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Detailed site investigation programme for the construction and operation of the Repository for spent nuclear fuel

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Svensk Kärnbränslehantering AB

Keywords: Detailed site investigations, Investigations, Modelling, Monitoring, Requirements, Design requirements, Repository for spent nuclear fuel, Construction, Operation, Deposition.

Update notice

The original report, dated December 2016, was found to contain both factual and editorial errors which have been corrected in this updated version. The corrected factual errors are presented below.

Updated 2023-09

Location	Original text	Corrected text
Page 24, paragraph 4, last sentence	Testing of methods and methodology for identification and quantification of critical structures of class 3 has been carried out at Äspö (SKB 2018).	Sentence removed.
Page 88, reference SKB 2018	Incorrect reference.	Reference removed.
Page 90, last paragraph, last sentence	… carried out at Äspö (SKB 2018).	… carried out at Äspö.

Preface

Since the framework programme for detailed site investigations during the construction and operation of the Repository for spent nuclear fuel (SKB 2010a) was published, the work with the reference design of the facility in Forsmark has continued, along with the work of updating the technical design requirements regarding safety after closure.

This report is an update of the detailed site investigation programme based on the technology development conducted by SKB so far with respect to investigation and rock construction techniques. This includes experience from the expansion of the Äspö HRL in 2012–2013 (Johansson et al. 2015) and experience from Posiva's investigations during the construction of the hard rock facility in Olkiluoto (Posiva 2012a, McEwen et al. 2012). The detailed site investigation programme is formulated at a general level and aims to provide an overview of the investigations that are needed during the different phases of the construction and operation of the Repository for spent nuclear fuel.

Detailed site investigations have several purposes. They should provide the information needed for progress in underground construction and contribute to improved knowledge concerning conditions of importance for the assessment of safety after closure. During construction of the Repository for spent nuclear fuel, and to an even greater extent during the operational phase when deposition tunnels are successively developed, an important task will be to adapt the facility layout to the prevailing rock conditions so that the requirements linked to the repository's nuclear safety (technical design requirements) will be met. Furthermore, collected data and updated models that describe the bedrock provide a comprehensive basis for updated assessments of safety after closure.

The work is a result of SKB's project Detum-1. A special thank you to the authors of the report Karl-Erik Almén (Kea Geo-Konsult AB), Kaj Ahlbom (SKB International) and Anders Winberg (Conterra AB).

The current report is an English translation of SKB report R-16-10, originally published in Swedish.

Stockholm, December 2016

Emmeli Winter, Client

Summary

A framework programme for detailed site investigations was published by SKB in 2010. Since then, a number of key activities have been completed and published, including the safety case SR-Site, the system design of the Repository for spent nuclear fuel, as well as an update of technical design requirements related to safety after closure. Furthermore, development work has been initiated related to characterization methods, modelling methodology and computer systems for detailed site investigations. These advances have collectively motivated an update of the programme for detailed site investigations during repository construction and operation.

The objectives of the current report are

- to present the information and data needs of repository engineering (design and construction) and safety assessment,
- to present an overview of the investigations to be conducted during construction and operation to meet the identified information needs,
- to present strategies for site-descriptive modelling during construction and operation.

The description of the detailed site investigations is made for repository accesses, the central area, the area for integration and commissioning tests and the individual deposition areas, respectively. This subdivision has been introduced to facilitate easy description and navigation amongst the investigation activities related to development of the various parts of the repository.

The report also presents an overview of the presently ongoing monitoring in boreholes drilled from the ground surface and the identified needs for additional monitoring in boreholes and tunnels during construction and operation. The monitoring is successively adapted to furnish the information required by repository engineering, safety assessment and for control and follow-up of how the repository activities affect the environment.

The programme is devised to provide a holistic overview of the various investigations and modelling activities required during the various stages of construction and operation of the repository for spent nuclear fuel. Detailed operational programmes will be presented prior to start of construction of different parts of the repository facility. A general prerequisite is that investigations needed to assess post-closure safety have priority and are allotted the time required in conjunction with construction activities.

The programme also presents an overview of the modelling that will be made as an integrated part of the investigations. A facility part scale model will be presented prior to start of construction of the repository accesses (access ramp and shafts) based on which prognoses will be made, identifying parts in the bedrock where stability problems and/or high groundwater inflows can be expected. During construction, the geological and hydrogeological models are updated jointly at regular intervals, while updates of hydrogeochemical, rock mechanics, and bedrock thermal and transport properties are made less frequently. Complementary rock stress measurements are performed during construction of the accesses and are corroborated relative to the facility part model for verification of repository depth. At defined milestones, an update of the fully integrated site descriptive model (SDM) will be made, including all geoscientific disciplines.

Certain activities may demand special attention in the modelling. This may e.g. include analysis of the occurrence, properties and extent of the subordinate rock types amphibolite and episyenite (vuggy rock), and their significance for bedrock thermal conditions and groundwater flow and transport conditions, respectively. Other aspects of importance include the identification and classification of "critical structures", geometries and properties of deformation zones and the discrete fracture network (DFN), and the orientation and magnitudes of rock stresses.

During the successive development of the deposition areas, modelling is carried out continuously, employing tunnel scale and facility parts scale models. Initially, the modelling will focus on structures that define the boundaries of the deposition area being considered. This is followed by modelling for adaptation of deposition tunnels to local bedrock conditions and modelling for demonstrating compliance with technical design requirements and modelling in support of approval of deposition holes for deposition.

At the defined end of the repository construction phase a major update is made of the current site descriptive model (SDM-Site) to the version SDM-SAR, which will define the basis for the safety assessment (SAR) that constitutes the backbone in the application to obtain permit for commencing trial operation.

Sammanfattning

Ett ramprogram för detaljundersökningar vid uppförande och drift av slutförvar för använt kärnbränsle publicerades 2010. Sedan dess har säkerhetsanalysen SR-Site publicerats och systemprojektering av Kärnbränsleförvaret genomförts, liksom en uppdatering av konstruktionsförutsättningar avseende säkerhet efter förslutning. Vidare har utveckling av metoder, modelleringsmetodik och datasystem för detaljundersökningar initierats. Detta har sammantaget motiverat en uppdatering av detaljundersökningsprogrammet.

