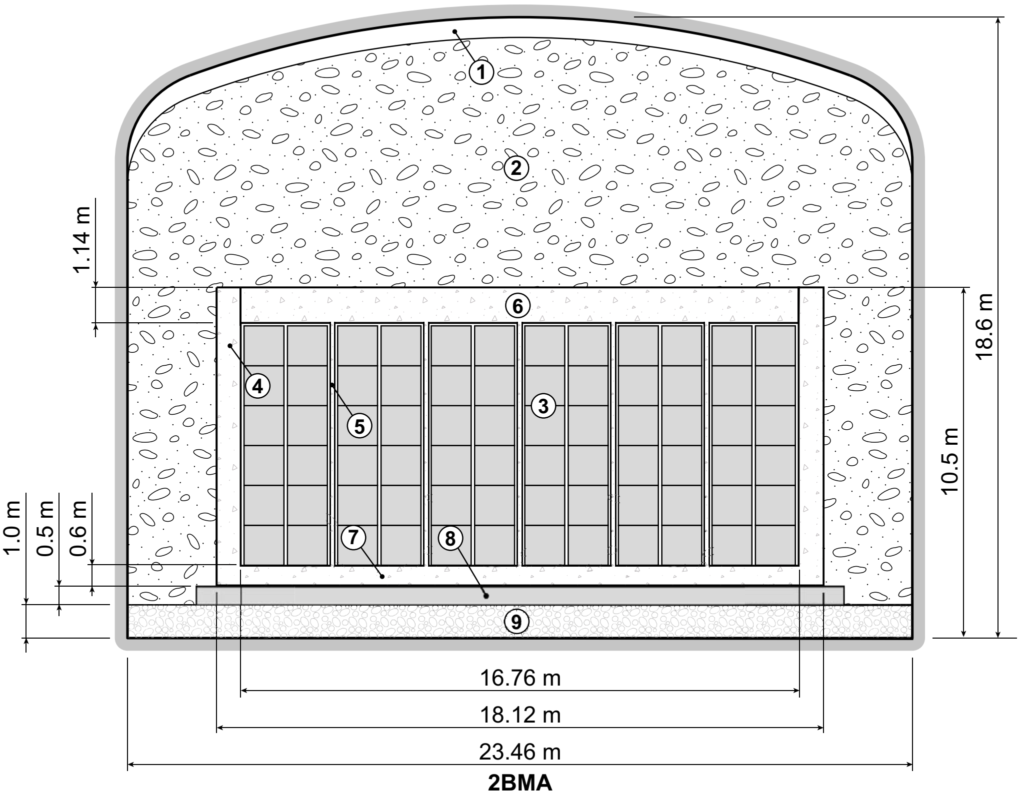

Figure 6-4. *Schematic cross-section of 2BMA after closure. Note that the figure shows Layout 2021 while the dimensions used in the post-closure safety analysis are from Layout 2020. In Table 6-1 dimensions are given for both layouts. Key to numbering: 1) Void 2) Macadam backfill 3) Waste domain 4) Outer wall 5) Inner wall 6) Lid 7) Caisson slab 8) Slab 9) Crushed rock.*

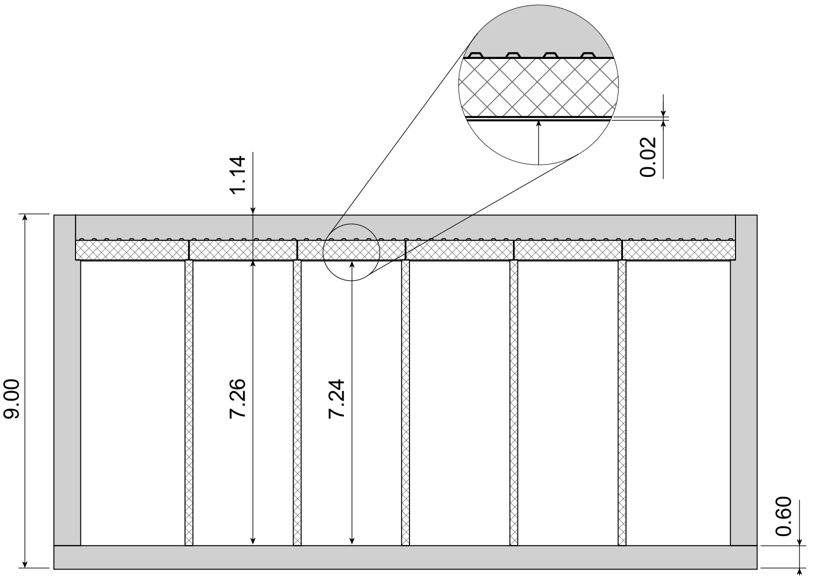

Figure 6-5. *Schematic cross-section of the inner walls in 2BMA. Layout 2021.*

6.2 Design considerations

The new design suggested for 2BMA was developed in response to experience with the existing vault for intermediate-level waste, 1BMA.

Safety features considered for the surrounding rock

The depth of 2BMA (~ 120 m) provides favourable anoxic redox conditions, mechanical stability of the rock and low groundwater flow.

Safety features considered for the system components in 2BMA

Level of radioactivity – The total radioactivity in 2BMA is of the same order of magnitude as in 1BMA, and is lower than in the silo, see Section 3.7. The most important radiological safety principle is the limited level of radioactivity in the waste packages. The waste consists mainly of concrete-embedded trash and scrap metal from decommissioning, see Section 3.6.4. The acceptance criteria for the waste packages are expected to be similar to those for 1BMA.

The criteria relating to the level of radioactivity and waste package design, together with the design of the system components in 2BMA, will provide radiation protection during the operational period and enhance post-closure safety.

Limited advective transport – In 2BMA, the hydraulic contrast between the permeable macadam backfill surrounding the concrete caissons and the less permeable concrete caissons will divert water flow away from the caissons to the more permeable surrounding materials. In addition, any flow within the caissons will occur preferentially in the void space between the waste packages and inner walls, further limiting flow through the waste packages.

The inflow of water to 2BMA from connecting tunnels will be limited by the plugs that will be constructed at both ends of the waste vault, see Section 11.1.

Mechanical stability – The post-closure stability of the waste vault and the integrity of concrete caissons (for example against rock fallout) is enhanced by the inner walls of the caissons and the macadam backfill around and on top of the caissons.

The gas release channels created between radiation shield and lid, and walls and lid of the caissons will allow gas produced inside the caissons to escape. The depth of the permeable grout in the vertical gas release channels along with the hydraulic conductivity of the material will control the maximum pressure that can accumulate in the caissons.

Limited dissolution – The concentration of some radionuclides, such as Ni-63 and Ni-59, will be within the range of their solubility limits. The release of radionuclides present as induced activity in metal will be determined by the corrosion rate of the metal.

Sorption – The vast majority of radionuclides released from the waste packages will be retained by sorption to the inner concrete walls, the concrete caisson structure and the macadam backfill outside the caissons. The amount of cellulose in the waste will be limited to such an extent that sorption will not be affected by degradation products e.g. ISA.

Favourable water chemistry – The chemistry of the water in the waste vault will be influenced by the chemical composition of intruding groundwater and the large amounts of cementitious materials in waste packages, caisson structures and inner walls of the caissons. Geochemically reducing conditions will also be established soon after closure of the vault due to metal corrosion and microbial degradation processes. Overall, the alkaline, anoxic environment that will be created is favourable for the sorption of many long-lived radionuclides e.g. technetium and some actinides, and will limit the rates of corrosion and microbial degradation processes.

6.3 Inspection and control of 2BMA

The inspection and control of 2BMA will take place in the following three steps.

- Control and inspection of the concrete caissons in the waste vault during construction.
- Control and inspection of the caissons and conditions in the waste vault during the emplacement of waste – the operational period.
- Final inspection of the waste vault and concrete caissons before casting the lids, backfilling with macadam and closure with plugs.

Specific requirements relating to the supply of materials and control and inspection will be defined during the detailed planning of the waste vault design. For the construction of the caissons, requirements are expected to be defined relating to e.g. personnel, controls when receiving material(s), casting methods and controls, methods for the inspection and control of cast caissons, and documentation. In addition, programmes will be defined for control and maintenance to ensure that the required initial conditions of the concrete caissons can be achieved at repository closure.

6.4 Uncertainties

Experience from the construction of 1BMA has been used to develop the design for 2BMA and avoid potential problems causing additional uncertainties. Specifically, the use of concrete reinforcement is omitted to avoid adverse effects of steel corrosion during the operational period on post-closure barrier performance.

For the 2BMA concrete structure, controls and inspections are undertaken during the construction, operation and before backfilling to ensure requirements are met. The inspections and controls are to ensure an adequate knowledge of the achieved initial state of the waste vaults, which reduces uncertainties.

A large-scale test of casting a caisson has been performed at the Äspö Hard rock Laboratory (Mårtensson and Vogt 2019, 2020). The results support the feasibility to construct the 2BMA concrete structures according to the proposed initial state, which reduces the uncertainties. Additional uncertainty reduction will be achieved by further development of the caissons and the method for construction, including verifying tests.

6.5 2BMA dimensions and material quantities

The main dimensions of the waste vault 2BMA are given in Table 6-1. The estimated volumes of different materials in the waste vault after closure are given in Table A-4 in Appendix A. The total void in the vault including void and porosities in the materials are also given in Table A-4 in Appendix A.

Table 6-1. 2BMA dimensions.

2BMA property	Value Layout 2020	Value Layout 2021	Comment[*]
Excavated rock cavity			
Total length (m)	275	275	Layout 2020: 3-D model (Berg), SKBdoc 1932070 ver 1.0 200611, Layout 2021: Systemhandling, SKBdoc 1858600 ver 4.0, Table 7-2
Width (m)	23.5	23.46	Layout 2020: 3-D model (Berg), SKBdoc 1932070 ver 1.0 200611, Layout 2021: Systemhandling, SKBdoc 1858600 ver 4.0, Table 7-2
Vertical cross sectional area (m^2)	418	414	Layout 2020: 3-D model (Berg), SKBdoc 1932070 ver 1.0 200611, Layout 2021: Systemhandling, SKBdoc 1858600 ver 4.0, Table 7-2
Height max (m)	18.8	18.6	Layout 2020: 3-D model (Berg), SKBdoc 1932070 ver 1.0 200611, Layout 2021: Systemhandling, SKBdoc 1858600 ver 4.0, Table 7-2
Height average (m)	17.8	17.6	Layout 2020: Calculated 418/23.5, Layout 2021: Calculated 414/23.46
Excavated volume (m^3)	114 950	113 850	Layout 2020: Calculated 275 × 418, Layout 2021: Calculated 275 × 414
Shotcrete thickness (m)	0.3	0.3	[9] (Figure 7-11)
Inner zone (at tunnel 2TT)			
Length (m)	2	2	Layout 2020[a], Layout 2021[b]
Waste disposal area			
Length outer (m)	253.56	253.56	Calculated number of caissons × width of a caisson + (number of caissons − 1) × distance between caissons. calculated 13 × 18.12 + (13 − 1) × 1.5 (SKBdoc 1939921 ver 1.0)
Concrete structures			
Bottom plate length (m)	274.4	274.4	Layout 2020[a], Layout 2021[b]
Bottom plate thickness (m)	0.5	0.5	Layout 2020[a], Layout 2021[b]
Bottom plate width (m)	18.25	18.25	Layout 2020[a], Layout 2021[b]
Bottom plate volume (m^3)	2 504	2 504	Calculated 274.4 x 0.5 x 18.25
Number of caissons	13	13	Layout 2020[a], Layout 2021[b]
Distance between caissons (m)	1.5	1.5	Layout 2020[a], Layout 2021[b]
Caisson width outer (m)	18.12	18.12	Layout 2020[a], Layout 2021[b]
Caisson height outer (walls + bottom) (m)	9.0	9.0	Layout 2020[a], Layout 2021[b]
Outer volume of 1 caisson (m^3)	2 955	2 955	Calculated 18.12 × 18.12 × 9.0
Caisson concrete lid thickness (m) (including radiation shield)	1.14	1.14	Layout 2020[a], Layout 2021[b]
13 caissons concrete lid volume (total including radiation shield) (m^3)	4 140	4 140	Layout 2020[a], Layout 2021[b]

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[9] Glamheden R, 2018. Systemhandling 2.0, SFR utbyggnad, Kapitel 2, Berg. SKBdoc 1667619 ver 1.0, Svensk Kärnbränslehantering AB. In Swedish (Internal document).

Table 6-1. Continued.

2BMA property	Value Layout 2020	Value Layout 2021	Comment*
Caisson outer wall thickness (m)	0.68	0.68	Layout 2020[a], Layout 2021[b]
13 caissons outer wall volume (total) (m^3)	5180	5180	Layout 2020[a], Layout 2021[b]
Caisson concrete slab thickness (m)	0.6	0.6	Layout 2020[a], Layout 2021[b]
13 caissons concrete slab volume (total) (m^3)	2561	2561	Layout 2020[a], Layout 2021[b]
13 caissons inner walls volume (total) (m^3)	3834	3834	Layout 2020[a], Layout 2021[b]
Height inner (m)	7.24	7.24	Layout 2020[a], Layout 2021[b]
Concrete crane support (m^3)	195.8	195.8	Layout 2020[a], Layout 2021[b]
Concrete hangarport (at 2TT) volume (m^3)	11.66	13	Layout 2020[a], Layout 2021[b]
Radiation shield (at 2TT) volume (m^3)	88.6	93	Layout 2020[a], Layout 2021[b]
Concrete gate (at 2TT)		32	Layout 2021[b]
Concrete gate roof volume (m^3)	10.58		Layout 2020[a]
Concrete gate walls volume (m^3)	23.4		Layout 2020[a]
Concrete walls at (2BST)		17	Layout 2021[b]
Bottom			
Macadam/Rock fill thickness (m)	1	1	Layout 2020[a], Layout 2021[b]
Reloading zone (at tunnel 2BST)			
Length (m)	19.44	19.44	Calculated 275 − 2 − 253.56

* Drawing numbers in column “Comment” refer to SKB’s internal documents.

[a] Layout 2020 (2020-05-30): 3-D model SKBdoc 1939922 ver 1.0.

[b] Layout 2021 (2020-12-11): 3-D model SKBdoc 1939921 ver 1.0.

7 1BRT

7.1 Design

As part of the planned extension of SFR, a vault will be built primarily for ten reactor pressure vessels (RPV). The pressure vessels will be cut into segments, placed in double moulds and stabilised with concrete (Section 3.6.5).

The rock walls and the roof of the waste vault will be lined with shotcrete and a concrete slab will be cast on a macadam layer. The concrete slab is designed to bear the load from a transport vehicle, the structural concrete and waste. A reinforced concrete structure will then be cast. One part of the concrete structure is intended for disposal of the double moulds and will be divided into compartments by inner walls, see Figure 7-1. The other part is intended as a flexible zone for the disposal of waste packages of different dimensions. Therefore, inner walls will be added between the waste packages as the space is filled. The structural concrete acts as a radiation shield during the operational period and is part of the engineered barrier after closure.

The double moulds will be positioned in the compartments using a remote-controlled overhead crane that is supported outside the concrete structure, see Figure 7-1. Waste will be transported into the flexible zone by truck. The space between the waste packages will be filled with self-compacting concrete so that a network of load-bearing structures is formed. When a compartment is full, a reinforced concrete lid will be cast on top of the pre-fabricated concrete elements that are placed over the compartment.

The dimensions of the 1BRT vault are larger than given in SKB (TR-14-02) to account for the inclusion of a concrete structure in the vault. Furthermore, the waste will now be transported into the vault via 2BST and the vault will drain into 2BST. The dimensions of the waste vault are given in Table 7-1 and Figure 7-2.

The demolition and dismantling of existing systems, for example the ventilation and electricity, will be adapted to the closure sequence. The closure plan for SFR describes measures for the sealing and closure of 1BRT (Mårtensson et al. 2022). The space between the concrete structure and the rock walls and roof is planned to be backfilled with macadam. The waste vault will be sealed at both ends by plugs, see Section 11.1.

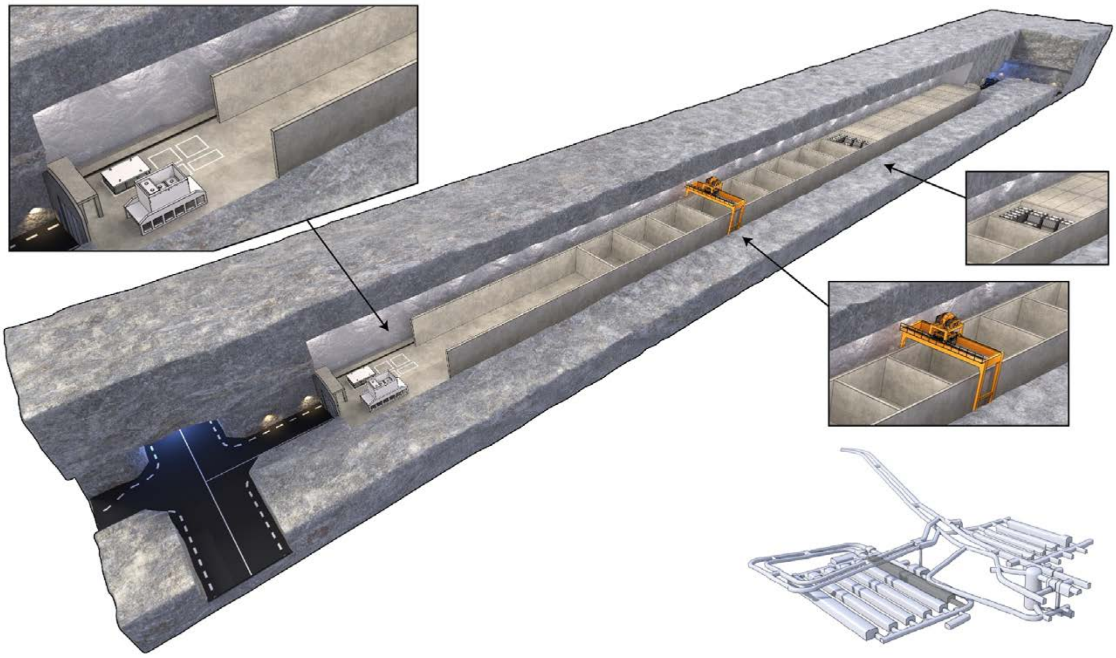

Figure 7-1. *Illustration of 1BRT during the operational period. The lower detail shows SFR with the position of 1BRT in darker grey.*

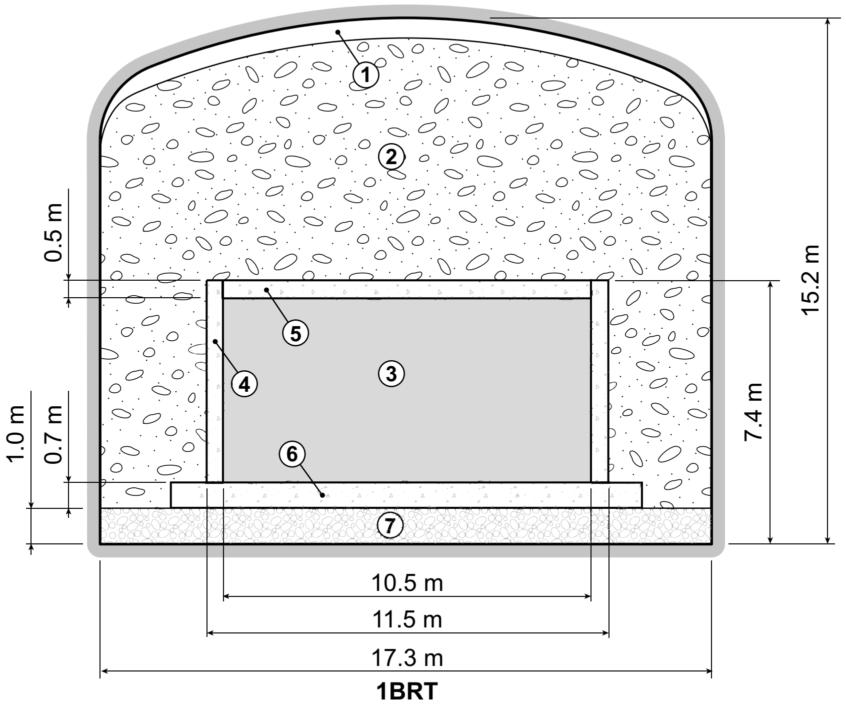

Figure 7-2. *Schematic cross-section of 1BRT during the operational period. Note that the figure shows Layout 2021 while the dimensions used in the post-closure safety analysis are from Layout 2020. In Table 7-1 dimensions are given for both layouts. Key to numbering: 1) Void 2) Macadam backfill 3) Waste domain 4) Outer wall 5) Lid 6) Slab 7) Crushed rock.*

7.2 Design considerations

The suggested design for the waste vault 1BRT embeds the moulds containing parts of the reactor pressure vessels in concrete and grout to ensure a low corrosion rate.

Safety features considered for the surrounding rock

The depth of 1BRT (~ 120 m) results in favourable conditions with respect to mechanical stability of the rock, low groundwater flow and anoxic redox conditions.

Safety features considered for the system components in 1BRT

Level of radioactivity – The most important radiological safety principle for 1BRT is the limited level of radioactivity in the waste. The pressure vessels will be cut into segments, placed in double moulds and stabilised with concrete, see Section 3.6.5. The acceptance criteria for the waste are given in Section 3.1.

Limited advective transport – The plugs in the end of the vault should limit the inflow of water from the tunnel system, see Section 11.1. In addition, the hydraulic contrast between the permeable macadam backfill and the less permeable concrete structure will divert water flow away from the waste.

Mechanical stability – The post-closure stability of the waste vault (for example stability against rock fallout) is enhanced by the concrete structure, the grouting around the waste packages and the macadam backfill of the waste vault.

Limited dissolution – The concentration of some radionuclides, such as Ni-63 and Ni-59, will be within the range of their solubility limits. The release of radionuclides present as induced activity in the vessels will be determined by the corrosion rate of the metal.

Sorption – Radionuclides released from the vessels will be retained by sorption to the cementitious materials inside and around the waste packages, the concrete of the structure, and the macadam backfill.

Favourable water chemistry – The water chemistry in the waste vault will be influenced by the large amounts of cementitious materials in the waste vault. The resulting alkaline environment will limit the rates of corrosion and thereby also the release of induced radioactivity.

In addition, the creation of reducing conditions in the vault caused by the consumption of oxygen by mainly metal corrosion favours the sorption of many radionuclides e.g. technetium and some actinides.

7.3 Inspection and control of 1BRT

The inspection and control of 1BRT can be divided into the following three steps.

- Control and inspection of concrete structures in the waste vault during construction.
- Control and inspection of conditions in the waste vault during the emplacement of waste and grouting – the operational period.
- Final inspection of the waste vault and concrete structures before backfilling with macadam and closure with plugs.

7.4 Uncertainties

No specific requirements on the hydraulic properties of the concrete barrier have been stipulated. A pessimistic strategy has been used in the radionuclide transport calculations main scenario to handle the uncertainty.

7.5 1BRT dimensions and material quantities

The main dimensions of the waste vault 1BRT are given in Table 7-1.

The estimated volumes of different materials in the waste vault after closure are given in Table A-5 in Appendix A. The total void in the vault including void and porosities in the materials are also given in Table A-5 in Appendix A.