Syftet med den aktuella rapporten är:

- Att presentera vilka informationsbehov som projektering/bergarbeten samt säkerhetsanalyser har.
- Att på en översiktlig nivå beskriva de undersökningar som krävs för att tillhandahålla det underlag som projektering/bergarbeten samt säkerhetsanalys behöver.
- Att beskriva strategier för modelleringsarbetet under uppförande och drift.

Beskrivningen av detaljundersökningarna är uppdelad på tillfarter, centralområde, området för integrationstester och samfunktionsprovning samt deponeringsområden. Uppdelningen är gjord för att underlätta beskrivningen av aktiviteter med tillhörande undersökningar under uppförandet av olika anläggningsdelar.

Rapporten beskriver också översiktligt de långtidsmätningar som pågår i borrhål från markytan samt tillkommande långtidsmätningar under jord. Långtidsmätningarna anpassas till de behov som projektering/berguttag och säkerhetsanalys har samt för kontroll och uppföljning av hur verksamheten påverkar den yttre miljön.

Programmet är på en övergripande nivå och syftar till att ge en helhetsbild över de undersökningar som behövs under olika skeden av slutförvarets uppförande och drift. Operativa program kommer att tas fram som mer detaljerat beskriver undersökningarna i samband med utbyggnad av olika anläggningsdelar. En grundläggande förutsättning är att mätningar kopplade till säkerhet efter förslutning ges tillräcklig tid och tillräckligt hög prioritet i samband med konstruktionsarbeten i berget.

Programmet beskriver också översiktligt den modellering som kommer att genomföras integrerat som en del av detaljundersökningarna. Innan uppförandet av tillfarter påbörjas kommer en anläggningsdelmodell för tillfartsområdet tas fram och prognos upprättas för partier som kan vara behäftade med stabilitetsproblem och/eller stora inflöden. Under uppförandet uppdateras de geologiska och hydrogeologiska modellerna regelbundet medan modelleringar av hydrogeokemiska, bergmekaniska och termiska förhållanden samt bergets transportegenskaper görs mer sällan. Kompletterande bergspänningsmätningar genomförs under uppförandet av tillfarter och stäms av mot anläggningsdelmodellen för verifiering av förvarsdjup. Vid några tydliga milstolpar görs en samlad redovisning där alla ämnesområden modelleras, integreras och rapporteras.

Vissa aktiviteter kan komma att kräva särskilda modelleringsinsatser. Exempel på detta är analys av förekomst, egenskaper och rumslig utbredning av de underordnade bergarterna amfibolit och episyenit (porös granit) samt deras betydelse för termiska förhållanden respektive grundvattenflöde och radionuklidtransport. Andra exempel är identifiering och klassning av kritiska strukturer, geometrier och egenskaper hos deformationszoner och spricknätverket (DFN) samt orientering och magnituder hos bergspänningar.

Under utbyggnaden av deponeringsområden sker modellering kontinuerligt i tunnel- och anläggningsdelskala. Inledningsvis kommer fokus vara på layoutstyrande strukturer som, där de förekommer, ger underlag för avgränsning av förvarsområdet och tillhörande deponeringsområden. Därefter följer modellering som ger underlag för anpassning av deponeringstunnlars läge och orientering i relation till lokala förhållanden i berggrunden för att avslutas med modellering för att påvisa uppfyllelse av konstruktionsförutsättningar för val av läge och godkännande av deponeringshål för deponering.

En mer omfattande uppdatering av den platsbeskrivande modellen, från SDM-Site till SDM-SAR kommer att göras mot slutet av uppförandeskedet och utgör underlag för den säkerhetsredovisning (SAR) som i sin tur kommer att utgöra underlag för ansökan om provdrift.

Contents

1 Introduction

The framework programme for detailed site investigations in conjunction with construction and operation of a final repository for spent nuclear fuel (SKB 2010a) was published in 2010. Since the publication of the framework programme, the work with system design of the Repository for spent nuclear fuel in Forsmark has continued, along with the work of updating the technical design requirements with respect to safety after closure. This update focuses on the information needs for design and construction and for safety during operation and after closure. Based on these information needs, this programme presents the investigations required in conjunction with construction and operation of the final repository. A general prerequisite for the programme is that investigations needed to assess safety after closure have priority and are allotted the time needed in conjunction with construction activities.

The programme is devised to provide a holistic overview of the various investigations and modelling activities required during the various stages of construction and operation of the Repository for spent nuclear fuel. In collaboration with detailed design, operational programmes will be produced with more detailed descriptions of investigations and modelling in conjunction with the construction and extension of various facility parts.

1.1 Background

The Repository for spent nuclear fuel is a nuclear facility that must meet fundamental requirements on rock facility stability during the construction and operational phases and requirements on radiological safety during the operational phase and after closure. Whereas the first requirement is primarily linked to construction, environmental and occupational safety aspects, the requirement on radiological safety is unique for the final repository and the overall compliance with that requirement is covered by safety assessments. The requirements on safety after closure are covered by the technical design requirements for the Repository for spent nuclear fuel defined by SKB.

Detailed site investigations are carried out in parallel with rock excavation work during facility construction and the successive development of deposition areas during the operational phase. Detailed site investigations have several purposes. They should provide the information required for progress of underground construction and contribute to improved knowledge concerning the conditions of importance for the assessment of safety after closure.

During the construction phase and to an even greater extent during the operational phase when the deposition tunnels are successively developed, an important task for the detailed site investigations is to provide the data required to adapt the repository and its layout to prevailing rock conditions, so that the technical design requirements for safety after closure are fulfilled. Collected data and updated models will also serve as a basis for updated safety assessments. Detailed site investigations should also meet the need of information for continued assessment of the facility's environmental impact and for monitoring and control of this impact.

The update of the detailed site investigation programme is based on the technology development conducted by SKB so far with respect to characterisation and rock construction techniques. This includes experience from the expansion of the Äspö Hard Rock Laboratory (Äspö HRL) in 2012–2013 (Johansson et al. 2015) and, as a part of the ongoing cooperation with Posiva, experience from Posiva's investigations during the construction of the hard rock facility in Olkiluoto (Posiva 2012a, McEwen et al. 2012). Experience from the application of investigation methods during construction of the Äspö HRL is described in Almén and Stenberg (2005).