Table 7-1. 1BRT dimensions.

BRT property	Value Layout 2020	Value Layout 2021	Comment*
Excavated rock cavity			
Total length (m)	255	255	Layout 2020: 3-D model (Berg), SKBdoc 1932070 ver 1.0 200611, Layout 2021: Systemhandling, SKBdoc 1858600 ver 4.0, Table 7-2
Width (m)	17.7	17.3	Layout 2020: 3-D model (Berg), SKBdoc 1932070 ver 1.0 200611, Layout 2021: Systemhandling, SKBdoc 1858600 ver 4.0, Table 7-2
Height max (m)	15.2	15.2	Layout 2020: 3-D model (Berg), SKBdoc 1932070 ver 1.0 200611, Layout 2021: Systemhandling, SKBdoc 1858600 ver 4.0, Table 7-2
Height average (m)	14.5	14.5	Layout 2020: Calculated (256/17.7) Layout 2021: Calculated (251/17.3)
Vertical cross-sectional area (m^2)	256	251	Layout 2020: 3-D model (Berg), SKBdoc 1932070 ver 1.0 200611, Layout 2021: Systemhandling, SKBdoc 1858600 ver 4.0, Table 7-2
Excavated volume (m^3)	65 280	64 005	Layout 2020: Calculated 255 × 256 Layout 2021: Calculated 255 × 251
Shotcrete thickness (m)	0.3	0.3	Pettersson (2017, Figure 3-1); [9] (Figure 7-9)

Table 7-1. Continued.

BRT property	Value Layout 2020	Value Layout 2021	Comment*
Inner zone (at tunnel TT)			
Length (m)	10.0	10.0	Layout 2020[a], Layout 2021[b]
Concrete structure			
Concrete slab			
Concrete slab volume (reinforced) (m^3)	2 190	2 190	Layout 2020[a], Layout 2021[b]
Concrete slab thickness (m)	0.7	0.7	Layout 2020[a], Layout 2021[b]
Concrete slab width (m)	12.3	12.3	Layout 2020[a], Layout 2021[b]
Concrete slab length (m)	254.4	254.4	Layout 2020[a], Layout 2021[b]
Walls and lid			
Length outer (m)	224.4	224	Layout 2020[a], Layout 2021[b]
Width outer (m)	11.5	11.5	Layout 2020[a], Layout 2021[b]
Height outer wall (m) (above slab)	5.7	5.7	Layout 2020[a], Layout 2021[b]
Concrete lid thickness (m)	0.5	0.5	Layout 2020[a], Layout 2021[b]
Thickness outer walls (reinforced) (m)	0.5	0.5	Layout 2020[a], Layout 2021[b]
Thickness outer wall facing inner zone at tunnel TT (reinforced) (m)	0.5	0.5	Layout 2020[a], Layout 2021[b]
Thickness outer wall facing reloading zone at tunnel BST (reinforced) (m)	0.5	0.5	Layout 2020[a], Layout 2021[b]
Storage compartments			
Number of small storage compartments	1	1	Layout 2020[a], Layout 2021[b]
Number of large storage compartments	20	20	Layout 2020[a], Layout 2021[b]
Small compartment inner length (m)	4.62**	4.11	Layout 2020[a], Layout 2021[b]
Large compartment inner length (m)	10.5	10.5	Layout 2020[a], Layout 2021[b]
Width inner (m)	10.5	10.5	Layout 2020[a], Layout 2021[b]
Height inner walls (m)	5.2	5.2	Layout 2020[a], Layout 2021[b]
Thickness inner walls (reinforced) (m)	0.5	0.5	Layout 2020[a], Layout 2021[b]
Other structures			
Concrete crane support (m^3)	226.5	226.5	Layout 2020[a], Layout 2021[b]
Radiation shield (at 2TT) volume (m^3)		18	Layout 2020[a]: not reported, Layout 2021[b]
Concrete hangarport (at 2TT) volume (in) (m^3)		13	Layout 2020[a]: not reported, Layout 2021[b]
Concrete gate incl roof (at 2TT) volume (m^3)		30	Layout 2020[a]: not reported, Layout 2021[b]
Concrete walls (at 2BST) volume (m^3)		17	Layout 2020[a]: not reported, Layout 2021[b]
Bottom			
Macadam/Rock filllid thickness (m)	1	1	Layout 2020[a], Layout 2021[b]
Reloading zone (at 2BST)			
Length (m) (outside concrete wall)	20.6	20.6	Calculated (255-10-224.4)

* Drawing numbers in column “Comment” refer to SKB’s internal documents.

** Part of the compartment is 4.62 m, but most of it is 4.11 m.

[a] Layout 2020 (2020-05-30): 3-D model SKBdoc 1939922 ver 1.0.

[b] Layout 2021 (2020-12-11): 3-D model SKBdoc 1939921 ver 1.0.

8 1BTF and 2BTF

8.1 Design

The vaults for concrete tanks, 1BTF and 2BTF, are primarily designed for storing concrete tanks and drums with low to medium radioactivity. The walls and roofs of the two vaults are lined with shotcrete. The concrete slab is cast on a drained foundation and the slab is finished with a 1 m high moulded skirting to divert possible leaking water. The skirting is shown in a detail in Figure 8-1. In addition, a number of concrete pillars are cast to divide the vault into sections to facilitate future grouting of the waste vault.

In 1BTF, disposal sections for the emplacement of steel drums with ash are built by using concrete tanks as the outer walls and concrete moulds with low activity content and low surface dose rate as the inner walls. The steel drums consist of drums placed in larger drums (Section 3.6.6), and the space between the inner and outer drum is filled with concrete. When six rows of drums have been piled, the supporting inner wall is mounted and prefabricated reinforced concrete elements are placed on top of the tanks, see Figure 8-1. Before closure, the section is grouted, and another concrete lid is cast on top. In the vault, there will be about eight sections with drums and the remaining disposal volume, more than 50 %, will be used for concrete tanks in the same way as in 2BTF.

In 2BTF, mainly reinforced concrete tanks will be stored; four abreast and two in height. The concrete tanks are emplaced by a truck on the slab, after which prefabricated concrete elements are placed on top as radiation shielding, see Figure 8-2. The waste in 2BTF is not conditioned (Section 3.6.7).

The dimensions of the waste vaults 1BTF and 2BTF are given in Table 8-1 and Table 8-2, respectively, and in Figure 8-3.

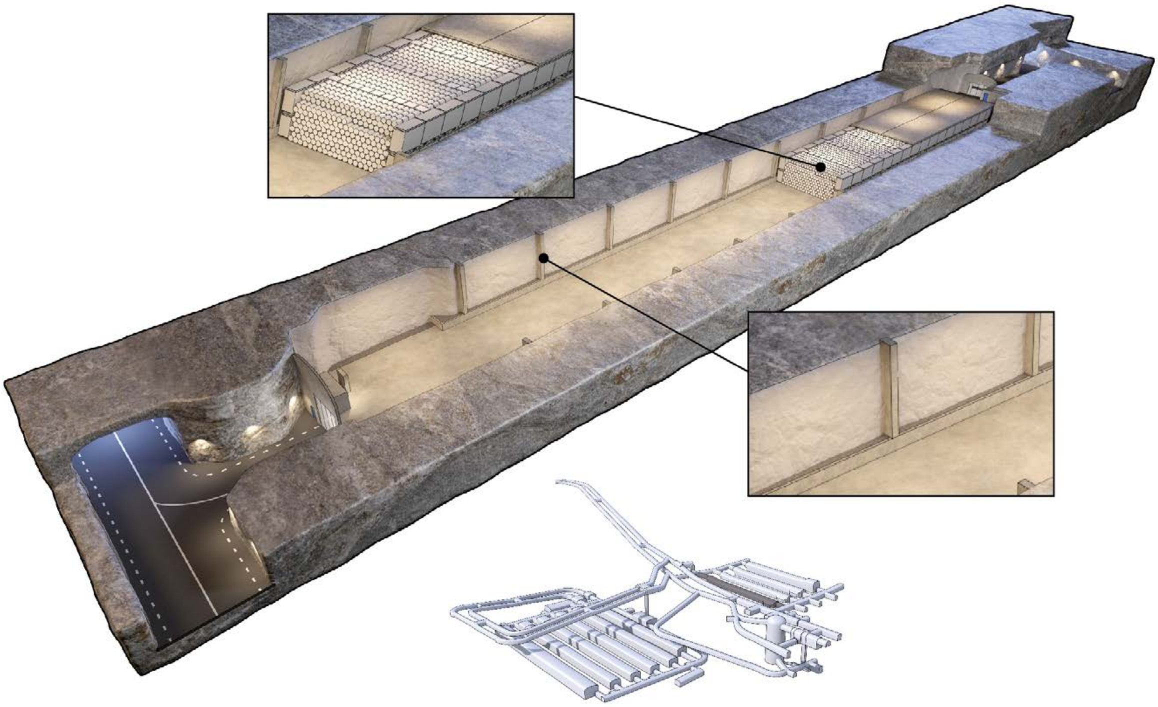

__Figure 8-1.__ Illustration of 1BTF during the operational period. The upper detail shows the emplacement of the ash drums between concrete tanks, the lower detail shows the skirting and concrete pillars. In addition, there is a view of SFR with the position of 1BTF highlighted.

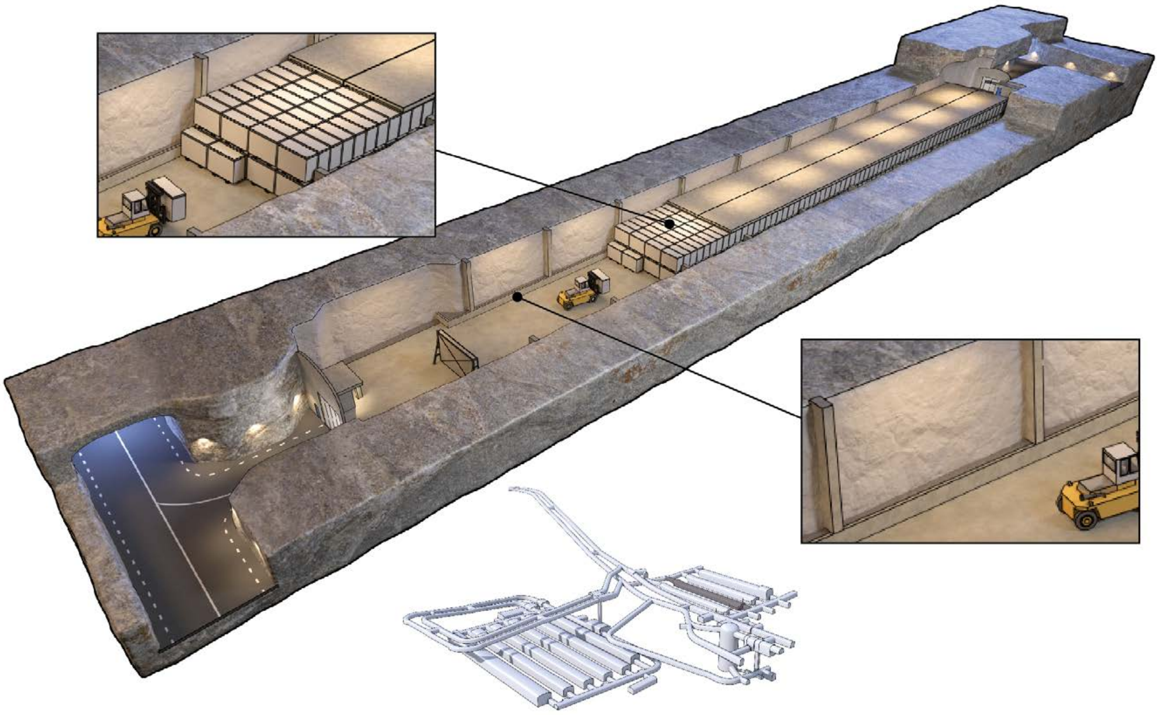

Figure 8-2. Illustration of 2BTF during the operational period. The upper detail shows the emplacement of concrete tanks, the lower detail shows the skirting and concrete pillars. In addition, there is a view of SFR with the position of 2BTF highlighted.

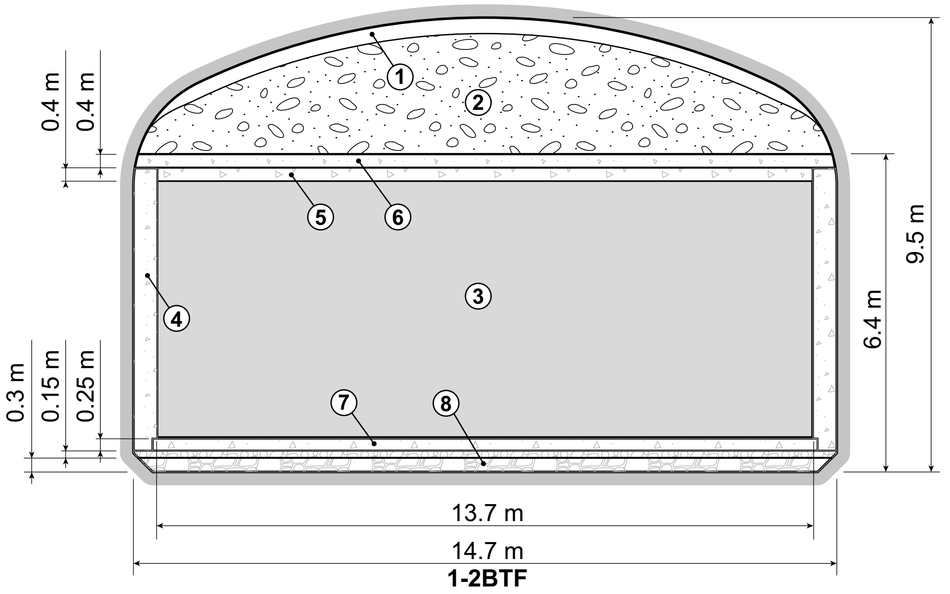

Figure 8-3. Schematic cross section of 1BTF and 2BTF after closure. The dimensions of 1BTF and 2BTF are given in detail in Tables 8-1 and 8-2, respectively. Key to numbering: 1) Void 2) Macadam backfill 3) Waste domain 4) Cementitious backfill 5) Pre-fabricated concrete elements 6) Cast concrete lid 7) Slab 8) Crushed rock (0.3 + 0.15 m).

The demolition and dismantling of existing systems, for example the ventilation and electricity, will be adapted to the closure sequence. The closure plan for SFR describes measures for the sealing and closure of 1BTF and 2BTF (Mårtensson et al. 2022). In both waste vaults the space between the outer concrete tanks and the rock walls will be filled with cementitious backfill.

In 2BTF, which will predominantly contain concrete tanks, the spaces between the concrete tanks will be filled with grout and a concrete slab will be cast on top of the prefabricated concrete elements to bear the weight of the macadam. In 1BTF, the ash drums in the inner half of the waste vault are grouted during the operational period, and the outer half, which only contains concrete tanks, will be grouted in the same way as in 2BTF near closure. Finally, the space above the grout and the concrete slab will be filled with macadam up to the ceiling, see Figure 8-3.

At the end of the vault that connects to the transverse tunnel (1TT), a concrete mechanical constraint will be installed as part of the plug. It is not possible to install a concrete mechanical constraint where the vault connects to the waste vault tunnel (BST); instead, here the mechanical constraint for the bentonite in the plug consists of a section with transition material and backfill material in the waste vault. The tunnels outside the vaults will be backfilled with bentonite.

8.2 Design considerations

Safety features considered for the surrounding rock

The location of 1BTF and 2BTF at a depth of about 70 m results in favourable conditions with respect to mechanical stability, low groundwater flow and anoxic redox conditions.

Safety features considered for the system components in 1BTF and 2BTF

Level of radioactivity – The most important radiological safety principle is the limited level of radioactivity in the waste packages. 1BTF and 2BTF contain a small proportion of the total radioactivity in SFR, see Section 3.7, and the activity concentration of the waste is relatively low. The waste in these waste vaults is mainly dewatered ion-exchange resins in concrete tanks. However, drums with ashes from incineration are also disposed in 1BTF, and concrete tanks and concrete moulds with low activity content are used as building components surrounding the piles of drums with ashes. The acceptance criteria for the waste packages are given in Section 3.1.

Limited advective transport – The flow through the waste packages will be limited. The plugs at the ends of the vaults should limit the inflow of water from the tunnel system, see Section 11.1. The water flow in the vault will be determined by the inflow to the waste vault from surrounding rock. In 1BTF and 2BTF the hydraulic contrast between the permeable macadam backfill and the less permeable stack of grouted waste packages will limit the flow through the waste.

In addition, the concrete tanks surrounding drums with ashes will limit the flow through the drums. As for all concrete packaging, the concrete will limit the flow through the waste form, i.e. the dewatered ion-exchange resins here.

Mechanical stability – The post-closure stability of the waste vault is enhanced by the cementitious grout between waste packages, the cementitious backfill between the waste packages and the rock wall, and the backfilling of the waste vault with macadam. In addition, the reinforced concrete-tank walls could further improve the mechanical stability.

Limited dissolution – The release of radionuclides from the dewatered ion-exchange resins and ashes is not considered to be limited by dissolution.

Sorption – The radionuclides released from the waste packages can be retarded by sorption mainly in concrete walls in tanks and moulds, cementitious grout surrounding the waste packages and secondarily on the macadam above the waste pile. In addition, for the drums containing ashes, radionuclides can be retarded by sorption in the concrete between the inner and outer drum.

Favourable water chemistry – The water chemistry in the waste vault will be influenced by the chemical composition of intruding groundwater and the large amounts of cementitious materials in waste packaging, concrete structures and cementitious grout. The resulting alkaline environment will limit the rates of corrosion and microbial degradation.

Reducing conditions will be established soon after closure of the vault due to metal corrosion and microbial degradation, which is favourable for the sorption of many radionuclides e.g. technetium and some actinides.

8.3 Inspection and control of 1BTF and 2BTF

The inspection and control of the waste vaults can be divided into the following three steps.

- Control and inspection of the concrete structures in the waste vault during construction.
- Control and inspection of conditions in the waste vault during emplacement of waste – the operational period.
- Final inspection of the waste vault and pile of waste packages before backfilling and closure with plugs.

8.4 Uncertainties

It has not yet been decided what type of grouting recipe will be used for grouting between the tanks and the space between tanks and rock walls in 1–2BTF at closure.

8.5 1BTF dimensions and material quantities

The main dimensions of 1BTF are given in Table 8-1. The excavated volume is 20 640 m^3 and the estimated volumes of different materials in the waste vault after closure are given in Table A-6 in Appendix A. The total void in the vault including void and porosities in the materials are also given in Table A-6 in Appendix A.

Table 8-1. 1BTF dimensions.

1BTF property	Value	Comment*
Excavated rock cavity		
Total length (m)	160	Calculated from values (120 + 40) given in drawing 1411-10020820
Width (m)	14.7	Value given in drawing 1411-10020820
Height (max) (m)	9.5	Value given in drawing 1411-10020820
Height (average) (m)	8.8	Calculated 129/14.7
Vertical cross-sectional area (m^2)	129	Value given in closure plan for SFR (Mårtensson et al. 2022)
Excavated volume (m^3)	20 640	Calculated 160 × 129
Shotcrete thickness (m)	0.05	From Carlsson and Christiansson (2007, Table 6-2), Un-reinforced 1 or 2 layers: 0.03 or 0.05 m Fibre reinforced: 0.05 or 0.08 m
Inner zone (at tunnel TT)		
Length (m) (between plug and concrete wall)	3.6	Value given in drawing 1411-10020820

Table 8-1. Continued.

1BTF property	Value	Comment*
Waste disposal area		
Concrete wall (reinforced) (m)	0.3	Calculated from values (180 − 3.6 − 176.1) given in drawings 1411-10020820 and 1440-10021840
Length where waste can be stored (m) (behind concrete wall)	130	Assumed value
Width outer (4 concrete tanks incl. tolerances) (m)	13.7	Calculated from values (2 × 6 840) given in drawing 1442-10111590
Height outer (2 concrete tanks incl. tolerances) (m)	4.9	Calculated from values (0.15 + 2.3 + 0.15 + 2.3) given in drawing 1440-10570770
Cast outer concrete lid (reinforced) (m)	0.4	Value given in closure plan for SFR (Mårtensson et al. 2022)
Prefabricated reinforced concrete element on concrete tanks and drums (inner lid) (m)	0.4	Assumed value. Based on values given in drawing 1442-10111600 (max 0.6, min 0.35 most of it 0.42 m)
Thickness of concrete grout between concrete tanks and rock wall (incl. concrete structures for drainage and stabilisation (m)	0.5	Calculated from values (14.7 − 13.7) / 2 given in drawings1411-10020820, 1442-10111590 and disposal of concrete tanks, see Section 3.6.6
Thickness supporting wall facing reloading zone (reinforced) (m)	0.3	Assumed same wall thickness as wall facing tunnel TT
Concrete slab (reinforced) (m)	0.25	Value given in drawing 1442-10153280
Bottom		
Macadam thickness (m)	0.15	Value given in drawing 1442-10153280
Rock fill thickness (m)	0.3	Value assumed from drawing 1442-10153280
Reloading zone (at tunnel BST)		
Length (m) (between outer supporting wall and plug)	25.8	Calculated from values given above: 160 − (3.6 (inner zone) + 2 × 0.3 (concrete wall)) − 130. Assumed same as 2BTF
1BTF disposal structure for drums		
Number of concrete tanks in outer “wall” in 1 section		
Height	2	See Section 3.6.6
Length	2	See Section 3.6.6
Number of concrete moulds in inner “wall”		
Height	4	See Section 3.6.6
Length	9	See Section 3.6.6
Number of drums in 1 section	1 110	6 rows with about 185 drums in each row, See Section 3.6.6
Total length (8 sections)	55.7	Assumed (1.3 + 2 × 8 × 3.3 + 2 × 8 × 0.1)
Height outer (2 concrete tanks incl. tolerances) (m)	4.9	Calculated from values (0.15 + 2.3 + 0.15 + 2.3) given in drawing 1440-10570770
Thickness outer “wall” (concrete tank) (m)	1.3	Inventory report (SKB R-18-07)
Thickness inner “wall” (concrete mould) (m)	1.2	Inventory report (SKB R-18-07)
Width inner (m)	11.1	Assumed (13.7 − 2 × 1.3)
Length inner (m)	5.6	Assumed (2 × 3.3 + 2 × 0.1 − 1.2)

* Drawing numbers in column “Comment” refer to SKB’s internal documents.

8.6 2BTF dimensions and material quantities

The main dimensions of 2BTF are given in Table 8-2. The excavated volume is 20 640 m^3 and the estimated volumes of different materials in the waste vault after closure are given in Table A-7 in Appendix A. The total void in the vault including void and porosities in the materials are also given in Table A-7 in Appendix A.

Table 8-2. 2BTF dimensions.