The development of detailed site investigation technology and modelling will continue and eventually focus more on the execution in the deposition areas. The most important tasks are to provide detailed data for deciding the location of deposition tunnels and deposition holes, for construction and excavation of these so that the technical design requirements are fulfilled, and to document the initial state of the underground openings at the time of deposition.

The report serves as a basis for SKB's production report for underground openings. The production report describes how the underground openings in the repository will be designed, constructed and investigated in order to verify compliance with the technical design requirements and to provide the information on rock properties required for future assessments of safety after closure. The production report for underground openings in turn serves as a reference for both a preliminary safety analysis report, PSAR, for the operational phase and after closure of the Repository for spent nuclear fuel, as well as a report on management of safety-related issues during the construction phase before the start of trial operation, Suus. Both of these reports must be approved by SSM before the construction of the Repository for spent nuclear fuel can begin.

A basic geoscientific description of the site (Forsmark) is provided by the site descriptive model SDM-Site (SKB 2008). Based on SDM-Site, the Site Engineering Report (SKB 2009c) was developed as a basis for the design of the final repository (SKB 2009b). The site and facility descriptions are in turn important for the assessment of safety after closure, SR-Site (SKB 2011).

A detailed description of all the investigations and geoscientific modelling conducted within the framework of the site investigations in Forsmark is provided by Andersson et al. (2013) and in popular form in SKB (2009d). Detailed descriptions of the geological modelling are found in Stephens and Simeonov (2015) and Stephens et al. (2015), while the hydrogeological and hydrogeochemical modelling used for the safety assessment is described by Selroos and Follin (2014) and Gascoyne and Laaksoharju (2008), respectively.

1.2 Purpose and prerequisites of the report

The objectives of the current report are:

- To present the information and data needs of repository engineering (design and construction) and safety assessment. Safety assessment involves safety during construction and operation as well as safety after closure.
- To present an overview of the investigations to be conducted during construction and operation to meet the identified information needs.
- To present strategies for site-descriptive modelling during construction and operation.

The report also presents an overview of the presently ongoing monitoring in boreholes drilled from the ground surface and the identified needs for additional monitoring in boreholes and tunnels during construction and operation. The monitoring is successively adapted to furnish the information required by repository engineering, safety assessment and for control and follow-up of how the repository activities affect the environment. The report does not cover biosphere monitoring.

An important prerequisite for the detailed site investigation programme is that it is based on the current technical design requirements (requirements related to safety after closure) and the current final repository design. If these prerequisites are revised, the programme may also need to be revised. Alternatively, the changed prerequisites can be considered in the preparation of the operational detailed site investigation programmes. Ongoing technology development may also lead to gradual changes of strategies, methods and equipment for detailed site investigations over the long period of time over which the final repository is constructed and in operation.

The need for investigations is partially governed by the uncertainties presented in SDM-Site (SKB 2008), SKB (2009b) and SR-Site (SKB 2011), which have been judged to be important for safety assessment, design and rock excavation and for environmental monitoring. SDM-Site contains descriptions and explanations of the various geoscientific concepts occurring in this report.

This report describes the detailed site investigations as applied to repository accesses, the central area, the area for integration and commissioning tests and the deposition areas. This subdivision has been introduced to facilitate easy description and navigation amongst the investigation activities related to development of the various parts of the repository. In practice, these repository parts are constructed partly in parallel. For example, construction of the central area begins when the skip shaft has reached the repository level, which is before the ramp reaches this depth. For modelling, this implies that the entire construction phase needs to be handled in an integrated model, which is updated with investigation results from the facility parts concerned.

1.3 Operational detailed site investigation programmes

The overall purpose of this report is to provide an overview of the detailed site investigations required during construction and operation of the final repository. For more detailed descriptions, operational programmes will be prepared, related to specific phases in repository development (or to specific parts of the repository) during construction and operation. Preferably, the operational programmes would cover repository accesses, the central area, the area for integration and commissioning tests and specific deposition areas, respectively.

The operational programmes will be based on this report. They should provide precise guidance for investigations and modelling. The operational programmes should supplement the generally described information needs in this report with specifications of the parameters to be determined. Furthermore, the operational programmes should specify the scope and level of detail of the investigations and coordinate them with the construction process, based on data from integrated process descriptions for detailed site investigations and construction. The operational programmes are developed in connection and collaboration with the detailed design. The operational programmes should specify methods for investigations and modelling with associated strategies for their application, as well as tools and computer systems, by way of controlling methodology documents, instructions, management documents, etc.

Given that the operational programmes are produced in close conjunction with the construction of each respective part of the repository, results from technology development, updated needs from design, modelling and safety assessment and experience of investigations in earlier phases of construction and at other locations can be incorporated prior to commencing the investigations.

2 Design and construction of the underground facility

Construction of the underground facility is a process that requires continuous information for estimating the needs of grouting and rock support. During the operational phase, when deposition areas are excavated and the locations of deposition tunnels and deposition positions are determined, the focus is on producing the information needed to adapt the facility to prevailing rock conditions so that the requirements linked to repository nuclear safety during operation and after closure can be met.

2.1 Introduction

According to SKB's overall plan for the Repository for spent nuclear fuel, repository accesses, the central area, tunnels for integration and commissioning tests and associated transport and main tunnels are built during what is denoted the construction phase. It is followed by the operational phase when deposition areas are successively developed and disposal of spent nuclear fuel is carried out. The operational phase will start with trial operation, when SSM has granted the requisite licence. After approval by SSM, routine operation begins.

2.2 Facility design

2.2.1 General

The planned location of the final repository is south of the cooling water canal for the Forsmark plant at a site called Söderviken, see Figure 2-1. The facility consists of a surface part and an underground part, which are connected by four vertical shafts and an access tunnel (ramp), see Figure 2-2. The ramp and shafts are collectively referred to as accesses. The underground facility is located about 470 metres below ground surface and consists of the central area and the repository area with its individual deposition areas. The repository area with associated tunnel systems is mainly situated south and east of the central area.