2BTF property	Value	Comment*
Excavated rock cavity		
Total length (m)	160	Calculated from values (120 + 40) given in drawing 1411-10020840
Width (m)	14.7	Value given in drawing 1411-10020840
Height (max) (m)	9.5	Value given in drawing 1411-10020840
Height (average) (m)	8.8	Calculated 129 / 14.7
Vertical cross-sectional area (m^2)	129	Value given in closure plan for SFR (Mårtensson et al. 2022)
Excavated volume (m^3)	20 640	Calculated 160 × 129
Shotcrete thickness (m)	0.05	From Carlsson and Christiansson (2007, Table 6-2), Un-reinforced 1 or 2 layers: 0.03 or 0.05 m Fibre reinforced: 0.05 or 0.08 m
Inner zone (at tunnel TT)		
Length (m) (between plug and concrete wall)	3.6	Value given in drawing 1411-10020840
Waste disposal area		
Concrete wall (reinforced) (m)	0.3	Assumed same as 1BTF
Length where waste can be stored (m) (behind concrete wall)	130	Assumed value
Width outer (4 concrete tanks incl. tolerances) (m)	13.7	Calculated from values (2 × 6 840) given in drawing 1442-10111590
Height outer (2 concrete tanks incl. tolerances) (m)	4.9	Calculated from values (0.15 + 2.3 + 0.15 + 2.3) given in drawing 1440-10570770
Cast outer concrete lid (reinforced) (m)	0.4	Value given in closure plan for SFR (Mårtensson et al. 2022)
Prefabricated reinforced concrete element on concrete tanks (inner lid) (m)	0.4	Assumed value. Based on values given in drawing 1442-10111600 (max 0.6, min 0.35 most of it 0.42 m)
Thickness of concrete grout between concrete tanks and rock wall (incl. concrete structures for drainage and stabilisation (m)	0.5	Calculated from values (14.7 − 13.7) / 2 given in 1411-10020840, 1442-10111590
Thickness supporting wall facing reloading zone (reinforced) (m)	0.3	Assumed same wall thickness as wall facing tunnel TT
Concrete slab (reinforced) (m)	0.25	Value given in drawing 1452-10153630
Bottom		
Macadam thickness (m)	0.15	Value given in drawing 1452-10153630
Rock fill thickness (m)	0.3	Value assumed from drawing 1452-10153630
Reloading zone (at tunnel BST)		
Length (m) (between outer supporting wall and plug)	25.8	Calculated from values given above: 160 − (3.6 (inner zone) + 2 × 0.3 (concrete wall)) − 130

* Drawing numbers in column “Comment” refer to SKB’s internal documents.

9 1BLA

9.1 Design

The waste vault for low-level waste, 1BLA, has a concrete slab cast on a drained foundation. The rock walls and the roof of the waste vault are lined with shotcrete. The waste packages are standard ISO-containers. A small fraction of the waste is conditioned in cement or bitumen. The containers are transported into 1BLA by forklift truck and stacked two abreast and three to six in height, depending on their size, see Figure 9-1. The dimensions of the waste vault are given in Table 9-1 and Figure 9-2.

The demolition and dismantling of existing systems, for example the ventilation and electricity, will be adapted to the closure sequence. The closure plan for SFR describes measures for the sealing and closure of 1BLA (Mårtensson et al. 2022). The ends of the vault will be plugged. A concrete wall will be installed at the end towards the transverse tunnel (1TT) and approximately 4 m will be backfilled with macadam, after which a concrete mechanical constraint will be cast as part of the plug. It is not possible to install a concrete mechanical constraint in the entrance to the waste vault tunnel (BST). Therefore, a retaining wall will be constructed 10 m from this end of the vault and the space will be backfilled with macadam to support the transition material mechanical constraint of the plug. The tunnels outside the vaults will be backfilled with bentonite as part of the plug.

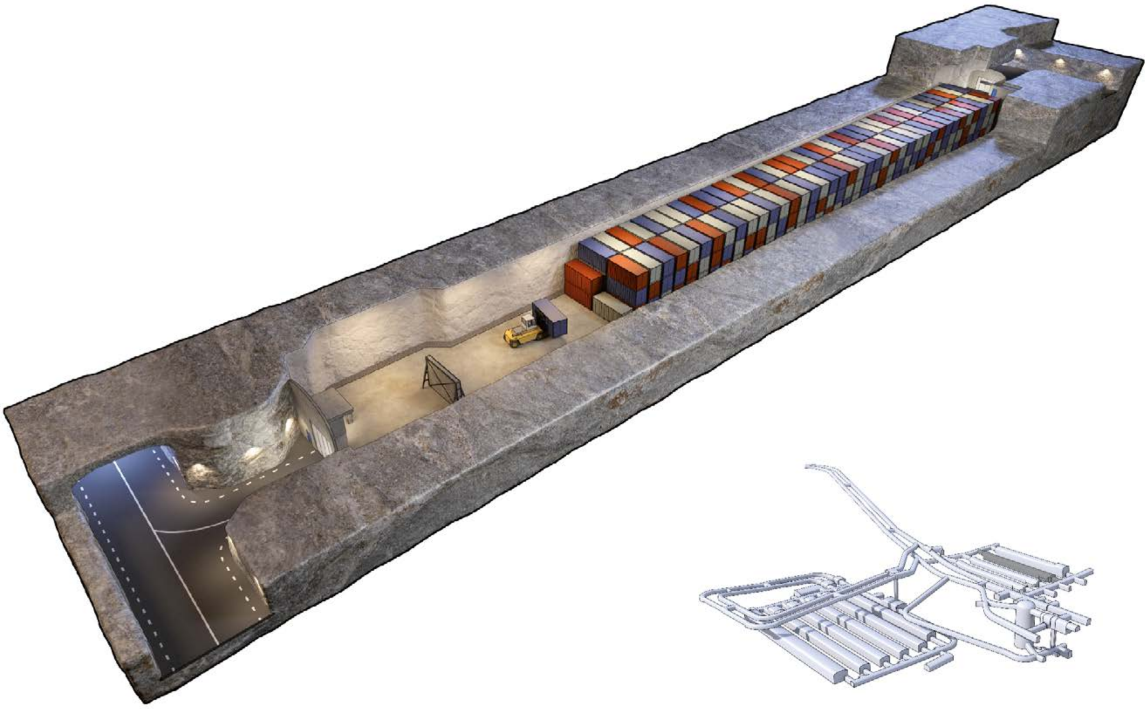

Figure 9-1. *Illustration of 1BLA during the operational period and below there is a view of SFR with the position of 1BLA highlighted.*

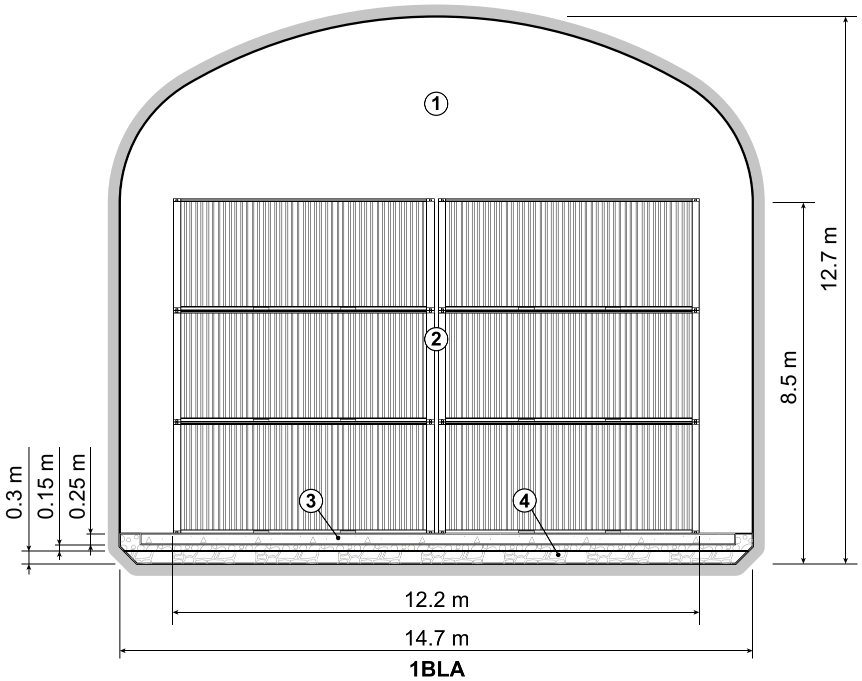

Figure 9-2. *Schematic cross-section of 1BLA after closure. The dimensions of 1BLA are given in detail in Table 9-1. Key to numbering: 1) Void 2) Waste domain 3) Slab 4) Crushed rock (0.3 + 0.15 m).*

9.2 Design considerations

Safety features considered for the surrounding rock

The depth of 1BLA (~70 m) results in favourable conditions with respect to mechanical stability of the rock, low groundwater flow and anoxic redox conditions.

Safety features considered for the system components in 1BLA

Level of radioactivity – The waste in 1BLA is mainly low-level trash and scrap metal, placed in standard ISO-containers, see Section 3.6.8. The most important safety principle is the limited level of radioactivity in the waste packages, see Section 3.7. The acceptance criteria for the waste packages are given in Section 3.1.

Limited advective transport – The plugs in the ends of the vault will limit the inflow of water from the tunnel system, see Section 11.1. The water flow through waste will then be determined by the inflow to the vault from surrounding rock.

In all vaults, the grout in the surrounding rock will limit the inflow of water during the operational period. However, in the BLA vaults, the system will also be affected by the influence of the grout on the inflow of water after closure, due to the lack of other barriers inside the waste vaults.

Mechanical stability – The stability of the waste vault during the operational period is increased by the shotcrete on the rock walls. The waste packages and the shotcrete will only marginally influence the stability of the waste vault for longer times after closure.

Limited dissolution – The release of radionuclides from the waste packages is not considered to be limited by dissolution.

Sorption – Sorption in 1BLA is very limited. However, as in all other waste vaults, sorption occurs on corrosion products, shotcrete and other cementitious materials.

Favourable water chemistry – The water chemistry in the waste vault will be determined by the chemical composition of intruding water but influenced by the leaching of shotcrete and other cementitious materials. Reducing conditions will be established soon after closure of the vault due to consumption of oxygen by metal corrosion and microbial degradation.

9.3 Inspection and control of 1BLA

The inspection and control of the waste vaults can be divided into the following three steps.

- Control and inspection of the shotcrete and rock reinforcements and the concrete slab in the waste vault during construction.
- Control and inspection of conditions in the waste vault during the emplacement of waste – the operational period.
- Final inspection and control of the waste vault before closure with plugs.

9.4 1BLA dimensions and material quantities

The main dimensions of the waste vault 1BLA are given in Table 9-1. The excavated volume is 27 680 m^3 and the estimated volumes of different materials in the waste vault after closure are given in Table A-8 in Appendix A. The total void in the vault including void and porosities in the materials are also given in Table A-8 in Appendix A.

Table 9-1. 1BLA dimensions.

1BLA property	Value	Comment*
Excavated rock cavity		
Total length (m)	160	Calculated from values (120 + 40) given in drawing 1411-10020780
Width (m)	14.7	Value given in drawing 1411-10020780
Height (max) (m)	12.7	Value given in drawing 1411-10020780
Height (average) (m)	11.77	Calculated (173/14.7)
Vertical cross-sectional area (m^2)	173	Value given in closure plan for SFR (Mårtensson et al. 2022)
Excavated volume (m^3)	27680	Calculated 173 × 160
Shotcrete thickness (m)	0.05	From Carlsson and Christiansson 2007, Table 6-2 Un-reinforced 1 or 2 layers: 0.03 or 0.05 m, Fibre reinforced: 0.05 or 0.08 m
Inner zone (at tunnel TT)		
Length (m)	3.7	Value given in drawing 1411-10020780
Waste disposal area		
Length where waste can be stored (m)	146.3	Max length (160 − 3.7(TT) – 10 (plug support at BST))
Width outer (2 ISO-containers) (m)	12.2	Calculated from ISO standard 6.06 m and emplacement of containers with 0.1 m spacing (2 × 6.06 + 0.1), see Sections 3.5.5 and 3.6.7
Height outer (3 ISO-containers full height) (m)	7.8	Calculated from ISO standard 2.59 m and emplacement of 3 containers without spacing (3 × 2.59), see Sections 3.5.5 and 3.6.7
Bottom		
Concrete slab (reinforced) (m)	0.25	Value given in drawing 1462-10153140
Concrete slab width (m)	13.7	Value given in drawing 1460-10021930
Macadam thickness (m)	0.15	Value given in drawing 1462-10153140
Rock fill thickness (m)	0.3	Value assumed from drawing 1462-10153140
Reloading zone (at tunnel BST)		
Length (m)	10	Required length for plug support given in closure plan for SFR (Mårtensson et al. 2022)

* Drawing numbers in column "Comment" refer to SKB's internal documents.

10 2–5BLA

10.1 Design

The four waste vaults 2–5BLA are similar in design to 1BLA. The main difference is that they are wider to facilitate inspection and maintenance during the operational period, see Figure 10-1. A concrete slab will be cast on top of a drained foundation within the vault. The rock walls and the ceiling of the waste vault will be lined with shotcrete. The waste packages are standard ISO-containers. The 20-foot half-height containers will be placed on the concrete slab two abreast and six in height. The dimensions of the waste vaults are given in Table 10-1 and Figure 10-2.

The demolition and dismantling of existing systems, for example the ventilation and electricity, will be adapted to the closure sequence. The closure plan for SFR describes measures for the sealing and closure of 2–5BLA (Mårtensson et al. 2022). The waste vaults are planned to be left unfilled. However, the ends of the vaults adjacent to the connecting tunnels are planned to be backfilled to provide mechanical support for the plugs. The support is achieved by backfilling the ends of the vault with macadam against retaining walls.

Figure 10-1. *Illustration of 2–5BLA during the operational period. The lower detail shows the position of the four waste vaults (highlighted) within SFR.*

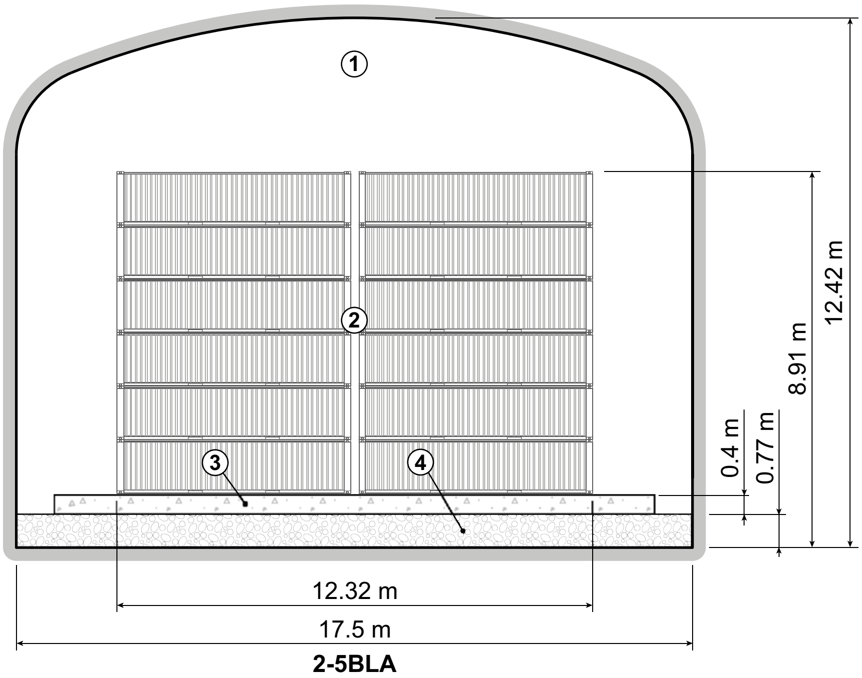

Figure 10-2. Schematic cross-section of 2–5BLA after closure. Note that the figure shows Layout 2021 while the dimensions used in the post-closure safety analysis are from Layout 2020. In Table 10-1 dimensions are given for both layouts. Key to numbering: 1) Void 2) Waste domain 3) Slab 4) Crushed rock.

10.2 Design considerations

The suggested design for the 2–5BLA waste vaults is similar to the existing 1BLA vault for low-level waste.

Safety features considered for the surrounding rock

The depth of 2–5BLA (~ 120 m) results in favourable conditions with respect to mechanical stability and low groundwater flow.

Safety features considered for the system components in 2–5BLA

Level of radioactivity – The waste in 2–5BLA is mainly low-level trash and scrap metal from decommissioning, placed in standard ISO-containers, see Section 3.6.9. The most important safety principle is the limited level of radioactivity in the waste packages. The waste acceptance criteria for the waste packages are given in Section 3.1.

Limited advective transport – The presence of plugs at the ends of the vault will limit the inflow of water from the tunnel system, see Section 11.1. The water flow through waste will then be determined by the inflow to the waste vault from surrounding rock.

In all vaults, the grout in the surrounding rock will limit the inflow of water during the operational period. However, in the BLA vaults, the system will also be affected by the influence of the grout on the inflow of water after closure, due to the lack of other barriers inside the waste vaults.

Mechanical stability – The stability of the waste vault during the operational period is increased by the shotcrete on the rock walls. The waste packages, supporting walls and shotcrete will have a marginal influence on the stability of the waste vault after closure.

Limited dissolution – The release of radionuclides from the ISO-containers is not considered to be solubility limited.

Sorption – Sorption in 2–5BLA is very limited. However, as in all other waste vaults, sorption occurs on corrosion products, shotcrete and other cementitious materials.

Favourable water chemistry – The water chemistry in the waste vaults will be determined by the chemical composition of intruding water and the leaching of shotcrete and other cementitious materials. Reducing conditions will be established soon after closure of the vaults due to consumption of oxygen by metal corrosion and microbial degradation.

10.3 Inspection and control of 2–5BLA

The inspection and control of the waste vaults can be divided into the following three steps.

- Control and inspection of the shotcrete and rock reinforcements in the waste vaults during and after construction.
- Control and inspection of the physical condition of the waste vaults during the emplacement of waste – the operational period.
- Final inspection and control of the waste vaults before backfilling the ends with macadam and closure with plugs.

10.4 2–5BLA dimensions and material quantities

The main dimensions of the waste vaults 2–5BLA are given in Table 10-1.

The estimated volumes of different materials in one waste vault after closure are given in Table A-9 in Appendix A. The total void in the vault including void and porosities in the materials are also given in Table A-9 in Appendix A.

Table 10-1. 2–5BLA dimensions.

2–5BLA property	Value Layout 2020	Value Layout 2021	Comment*
Excavated rock cavity			
Total length (m)	275	275	Layout 2020: 3-D model (Berg), SKBdoc 1932070 ver 1.0 200611, Layout 2021: Systemhandling, SKBdoc 1858600 ver 4.0, Table 7-2
Width (m)	17.9	17.5	Layout 2020: 3-D model (Berg), SKBdoc 1932070 ver 1.0 200611, Layout 2021: Systemhandling, SKBdoc 1858600 ver 4.0, Table 7-2
Width reloading zone (m)	20.0	19.6	Layout 2020: 3-D model (Berg), SKBdoc 1932070 ver 1.0 200611, Layout 2021: Systemhandling, SKBdoc 1858600 ver 4.0, Table 7-2
Height max (m)	13.7	12.42	Layout 2020: 3-D model (Berg), SKBdoc 1932070 ver 1.0 200611, Layout 2021: Systemhandling, SKBdoc 1858600 ver 4.0, Table 7-2
Height average (m)	13.0	11.4	Layout 2020: Calculated (232/17.9), Layout 2021: Calculated (205/17.5)
Vertical cross-sectional area (m^2)	232	205	Layout 2020: 3-D model (Berg), SKBdoc 1932070 ver 1.0 200611, Layout 2021: Systemhandling, SKBdoc 1858600 ver 4.0, Table 7-2
Vertical cross-sectional area re-loading zone (m^2)	260	230	Layout 2020: 3-D model (Berg), SKBdoc 1932070 ver 1.0 200611, Layout 2021: Systemhandling, SKBdoc 1858600 ver 4.0, Table 7-2
Excavated volume (m^3) (per vault)	64466	56970	Layout 2020: Calculated (275 − 23.8) × 232 + 23.8 × 260, Layout 2021: Calculated (275 − 23.8) × 205 + 23.8 × 230
Shotcrete thickness (m)	0.14		Varies between 0.11 − 0.18 m according to SKBdoc 1689213 SKB_PSU_Mängdning-Berg

Table 10-1. Continued.

2–5BLA property	Value Layout 2020	Value Layout 2021	Comment*
Inner zone (at tunnel 2TT)			
Length (m)	8.2	8.2	Calculated from values (275 − 243 − 23.8 m)
Waste disposal area			
Length where waste can be stored (m)	243	228	1 080 containers (20-foot half-height) (Systemhandling 3.0, SKBdoc 1717465, ver 4.0) gives 90 containers in length (90 × 2.5 + 60 × 0.1 + 29 × 0.4) = 243, Layout 2021[b]
Width outer (2 ISO-containers) (m)	12.36	12.32	ISO standard 6.06 m plus a space between the 2 containers. Layout 2020[a], Layout 2021[b]
Height outer (3 ISO-containers full height) (m)	7.8	7.74	Calculated from ISO standard 2.59 m and emplacement of 3 containers without spacing (3 × 2.59), see Sections 3.5.5 and 3.6.8, Layout 2021[b]
Bottom			
Concrete slab (reinforced) thickness (m)	0.4	0.4	Layout 2020[a], Layout 2021[b]
Concrete slab width (m)	15.9	15.5	Layout 2020[a], Layout 2021[b]
Macadam/Rock fill thickness (m)	1	0.77	Layout 2020[a], Layout 2021[b]
Reloading zone (at tunnel 2BST)			
Length (m)	23.8	23.8	Layout 2020: 3-D model (Berg), SKBdoc 1932070 ver 1.0 200611, Layout 2021: Systemhandling, SKBdoc 1858600 ver 4.0, Table 7-2
Concrete slab width re-loading zone (m)	18	17.6	Layout 2020[a], Layout 2021[b]
Concrete slab thickness reloading zone (m)	0.5	0.4	Layout 2020[a], Layout 2021[b]

* 3D-models refer to SKB´s internal documents.

[a] Layout 2020 (2020-05-30): 3-D model SKBdoc 1939922 ver 1.0.

[b] Layout 2021 (2020-12-11): 3-D model SKBdoc 1939921 ver 1.0.

11 Plugs and other closure components

11.1 Design

The closure plan for SFR (Mårtensson et al. 2022) describes the planned measures for the plugging and closure of SFR. An overview of the plugs and other closure components in SFR is shown in Figure 11-1. The plugs consist of hydraulically tight sections of bentonite, held in place by mechanical constraints. This type of plug is called an earth dam plug. Mechanical constraints of standard concrete will be used in SFR3, the silo and the 1TT tunnel end of the SFR1 vaults. However, a transition material of 30/70 bentonite/crushed rock (dry weight) will be used as the mechanical constraint at the BST end of SFR1.