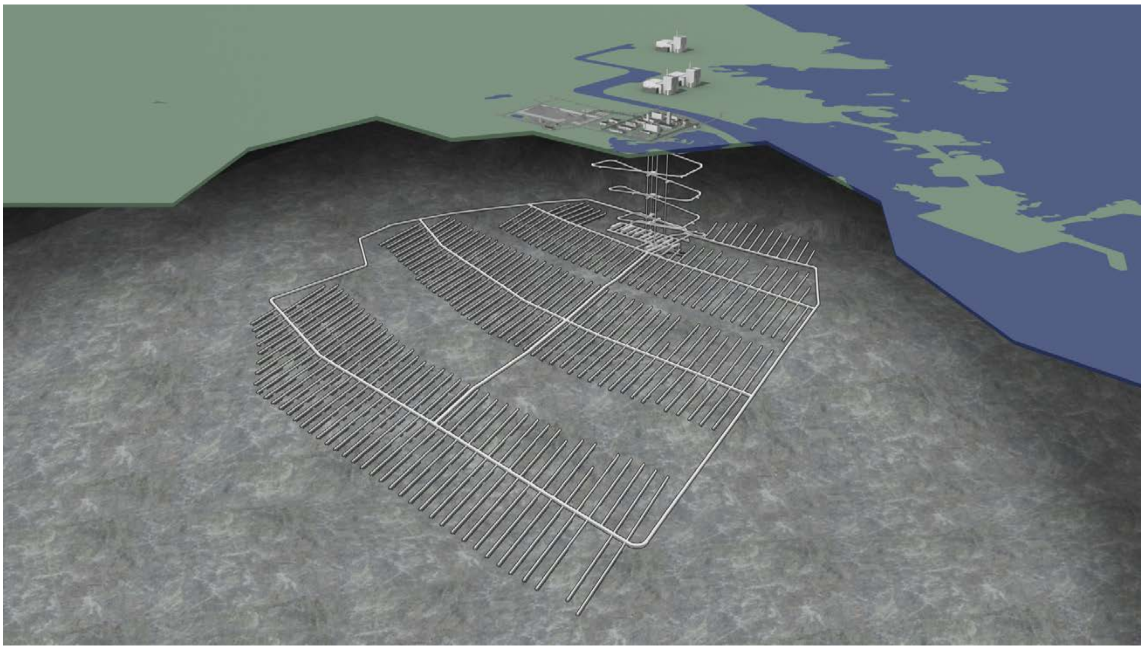

Figure 2-1. *The final repository viewed from the north-west.*

Figure 2-2. Parts of the final repository viewed from the north, showing accesses (four shafts and a ramp) between facilities above ground and the central area at repository depth.

2.2.2 Accesses

Ramp

The ramp used for transportation of spent nuclear fuel canisters is designed as an extended rectangle with sides of about 400 m and 100 m, respectively. The total length is 4 800 m with 4.5 loops from the ground surface down to the repository level at a depth of 470 m. The average inclination is 10%.

The ramp access is placed in the ramp access building. Up to the tunnel collar, the ramp consists of a concrete structure. Below, the ramp is excavated by drill-and-blast, with the dimensions provided in Table 2-1. In addition to the repository level, the ramp connects to the elevator shaft and the fresh air and exhaust air shafts at four levels and to the skip shaft at two levels.

The route slopes perpendicular to its extension, so that inflowing groundwater flows into drainage ditches along the route. The water is collected by intersecting pipes and led to sumps placed in the connecting tunnels between the ramp and the elevator shaft. From there, the drainage water is pumped up to the ground surface through the elevator shaft after which it is treated and discharged to the water recipient. Passing places are planned at the longer straight sections of the ramp.

Skip shaft

The skip shaft is used for transportation of muck and buffer and backfill material and contains power supply cables to the central area and the repository area.

The skip shaft is constructed by shaft sinking with a circular cross-section, i.e. from the ground surface and downwards, with the dimensions provided in Table 2-1. The shaft bottom is about 535 m below the ground surface, where it connects to the lower parts of the rock loading station. The lower part of the skip shaft is used for collecting drainage water in case of a power failure.

Elevator and ventilation shafts

The elevator shaft is used for passenger transport and other light transport. The elevator is also an escape route from the central area and constitutes an access route for rescue services. The two ventilation shafts are used for supply of fresh air and exhaust of used air.

The shafts are excavated by raise boring, a method for excavation of shafts with circular cross-sectional areas. The drilling is carried out in stages between the ground surface and an underground level or between two underground levels, as the ramp construction passes these levels. The successive excavation of ventilation shafts means that there is a good supply of fresh air during excavation.

Table 2-1 Geometric dimensions of the final repository underground openings according to current plans, see also Figures 2-3 and 2-4.

Underground opening	Cross-section (width x height)	Length/depth
Ramp	about 5.9 × 6.6 m	4 800 m
Skip shaft	Ø 6.1 m (rock excavation) Ø 5.7 m (after concrete lining)	535 m
Elevator shaft	Ø 5.5 m (rock excavation) Ø 5.1 m (after concrete lining)	490 m
Ventilation shafts (2)	Ø 5.5 m (rock excavation) Ø 5.1 m (after concrete lining)	450 m
Central area halls	about 15 × 10 m	40–65 m
Central area transport tunnels	about 8 × 7.5 m	about 500 m in total
Repository area transport tunnels	about 7 × 7.6 m	about 5 km in total
Main tunnels	about 10 × 8 m	750–1 100 m, about 6 km in total
Deposition tunnels (approx. 230)	about 4.2 × 4.8 m	100–300 m, about 52 km in total
Deposition holes	diameter 1.75 m	8 m, approx. 6 000 holes

2.2.3 Central area

The central area, see Figure 2-2, contains openings for the functions and processes that need to be located close to the repository area. They are divided into a number of separate rock caverns (in the following denoted rooms). The cross-sections of the rooms are similarly designed, see dimensions in Table 2-1. The rock pillar between the rooms varies in width between about 10 to 18 m. The areal extent of the central area is about 175 × 300 m.

Tunnels around the central area connect the rooms with each other and with the repository area and the ramp.

Rooms and tunnels in the central area are constructed using drill-and-blast. Rooms and tunnels in the central area are constructed with an inclination so that they are drained by gravity towards the skip shaft bottom.

2.2.4 Repository area

The repository area, see Figure 2-3, consists of a number of deposition areas and connecting transport tunnels. A central transport tunnel leads from the central area into the repository area. There are a number of main tunnels at both sides of the central transport tunnel. The outer endpoints of the main tunnels are connected with transport tunnels. A number of deposition tunnels start from each main tunnel, together comprising a deposition area. Geometric dimensions for the tunnels are provided in Table 2-1.

The areal extent of the repository area is about 2 × 2.5 km. Deposition tunnels will be spaced at a distance of about 40 m.

All tunnels in the repository area are constructed by drill-and-blast according to current plans. Inflowing groundwater and utility water from the repository area is collected in local sumps in main and transport tunnels. The deposition tunnels are drained by gravity (about 1:100) towards the main tunnels. Deposition holes are drilled in the deposition tunnels by downward full-face push reaming. The holes are spaced at a distance of 6.0 m and 6.8 m in the rock domains occurring in the repository area according to the current design.

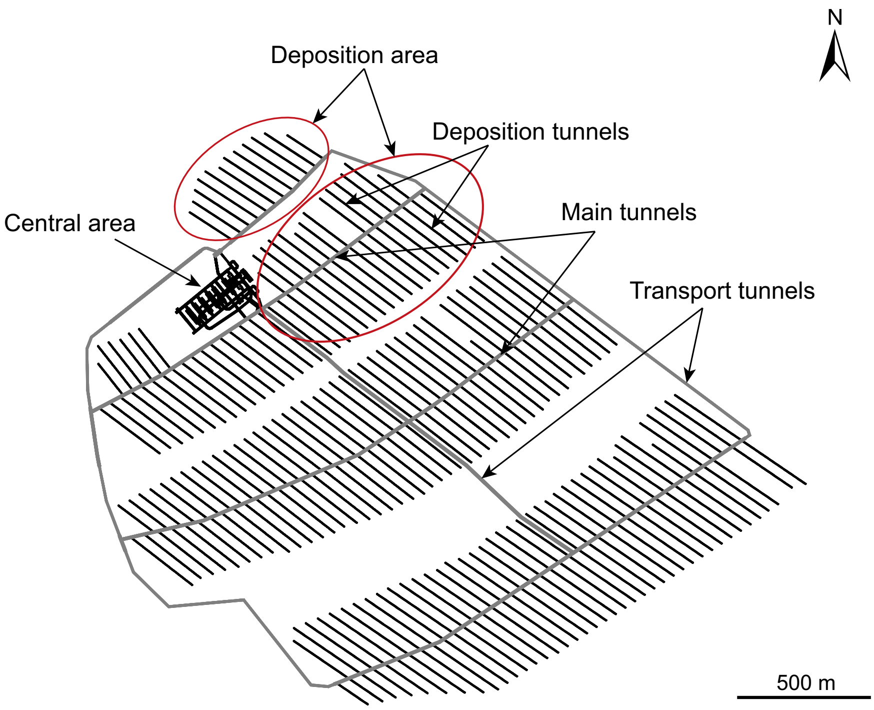

Figure 2-3. *Tentative layout of the repository area with its deposition areas and the central area.*

2.3 Development of the repository area

During the development of the repository area, underground construction and deposition will be carried out continuously and separated from each other along a tunnel loop consisting of two main tunnels with connecting transport tunnels. The physical separation is achieved by designing the central area so that the rock excavation and deposition processes are kept separate from each other. Furthermore, a specially designed partition wall between underground construction and deposition work is mounted in the main tunnel. The partition is moved forward step by step in the tunnel loop, as the excavation of deposition tunnels and deposition holes is completed and deposition can begin. Deposition tunnels and other tunnels at the deposition side of the partition constitute a designated controlled area from the deposition of the first canister until all deposition tunnels in the area have been sealed.

Before the start of the development described above, integration and commissioning tests as well as trial operation are carried out in the first deposition area. Construction of the main tunnels of the first tunnel loop starts from the central area. Thereafter, the intermediate outer transport tunnel is excavated. The size of the deposition area is determined by investigations from the main tunnels, and thereby the location of the transport tunnel is also determined.

The first part of the first main tunnel is investigated and the locations of two tunnels for integration and commissioning tests are determined, see Figure 2-4. These tests will be used to verify the rock excavation and deposition processes and constitute a part of the basis for the application for trial operation. A third tunnel for more long-term demonstration of processes of importance for safety after closure could also be constructed, see a more detailed description in Chapter 6.