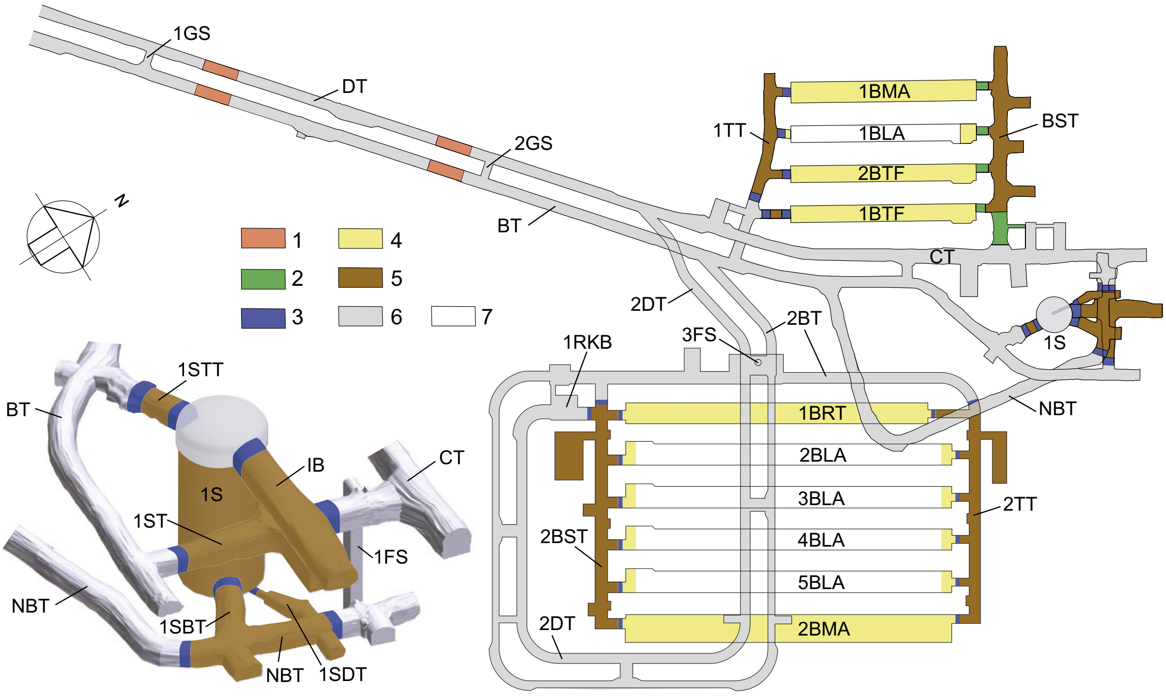

Figure 11-1. *Schematic plan for backfill and plugs in SFR1 and SFR3, with a detailed view of the silo. Key to numbering: 1) Plugs in access tunnels 2) Transition material 3) Mechanical constraint of concrete 4) Backfill material of macadam 5) Silo bentonite and hydraulically tight section of bentonite 6) Backfill material in silo top, access tunnels and the central area of the tunnel system 7) Non-backfilled openings. The labels in the figure will be referred to in the text.*

Plugs for the silo

The closure of the silo will be achieved using three plugs: lower silo plug (NSP), upper silo plug (ÖSP) and silo roof plug (STP), see Figure 11-2. An important consideration when designing the plugs is to find suitable tunnel geometries for the installation of the mechanical constraints that hold the hydraulically tight sections of bentonite in place. The installation starts with plugging the silo bottom tunnel (1SBT) and the silo drainage tunnel (1SDT) with four concrete plugs and bentonite. Thereafter the silo roof tunnel (1STT) is plugged and finally three concrete plugs and bentonite are installed to plug the silo tunnel (1ST) and the loading-in building (IB).

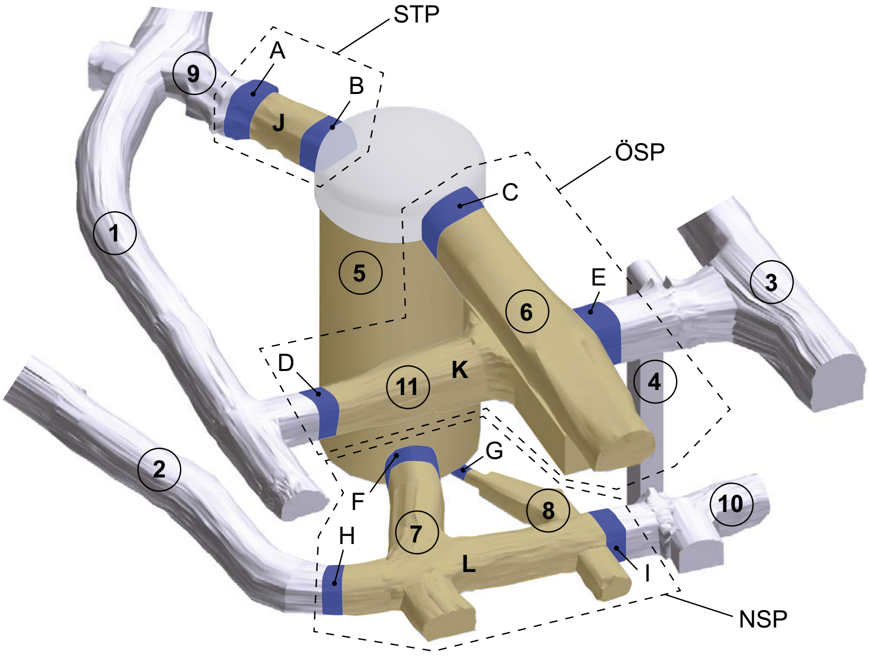

Figure 11-2. *Illustration of the silo after closure, with three plugs (NSP, ÖSP and STP). Blue colour shows concrete plugs (A,B,…I) and brown colour shows hydraulically tight sections (J, K, L). Key to numbering: 1) Construction tunnel, BT 2) Lower construction tunnel, NBT 3) Central tunnel, CT 4) Connecting shaft 5) The silo 6) Loading-in building, IB 7) The silo bottom tunnel, 1SBT 8) Silo drainage tunnel 1SDT 9) The silo roof tunnel, 1STT 10) Terminal part of lower construction tunnel 11) The silo tunnel, 1ST. Tunnel parts 1, 2, 3, 4 and 10 belong to the tunnel system.*

Plugs for waste vaults (except the silo)

A total of five plugs (P1TT, P1BTF, P1BST, P2TT and P2BST) are to be installed to seal the waste vaults in SFR1 and SFR3, see Figure 11-3. Concrete mechanical constraints will be used in four of these plugs. P1BST will be constructed as an earth dam plug since the geometry and local geology make it difficult to construct concrete mechanical constraints.

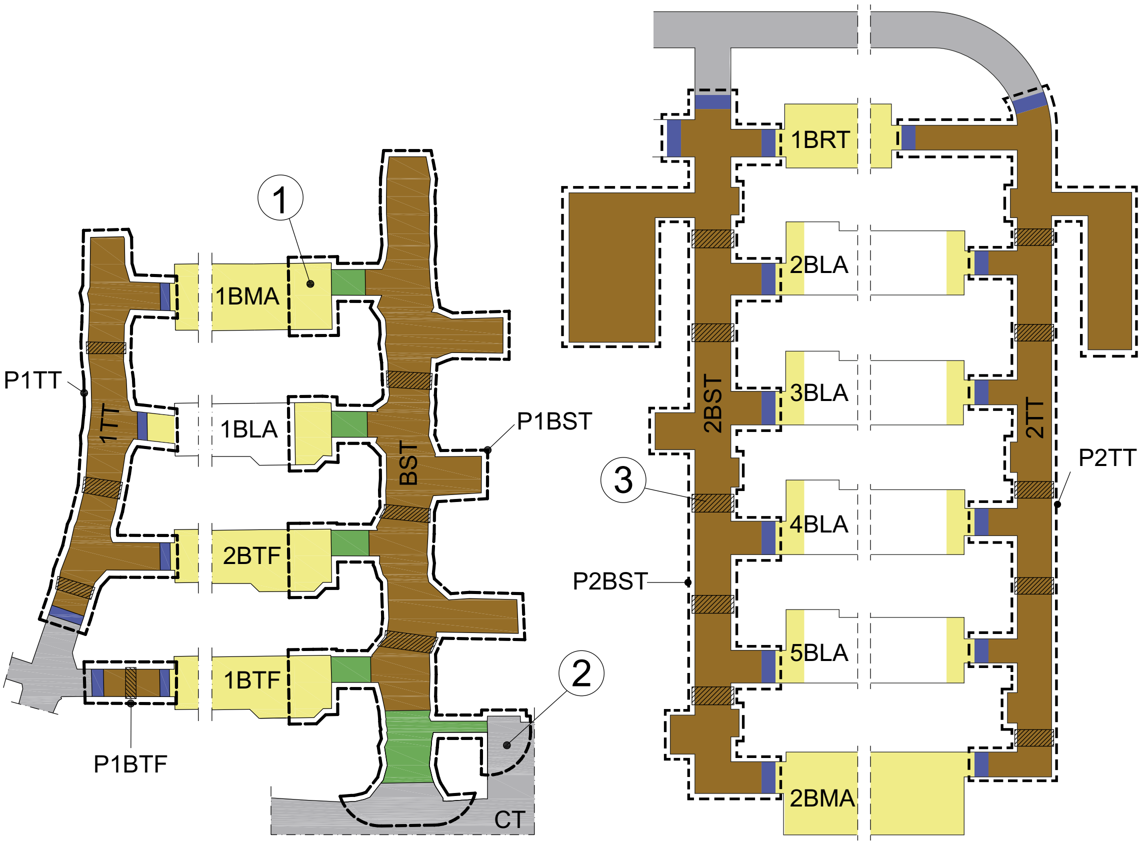

***Figure 11-3.** Plugs adjacent to waste vaults are marked with a dashed line. Key to numbering: 1) Yellow colour within borderline for plug shows parts of backfill in rock that are active parts of the earth dam plug, green colour shows transition material and brown colour shows hydraulically tight material 2) Grey colour within borderline for plug shows parts of backfill in tunnel system that are active parts of the earth dam plug 3) Hatched areas indicate where the damaged zone should be removed by controlled methods.*

Closure of the tunnel system

The tunnel system will be backfilled with crushed rock. The selected material has the required high hydraulic conductivity and favourable mechanical properties for limiting subsidence in the tunnels.

In addition, the construction tunnel, BT, and the operational tunnel, DT, will be isolated by the installation of plugs between the connecting tunnels, 1GS and 2GS. The plug design is shown in Figure 11-4 and involves a hydraulically tight section of bentonite that is 10 m long.

Closure of the upper part of access tunnel

The first fifty metres of the access tunnels (in length) will be backfilled with boulders. A concrete plug will be cast to obstruct unintentional intrusion into the repository. Finally, the ground surface will be restored to match the surroundings.

Closure of shafts

The connecting shaft 3FS will be plugged during closure. This is planned to be carried out by installing a vertical plug of hydraulically tight bentonite with upper and lower concrete mechanical constraints. In total, the plug is 40 m long in the vertical direction.

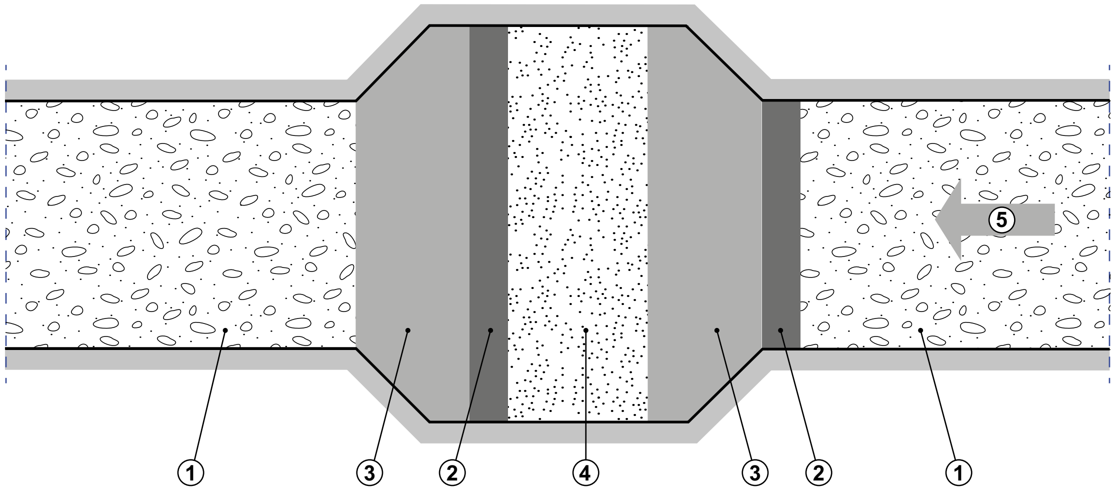

Figure 11-4. *Conceptual reference design of plugs in access tunnels. Key to numbering: 1) Macadam backfill 2) Supporting wall 3) Concrete 4) Bentonite 5) Working direction.*

Sealing of boreholes

There are a large number of boreholes in the repository area that were drilled during site investigations for the Forsmark nuclear site, SFR and the final repository for spent fuel. The boreholes have been classified into three categories, BHK1, BHK2 and BHK3 according to their depth, proximity to the repository and hydraulic contact with the repository.

- BHK1: shallow boreholes with no hydraulic connection to the repository.
- BHK2: deeper boreholes that lie > 400 m from the repository and have no hydraulic connection to the repository.
- BHK3: deeper boreholes that lie < 400 m from the repository as well as those that have a hydraulic connection to the repository.

Some boreholes used in the preliminary investigations were sealed prior to the construction of SFR, according to the requirements of that time. Others are sealed during the operational period of SFR, including prior to the construction of SFR3, and the remainder will be sealed during closure.

The aim when sealing the boreholes is to prevent the formation of new flow paths that could affect the long- or short-term safety of the repository after closure. The borehole closure concept described in Mårtensson et al. (2022) predates a new investigation in which different components were suggested (Sandén et al. 2020). Therefore, the concept is only described in general here, and only for BHK3 boreholes. Bentonite will be used to achieve a low hydraulic conductivity in the sections of the BHK3 boreholes that pass through intact rock. Sand will be used where the borehole passes through cracked rock or a deformation zone, to provide mechanical stability. Concrete will be used to prevent the sand and bentonite mixing over time and copper expanders will be placed at every material transition point. The copper expanders will facilitate the installation process and prevent mixing of the materials, but have no post-closure function.

11.2 Design considerations

The design of the plugs and closure components are expected to be further developed and optimised before closure of SFR, e.g. the new suggestions by Sandén et al. (2020).

Safety features considered for the upper parts of the access tunnel

The closure of the upper parts of the access tunnels will be designed to hinder unintentional intrusion from the surface to the repository.

Safety features considered for plugs and other closure components

Level of radioactivity – Not applicable.

Limited advective transport – The main safety feature of the plugs is to limit the flow through the waste vaults. If the wall of a tunnel where a plug will be installed contains hydraulically conductive damaged rock, the damaged rock will be removed before installation of the plug. The plugs will be placed so that they are not short-circuited by water-bearing cracks.

The boreholes will be sealed to prevent the formation of new flow paths that could affect the post-closure safety of the repository after closure. Materials of selected hydraulic conductivity will be used to achieve this.

Mechanical stability – The post-closure stability of the tunnels (for example the stability against rock fallout) will be enhanced by backfilling the tunnels with e.g. crushed rock, bentonite and bentonite mixtures.

Limited dissolution – Not considered.

Sorption – Radionuclide transport from the waste vaults via the plugs will be reduced by sorption to the bentonite and concrete of the plugs.

Favourable water chemistry – Not considered.

11.3 Inspection and control

The production of plugs and other closure components will follow the general procedures applied for manufacturing, installation, inspection and control. A selection of tests and experiments have been performed by SKB at the Äspö hard rock laboratory and the Bentonite laboratory (SKB TR-13-10). These laboratories also provide the opportunity to demonstrate that plugs and other closure components can be fabricated and installed with the quality required to meet the requirements for post-closure safety.

SKB has studied and developed several concepts for borehole sealing. The main principles for sealing of boreholes as well as results from experiments and tests are summarised in Pusch and Ramqvist (2007) and Sandén et al. (2018). However, investigation boreholes drilled for SFR1 exist that were sealed in accordance with former requirements that may not fulfil present requirements.

11.4 Condition of closure components

Plugs and other closure components are installed near the time of closure and are expected to be in good condition at closure.

11.5 Dimensions and material volumes

The volumes of materials to be used in the plugs are summarised in Table 11-1, based on Mårtensson et al. (2022).

Table 11-1. Estimated volumes (m^3) of materials in the plugs.

Tunnels	Transition material	Concrete	Bentonite
Plugs for the waste vaults (SFR1 and SF3)	7360	6100	73479
Plugs for the silo		3250	19700
Access tunnels and shafts		4500	4200
Total volumes	7360	13850	97379

12 Variables for the system components

12.1 Variables for the waste form

The waste packages (moulds and drums) in the silo shafts are grouted with concrete during the operational period. For this reason, the condition of the waste packages cannot be inspected.

For the BMA, 2BTF and BLA repository components, the waste packages are not grouted during the operational period. Hence, it is possible to relocate waste packages and inspect them before closure if deemed necessary. The drums containing ash placed in 1BTF need stabilising walls. These walls are constructed using concrete tanks and moulds. When six rows of drums have been piled, moulds are placed across the waste vault and concrete is poured over the drums in order to stabilise them. After this, the condition of the waste packages cannot be inspected.

Table 12-1 shows the variables for the waste form in SFR.

Table 12-1. Variables for the waste form and their definition from the Waste process report.

Variable	Definition
Geometry	Volume and dimensions of the waste form and voids inside the waste packaging
	Porosity and pore characteristics of the waste form
	Amount and characteristics of cracks in the waste form
Radiation intensity	Intensity of alpha, beta and gamma radiation
Temperature	Temperature
Hydrological variables	Magnitude, direction and distribution of water flow
	Degree of water saturation
	Water pressure
	Aggregation state (water and/or ice)
Mechanical stresses	Stress and strain in waste form
Radionuclide inventory	Inventory of radionuclides as a function of time within the waste package
	Type, amount, chemical and physical form
Material composition	Amount and surface characteristics of materials inside the waste package (excluding radionuclides)
	Type and amount of chemicals
	Type and amount of organic materials and other substances that can be used by microbes as nutrients and energy sources
	Types and amount of microbes and bacteria and other types of biomass
Water composition	Composition of water including radionuclides
	Redox, pH, ionic strength, concentration of dissolved species, type and amount of colloids and/or particles, amount and composition of dissolved gas
	Types and amount of microbes and bacteria and other types of biomass
	Density and viscosity
Gas variables	Amount and composition including radionuclides
	Volume, pressure and degree of saturation
	Magnitude, direction and distribution of gas flow

12.1.1 Geometry

The geometry of the waste is described in Chapter 3 and in Appendix A. The internal initial void volume and pore volume of the different waste types are presented in the inventory report (SKB R-18-07).

12.1.2 Radiation intensity

The energy liberated during decay is converted for the most part into heat. However, the effect of radioactive decay on the temperature in the waste is negligible (**Waste process report**). For the low- and intermediate-level waste in SFR, radiolysis is not considered to have a significant effect on the waste since the time-integrated dose is less than 10^6 Gy (**Waste process report**).

12.1.3 Temperature

The temperature of the waste is set by the temperature of the surroundings. The temperature in the rock in the Forsmark area at about 50 metres depth is 5–7 °C (Sundberg et al. 2009, Väisäsvaara 2009). The increase in temperature due to heat from decay, corrosion and concrete hydration is judged to be small (**Waste process report**).

12.1.4 Hydrological variables

Directly after plugging and the cessation of drainage pumping, water will start to saturate the repository. Bounding calculations have estimated that it will take about 25 years for water to fully saturate the concrete cylinder of the silo, which is surrounded by bentonite (Holmén and Stigsson 2001). In more recent calculations, the silo repository was estimated to be fully saturated in the interval between 13 and 53 years (Börgesson et al. 2015). The largest uncertainty came from the host rock representation, both in terms of using undrained/drained and dry representations. The properties of the silo content as well as the top backfill also had significant effect on the overall saturation interval.

Full resaturation of the other waste vaults has been calculated to take a few years (Holmén and Stigsson 2001). The cement conditioned waste will become saturated shortly after repository closure (Holmén and Stigsson 2001). Saturation of the bitumen conditioned waste will take a longer time due to the hydrophobic character of bitumen. The driving force for water saturation of the bituminised waste form is the hydroscopic character of the ion-exchange resins as well as different salts (**Waste process report**). In the perspective of the long duration of the safety assessment period, the resaturation process is assumed to be instantaneous and the repository is considered saturated at initial state.

The hydraulic conductivity of the waste forms varies from very permeable to almost completely tight depending both on the type of waste and conditioning material.

The water pressure in the waste form is estimated to be the same as the hydrostatic pressure. For waste forms in the silo, this varies depending on the position of each waste package within the concrete cylinder. For waste packages in other waste vaults this effect is deemed negligible.

Initially, all water within the waste form is liquid due to the temperature, see Section 12.1.3.

12.1.5 Mechanical stresses

Mechanical stresses, caused by external pressure on the waste form, may lead to cracking of the waste form.

12.1.6 Radionuclide inventory

The initial state of the radioactivity in the waste packages is determined at the time when the waste is conditioned. No or negligible release is deemed possible during the operational period. Thus, only radioactive decay is considered during this period.

The calculated reference radionuclide inventory in each waste vault is given in Table 3-9. This is based on the activity of the radionuclides present in each waste type given in the inventory report (SKB R-18-07). The radionuclides are present in such low concentrations that they in most cases are unlikely to exceed their solubility limits. The chemical form of each radionuclide is set by the surrounding environment i.e. pH, Eh and presence of complexing agents. Initially, negligible activities of radioactive gases are present within the repository.

12.1.7 Material composition

The different materials in the waste form are presented in the inventory report (SKB R-18-07) and a summary is given in Section 3.7. Corrosion is the only process considered that influences the material composition during the operational period, however, other processes such as carbonatisation of cementitious materials and degradation of organic materials may occur. Initially, organic complexing agents can be present within different waste forms. These chemicals originate from cleaning and decontamination processes at the nuclear power plants. The masses and concentrations of complexing agents in SFR are presented in Keith-Roach et al. (2021). The mass of complexing agents disposed is regulated by the means of waste acceptance criteria. Microbes may utilise some materials in SFR as energy sources. Cellulose, for example, is a favourable energy source for microbes. The microbial population initially present in the waste form depends on the origin of the waste form, the pH and whether microbes have been transported to the waste by the infiltrating groundwater.

The amounts of cement and concrete that are used in the different waste types are summarised in Table C-4 in the inventory report (SKB R-18-07). The HCP (hydrated cement paste) that has been anticipated in the calculations is 60 % for cement-solidified wastes and 10 % for concrete-embedded wastes (**Radionuclide transport report**, Appendix A).

12.1.8 Water composition

For cement-solidified waste, the composition of the groundwater will affect the concrete pore water composition. However, the concentration of dissolved substances in the groundwater is lower than in the concrete pore water, hence the pore water is anticipated to have the initial composition of fresh and/or leached cement and the influence of the ground water is negligible, see Table 12-2. Shortly after closure, reducing conditions will prevail in SFR due to for example corrosion of the large amount of iron present in the repository (Duro et al. 2012).

The radionuclide concentrations in the pore water depend on the radioactivities and volume of pore water in each individual waste package. It is assumed that all radionuclides dissolve in the pore water of the waste form immediately after saturation. Colloids are not deemed to be stable within the waste forms that have a high ionic strength and a high dissolved Ca^{2+} concentration, i.e. waste forms within the silo, 1-2BMA, 1-2BTF and 2-5BLA. In 1BLA, colloids originating both from the groundwater and the waste may be present (**Waste process report**). Initially, dissolved gases in the water originate from the dissolution of air trapped in the waste form during saturation. The abundance of microbes within the different waste forms is discussed in Section 12.1.7.