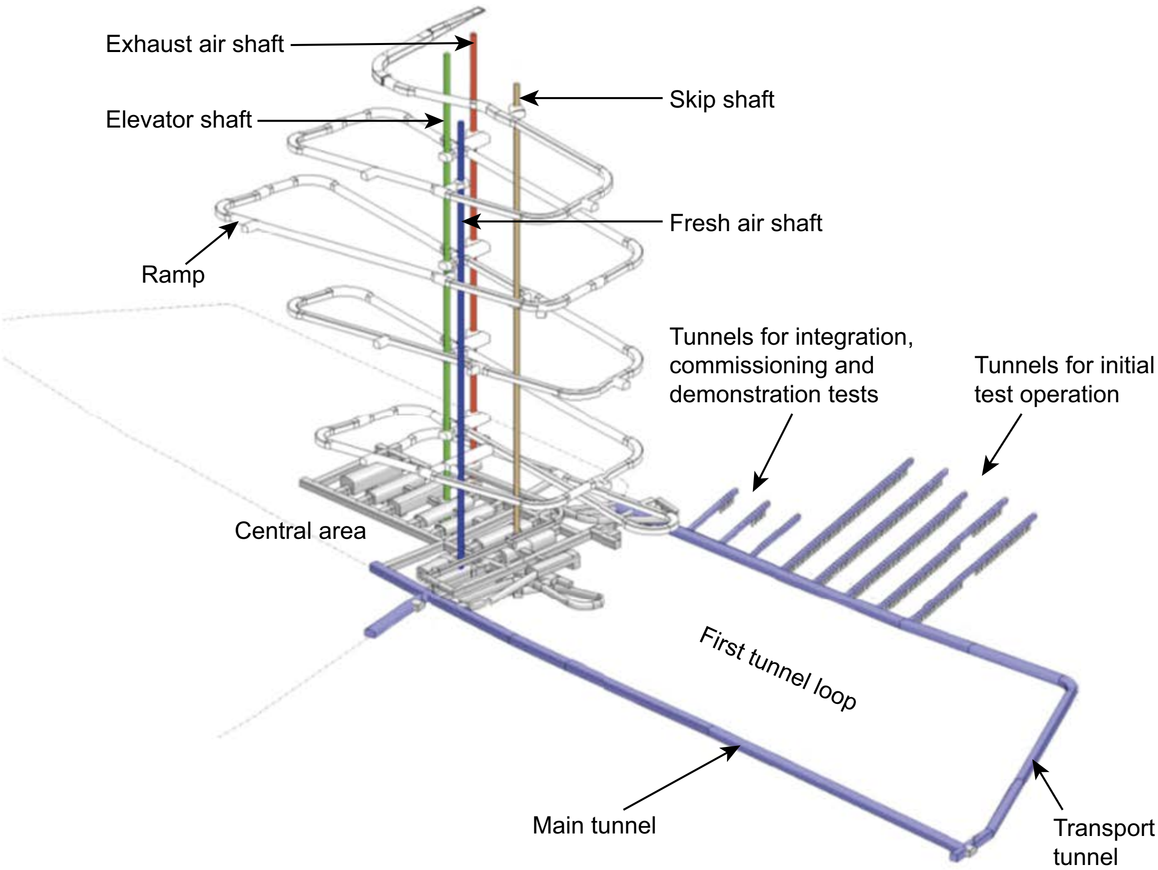

Figure 2-4. *Extent of the underground facility during trial operation. The tunnels for integration and commissioning tests were used prior to the application as a basis for trial operation, as a means to verify the rock excavation and deposition processes.*

After commissioning tests, application and licences from SSM, trial operation is carried out in a number of deposition tunnels in the first deposition area, see Figure 2-4. When a new licence is received from SSM, routine operation begins with successive development of additional deposition areas. The extension of each deposition area begins with preparation of the infrastructure, in the form of a loop with transport and main tunnels. Thereafter, the locations for deposition tunnels and deposition holes are determined successively.

An important task for detailed site investigations in deposition areas is the verification of rock properties between tunnels and boreholes and fulfilment of the technical design requirements. This means that a number of pilot boreholes and deposition tunnels must be investigated in batches, the same applies for deposition holes and preceding pilot boreholes. This requires good planning and allotment of sufficient time for detailed site investigations and excavation before deposition can begin. The role of detailed site investigations in this process is described in Chapter 7. Figure 2-5 shows an overview of the work sequences that will be used in the development of the repository area.

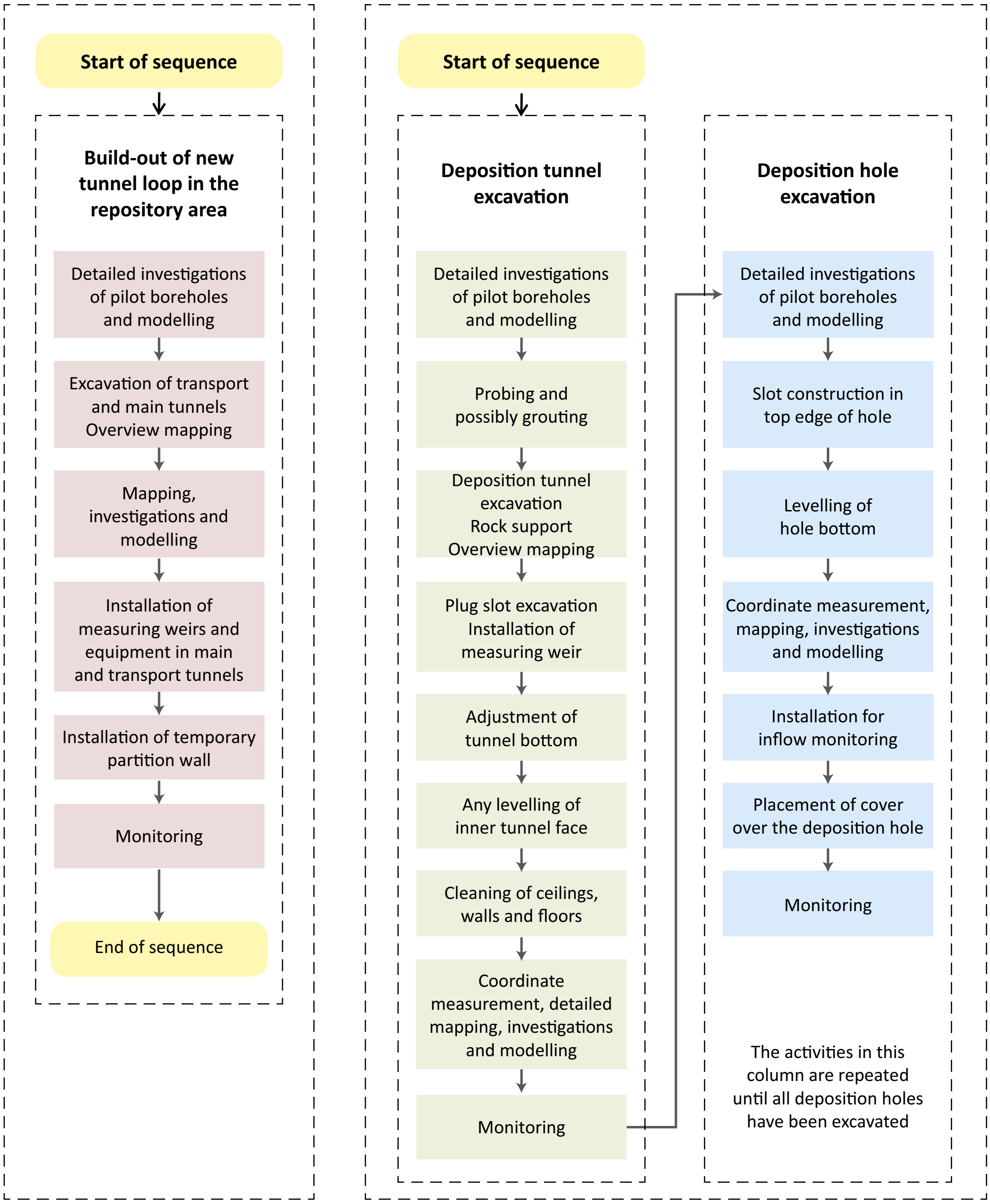

Figure 2-5. *Overview of work and investigation operations during deposition area development.*

2.4 Excavation methods

Excavation of the ramp and sinking of the skip shaft will be initiated approximately at the same time. The skip shaft will reach the repository level first and then construction of the central area begins, which means that parts of the central area will have been constructed when the ramp reaches the repository level.