Values for the density and viscosity of the water are selected from the literature for the current temperature of the system.

Table 12-2. Analysis of pore water from fresh and leached cement (ion concentrations in mmol/L).

Parameter	Fresh cement (Lagerblad and Trägårdh 1994)	Leached cement (Engkvist et al. 1996)
pH	> 13	12.6
SO_4^{2-}	0.04	0.02
Cl^-	< 0.06	2
Na^+	28	3
K^+	83	0.1
Ca^{2+}	0.9	20
Si_{tot}	0.8	0.003
Al_{tot}	0.04	0.002
OH^-	114	36

12.1.9 Gas variables

As the repository fills with water, the most abundant gas in the interior of the waste packages is the undissolved air that may be found in air pockets and pores. Small amounts of Rn-222 might be present in the interior of the waste packaging, because Rn-222 forms from the decay of Ra-226 within the U-238 decay chain.

If the waste packages corrode in the silo under anaerobic conditions, hydrogen may form. Simulations of corrosion of the waste packages show that the hydrogen concentration in the air will increase (Moreno et al. 2001). Aerobic corrosion will form Fe(III) oxides and hydroxides (rust) and may lead to altered initial conditions of the waste packages.

Aluminium is covered by a passivating oxide layer, and alkaline conditions cause the oxide to dissolve. Alkaline conditions are obtained when the groundwater has reacted with concrete. While the repository is drained by pumping during the operational period, the aluminium waste will be covered by this passivating oxide layer. Corrosion of aluminium is therefore negligible during the operational period, but will increase after saturation leading to production of hydrogen.

12.2 Variables for the waste packaging

SFR waste is mainly packaged in the following types of packaging.

- Concrete moulds (with cement-solidified ion-exchange resins, filter aids and evaporator concentrate as well as concrete-embedded trash and scrap metal).
- Steel moulds (with cement or bitumen-solidified ion-exchange resins or concrete-embedded trash and scrap metal).
- Steel drums (with concrete-embedded ash or bitumen-solidified ion-exchange resins).
- Standard ISO-containers (mainly with trash and scrap metal).
- Concrete tanks (with dewatered ion-exchange resins).

There may be certain other odd packaging, and, in some cases, large items of waste (components) may be disposed without packaging. For more detailed information about the different packaging types, see Section 3.5 and Figure 3-1.

Oxygen is available during the operational period, which means that aerobic corrosion can occur (**Waste process report**). General aerobic corrosion, while faster than anaerobic, is still too slow to noticeably affect the integrity of steel packaging during the relatively short operational period. However, chloride-induced pitting corrosion is faster and can cause more serious, albeit local, damage to steel packaging exposed to saline groundwater dripping from various points in the ceiling of the vaults (**Waste process report**). This issue has diminished thanks to recent installation of waterproofing membranes in all vaults except 1–2BTF.

Anaerobic corrosion can occur during the operational period in parts of the repository where oxygen is not present. There are however no requirements with regard to the post-closure function of steel packaging.

Initially, the packaging is not deemed to contain a significant activity of radionuclides.

Table 12-3 shows the variables for the concrete and steel packaging that are used for the waste in SFR.

Table 12-3. Variables for steel and concrete packaging and their definition from the Waste process report.

Variable	Definition
Geometry	Volume and dimensions of the packaging
	Porosity and pore characteristics of the packaging
	Amount and characteristics of cracks in the packaging
Temperature	Temperature
Hydrological variables	Magnitude, direction and distribution of water flow
	Degree of saturation
	Water pressure
	Aggregation state (water and/or ice)
Mechanical stresses	Stress and strain in waste packaging
Material composition	Amount, composition and surface characteristics of materials in the waste packaging
	Type and amount of chemicals
	Extent of cement hydration in concrete
	Type, amount of organic materials and other substances that can be used by microbes as nutrients and energy sources
	Types and amount of microbes and bacteria and other types of biomass
Water composition	Composition of water including radionuclides
	Redox, pH, ionic strength, concentration of dissolved species, type and amount of colloids and/or particles, amount and composition of dissolved gas
	Types and amount of microbes and bacteria and other types of biomass
	Density and viscosity
Gas variables	Amount and composition including radionuclides
	Volume, pressure and degree of saturation
	Magnitude, direction and distribution of gas flow

12.2.1 Condition of the waste packaging at closure

Steel waste packaging will probably start to corrode during the operational period. The possibility of small cracks, of more than 0.1 mm wide, forming in the concrete packaging during the operational period cannot be ruled out.

The waste packages in the silo are embedded in grout as they are emplaced and the waste packages in 1BTF (drums with ashes) are embedded in grout as they are emplaced. This means that the condition of the waste packages in these waste vaults cannot be inspected afterwards.

The condition of other waste vault subcomponents is described in Sections 12.3 to 12.7.

12.2.2 Geometry

The volume and dimensions of the waste packaging are described in detail in Section 3.5 and Appendix A.

The steel in the packaging has no porosity whereas the concrete packaging has a porosity of 9–15 %.

Steel waste packaging will probably start to corrode during the operational period. The amount and character of the cracks initially present in the concrete packaging in SFR are generally not known.

12.2.3 Temperature

The temperature in the different waste packages is controlled by the temperature of the surroundings as described in Section 12.1.3.

12.2.4 Hydrological variables

Directly after plugging and cessation of drainage pumping, water will start to saturate the repository. The same bounding calculations as for the waste applies for the waste packaging, Section 12.1.4.

The water pressure in the concrete packaging is anticipated to be the same as the hydrostatic pressure. For waste packaging in the silo, this varies depending on the position of each waste package within the concrete cylinder. For packaging in other waste vaults, this effect is deemed negligible. In the perspective of the long duration of the safety assessment period, the resaturation process is assumed to be instantaneous and the repository is considered saturated at initial state.

The hydraulic conductivities of different types of concrete are given in the **Data report**.

Initially, all water within the waste packaging is liquid due to the temperature, see Section 12.1.3. This variable is not relevant for steel packaging.

12.2.5 Mechanical stresses

Mechanical stresses, caused by corrosion of reinforcement bars in the concrete moulds and tanks during operation, may lead to cracking of the packaging. However, for some waste packages corrosion is prevented by the use of e.g. paint that reduces the penetration of water into the packaging.

Insignificant deterioration of the 2BTF concrete tanks was observed during inspections in 2010 and 2021.

12.2.6 Material composition

The packaging is composed of carbon steel, stainless steel or reinforced concrete. In the inventory report (SKB R-18-07), the composition of different packaging is described in further detail, however, the exact composition varies between different waste suppliers and over time due to changed concrete recipes. The microbial population initially present in the packaging mainly depends on if microbes have been transported to the packaging by the infiltrating groundwater. After saturation, it is anticipated that the concrete in the packaging is fully hydrated.

12.2.7 Water composition

The water compositions for the concrete packaging are mainly the same as for the waste form, see Section 12.1.8 for details. This variable is not relevant for steel packaging.

12.2.8 Gas variables

As the repository fills with water, the most abundant gas in the concrete packaging is the undissolved air that may be found in pores. This variable is not relevant for steel packaging.

12.3 Variables for the silo system components

The waste packages are embedded in grout which, together with the compartment walls and the concrete cylinder walls of reinforced concrete, constitute the concrete barriers. The concrete cylinder walls are completely surrounded by bentonite, which constitutes a barrier between the concrete cylinder and the rock. The rock is covered with shotcrete. The bottom part of the concrete cylinder consists of a reinforced concrete pad resting on a layer of sand mixed with bentonite.

Table 12-4 shows the variables for the engineered barriers in SFR.

Table 12-4 Variables for the engineered barriers in SFR and their definition from the Barrier process report.

Variable	Definition
Geometry[a]	Volume and dimensions of the barriers
	Porosity and pore characteristics of the barriers
Temperature	Temperature
Hydrological variables[b]	Magnitude, direction and distribution of water flow
	Degree of saturation
	Water pressure
	Aggregation state (water and/or ice)
Mechanical stresses	Stress and strain in the barriers
Material composition	Amount, composition and surface characteristics of materials in the barriers
	Type and amount of chemicals
	Type, amount of organic materials and other substances that can be used by microbes as nutrients and energy sources
	Type and amount of microbes and bacteria
Water composition	Composition of water including radionuclides
	Redox, pH, ionic strength, concentration of dissolved species, type and amount of colloids and/or particles, amount and composition of dissolved gas
	Density and viscosity
	Type and amount of microbes, bacteria and other types of biomass
Gas variables	Amount, composition including radionuclides
	Volume, pressure and degree of saturation
	Magnitude, direction and distribution of gas flow

[a] Amount and characteristics of cracks in the barrier is also an important variable.

[b] The hydraulic conductivity for the barriers is also an important variable, directly affecting the defined hydraulic variables.

12.3.1 Geometry

The design of the silo barriers is described in Section 4.1. The dimensions and material volumes are given in Section 4.5 and Appendix A.

The porosity of pure bentonite at the walls of the concrete cylinder (calculated from an average dry bulk density of about 1 000 kg/m^3 (Pusch 2003)) is about 60 %. The porosity of the sand/bentonite (90/10) at the bottom and top of the concrete cylinder (calculated from a dry bulk density of about 2 170 kg/m^3 for the bottom (Pusch 2003) and an estimate for the less compacted top layer) is about 15–25 %. The porosity of the crushed rock is 30 %.

The porosity of the structural concrete can vary between 9–15 %, see for example Höglund (1992, 2014). For the evaluation of the post-closure safety, the porosity of concrete in the concrete cylinder of the silo is estimated to be 11 %. Shotcrete is estimated to have a 30 % porosity. Cracks up to a width of 0.1 mm may be present in the structural concrete.

12.3.2 Temperature

The temperature in the waste vault is set by the surrounding rock temperature, see Section 12.1.3.

12.3.3 Hydrological variables

Directly after plugging and cessation of drainage pumping, water will start to saturate the repository. Bounding calculations have estimated that it will take about 25 years for water to fully saturate the silo (Holmén and Stigsson 2001). This means that within 25 years the bentonite and all the concrete structures will be fully water saturated. In more recent calculations, the silo repository was estimated to be fully saturated in the interval between 13 and 53 years (Börgesson et al. 2015). The largest uncertainty came from the host rock representation, both in terms of using undrained/drained and dry representations. The properties of the silo content as well as the top backfill also had significant effect on the overall saturation interval. In the perspective of the long duration of the safety assessment period, the resaturation process is assumed to be instantaneous and the repository is considered saturated at initial state.

The water pressure is anticipated to be the same as the hydrostatic pressure. This varies with location within the concrete cylinder.

The hydraulic conductivity in the pure bentonite surrounding the walls of the concrete cylinder varies from the bottom to the top depending on the degree of self-compaction. It has been concluded that the hydraulic conductivity of all parts of the wall fill will be less than about 1×10^{-10} m/s (Pusch 2003). The lower part has a hydraulic conductivity of about 9×10^{-12} m/s and the upper part about 9×10^{-11} m/s (Pusch 1985). The hydraulic conductivity in the bottom and top sand-bentonite layer will be less than 1×10^{-9} m/s (Pusch 2003).

12.3.4 Mechanical stresses

The bottom of the concrete cylinder is subjected to loads from the waste. The surrounding walls are subjected to pressure from the groundwater and backfill.

During casting of the concrete, the hydration process generates heat. As the hydrated concrete then cools, stresses may be induced within the concrete structure, which may eventually lead to cracking (micro cracks).

In addition, mechanical stresses can arise during operation due to settling of the concrete structure. Details of how this is quantified and controlled are given in Section 4.3.

One of the design considerations for the silo is that the concrete structure must be able to withstand the swelling pressure from the surrounding bentonite.

12.3.5 Material composition

The cement used for the major concrete structures in SFR1 is Degerhamn Anläggningscement. The chemical composition of this cement is presented in Table 12-5.

Degerhamn Anläggningscement satisfies the requirements of EN 197-1 Cement-Part 1: Composition, specifications and conformity criteria for common cements and is in accordance with SS 13 42 02–03 for MH/LA. The low C_3A content of Anläggningscement satisfies the requirements (i) for sulphate resistance of SR 3 type cement in EN 197-1, for low alkali cement in accordance with SS 13 42 03 and (ii) for cement with moderate heat development in accordance with SS 13 42 02.

The aggregate material used in the concrete is selected to comply with Swedish standards on resistance to alkali-silica reactions. The aggregate material in structural concrete consists of Baskarpsand, the chemical composition of this material is given in Table 12-6.

The mixing proportions used for most cementitious materials in SFR1 are given in Table 12-7.

Table 12-5. Chemical composition of Degerhamn Anläggningscement, including both the oxide composition and the corresponding clinker mineral composition as given in Alemo (1992).

Component	Content % by weight
Ca	64
SiO_2	21
Al_2O_3	3.5
Fe_2O_3	4.6
MgO	0.7
K_2O	0.62
Na_2O	0.07
SO_3	2.2
Cl	< 0.1
Free $CaCO_3$	0.9
Corresponding clinker components	
Tricalcium silicate, C_3S	64.4
Dicalcium silicate, C_2S	10.9
Tricalcium aluminate, C_3A	2.0
Tetracalcium aluminate ferrite, C_4AF	13.9
Calcium sulphate (gypsum), $C\hat{s}H_2$	3.7
Alkali hydroxides, N + K	0.7

Abbreviations used for the clinker components: C = CaO, S = SiO_2, A = Al_2O_3, F = Fe_2O_3, H = H_2O, $C\hat{s}H_2$ = $CaSO_4 \times 2H_2O$, N = Na_2O, K = K_2O.

Table 12-6. Chemical composition of Baskarpsand* ballast (Sundborg 2005).

Component	Content % by weight
CaO	1.12
SiO_2	78.8
Al_2O_3	11.6
Fe_2O_3	1.21
MgO	0.28
K_2O	3.86
Na_2O	3.09
Loss on ignition, 1 000 °C	0.48
Fraction free quartz	43

* Sintering temperature 1 250 °C.

Table 12-7. Mixing proportions for cementitious materials in SFR1, amounts given in kg/m^3.

Component	Strucural concrete (Jacobsen and Gjörv 1987)	Grout (Björkenstam 1997)	Conditioning cement
Degerhamn anläggningscement	350	325	1 180
Water	164.5	366	437
Ballast	1 829 (total)	1 302	
	0–8 mm 920 kg/m^3		
	8–16 mm 374 kg/m^3		
	16–32 mm 535 kg/m^3		-
Additives (anti-foaming, cellulose)*	0.5 % Sika Plastiment BV-40 0.05–0.2 % Sika Retarder	6.5	-
Air	-	2.5 % by volume	-
w/c ratio	0.47 (0.46–0.49)	1.125	0.37

* Not allowed in future grout.

The concrete cylinder is surrounded by a layer of bentonite (the side bentonite layer), which fills the space between the reinforced concrete and the rock. The bentonite comes from Greece (Milos) and is converted from its original Ca-form to the Na-state by soda treatment (Pusch 2003). The product name of the bentonite is GEKO/QI. The bentonite contains various accessory minerals in addition to the montmorillonite. The mineralogical and chemical composition of the bentonite used is given in Table 12-8.

In addition, small amounts of iron oxides, cristobalite, feldspar and mica have been identified in the original quality control of the bentonite (Pusch and Cederström 1987).

Table 12-8. Mineralogical and chemical composition of the side bentonite layer.

Mineral phase	Chemical formula	Content in bentonite	Comment
Montmorillonite		~ 80 wt%	72 % Na-form 27 % Mg-form Small amounts of K- and Ca-forms
Soluble sulphate	SO_4^{2-}	0.12–0.18 wt%	
Carbonate	CO_3^{2-}	< 2 %	
Pyrite	FeS_2	-	-
pH (of the porewater)		10.1–10.35	

12.3.6 Water composition

Initially, SFR vaults will be filled by the groundwater that surrounds the SFR repository (Auqué et al. 2013). No radionuclides, except for those naturally occurring in the groundwater, are deemed to be initially present. The composition of the groundwater will affect the concrete pore water composition. Reducing conditions will prevail in SFR from shortly after closure due to, for example, corrosion of the extensive amount of iron present in the repository (Duro et al. 2012). Colloids are not deemed to be stable within the concrete structures for the same reasons as given in Section 12.1.8. Initially, dissolved gases may be present in the concrete structures originating from air that might have been trapped and subsequently dissolved during saturation. The abundance of microbes within the different structures is discussed in Section 12.4.5.

The water composition of the side bentonite layer will be affected by both the surrounding groundwater composition and dissolved species from the concrete. The composition of the bentonite pore water depends on the chemical composition of the bentonite, degree of saturation and the chemical composition of the infiltrating water.

The density and viscosity of the free water are anticipated to be the same as tabulated values found in the literature for the prevailing salinity and temperature.

12.3.7 Gas variables

As the repository fills with water, the most abundant gas is the undissolved air that may be found in air pockets and pores in the materials surrounding the waste packaging, backfill materials and concrete structures.

Initially, some undissolved air may also be present in the pores of the side bentonite layer.

12.4 Variables for the 1BMA and 2BMA system components

The system components are valid for both 1BMA and 2BMA.

The concrete in the different waste vaults comprises the slab, lid, outer and inner walls in 1BMA, caissons in 2BMA, and shotcrete. The shotcrete is used to stabilise the rock during the operational period.

A prefabricated concrete element is placed over each full compartment or caisson in BMA. The elements provide radiation shielding and fire protection.

At closure, the existing 1BMA walls will be repaired as described in Mårtensson et al. (2022) and an additional hydraulic barrier will be constructed around the existing 1BMA structure.

Table 12-4 shows the variables for the engineered barriers in SFR.

12.4.1 Geometry

The design of the 1BMA and 2BMA vaults is described in Sections 5.1 and 6.1 respectively. The dimensions and material volumes are described in Sections 5.5 and 6.5, respectively and Appendix A.

The porosity can vary between 9–15 % in the structural concrete, see for example Höglund (1992, 2014). For the evaluation of the post-closure safety, the porosity of the existing 1BMA concrete structure is estimated to be 14 %, while the porosity of the additional 1BMA concrete walls and 2BMA structural concrete is estimated to be 11 %. Shotcrete, grout and macadam are estimated to have a 30 % porosity.

Cracks up to a width of 0.1 mm that e.g. arise during shrinkage may be present in the structural concrete. Larger cracks are possible to inject before closure, which ensures a low hydraulic conductivity (Mårtensson 2014). Cracks with a geometrical aperture less than 0.1 mm tend not to be penetrating (Mårtensson 2014).

12.4.2 Temperature

The temperature in the waste vault is set by the surrounding rock temperature, see Section 12.1.3.

12.4.3 Hydrological variables

Directly after plugging and cessation of drainage pumping, water will start to saturate the repository. Full resaturation of the waste vaults, except the silo, has been calculated to take a few years (Holmén and Stigsson 2001). This means that within a few years the 1BMA concrete structures will be fully water saturated. For SFR3, the same resaturation rate is anticipated even though the hydrostatic pressure differs at the greater depth. In the perspective of the long duration of the safety assessment period, the resaturation process is assumed to be instantaneous and the repository is considered saturated at initial state.

The water pressure is anticipated to be the same as the hydrostatic pressure. The hydrostatic pressure differs between 1BMA and 2BMA due to the different depths.

The hydraulic conductivities of the different concrete types are given in the **Data report**. The hydraulic conductivity in the macadam is high, initially higher than 10^{-2} m/s (Mårtensson et al. 2022).

Initially, all of the water within the waste packaging is liquid due to the temperature, see Section 12.1.3. However, this variable is not relevant for the steel packaging.

12.4.4 Mechanical stresses

The slabs of 1BMA and 2BMA are subjected to loads from the waste. The surrounding walls are subjected to pressure from the groundwater and backfill. The 2BMA structure will furthermore be subjected to unilateral water pressure since the slab is not expected to be hydraulically transmissible. The slab in 1BMA on the other hand is considered to be hydraulically transmissible.

During casting of the concrete, the hydration process generates heat. As the hydrated concrete then cools, stresses may be induced within the concrete structure, which may eventually lead to cracking. Due to the lack of reinforcement in 2BMA which otherwise could limit crack formation, larger cracks could not be completely ruled out in the 2BMA structural concrete. Cracking can however be prevented by a correct choice of concrete mix, design and construction methods (Mårtensson and Vogt 2020).

12.4.5 Material composition

The composition of the cement is presented in Table 12-5, 12-6 and 12-7.

The mixing proportions of the concrete that will be used to make the new walls around the existing 1BMA walls and the 2BMA caissons are shown in Table 12-9.

The caissons in 2BMA contain inner walls that will allow the unreinforced outer walls to withstand the water pressure during saturation without the need for grouting.

Table 12-9. Mixing proportions for the concrete used to cast the new walls in 1BMA and the 2BMA caissons (Lagerblad et al. 2017).

Component	Amount (kg/m^3)
Anläggningscement	320
OMYACARB 2GU*	130
Myanit 10**	33.3
Water	156.8
16–22 mm	393.3
8–16 mm	425.7
4–8 mm	92.0
0–4 mm Swerock	840.9
MasterGlenium Sky 558	1.30
Master Sure	1.70
Master Set RT 401	0.96

* $CaCO_3$.

** Dolomite product.

The BMA waste vaults are planned to be backfilled with macadam in the size range 16–32 mm. This type of material has high hydraulic conductivity and is a suitable backfill according to the closure plan for SFR (Mårtensson et al. 2022). The concrete structures found within the SFR repository are not deemed to contribute to any significant amounts of nutrients for microbes compared to the nutrient amounts found in the infiltrating groundwater. The microbial population initially present in the concrete structures mainly depends on the transport of microbes into the repository by the infiltrating groundwater as well as the microbial population established during the operational period.

12.4.6 Water composition

Initially, SFR vaults will be filled by the groundwater that surrounds the SFR repository (Auqué et al. 2013). No radionuclides, except for those naturally occurring in the groundwater, are deemed to be initially present. The composition of the groundwater will affect the concrete pore water composition. Reducing conditions will prevail in SFR from shortly after closure due to, for example, corrosion of the extensive amount of iron present in the repository (Duro et al. 2012). Colloids are not deemed to be stable within the concrete structures for the same reasons as given in Section 12.1.8. Initially, dissolved gases may be present in the concrete structures originating from air that might have been trapped and subsequently dissolved during saturation. The abundance of microbes within the different structures is discussed in Section 12.4.5.

The density and viscosity of the free water are anticipated to be the same as tabulated values found in the literature for the prevailing salinity and temperature present.

12.4.7 Gas variables

As the repository fills with water, the most abundant gas is the undissolved air that may be found in air pockets and pores in the materials surrounding the waste packaging, backfill materials and concrete structures.

12.5 Variables for the 1BRT system components

The reactor pressure vessels (RPVs) are planned to be cut into segments, placed in double moulds and stabilised with concrete. The waste packages will be placed in concrete compartments of the 1BRT concrete structure and the space between the waste packages will be filled with self-compacting concrete so that a network of load-bearing structures is formed. 1BRT will be backfilled with macadam.

Table 12-4 shows the variables for the engineered barriers in SFR.

12.5.1 Geometry

The design of the 1BRT waste vault is described in Section 7.1. The dimensions and material volumes are given in Section 7.5 and Appendix A.

For the evaluation of the post-closure safety, the porosity of the 1BRT structural concrete is estimated to be 14 %. Shotcrete, grout and macadam are estimated to have a 30 % porosity. Cracks (> 0.1 mm) may be present in the structural concrete and grout.

12.5.2 Temperature

The temperature in the waste vault is set by the surrounding rock temperature, see Section 12.1.3.

12.5.3 Hydrological variables

For the 1BRT waste vault, these system variables are the same as for the BMA vaults, see Section 12.4.3.

12.5.4 Mechanical stresses

For the 1BRT waste vault, this system variable is the same as for the BMA vaults, see Section 12.4.4.

12.5.5 Material composition

The structural concrete used in the 1BRT waste vault will be similar to the materials described in Table 12-9.

Macadam in the size range 16–32 mm will be used.

12.5.6 Water composition

For the 1BRT waste vault, this system variable is the same as for the BMA vaults, see Section 12.4.6.

12.5.7 Gas variables

For the 1BRT waste vault, these system variables are the same as for the BMA vaults, see Section 12.4.7.

12.6 Variables for the 1BTF and 2BTF system components

The 1BTF and 2BTF waste vaults have been designed primarily for storing concrete tanks and drums with low to medium activity waste. The waste vaults have a concrete slab, and the rock walls and ceilings are lined with shotcrete. The space between the concrete tanks and drums will be grouted. Shotcrete is used to stabilise the rock during the operational period. The only post-closure function of the shotcrete is that it contributes to the high pH, through the dissolution of cement minerals.

Table 12-4 shows the variables for the engineered barriers in SFR.

12.6.1 Geometry

The design of 1BTF and 2BTF is described in Section 8.1. The dimensions are given in Sections 8.5 and 8.6, respectively and Appendix A.

For the evaluation of the post-closure safety, the porosity of the BTF structural concrete is anticipated to be the same as for the existing 1BMA concrete structure, 14 %. Shotcrete and macadam are estimated to have a 30 % porosity. BTF grout is estimated to have a porosity of 20 %. Cracks (> 0.1 mm) may be present in the grouting concrete at closure.

12.6.2 Temperature

The temperature in the waste vaults is set by the surrounding rock temperature, see Section 12.1.3.

12.6.3 Hydrological variables

For the BTF waste vaults, this system variable is the same as for the BMA vaults, see Section 12.4.3.

12.6.4 Mechanical stresses

For the BTF waste vaults, this system variable is the same as for the BMA vaults, see Section 12.4.4.

12.6.5 Material composition

The structural concrete used in the BTF waste vaults will be similar to the concrete in the 1BMA concrete structure. This safety assessment is based on the usage of two different grouts and their mixing proportions as given in Table 12-10. Around the concrete tanks and also up to half the height of the uppermost layer of steel drums, the main grout is applied. Around the topmost half of the uppermost drum layer the other "top grout" is applied. Table 12-10 also gives the recipe for an additional grout that is likely to be used, however, this recipe is not applied in this safety assessment

Macadam in the size range 16–32 mm will be used.

Table 12-10. Mixing proportions for BTF grout (kg/m^3) based on SKB (R-01-14) and (Systembeskrivning SFR – System 195 – Kringgjutning och driftförslutning av avfall).

Component	Main grout (tanks and bottom drum layer)	Top drum layer grout	Additional recipe
Cement	340	265	523
Water	252	141	424
Aggregates	1630	1890	1001
Bentonite			25
Silica			21

12.6.6 Water composition

For the BTF waste vaults, this system variable is the same as for the BMA vaults, see Section 12.4.6.

12.6.7 Gas variables

For the BTF waste vaults, this system variable is the same as for the BMA vaults, see Section 12.4.7.

12.7 Variables for the 1BLA and 2–5BLA system components

BLA is considered to have limited barrier functions in the post-closure safety assessment. Although intact waste containers can limit the water flow through the waste to some extent, they are not considered to be a barrier. Shotcrete is used to stabilise the rock during the operational period. The only post-closure function of the shotcrete considered is that it contributes to the high pH through the dissolution of its cement mineral content. The concrete bottom plate is also included in the assessment of the pH conditions.

Table 12-4 shows the variables for the engineered barriers in SFR.

12.7.1 Geometry

The design of the 1BLA and 2–5BLA vaults is described in Sections 9.1 and 10.1, respectively. The dimensions of the 1BLA and 2–5BLA vaults are presented in Sections 9.4 and 10.4, respectively and Appendix A.

For the evaluation of the post-closure safety, the porosity of the BLA slab structures is estimated to be 11 %. Shotcrete is estimated to have a 30 % porosity.

12.7.2 Temperature

The temperature in the waste vaults is set by the surrounding rock temperature, see Section 12.1.3.

12.7.3 Hydrological variables

For the 1BLA and 2–5BLA vaults, this system variable is the same as for the BMA vaults, see Section 12.4.3. The water pressure is anticipated to be the same as the hydrostatic pressure.

Initially, all water is liquid due to the temperature, see Section 12.1.3. However, this variable is not relevant for the steel packaging.

12.7.4 Mechanical stresses

Mechanical stresses may occur at the concrete slabs due to the waste loads.

12.7.5 Material composition

Macadam will not be used as backfill material in the BLA waste vaults.

12.7.6 Water composition

Initially, the BLA vaults will be filled by the groundwater that surrounds the SFR repository (Auqué et al. 2013). No radionuclides, except for those naturally occurring in the groundwater, are deemed to be initially present. The groundwater will affect the concrete pore water composition, as discussed in Section 12.3.6. The groundwater will be affected by cement leachate to differing extents in the different vaults, depending on the composition and amounts of concrete and shotcrete.

Colloids are not expected to be stable within the concrete structures for the reasons given in Section 12.1.8. The presence of colloids in 1BMA at closure cannot be excluded, see Section 12.1.8.

Dissolved gases may be present initially in the pore water of the concrete structures due to the dissolution of air trapped during saturation, as well as from the groundwater. The abundance of microbes within the different structures is discussed in Section 12.4.5.

The density and viscosity of the water are anticipated to be the same as tabulated values found in the literature at the temperature present.

12.7.7 Gas variables

As the vaults fills with water, the most abundant gas is the undissolved air that may be found in air pockets and pores in the materials.

12.8 Variables for plugs and other closure components

The closure of SFR will be performed according to the closure plan for SFR (Mårtensson et al. 2022), see also Section 11.1. The plugs consist of tunnel sections filled with bentonite that are confined by mechanical constraints. In most positions, concrete mechanical constraints are used. In some sections, where the geometry and the local geology make it difficult or impossible to construct concrete mechanical constraints, transition materials are used. Transition materials do not require local mechanical support from the rock walls. The function of the bentonite-filled sections is to act as hydraulic seals. The function of the mechanical constraints is to confine the bentonite sections. The remaining parts of the tunnel system will be filled with crushed rock.

12.8.1 Geometry

The porosity can vary between 9–15 % in the structural concrete, see for example Höglund (1992, 2014). For the evaluation of the post-closure safety 11 % is used as the porosity in the concrete, and 30 % in the macadam. The properties for the bentonite are described in the closure plan for SFR (Mårtensson et al. 2022).

12.8.2 Temperature

For the plugs and other closure components, this system variable is set by the surrounding rock temperature, see Section 12.1.3.

12.8.3 Hydrological variables

The hydraulic conductivity of the concrete used in plugs and other concrete closure components is anticipated to be the same as the concrete in the BMA vaults. The water pressure is anticipated to be the same as the hydrostatic pressure at the depth where the plugs and other closure components are placed. The hydraulic conductivities of the different concrete types are given in the **Data report**. The hydraulic conductivity in the macadam is high, initially higher than 10^{-2} m/s (Mårtensson et al. 2022).

The hydraulic conductivity of the bentonite in the connecting tunnels (brown in Figure 11-1) is expected to be less than 10^{-10} m/s, i.e. the same as the hydraulic conductivity for the deposition tunnels in the repository for spent fuel (SKB TR-10-52, p 151). The initial hydraulic conductivity could be as low as $10^{-13} - 10^{-12}$ m/s (Mårtensson et al. 2022). The hydraulic conductivity of the low hydraulic conductivity sections in the access tunnels (orange in Figure 11-1) is calculated from the requirement of a resistance of at least 2×10^{9} s that correspond to 5×10^{-10} m/s for a 1 m section.

12.8.4 Mechanical stresses

For the plugs, the swelling pressure of the bentonite will dominate the mechanical stresses on the concrete structures. In the PSAR, it is anticipated that the concrete closure components will be designed to withstand the swelling pressure from the bentonite.

12.8.5 Material composition

The transition materials in the earth dam plugs are anticipated to consist of 30 % bentonite and 70 % crushed rock (dry weight) (Mårtensson et al. 2022). The concrete mechanical constraints will consist of standard concrete. The bentonite consists of a high quality bentonite, the properties of which are described in the closure plan for SFR (Mårtensson et al. 2022).

12.8.6 Water composition

Initially, the plugs and other components will be filled by the groundwater that surrounds the SFR repository (Auqué et al. 2013). The composition of the groundwater will affect the concrete pore water composition. Reducing conditions will prevail in SFR from shortly after closure due to, for example, corrosion of the extensive amount of iron present in the repository (Duro et al. 2012). Colloids are not expected to be stable within the concrete structures for the reasons given in Section 12.1.8. Initially, dissolved gases may be present in the concrete structures originating from air that might have been trapped and subsequently dissolved during saturation. The microbial population initially present in the structures mainly depends on the transport of microbes into the repository by the infiltrating groundwater as well as the microbial population established during the operational period.

The density and viscosity of the free water are anticipated to be the same as tabulated values found in the literature for the prevailing salinity and temperature present.

12.8.7 Gas variables

As the repository fills with water, the most abundant gas is the undissolved air that may be found in air pockets and pores in the material.

References

SKB's (Svensk Kärnbränslehantering AB) publications can be found at www.skb.com/publications. SKBdoc documents will be submitted upon request to document@skb.se.

References with abbreviated names

Post-closure safety report, 2023. Post-closure safety for SFR, the final repository for short-lived radioactive waste at Forsmark. Main report, PSAR version. SKB TR-23-01, Svensk Kärnbränslehantering AB.

Barrier process report, 2023. Post-closure safety for SFR, the final repository for short-lived radioactive waste at Forsmark. Engineered barrier process report, PSAR version. SKB TR-23-04, Svensk Kärnbränslehantering AB.

Biosphere synthesis report, 2023. Post-closure safety for SFR, the final repository for short-lived radioactive waste at Forsmark. Biosphere synthesis report, PSAR version. SKB TR-23-06, Svensk Kärnbränslehantering AB.

Climate report, 2023. Post-closure safety for SFR, the final repository for short-lived radioactive waste at Forsmark. Climate and climate-related issues, PSAR version. SKB TR-23-05, Svensk Kärnbränslehantering AB.

Data report, 2023. Post-closure safety for SFR, the final repository for short-lived radioactive waste at Forsmark. Data report, PSAR version. SKB TR-23-10, Svensk Kärnbränslehantering AB.

FEP report, 2014. FEP report for the safety assessment SR-PSU. SKB TR-14-07, Svensk Kärnbränslehantering AB.

FHA report, 2023. Post-closure safety for SFR, the final repository for short-lived radioactive waste at Forsmark. Handling of future human actions, PSAR version. SKB TR-23-08, Svensk Kärnbränslehantering AB.

Geosphere process report, 2014. Geosphere process report for the safety assessment SR-PSU. SKB TR-14-05, Svensk Kärnbränslehantering AB.

Model tools report, 2023. Post-closure safety for SFR, the final repository for short-lived radioactive waste at Forsmark. Model tools summary report, PSAR version. SKB TR-23-11, Svensk Kärnbränslehantering AB.

Radionuclide transport report, 2023. Post-closure safety for SFR, the final repository for short-lived radioactive waste at Forsmark. Radionuclide transport and dose calculations, PSAR version. SKB TR-23-09, Svensk Kärnbränslehantering AB.

Waste process report, 2023. Post-closure safety for SFR, the final repository for short-lived radioactive waste at Forsmark. Waste form and packaging process report, PSAR version. SKB TR-23-03, Svensk Kärnbränslehantering AB.

Regular references

Abarca E, Sampietro D, Sanglas J, Molinero J, 2020. Modelling of the near-field hydrogeology. Report for the safety assessment SR-PSU (PSAR). SKB R-19-20, Svensk Kärnbränslehantering AB.

Alemo J, 1992. Typanalys degerhamns anläggningscement använd vid byggandet av SFR1. Vattenfall Utveckling AB. SKBdoc 1430502 ver 1.0, Svensk Kärnbränslehantering AB. (In Swedish.)

Auqué L F, Gimeno M, Acero P, Gómez J, 2013. Compositions of groundwater for SFR and its extension, during different climatic cases, SR-PSU. SKB R-13-16, Svensk Kärnbränslehantering AB.

Björkenstam E, 1997. Referensdokument till driftsinstruktioner – avser kringgjutningsbruket i SFR. UC 97:6Ö, Vattenfall Utveckling AB. SKBdoc 1439833 ver 1.0, Svensk Kärnbränslehantering AB.

Börgesson L, Åkesson M, Kristensson O, Malmberg D, Birgersson M, Hernelind J, 2015. Modelling of critical H-M processes in the engineered barriers of SFR. SKB TR-14-27, Svensk Kärnbränslehantering AB.

Canderyd S, 2022. Avfallshandbok – låg- och medelaktivt avfall. SKBdoc 1195328 ver 10.0, Svensk Kärnbränslehantering AB. (In Swedish.)

Carlsson A, Christiansson R, 2007. Construction experiences from underground works at Forsmark. Compilation report. SKB R-07-10, Svensk Kärnbränslehantering AB.

Duro L, Grivé M, Domènech C, Roman-Ross G, Bruno J, 2012. Assessment of the evolution of the redox conditions in SFR1. SKB TR-12-12, Svensk Kärnbränslehantering AB.

Elfwing M, Mårtensson M, Pettersson A, 2015. Rapport över aktuell status för 1BMA i SFR1. SKBdoc 1440875 ver 2.0, Svensk Kärnbränslehantering AB. (In Swedish.)

Elfwing M, Lundin M, von Schenck H, 2017. Vidareutvecklad utformning av förvarsutrymmet 2BMA i utbyggd del av SFR. SKBdoc 1569813 ver 1.0, Svensk Kärnbränslehantering AB. (In Swedish.)

Elfwing M, von Schenck H, Åstrand P-G, 2018. Uppdaterad analys av strålsäkerheten efter förslutning för 1BMA i SFR1. SKBdoc 1686798 ver 1.0, Svensk Kärnbränslehantering AB. (In Swedish.)

Engkvist I, Albinsson Y, Johansson Engkvist W, 1996. The long-term stability of cement – Leaching tests. SKB TR 96-09, Svensk Kärnbränslehantering AB.

Eriksson Örtengren M, Eriksson A, 2014. Acceptanskriterier för avfall, Projekt SFR-utbyggnad. SKBdoc 1368638 ver 1.0, Svensk Kärnbränslehantering AB. (In Swedish.)

Hejll A, Hassanzadeh M, Hed G, 2012. Sprickor i BMA:s betongbarriär – Inspektion och orsak. AE-NCC 12-004 Rev 1.0, Vattenfall AB. SKBdoc 1430853 ver 1.0, Svensk Kärnbränslehantering AB. (In Swedish.)

Holmén J G, Stigsson M, 2001. Modelling of future hydrogeological conditions at SFR. SKB R-01-02, Svensk Kärnbränslehantering AB.

Höglund L O, 1992. Some notes of ettringite formation in cementitous materials; Influence of hydration and thermodynamic constraints for durability. Cement and Concrete Research 22, 217–228.

Höglund L O, 2014. The impact of concrete degradation on the BMA barrier functions. SKB R-13-40, Svensk Kärnbränslehantering AB.

IAEA, 2006. Joint convention on the safety of spent fuel management and on the safety of radioactive waste management. Vienna: International Atomic Energy Agency.

Jacobsen S, Gjörv O, 1987. Hydraulisk konduktivitet i SFR Silobetong. SKB Projekt SFR Teknisk PM 45. Bilaga 1: Ingemar Lundholm, Vattenfall Forsmark 87-04-02, SFR1 – Siloglidgjutning Provkuber. (In Swedish.)

Keith-Roach M, Lindgren M, Källström K, 2021. Assessment of complexing agent concentrations for the post-closure safety assessment in PSAR SFR. SKB R-20-04, Svensk Kärnbränslehantering AB.

Lagerblad B, Trägårdh J, 1994. Conceptual model for concrete long time degradation in a deep nuclear waste repository. SKB TR 95-21, Svensk Kärnbränslehantering AB.

Lagerblad B, Rogers P, Vogt C, Mårtensson P, 2017. Utveckling av konstruktionsbetong till kassunerna i 2BMA. SKB R-17-21, Svensk Kärnbränslehantering AB. (In Swedish.)

Malmberg D, Kristensson O, 2015. SFR Rapport silorörelser, tryck och dränage 2015. SKBdoc 1528019 ver 1.0, Svensk Kärnbränslehantering AB. (In Swedish.)

Moreno L, Skagius K, Södergren S, Wiborgh M, 2001. Project SAFE. Gas related processes in SFR. SKB R-01-11, Svensk Kärnbränslehantering AB.

Mårtensson P, 2014. Heliumläcksökning av sprickor i betongkonstruktionen i 1BMA. SKBdoc 1452199 ver 1.0, Svensk Kärnbränslehantering AB. (In Swedish.)

Mårtensson P, Vogt C, 2019. Concrete caissons for 2BMA. Large scale test of design and material. SKB TR-18-12, Svensk Kärnbränslehantering AB.

Mårtensson P, Vogt C, 2020. Concrete caissons for 2BMA. Large scale test of design, material and construction method. SKB TR-20-09, Svensk Kärnbränslehantering AB.

Mårtensson P, Luterkort D, Nyblad B, Wimelius H, Pettersson A, Aghili B, Andolfsson T, 2022. SFR förslutningsplan. SKBdoc 1358612 ver 4.0, Svensk Kärnbränslehantering AB. (In Swedish.)

Pettersson A, 2017. Redovisning av teknisk barriär vid övergång till segmenterade reaktortankar. SKBdoc 1604614 ver 2.0, Svensk Kärnbränslehantering AB. (In Swedish.)

Pusch R, 1985. Buffertar av bentonitbaserade material i siloförvaret. Funktion och utförande. SKB SFR 85-08, Svensk Kärnbränslehantering AB. (In Swedish.)

Pusch R, 2003. Design, construction and performance of the clay-based isolation of the SFR silo. SKB R-03-30, Svensk Kärnbränslehantering AB.

Pusch R, Cederström M, 1987. Material- och byggnadskontroll av bentonitbarriärer i SFR, Forsmark. SKB SFR 87-08, Svensk Kärnbränslehantering AB. (In Swedish.)

Pusch R, Ramqvist G, 2007. Borehole project – Final report of Phase 3. SKB R-07-58, Svensk Kärnbränslehantering AB.

Sandén T, Nilsson U, Johannesson L-E, Hagman P, Nilsson G, 2018. Sealing of investigation boreholes. Full scale field test and large-scale laboratory tests. SKB TR-18-18, Svensk Kärnbränslehantering AB.

Sandén T, Nilsson U, Johannesson L-E, 2020. PM Uppdatering av koncept för borrhålsförslutning Projekt UPP018-19-1. SKBdoc 1885331 ver 1.0, Svensk Kärnbränslehantering AB. (In Swedish.)

SFS 1984:3. Lag om kärnteknisk verksamhet (Nuclear Activities Act). Stockholm: Ministry of the Environment. (In Swedish.)

SFS 1977:1160. Arbetsmiljölag (Work Environment Act). Stockholm: Ministry of Employment. (In Swedish.)

SFS 1998:808. Miljöbalk (Environmental Code). Stockholm: Ministry of the Environment. (In Swedish.)

SFS 2010:900. Plan- och bygglag (Planning and Building Act). Stockholm: Ministry of the Environment. (In Swedish.)

SFS 2018:396. Strålskyddslag (Radiation Protection Act). Stockholm: Ministry of the Environment. (In Swedish.)

SKB R-01-14. SKB 2001. Project SAFE. Compilation of data for radionuclide transport analysis. Svensk Kärnbränslehantering AB.

SKB R-08-130. SKB 2008. Safety analysis SFR1. Long-term safety. Svensk Kärnbränslehantering AB.

SKB R-15-15. SKB 2015. Low and intermediate level waste in SFR. Reference inventory for waste 2013. Svensk Kärnbränslehantering AB.

SKB R-18-07. SKB 2019. Låg- och medelaktivt avfall i SFR. Referensinventarium för avfall 2016. Svensk Kärnbränslehantering AB. (In Swedish.)

SKB TR-10-52. SKB 2010. Data report for the safety assessment SR-Site. Svensk Kärnbränslehantering AB.

SKB TR-11-04. SKB 2013. Site description of the SFR area at Forsmark at completion of the site investigation phase. SDM-PSU Forsmark. Svensk Kärnbränslehantering AB.

SKB TR-13-10. SKB 2013. Äspö Hard Rock Laboratory. Annual report 2012. Svensk Kärnbränslehantering AB.

SKB TR-14-01. SKB 2015. Safety analysis for SFR. Long-term safety. Main report for the safety assessment SR-PSU. Revised edition. Svensk Kärnbränslehantering AB.

SKB TR-14-02. SKB 2014. Initial state report for the safety assessment SR-PSU. Svensk Kärnbränslehantering AB.

SSMFS 2008:1. Strålsäkerhetsmyndighetens föreskrifter och allmänna råd om säkerhet i kärntekniska anläggningar. (Regulations concerning safety in nuclear facilities) Stockholm: Strålsäkerhetsmyndigheten (Swedish Radiation Safety Authority) (In Swedish).

SSMFS 2008:12. Strålsäkerhetsmyndighetens föreskrifter och allmänna råd om fysiskt skydd av kärntekniska anläggningar (Regulations concerning physical protection of nuclear facilities). Stockholm: Strålsäkerhetsmyndigheten (Swedish Radiation Safety Authority) (In Swedish).

SSMFS 2008:21. Strålsäkerhetsmyndighetens föreskrifter och allmänna råd om säkerhet vid slutförvaring av kärnämne och kärnavfall (Regulations concerning safety in connection with the disposal of nuclear material and nuclear waste). Stockholm: Strålsäkerhetsmyndigheten (Swedish Radiation Safety Authority) (In Swedish).

SSMFS 2008:37. Strålsäkerhetsmyndighetens föreskrifter och allmänna råd om skydd av människors hälsa och miljön vid slutligt omhänder-tagande av använt kärnbränsle och kärnavfall (Regulations on the protection of human health and the environment in connection with the final management of spent nuclear fuel and nuclear waste). Stockholm: Strålsäkerhetsmyndigheten (Swedish Radiation Safety Authority) (In Swedish).

SSMFS 2018:3. Strålsäkerhetsmyndighetens föreskrifter om undantag från strålskyddslagen och om friklassning av material, byggnadsstrukturer och områden (Regulations concerning exemption from the radiation protection law and clearance of materials, building structures and sites). Stockholm: Strålsäkerhetsmyndigheten (Swedish Radiation Safety Authority) (In Swedish).

Sundberg J, Back P-E, Ländell M, Sundberg A, 2009. Modelling of temperature in deep boreholes and evaluation of geothermal heat flow at Forsmark and Laxemar. SKB TR-09-14, Svensk Kärnbränslehantering AB.