Table 2-2 describes the methods that will be used to create underground openings both during construction and during operation of the final repository. A general requirement is that the excavation methods must not give rise to such damage to the repository host rock that its barrier functions are impaired in such a way that the safety of the final repository is compromised.

Table 2-2. Excavation methods in different parts of the repository.

Underground opening	Excavation methods
Skip shaft	Shaft sinking, i.e. stepwise shaft excavation from the ground surface by drilling, drill-and-blast (careful blasting) and mucking.
Other shafts	Raise boring. The shafts will be constructed in stages as the ramp reaches the planned intermediate levels. At each stage, a pilot borehole is drilled down to the lower intermediate level. A large reamer head (with appropriate diameter) is mounted on the drill stem and then pulled upwards during rotation.
Ramp	Drill-and-blast, careful blasting.
Central area openings, transport and main tunnels	Drill-and-blast, careful blasting.
Deposition tunnels	Drill-and-blast, careful blasting. Levelling of tunnel floor.
Deposition holes	Full-face boring (push reaming).

According to Table 2-2, careful blasting is used for shafts and tunnels. Below the top seal[1], the technical design requirements for the excavation-damaged zone (EDZ) surrounding different facility parts apply.

Tunnel excavation

Drill-and-blast is employed for all tunnels and rooms, a methodology that allows flexibility relative to any modifications in the facility layout as the construction work proceeds.

Tunnel excavation by drill-and-blast entails that rock excavation is carried out in accordance with the operating cycle illustrated in Figure 2-6. The operating cycle includes 4 to 5 blast rounds, as described in points 2 through 7 below. It is preceded by a drilling of a long pilot borehole according to point 1:

1. Pilot hole drilling (core drilling with borehole investigations). The borehole is drilled within the theoretical tunnel contour. Continuous pilot drilling is employed for tunnel excavation within the repository area. In the ramp and central area, pilot hole drilling is used selectively, both as a basis for predicting in advance of the excavation front and for special investigations related to site understanding and safety after closure.
2. Probe hole drilling provides information on rock conditions, including hydraulic properties for the next 4 to 5 blast rounds. The number of probe holes in a given batch is adapted to the expected rock conditions.
3. Possible pre-grouting. In addition to dedicated grouting holes, the probe holes (2) are also used for grouting. The grouting holes do not need to be within the theoretical tunnel contour. Grouted sections where boreholes are drilled outside the tunnel contour need to be evaluated based on their impact on backfill and positioning of deposition holes.
4. Drilling of blast holes, blasting, mucking and temporary support measures.
5. Levelling of the floor of deposition tunnels.
6. Mapping and investigations in the excavated tunnel. Divided into steps, with one instant effort at the tunnel face and thereafter stepwise efforts, adapted to the construction activities. The mode of execution differs between tunnels.
7. Installation of permanent rock support and reinforcement. Different requirements for different tunnels depending on how long they will remain open.

Repetition of steps 4 to 7 for 3 to 4 blast rounds. Thereafter, a new sequence is initiated with steps 2 to 3 such that the probe holes (and possible grouting fans) overlap. If necessary, the sequence is repeated with new pilot hole drilling and investigations. Although the operating cycle is principally the same for all tunnels, the mode of execution varies. The execution in the deposition tunnels differs the most from the execution in other tunnels. For instance, the tunnel floor will be levelled.

[1] Top seal refers to the seal introduced in the upper part of the accesses (ramp and shafts) of the Repository for spent nuclear fuel, with the purpose of considerably impeding unintentional intrusion into the final repository. The top seal covers the interval from the ground surface to a depth of 370 m.

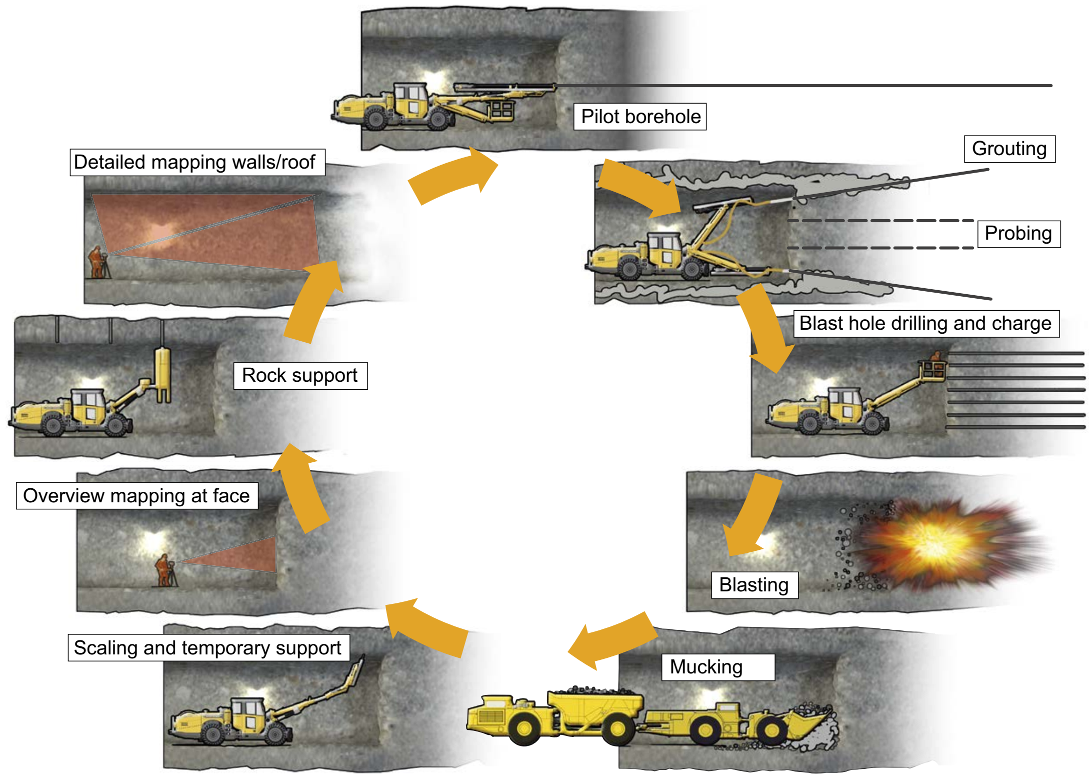

Figure 2-6. *Rock excavation operating cycle for tunnel excavation.*

Detailed site investigations in repository accesses and the central area take place mainly in conjunction with pilot hole drilling and tunnel mapping after reinforcement. Construction-related data will also be produced, for example from probe hole drilling with outflow measurements and pressure build-up tests, which are also of importance for site understanding and safety assessment. Detailed site investigations in deposition areas have a somewhat different purpose and a broader scope, which is described in Chapter 7. All investigations are documented and results are stored in a database.