Sundborg P, 2005. Analys av sand. Glasforskningsinstitutet. SKBdoc 1392924 ver 1.0, Svensk Kärnbränslehantering AB. (In Swedish).

Väisäsvaara J, 2009. Site investigation SFR. Difference flow logging in borehole KFR105. SKB P-09-09, Svensk Kärnbränslehantering AB.

Öhman J, Odén M, 2018. SR-PSU (PSAR) Bedrock hydrogeology. TD18 – Temperate climate conditions. SKB P-18-02, Svensk Kärnbränslehantering AB.

Appendix A

Estimated material and void + pore volumes in the waste vaults

Table A-1. Estimated material and void/pore volumes in the silo.

Material silo	Volume (m^3)	Void + pore volume* (m^3)	Comment
Concrete structures			
Bottom	538	59	Calculated π × (27.6 / 2) ^ 2 × 0.9
Outer wall	3 540	389	Calculated π × (27.6 / 2) ^ 2 × 52.55 − π × ((27.6 − 2 × 0.8) / 2) ^ 2 × 52.55
Inner walls	5 518	607	Calculated inner volume – total inside shaft
Lid	531	58	Calculated π × ((27.6 − 2 × 0.8) / 2) ^ 2 × 1
Total concrete structure	10 127	1 114	
Inside in shafts			
Shafts full-size	19 014		Calculated 57 × 2.55 × 2.55 × 51.3
Shafts half-size – B, C, D	2 119		Calculated 12 × 2.55 × 1.35 × 51.3
Shafts quarter-size – E	347		Calculated 4 × 1.3 × 1.3 × 51.3
Small shafts – F, G	239		Calculated 8 × (0.75 × 0.64 + 1 / 2 × (0.91 − 0.64) × 0.75) × 51.3
Total inside shafts	21 718		
Waste			
All waste	15 640	3 308	Outer volume of waste in silo from the inventory report (SKB R-18-07). Pore volume of concrete packaging (0.11 m^3/m^3) added to the pore volume given in SKB (R-18-07).
Concrete grout			
Concrete grout (waste section)	6 131	1 839	Calculated total inside shaft – total waste volume + upper 0.1 m sand layer for leveling (21 718 − 15 640 + 53)
Bentonite			
Surronding concrete structure	4 126	2 517	Calculated π × (29.4 / 2) ^ 2 × 51.2 − π × (27.6 / 2) ^ 2 × 51.2, bentonite porosity 61 %
Sand-bentonite			
Bottom	1 018	255	Calculated π × (29.4 / 2) ^ 2 × 1.5, sand-bentonite porosity 25 %
Top	1 492	373	Calculated π × (31 / 2) ^ 2 × 1.5 + π × (31 / 2) ^ 2 × 2.3 − π × (27.6 / 2) ^ 2 × 2.3, sand-bentonite porosity 25 %
Total sand-bentonite	2 510	628	
Additional materials			
Bottom – Cast coarse concrete for drainage system (m)	68	20	Calculated π × (29.4 / 2) ^ 2 × 0.1, porosity as concrete grout
Bottom – Concrete plate with drainage system	136	41	Calculated π × (29.4 / 2) ^ 2 × 0.2, porosity as concrete grout
Bottom – Thin concrete layer	30	9	Calculated π × ((27.6 / 2) ^ 2 × 0.05, porosity as concrete grout
Top lid – Sand layer above concrete grout	27	8	Calculated π × ((27.6 − 2 × 0.8) / 2) ^ 2 × 0.05, porosity 30 %
Top lid – Sand above concrete part of lid	53	16	Calculated π × ((27.6 − 2 × 0.8) / 2) ^ 2 × 0.1, porosity 30 %
Backfill – Friction material in cupola	6 347	1 904	90 % of remaing volume in cupola, porosity 30 %
Backfill – Cement-stabilised sand in cupola	705	212	10 % of remaining volume in cupola, porosity 30 %
Total additional materials	7 365	2 210	
Total additional materials excluding sand above the grout and lid	7 285	2 186	
Totals			
Total concrete silo including waste	31 978	6 285	
Total	45 900	11 615	

* Estimated porosities: Shotcrete and grout 0.3, structural concrete 0.11, macadam/rock fill 0.3.

Table A-2. Estimated volumes and void including porosity in materials in 1BMA, based on the repair measures given in Elfwing et al. (2018).

Material 1BMA	Volume (m^3)	Void + pore volume* (m^3)	Comment
Shotcrete			
Shotcrete (waste section + walls, i.e. 140.45 m)	352	106	Assumed 0.05 m thickness on walls and roof (2 × average height + width). Calculated 140.45 × (2 × (300 / 19.6 − 0.05) + 19.6) × 0.05
Shotcrete inner zone	12	3	Assumed 0.05 m thickness on walls and roof (2 × average height + width). Calculated (2.55 + 2.1) × (2 × (300 / 19.6 − 0.05) + 19.6) × 0.05
Shotcrete reloading zone	37	11	Assumed 0.05 m thickness on walls and roof (2 × average height + width). Calculated 14.9 × (2 × (300 / 19.6 − 0.05) + 19.6) × 0.05
Total shotcrete	401	120	
Concrete slab in inner and reloading zone			
Slab inner zone	18	3	Calculated (2.1 + 2.55) × 15.62 × 0.25
Slab reloading zone	58	8	Calculated 14.9 × 15.62 × 0.25
Total concrete slab in inner and reloading zone	76	11	
Original concrete structure			
Slab	514	72	Calculated (139.85 − 0.4 − 0.6) × (15.62 − 2 × 0.4) × 0.25. The edges of the slab are not included here – they are included in the calculation of the walls
Outer long walls	996	139	Calculated 2 × 139.85 × 8.9 × 0.4
Outer short wall (TT)	53	7	Calculated 14.82 × 8.9 × 0.4
Outer short wall (BST)	79	11	Calculated 14.82 × 8.9 × 0.6
Inner walls	563	79	Calculated 13 × 7.3 × 14.82 × 0.4 (between slab and lid)
Inner wall (between small compartments)	14	2	Calculated 1 × 7.3 × 4.95 × 0.4 (between slab and lid)
Total original concrete structure	2 220	311	
Additional reinforced external concrete walls (lower porosity concrete)			
Outer long walls	750	83	Calculated 2 × 140.45 × 8.9 × 0.3
Outer short wall (TT)	42	5	Calculated 15.62 × 8.9 × 0.3
Outer short wall (BST)	42	5	Calculated 15.62 × 8.9 × 0.3
Lid	2 507	276	Calculated ((139.85 − (0.4 + 0.6)) × 14.82 × (0.4 + 0.5) + 139.85 × 15.62 × 0.3 (inside outer walls)
Total additional reinforced external concrete walls and lid	3 341	367	
Concrete structures divided into compartments			
Compartment 1			
Slab	37	5	Calculated (9.9 + 0.4 + 0.4 / 2) × 15.62 × 0.25
Outer long walls (original concrete)	75	10	Calculated 2 × ((9.9 + 0.4 + 0.4 / 2) × 8.9 × 0.4
Outer long walls (new concrete)	58	6	Calculated 2 × ((9.9 + 0.4 + 0.3 + 0.4 / 2) × 8.9 × 0.3
Outer short wall (TT) (original concrete)	53	7	Calculated 14.82 × 8.9 × 0.4
Outer short wall (TT) (new concrete)	42	5	Calculated 15.62 × 8.9 × 0.3
Inner walls	22	3	Calculated (half inner wall) 7.3 × 14.82 × 0.4 / 2
Lid	184	20	Calculated (9.9 + 0.4 / 2) × 14.82 × (0.4 + 0.5) + (9.9 + 0.4 / 2 + 0.4) × 15.62 × 0.3
Total original concrete in compartment 1	187	26	
Total new concrete in compartment 1	283	31	
Total concrete structure Compartment 1	470	57	
Compartment 2–13			
Slab	38	5	Calculated (9.9 + 0.4 / 2 + 0.4 / 2) × 15.62 × 0.25
Outer long walls (original concrete)	73	10	Calculated 2 × ((9.9 + 0.4 / 2 + 0.4 / 2) × 8.9 × 0.4
Outer long walls (new concrete)	55	6	Calculated 2 × ((9.9 + 0.4 / 2 + 0.4 / 2) × 8.9 × 0.3
Inner walls	43	6	Calculated 2 × 7.3 × 14.82 × 0.4 / 2
Lid	186	20	Calculated (9.9 + 0.4 / 2 + 0.4 / 2) × 14.82 × (0.4 + 0.5) + (9.9 + 0.4 / 2 + 0.4 / 2) × 15.62 × 0.3
Total original concrete in compartments 2–13	155	22	

Table A-2. Continued.

Material 1BMA	Volume (m^3)	Void + pore volume* (m^3)	Comment
Total new concrete in compartment 2–13	241	26	
Total concrete structure per compartment	395	48	
Compartment 14 and 15			
Slab	10	1	Calculated (7.21 + 0.4 / 2) × (4.95 + 0.4 / 2) × 0.25
Outer long walls (original concrete)	20	3	Calculated (4.95 + 0.6 + 0.4 / 2) × 8.9 × 0.4
Outer long walls (new concrete)	16	2	Calculated (4.95 + 0.6 + 0.3 + 0.4 / 2) × 8.9 × 0.3
Outer short wall (BST) (original concrete)	40	6	Calculated 14.82 / 2 × 8.9 × 0.6
Outer short wall (BST) (new concrete)	21	2	Calculated 14.82 / 2 × 8.9 × 0.3
Inner walls	18	3	Calculated 7.3 × 4.95 × 0.4 / 2 + 7.3 × 14.82 × 0.4 / 2 / 2
Lid	48	5	Calculated (4.95 + 0.4 / 2) × (14.82 / 2) × (0.4 + 0.5) + (4.95 + 0.4 / 2 + 0.6) × 15.62 / 2 × 0.3
Total original concrete in compartments 14 and 15	88	12	
Total new concrete in compartments 14 and 15	85	9	
Total concrete structure per compartment	172	22	
Waste in compartments 1–15			
Compartment 1	995	171	Inventory report (SKB R-18-07)
Compartment 2	803	203	Inventory report (SKB R-18-07)
Compartment 3	874	184	Inventory report (SKB R-18-07)
Compartment 4	995	212	Inventory report (SKB R-18-07)
Compartment 5	825	164	Inventory report (SKB R-18-07)
Compartment 6	798	159	Inventory report (SKB R-18-07)
Compartment 7	995	186	Inventory report (SKB R-18-07)
Compartment 8	995	300	Inventory report (SKB R-18-07)
Compartment 9	995	213	Inventory report (SKB R-18-07)
Compartment 10	978	252	Inventory report (SKB R-18-07)
Compartment 11	527	177	Inventory report (SKB R-18-07)
Compartment 12	93	17	Inventory report (SKB R-18-07)
Compartment 13	73	14	Inventory report (SKB R-18-07)
Compartment 14	149	29	Inventory report (SKB R-18-07)
Compartment 15	133	26	Inventory report (SKB R-18-07)
Total	10 229	2 038	
Void in compartments 1–15			
Compartment 1	76	76	Inner voloume of compartment (9.9 × 14.82 × 7.3) − waste volume
Compartment 2	269	269	See compartment 1
Compartment 3	197	197	See compartment 1
Compartment 4	76	76	See compartment 1
Compartment 5	246	246	See compartment 1
Compartment 6	273	273	See compartment 1
Compartment 7	76	76	See compartment 1
Compartment 8	76	76	See compartment 1
Compartment 9	76	76	See compartment 1
Compartment 10	93	93	See compartment 1
Compartment 11	544	544	See compartment 1
Compartment 12	978	978	See compartment 1
Compartment 13	998	998	See compartment 1
Compartment 14	112	112	Inner voloume of compartment (4.95 × 7.21 × 7.3) − waste volume
Compartment 15	127	127	See compartment 14
Total	4 216	4 216	
Macadam/Rock fill			
Bottom (below compartments out to vault walls, excluding the volume filled by the walls of the barrier and concrete structure)	1 160	348	Calculated 140.45 × (19.6 − 2 × 0.05) × (0.15 + 0.3) − 2 × 139.85 × 0.4 × 0.3 − 2 × 140.45 × (0.4 + 0.3) × 0.15 − 14.82 × (0.4 + 0.6) × 0.3 − 15.62 × (0.4 + 0.3 + 0.6 + 0.3) × 0.15

Table A-2. Continued.

Material 1BMA	Volume (m^3)	Void + pore volume* (m^3)	Comment
Sides (between compartments and rock)	4 031	1 209	Calculated 140.45 × (19.6 − 15.62 − 2 × 0.3 − 2 × 0.05) × (9.2 − 0.15)
Top (above compartments)	13 848	4 154	Calculated 140.45 × (19.6 − 2 × 0.05) × (300 / 19.6 − 1 − 0.05 − 8.9 − 0.3) (the top is assumed to be filled to1 m below the ceiling))
Bottom at inner zone (TT)	41	12	Calculated 4.65 × (19.6 − 2 × 0.05) × (0.15 + 0.3)
Macadam inner zone (TT)	1 234	370	Calculated (4.65 × (19.6 − 2 × 0.05) × (300 / 19.6 − 1 − 0.3 − 0.15 − 0.05) − 18) (assumed to be filled to 1 m below the ceiling)). The calculation has been simplified by assigning the same cross-sectional area for the whole length (4.95 m), even though 2.55 m has a smaller cross-sectional area.
Bottom at reloading zone (BST)	131	39	Calculated 14.9 × (19.6 − 2 × 0.05) × (0.15 + 0.3)
Macadam reloading zone (BST)	3 953	1 186	Calculated (14.9 × 19.6 × (300 / 19.6 − 1 − 0.3 − 0.15 − 0.05) − 58) (assumed to be filled to 1 m below the ceiling))
Total macadam	24 398	7 320	
Non filled volume			
Top of waste section (empty space over macadam)	2 739	2 739	Calculated 140.45 × (19.6-2 × 0.05) × 1 (1 m gap between the ceiling and macadam)
Top of inner zone	91	91	Calculated 4.65 × (19.6-2 × 0.05) × 1 (1 m gap between the ceiling and macadam)
Top of reloading zone	291	291	Calculated (14.9 × (19.6 − 2 × 0.05) × 1) (1 m gap between the ceiling and macadam)
Total non filled volume	3 120	3 120	
Totals			
Structural concrete including waste and void space	20 000	7 202	
Total waste section, i.e 140.45 m	42 135	15 759	
Total rock vault	48 000	17 773	

* Estimated porosities: Shotcrete and grout 0.3, structural concrete 0.11 (new) and 0.14 (existing) and macadam/rock fill 0.3.

Table A-3. For comparison with Table A-2: Estimated material and void/pore volumes in 1BMA in the absence of any repair measures. Note that, in this case, macadam backfill is not used.

Material 1BMA	Volume (m^3)	Void + pore volume* (m^3)	Comment
Shotcrete			
Shotcrete (waste section + walls, i.e.139.85 m)	350	105	Assumed 0.05 m thickness on walls and roof (2 × average height + width). Calculated 139.85 × (2 × (300 / 19.6 − 0.05) + 19.6) × 0.05
Shotcrete inner zone	12	4	Assumed 0.05 m thickness on walls and roof (2 × average height + width). Calculated (2.55 + 2.1 + 0.3) × (2 × (300 / 19.6 − 0.05) + 19.6) × 0.05
Shotcrete reloading zone	38	11	Assumed 0.05 m thickness on walls and roof (2 × average height + width). Calculated (14.9 + 0.3) × (2 × (300 / 19.6 − 0.05) + 19.6) × 0.05
Total shotcrete	401	120	Note, doesn't take the smaller cross sectional area of a part of the inner zone – a small difference
Concrete slab in inner and reloading zone			
Slab inner zone	19	3	Calculated (2.1 + 2.55 + 0.3) × 15.62 × 0.25
Slab reloading zone	59	8	Calculated (14.9 + 0.3) × 15.62 × 0.25
Total concrete slab in inner and reloading zone	78	11	
Concrete structure			
Slab	514	72	Calculated (139.85 − 0.4 − 0.6) × (15.62 − 2 × 0.4) × 0.25. The edges of the slab are not included here – they are included in the calculation of the walls
Outer long walls	996	139	Calculated 2 × 139.85 × 8.9 × 0.4

Table A-3. Continued.

Material 1BMA	Volume (m^3)	Void + pore volume* (m^3)	Comment
Outer short wall (TT)	53	7	Calculated 14.82 × 8.9 × 0.4
Outer short wall (BST)	79	11	Calculated 14.82 × 8.9 × 0.6
Lid	1 852	259	Calculated ((139.85 − (0.4 + 0.6)) × 14.82 × (0.4 + 0.5) (inside outer walls)
Inner walls	563	79	Calculated 13 × 7.3 × 14.82 × 0.4 (between slab and lid)
Inner wall (between small compartments)	14	2	Calculated 1 × 7.3 × 4.95 × 0.4 (between slab and lid)
Total concrete structure	4 071	570	
Alternative division of concrete structures			
Compartment 1			
Slab	37	5	Calculated (9.9 + 0.4 + 0.4/2) × 15.62 × 0.25
Outer long walls (original concrete)	75	10	Calculated 2 × (9.9 + 0.4 + 0.4/2) × 8.9 × 0.4
Outer short wall (TT) (original concrete)	53	7	Calculated 14.82 × 8.9 × 0.4
Inner walls	22	3	Calculated (half inner wall) 7.3 × 14.82 × 0.4/2
Lid	135	19	Calculated (9.9 + 0.4/2) × 14.82 × (0.4 + 0.5)
Total structural concrete in Compartment 1	321	45	
Compartment 2–13			
Slab	38	5	Calculated (9.9 + 0.4/2 + 0.4/2) × 15.62 × 0.25
Outer long walls (original concrete)	73	10	Calculated 2 × ((9.9 + 0.4/2 + 0.4/2) × 8.9 × 0.4
Inner walls	43	6	Calculated 2 × 7.3 × 14.82 × 0.4/2
Lid	137	19	Calculated (9.9 + 0.4/2 + 0.4/2) × 14.82 × (0.4 + 0.5)
Total structural concrete in Compartment 2–13	292	41	
Compartment 14 and 15			
Slab	10	1	Calculated (7.21 + 0.4/2) × (4.95 + 0.4/2) × 0.25
Outer long walls (original concrete)	20	3	Calculated (4.95 + 0.6 + 0.4/2) × 8.9 × 0.4
Outer short wall (BST) (original concrete)	40	6	Calculated 14.82/2 × 8.9 × 0.6
Inner walls	18	3	Calculated 7.3 × 4.95 × 0.4/2 + 7.3 × 14.82 × 0.4/2/2
Lid	34	5	Calculated (4.95 + 0.4/2) × (14.82/2) × (0.4 + 0.5)
Total structural concrete in Compartment 14 and 15	122	17	
Waste			
Total	10 229	2 308	From inventory report (SKB R-18-07), but pore volume of concrete packaging (0.11 m^3/m^3) added here
Alternative division of waste			
Compartment 1	995	171	From inventory report (SKB R-18-07)
Compartment 2	803	203	From inventory report (SKB R-18-07)
Compartment 3	874	184	From inventory report (SKB R-18-07)
Compartment 4	995	212	From inventory report (SKB R-18-07)
Compartment 5	825	164	From inventory report (SKB R-18-07)
Compartment 6	798	159	From inventory report (SKB R-18-07)
Compartment 7	995	186	From inventory report (SKB R-18-07)
Compartment 8	995	300	From inventory report (SKB R-18-07)
Compartment 9	995	213	From inventory report (SKB R-18-07)
Compartment 10	978	252	From inventory report (SKB R-18-07)
Compartment 11	527	177	From inventory report (SKB R-18-07)
Compartment 12	93	17	From inventory report (SKB R-18-07)
Compartment 13	73	14	From inventory report (SKB R-18-07)
Compartment 14	149	29	From inventory report (SKB R-18-07)
Compartment 15	133	26	From inventory report (SKB R-18-07)
Total	10 229	2 308	
Void around waste packages			
Compartment 1	76	76	Inner voloume of comartment (9.9 × 14.82 × 7.3) − waste volume
Compartment 2	269	269	See compartment 1
Compartment 3	197	197	See compartment 1

Table A-3. Continued.

Material 1BMA	Volume (m^3)	Void + pore volume* (m^3)	Comment
Compartment 4	76	76	See compartment 1
Compartment 5	246	246	See compartment 1
Compartment 6	273	273	See compartment 1
Compartment 7	76	76	See compartment 1
Compartment 8	76	76	See compartment 1
Compartment 9	76	76	See compartment 1
Compartment 10	93	93	See compartment 1
Compartment 11	544	544	See compartment 1
Compartment 12	978	978	See compartment 1
Compartment 13	998	998	See compartment 1
Compartment 14	112	112	Inner voloume of comartment (4.95 × 7.21 × 7.3) − waste volume
Compartment 15	127	127	See compartment 14
Total	4 216	4 216	
Macadam/Rock fill			
Bottom (below compartments out to vault walls, excluding the volume filled by the walls of the barrier and concrete structure)	1 170	351	Calculated 139.85 × (19.6 − 2 × 0.05) × (0.15 + 0.3) − 14.82 × 0.4 × (0.15 + 0.3) − 14.82 × 0.6 × (0.15 + 0.3) − 2 × 139.85 × 0.4 × (0.15 + 0.3)
Bottom at inner zone (TT)	43	13	Calculated (4.65 + 0.3) × (19.6 − 2 × 0.05) × (0.15 + 0.3)
Macadam inner zone (TT)	1 314	394	Calculated ((4.65 + 0.3) × (19.6 − 2 × 0.05) × (300/19.6 − 1 − 0.3 − 0.15 − 0.05) − 19) (assumed to be filled to × 1 m below the ceiling)). The calculation has been simplified by assigning the same cross-sectional area for the whole length (4.95 m), even though 2.55 m has a smaller cross-sectional area.
Bottom at reloading zone (BST)	133	40	Calculated (14.9 + 0.3) × (19.6 − 2 × 0.05) × (0.15 + 0.3)
Macadam reloading zone (BST)	4 033	1 210	Calculated ((14.9 + 0.3) × (19.6 − 2 × 0.05) × (300/19.6 − 1 − 0.3 − 0.15 − 0.05) − 59) (assumed to be filled to 1 m below the ceiling))
Total macadam	6 693	2 008	
Non filled volume			
Sides (between compartments and rock)	4 585	4 585	Calculated 139.85 × (19.6 − 15.62 − 2 × 0.05) × (8.9 − 0.3 − 0.15)
Top (above compartments)	17 334	17 334	Calculated 139.85 × (19.6 − 2 × 0.05) × (300/19.6 − 0.05 − 8.9)
Top of inner zone	97	97	Calculated (4.65 + 0.3) × (19.6 − 2 × 0.05) × 1 (1 m gap between the ceiling and macadam)
Top of reloading zone	296	296	Calculated ((14.9 + 0.3) × (19.6 − 2 × 0.05) × 1) (1 m gap between the ceiling and macadam)
Total non filled volume	22 312	22 312	
Totals			
Structural concrete with waste	18 516	7 094	
Total waste section, i.e 139.85 m	41 955	29 469	
Total rock vault	48 000	31 545	

* Estimated porosities: Shotcrete 0.3, structural concrete 0.14 and macadam/rock fill 0.3.

Table A-4. Estimated material and void/pore volumes in 2BMA.

Material 2BMA	Volume (m^3)	Void + pore volume* (m^3)	Comment
Shotcrete			
Shotcrete (waste section, i.e. 253.6 m)	4 448	1 334	Assumed 0.3 m thickness on walls and roof (2 × average height + width). Calculated 253.6 × (2 × (17.8 − 0.3) + 23.5) × 0.3
Shotcrete inner zone	35	11	Assumed 0.3 m thickness on walls and roof (2 × average height + width). Calculated 2 × (2 × (17.8 − 0.3) + 23.5) × 0.3
Shotcrete reloading zone	341	102	Assumed 0.3 m thickness on walls and roof (2 × average height + width). Calculated 19.44 × (2 × (17.8 − 0.3) + 23.5) × 0.3
Total shotcrete	4 824	1 447	
Concrete in caisson structures			
Slab 1 caisson	197	22	Calculated 2 562 / 13
Outer walls 1 caisson	398	44	Calculated 5 180 / 13
Inner walls 1 caisson	295	32	Calculated 3 834 / 13
Lid 1 caisson	318	35	Calculated 4 140 / 13
Total 1 caisson	1 209	133	
Total in all caissons	15 715	1 729	
Waste			
One caisson	1 110	294	Outer volume of waste in 2BMA (inventory report (SKB R-18-07)) divided by the 13 caissons. Calculated 14 425 / 13. Pore volume of concrete packaging (0.11 m^3/m^3) added to the pore volume given in SKB (R-18-07).
All caissons	14 425	3 816	
Empty space in caissons			
One caisson	637	637	Calculated as the volume of a cassion minus the volume of concrete and waste, 2 955 − 1 209 − 1 110
All caissons	8 275	8 275	
Concrete in other structures			
Concrete bottom plate – inner zone	18.3	2	Calculated as a proportion of the bottom plate: 2 504 × 2 / 274.4
Concrete bottom plate – waste zone	2 314	255	Calculated as a proportion of the bottom plate: 2 504 × 253.6 / 274.4
Concrete bottom plate – reloading zone	175	19	Calculated as a proportion of the bottom plate: 2 504 × (19.44 − 0.3) / 274.4
Radiation shield in the loading area	89	10	3D model 200515
Concrete hangarport	12	1	3D model 200515
Concrete gate roof	11	1	3D model 200515
Concrete gate walls	23	3	3D model 200515
Concrete crane support	196	22	3D model 200515
Total in other concrete structures	2 837	312	
Macadam/Rock fill			
Bottom (below caissons, out to vault walls, subtracting volume of bottom plate and concrete crane support)	6 200	1 860	Calculated 253.6 × (23.5 − 2 × 0.3) × (1 + 0.5) − 2 314 − 196
Sides (beside caissons)	10 908	3 272	Calculated 253.6 × (23.5 − 18.12 − 2 × 0.3) × 9
Between caissons	2 935	881	Calculated (253.6 − 13 × 18.12) × 18.12 × 9
Top (above caissons)	34 765	10 430	Calculated 253.6 × (23.5 − 2 × 0.3) × (17.8 − 1 − 1 − 9.0 − 0.5 − 0.3) (the top volume is assumed to be filled to 1 m below the ceiling)
Bottom at inner zone (out to vault walls)	50	15	Calculated 2 × (23.5 − 2 × 0.3) × (1 + 0.5) − 18.3
Macadam inner zone (TT)	686	206	Calculated 2 × (23.5 − 2 × 0.3) × (17.8 − 1 − 0.3 − 0.5 − 1) (assumed to be filled to 1 m below the ceiling))
Bottom at reloading zone (out to vault walls)	493	148	Calculated 19.44 × (23.5 − 2 × 0.3) × (1 + 0.5) − 175

Table A-4. Continued.

Material 2BMA	Volume (m^3)	Void + pore volume* (m^3)	Comment
Macadam reloading zone (BST)	6 538	1 961	Calculated 19.44 × (23.5 − 2 × 0.3) × (17.8 − 1 − 0.3 − 1 − 0.5) − 88.6 − 11.66 − 10.58 − 23.4 (assumed to be filled to 1 m below the ceiling))
Total macadam	62 041	18 612	
Non filled volume			
Top (empty space above top macadam)	5 807	5 807	Calculated 253.6 × (23.5 − 2 × 0.3) × 1 (filled to 1 m below the ceiling)
Top of inner zone	46	46	Calculated 2 × (23.5 − 2 × 0.3) × 1 (filled to 1 m below the ceiling)
Top of reloading zone	445	445	Calculated 19.44 × (23.5 − 2 × 0.3) × 1 (filled to 1 m below the ceiling)
Total non filled volume	6 298	6 298	
Totals			
Total waste section, i.e. 253.6 m	105 988	37 403	
Total rock vault	114 950	40 649	

* Estimated porosities: Shotcrete 0.3, structural concrete 0.11 and macadam/rock fill 0.3.

Table A-5. Estimated material and void/pore volumes in 1BRT.

Material 1BRT	Volume (m^3)	Void + pore volume × (m^3)	Comment
Shotcrete			
Shotcrete (waste section + walls, i.e. 224.4 m)	3 098	929	Assumed 0.3 m thickness on walls and roof (2 × average height + width). Calculated 224.4 × (2 × (14.5 − 0.3) + 17.7) × 0.3
Shotcrete inner zone	138	41	Assumed 0.3 m thickness on walls and roof (2 × average height + width). Calculated 10 × (2 × (14.5 − 0.3) + 17.7) × 0.3
Shotcrete reloading zone	285	85	Assumed 0.3 m thickness on walls and roof (2 × average height + width). Calculated 20.64 × (2 × (14.5 − 0.3) + 17.7) × 0.3
Total shotcrete	3 521	1 056	
Concrete slab in vault			
Slab (waste section, i.e. 224.4 m)	1 932	212	Calculated 224.4 × 12.3 × 0.7
Slab zone at 2TT	86	9	Calculated 10 × 12.3 × 0.7
Slab zone at 2BST	178	20	Calculated 20.64 × 12.3 × 0.7
Total concrete slab	2 196	242	
Concrete structure			
Outer long walls	1 279	141	Calculated 2 × 224.4 × 0.5 × 5.7
Outer short wall (TT)	30	3	Calculated 10.5 × 5.7 × 0.5
Outer short wall (BST)	30	3	Calculated 10.5 × 5.7 × 0.5
Inner walls	546	60	Calculated (1 + 20 − 1) × 10.5 × 5.2 × 0.5 (between slab and lid)
Lid	1 173	129	Calculated (224.4 − 0.5 − 0.5) × (11.5 − 2 × 0.5) × 0.5 (inside outer walls)
Total concrete structure	3 057	336	
Waste			
Total waste	6 666	1 728	Inventory report (SKB R-18-07). Pore volume of concrete packaging (0.11 m^3/m^3) added to the pore volume given in SKB (R-18-07)
Concrete grout			
Total (all compartments)	4 983	1 495	Volume of concrete structure – total concrete in structure – waste, calculated 224.4 × 11.5 × 5.7 − 3 057 − 6 666

Table A-5. Continued.

Material 1BRT	Volume (m^3)	Void + pore volume × (m^3)	Comment
Concrete in other structures			
Concrete crane support	227	25	3D model 200515
Macadam/Rock fill			
Bottom (waste section, i.e. 224.4 m)	3 837	1 151	Calculated 224.4 × (17.7 − 2 × 0.3) × 1
Bottom at 2TT	171	51	Calculated 10 × (17.7 − 2 × 0.3) × 1
Bottom at 2BST	353	106	Calculated 20.65 × (17.7 − 2 × 0.3) × 1
Sides (waste section, subtracting volume of concrete crane support)	7 689	2 307	Calculated 224.4 × (17.7 − 11.5 − 2 × 0.3) × (5.7 + 0.7) − 224.4 × (12.3 − 11.5) × 0.7 − 226.5
Top (waste section)	22 111	6 633	Calculated 224.4 × (17.7 − 2 × 0.3) × (14.5 − 0.3 − 5.7 − 0.7 − 1 − 1)
Inner zone (TT)	1 994	598	Calculated 10 × (17.7 − 2 × 0.3) × (14.5 − 0.3 − 1 − 1) − 86
Reloading zone (BST)	4 115	1 235	Calculated 20.64 × (17.7 − 2 × 0.3) × (14.5 − 0.3 − 1 − 1) − 178 (Filled to 1 m below ceiling)
Total macadam	40 270	12 081	
Non filled volume			
Top (waste section)	3 837	3 837	Calculated 224.4 × 1 × (17.7 − 2 × 0.3)
Top zone at 2TT	171	171	Calculated 10 × 1 × (17.7 − 2 × 0.3)
Top zone at 2BST	353	353	Calculated 20.6 × 1 × (17.7 − 2 × 0.3) (Filled to 1 m below ceiling).
Total non filled volume	4 361	4 361	
Totals			
Structural concrete with waste and grout	16 513	3 758	
Total waste section, 224.4 m	57 436	18 654	
Total rock vault	65 280	21 324	

* Estimated porosities: Shotcrete and grout 0.3, structural concrete 0.11 and macadam/rock fill 0.3.

Table A-6. Estimated material and void/pore volumes in 1BTF.

Material 1BTF	Volume (m^3)	Void + pore volume* (m^3)	Comment
Shotcrete			
Shotcrete (waste section + walls, i.e.130.6 m)	210	63	Assumed 0.05 m thickness on walls and roof (2 × average height + width). Calculated 130.6 × (2 × (129 / 14.7 − 0.05) + 14.7) × 0.05.
Shotcrete inner zone	6	2	Assumed 0.05 m thickness on walls and roof (2 × average height + width). Calculated 3.6 × (2 × (129 / 14.7 − 0.05) + 14.7) × 0.05.
Shotcrete reloading zone	41	12	Assumed 0.05 m thickness on walls and roof (2 × average height + width) Calculated 25.8 × (2 × (8.8 − 0.05) + 14.7) × 0.05
Total shotcrete	257	77	
Concrete structures			
Slab (waste section + walls, i.e.130.6 m)	477	67	Calculated 130.6 × (14.7 − 2 × 0.05) × 0.25
Prefabricated concrete element	712	100	Calculated 130 × 13.7 × 0.4 (above waste)
Lid	759	106	Calculated 130 × (14.7 − 2 × 0.05) × 0.4 (above prefabricated concrete element)
Walls (both sides)	50	7	Calculated 2 × 0.3 × (4.9 + 0.4 + 0.4) × (14.7 − 2 × 0.05)
Slab inner zone	13	2	Calculated 3.6 × (14.7 − 2 × 0.05) × 0.25
Slab reloading zone	94	13	Calculated 25.8 × (14.7 − 2 × 0.05) × 0.25
Total concrete structures	2 106	295	
Waste			
Total waste	5 218	1 274	Inventory report (SKB R-18-07). Pore volume of concrete packaging (0.11 m^3/m^3) added to the pore volume given in SKB (R-18-07)
Concrete grout			
Concrete grout (waste section)	4 129	826	Calculated 130 × (14.7 − 2 × 0.05) × (4.9 + 0.4) − 5 218 − 712
Macadam/Rock fill			
Bottom (waste section + walls, i.e.130.6 m)	858	257	Calculated 130.6 × (14.7 − 2 × 0.05) × (0.3 + 0.15)
Top (waste section)	2 527	758	Calculated 130.6 × (14.7 − 2 × 0.05) × (129 / 14.7 − 1 − 0.05 − 0.4 − 0.4 − 4.9 − 0.25 − 0.15 − 0.3) (assumed to be filled to 1 m below ceiling)
Bottom at inner zone	24	7	Calculated 3.6 × (14.7 − 2 × 0.05) × (0.15 + 0.3)
Bottom at reloading zone	170	51	Calculated 25.8 × (14.7 − 2 × 0.05) × (0.15 + 0.3)
Macadam inner zone	369	111	Calculated 3.6 × (129 / 14.7 − 1 − 0.05) × (14.7 − 2 × 0.05) − 13 − 24 (assumed to be filled to 1 m below ceiling)
Macadam reloading zone	2 646	794	Calculated 25.8 × (129 / 14.7 − 1 − 0.05) × (14.7 − 2 × 0.05) − 94 − 170 (assumed to be filled to 1 m below the ceiling)
Total macadam/rock fill	6 594	1 978	
Non filled volume			
Top (waste section)	1 907	1 907	Calculated 130.6 × (14.7 − 2 × 0.05) × 1 (assumed to be filled to 1 m below ceiling)
Top of inner zone	53	53	Calculated 3.6 × 1 × (14.7 − 2 × 0.05) (assumed to be filled to 1 m below ceiling)
Top of reloading zone	377	377	Calculated 25.8 × 1 × (14.7 − 2 × 0.05) (assumed to be filled to 1 m below ceiling)
Total non filled volume	2 336	2 336	
Totals			
Total waste section, i.e.130.6 m	16 847	5 365	
Total rock vault	20 640	6 786	

* Estimated porosities: Shotcrete 0.3, grout 0.2, structural concrete 0.14 and macadam/rock fill 0.3.

Table A-7. Estimated material and void/pore volumes in 2BTF.

Material 2BTF	Volume (m^3)	Void + pore volume* (m^3)	Comment
Shotcrete			
Shotcrete (waste section + walls, i.e.130.6 m)	210	63	Assumed 0.05 m thickness on walls and roof (2 × average height + width). Calculated 130.6 × (2 × (129 / 14.7 − 0.05) + 14.7) × 0.05
Shotcrete inner zone	6	2	Assumed 0.05 m thickness on walls and roof (2 × average height + width). Calculated 3.6 × (2 × (129 / 14.7 − 0.05) + 14.7) × 0.05.
Shotcrete reloading zone	41	12	Assumed 0.05 m thickness on walls and roof (2 × average height + width). Calculated 25.8 × (2 × (8.8 − 0.05) + 14.7) × 0.05.
Total shotcrete	257	77	
Concrete structures			
Slab (waste section + walls, i.e.130.6 m)	477	67	Calculated 130.6 × (14.7 − 2 × 0.05) × 0.25
Prefabricated concrete element	712	100	Calculated 130 × 13.7 × 0.4 (above waste)
Lid	759	106	Calculated 130 × (14.7 − 2 × 0.05) × 0.4 (above prefabricated concrete element)
Walls (both sides)	50	7	Calculated 2 × 0.3 × (4.9 + 0.4 + 0.4) × (14.7 − 2 × 0.05)
Slab inner zone	13	2	Calculated 3.6 × (14.7 − 2 × 0.05) × 0.25
Slab reloading zone	94	13	Calculated 25.8 × (14.7 − 2 × 0.05) × 0.25
Total concrete structres	2 106	295	
Waste			
Total waste	7 578	1 881	Inventory report (SKB R-18-07). Pore volume of concrete packaging (0.11 m^3/m^3) added to the pore volume given in SKB (R-18-07)
Concrete grout			
Concrete grout (waste section)	1 769	354	Calculated 130 × (14.7 − 2 × 0.05) × (4.9 + 0.4) − 7 578 − 712
Macadam/Rock fill			
Bottom (waste section + walls, i.e.130.6 m)	858	257	Calculated 130.6 × (14.7 − 2 × 0.05) × (0.3 + 0.15)
Top (waste section)	2 527	758	Calculated 130.6 × (14.7 − 2 × 0.05) × (129 / 14.7 − 1 − 0.05 − 0.4 − 0.4 − 4.9 − 0.25 − 0.15 − 0.3) (assumed to be filled to 1 m below ceiling)
Bottom at inner zone	24	7	Calculated 3.6 × (14.7 − 2 × 0.05) × (0.15 + 0.3)
Bottom at reloading zone	170	51	Calculated 25.8 × (14.7 − 2 × 0.05) × (0.15 + 0.3)
Macadam inner zone	369	111	Calculated 3.6 × (129 / 14.7 − 1 − 0.05) × (14.7 − 2 × 0.05) − 13 − 24 (assumed to be filled to 1 m below ceiling)
Macadam reloading zone	2 646	794	Calculated 25.8 × (129 / 14.7 − 1 − 0.05) × (14.7 − 2 × 0.05) − 94 − 170 (assumed to be filled to 1 m below the ceiling
Total macadam/rock fill	6 594	1 978	
Non filled volume			
Top (waste section)	1 907	1 907	Calculated 130.6 × (14.7 − 2 × 0.05) × 1 (assumed to be filled to 1 m below ceiling)
Top of inner zone	53	53	Calculated 3.6 × 1 × (14.7 − 2 × 0.05) (assumed to be filled to 1 m below ceiling)
Top of reloading zone	377	377	Calculated 25.8 × 1 × (14.7 − 2 × 0.05) (assumed to be filled to 1 m below ceiling)
Total non filled volume	2 336	2 336	
Totals			
Total waste section, i.e.130.6 m	16 847	5 500	
Total rock vault	20 640	6 922	

* Estimated porosities: Shotcrete 0.3, grout 0.2, structural concrete 0.14 and macadam/rock fill 0.3.

Table A-8. Estimated material and void/pore volumes in 1BLA.

Material 1BLA	Volume (m^3)	Void + pore volume* (m^3)	Comment
Shotcrete			
Shotcrete (waste section, i.e.146.3 m)	279	84	Assumed 0.05 m thickness on walls and roof (2 × average height + width). Calculated 146.3 × (2 × (11.8 − 0.05) + 14.7) × 0.05.
Shotcrete inner zone	7	2	Assumed 0.05 m thickness on walls and roof (2 × average height + width). Calculated 3.7 × (2 × (11.8 − 0.05) + 14.7) × 0.05.
Shotcrete reloading zone	19	6	Assumed 0.05 m thickness on walls and roof (2 × average height + width). Calculated 10 × (2 × (11.8 − 0.05) + 14.7) × 0.05.
Total shotcrete	305	92	
Concrete structures			
Slab (waste section, i.e. 146.3 m)	501	55	Calculated 146.3 × 13.7 × 0.25
Slab inner zone	13	1	Calculated 3.7 × 13.7 × 0.25
Slab reloading zone	34	4	Calculated 10 × 13.7 × 0.25
Total concrete	548	60	
Waste			
ISO-containers	13652	10341	Outer volume of waste in 1BLA from the inventory report (SKB R-18-07). Pore volume of concrete packaging (0.11 m^3/m^3) added to the pore volume given in SKB (R-18-07).
Concrete grout			
Waste section	0	0	No grout surrounding waste
Macadam/Rock fill			
Bottom (waste section, i.e.146.3 m)	961	288	Calculated 146.3 × (14.7 − 2 × 0.05) × (0.3 + 0.15)
Bottom inner zone	24	7	Calculated 3.7 × (14.7 − 2 × 0.05) × (0.3 + 0.15)
Bottom reloading zone**	66	20	Calculated 10 × (14.7 − 2 × 0.05) × (0.3 + 0.15)
Macadam/rock fill inner zone	542	163	Calculated to 1 m below the ceiling 3.7 × (14.7 − 2 × 0.05) × (11.77 − 1 − 0.05) − 13 − 24
Macadam/rock fill reloading zone	1465	439	Calculated to 1 m below the ceiling, 10 × (14.7 − 2 × 0.05) × (11.8 − 1 − 0.05) − 34 − 66
Total macadam/rock fill	3058	917	
Non filled volume			
Empty space outside ISO-containers (waste section, i.e.146.3 m)	9917	9917	Calculated 146.3 × (14.7 − 2 × 0.05) × (11.8 − 0.05) − 501 − 13652 − 961
Top of inner zone	54	54	Calculated 3.7 × (14.7 − 2 × 0.05) × 1 (assumed to be filled to 1 m below the ceiling)
Top of reloading zone	146	146	Calculated 10 × (14.7 − 2 × 0.05) × 1 (assumed to be filled to 1 m below the ceiling)
Total non filled volume	10117	10117	
Totals			
Total waste section, i.e.146.3 m	25310	20685	
Total rock vault	27680	21527	

* Estimated porosities: Shotcrete 0.3, structural concrete 0.11 and macadam/rock fill 0.3.

** The backfill is anticipated to consist of macadam alone, although the top edge nearest the plug is planned to consist of concrete.

Table A-9. Estimated material and void/pore volumes in 2–5BLA (one waste vault).

Material 2–5BLA	Volume (m^3)	Void + pore volume* (m^3)	Comment
Shotcrete			
Shotcrete (waste section, i.e. 243 m)	1 481	444	Assumed 0.14 m thickness on walls and roof (2 × average height + width) Calculated 243 × (2 × (14 − 0.14) + 17.9) × 0.14 (2 × average height + width).
Shotcrete inner zone	50	15	Assumed 0.14 m thickness on walls and roof (2 × average height + width) Calculated 8.2 × (2 × (13.0 − 0.14) + 17.9) × 0.14
Shotcrete reloading zone	152	46	Assumed 0.14 m thickness on walls and roof (2 × average height + width) Calculated 23.8 × (2 × (13.0 − 0.14) + 20) × 0.14
Total shotcrete	1 683	505	
Concrete structures			
Slab (waste section, i.e. 243 m)	1 545	170	Calculated 243 × 15.9 × 0.4
Slab inner zone	52	6	Calculated 8.2 × 15.9 × 0.4
Slab reloading zone	214	24	Calculated 23.8 × 18 × 0.5
Total concrete	1 812	199	
Waste			
ISO-containers	18 818	11 423	Outer volume of waste in 2BLA from the inventory report (SKB R-18-07) divided by 4. Pore volume of concrete packaging (0.11 m^3/m^3) added to the pore volume given in SKB (R-18-07).
Concrete grout			
Waste section	0	0	No grout surrounding waste
Macadam			
Bottom (waste section, i.e. 243 m)	4 282	1 284	Calculated 243 × (17.9 − 2 × 0.14) × 1
Bottom inner zone	144	43	Calculated 8.2 × (17.9 − 2 × 0.14) × 1
Bottom reloading zone	469	141	Calculated 23.8 × (20 − 2 × 0.14) × 1
Macadam inner zone	1 511	453	Calculated 8.2 × (17.9 − 2 × 0.14) × (13 − 1 − 0.14) − 52 − 144 (assumed to be filled to 1 m below the ceiling)
Macadam reloading zone**	4 883	1 465	Calculated 23.8 × (20 − 2 × 0.14) × (13 − 1 − 0.14) − 214 − 469 (assumed to be filled to 1 m below the ceiling)
Total macadam	11 290	3 387	
Non filled volume			
Empty space outside ISO-containers (waste section, i.e. 243 m)	30 250	30 250	Calculated 243 × (13 − 0,14) × (17,9 − 2 × 0,14) − 1 545 − 18 818 − 4 282
Top of inner zone	144	144	Calculated as the 1 m gap between the macadam and ceiling 8.2 × (17.9 − 2 × 0.14) × 1
Top of reloading zone	469	469	Calculated as the 1 m gap between the macadam and ceiling 23.8 × (20 − 2 × 0.05) × 1
Total non filled volume	30 864	30 864	
Totals			
Total waste section, i.e. 243 m	56 376	43 571	
Total rock vault	64 466	46 378	

* Estimated porosities: Shotcrete 0.3, structural concrete 0.11 and macadam/rock fill 0.3.

** The backfill is anticipated to consist of macadam alone, although the top edges nearest the plugs are planned to consist of concrete.

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