Shaft sinking

The same work operations as for tunnel excavation are carried out in shaft sinking, i.e. probe drilling, pre-grouting and mapping. The work operations are adapted to the special conditions associated with excavation of a vertical rock opening. Casting of a concrete lining is done continuously. All work is performed from a work platform that is designed to allow several operations to be carried out simultaneously.

Raise boring

When constructing the elevator and ventilation shafts, raise boring will be carried out between different levels in side tunnels to the ramp, which are then connected to form a continuous shaft. Mapping of the shaft wall is done when each subsection of raise boring has been completed, after which lining of the subsection is performed.

Backfilling and sealing

After completion of deposition, the repository will be backfilled and sealed. Below the top seal at the 370 m level, limitations in groundwater inflow apply. In addition to requirements on backfill and grout materials, there are requirements on the excavation-damaged zone (EDZ) along underground openings below the top seal, which must be verified by the detailed site investigations.

3 Information needs to be satisfied by detailed site investigations

The site descriptive model for Forsmark, SDM-Site (SKB 2008), contains information on site material properties, conditions and processes as well as remaining uncertainties for all disciplines concerning the geosphere and the biosphere. The description has served as a basis for safety assessment, repository engineering (design and construction) and for assessment of environmental impact. These end users have assessed what information is important to collect in detailed site investigations during construction and operation of the Repository for spent nuclear fuel. This assessment is presented in this chapter. The chapter is concluded with a general description of quality assurance applicable to detailed site investigations.

3.1 Information needs for the site model and updated safety assessments

The integrated site descriptive model from the surface-based site investigation, SDM-Site, which serves as a basis for SKB's application for a licence to build the final repository, is the relevant overall site description at the time of this report. The concluding surface-based site investigations after SDM-Site, which resulted in model version 2.3 with respect to geology (Stephens and Simeonov 2015), have not affected the model as a whole. The same applies to the investigations made in preparation of construction, applicable to the shallow bedrock conditions adjacent to the repository accesses performed in 2010–2012.

During the construction of accesses, the central area and the area for integration and commissioning tests, working models for various purposes (with varying limitations in terms of discipline, size and geography) are updated regularly with results from complementary detailed site investigations. The construction of accesses (ramp and sink shaft) is in part carried out parallel in time. Results from different parts of the repository therefore need to be modelled collectively and fully integrated in a facility part model including all facility parts involved in the construction phase, see Chapter 8. After the construction phase, a complete integrated update of the site descriptive model should be made, which will be called SDM-SAR, see Chapter 6. This site descriptive model serves as a basis for the assessment of safety after closure included in the safety analysis report (SAR) that must be approved by SSM before trial operation can begin. Modelling at the facility part scale for specific deposition areas, with progressive integration into larger model scales, is performed as a basis for various decisions during the operational phase. Complete updates of the site descriptive model, SDM, are made as a basis for the periodic overall assessments of repository safety and radiation protection that must be carried out at least every ten years.

In the SR-Site safety assessment (SKB 2011, Section 15.6), reference is made to the detailed site investigations and site modelling to be performed during construction and operation of the final repository. The conclusion is that the confidence in site understanding is satisfactory and that the remaining uncertainties are sufficiently delimited to allow necessary risk estimates. Based on an analysis of technical design requirements, the report states that most potential improvements concern possibilities for local adaptation of deposition tunnels and deposition holes, as well as other underground openings, to ambient bedrock conditions. In addition, some issues remain concerning the rock mass properties outside the immediate vicinity of the deposition areas. The following information needs are mentioned in SR-Site:

- Continued characterisation of deformation zones with potential to generate large earthquakes.
- Further development of tools for delineating the size of fractures/structures that are allowed to intersect deposition holes.
- Reduction of uncertainties in DFN models.
- Identification of connected transmissive fractures.
- Improvement of the description of the hydraulic properties of the repository volume.
- Verification of compliance with the technical design requirements for EDZ.

Most of the feedback from SR-Site concerns the prospects of obtaining data that allows adaptation of the repository and verification of applicable technical design requirements. This aspect is discussed in more detail in Section 3.2.

One conclusion in SR-Site is that thermally-induced spalling in deposition holes is likely to occur. Although this has no significant impact on the compliance with the risk criterion for safety after closure, there is reason to increase the understanding of rock strength and rock stresses in situ.

The available hydrogeochemical data are clearly sufficient to demonstrate suitable conditions today and during the temperate period of at least several thousand years from now. In order to increase the confidence in important evaluations, more information would nevertheless be valuable. The report specifically mentions groundwater analyses data with respect to sulphides and dissolved organic carbon, microbial populations, concentrations of hydrogen and methane and isotope ratios for these substances, as well as isotope data on noble gases and additional analyses of uranium and radium.

Regarding surface ecosystems, the accuracy in the models for radionuclide migration and retention in the biosphere will probably increase if partition coefficients and parameters describing biological uptake of certain important radionuclides could reflect site conditions to a greater extent without needing to rely on generic data from other sites. The report specifically mentions the need for more comprehensive measurements of the concentrations of a few elements (including Ra and I) and measurements of the concentrations of all elements in locally produced agricultural products and in the soil where they are cultivated. Furthermore, chemical data from precipitation samples are needed. (Biosphere monitoring is not included in the detailed site investigation programme, as mentioned previously.)

SR-Site concludes that the framework programme for detailed site investigations and the plans presented for further development of the detailed site investigation programme are adequate.

Although detailed site investigations are primarily focused on providing the data required by safety assessment, repository engineering and environmental monitoring, they must also result in an updated integrated description of the bedrock and surface system. This provides the broad fundamental basis for understanding of geoscientific conditions and processes, which should be described in the site-descriptive model.

Conclusions for the detailed site investigation programme

The investigations need to deliver the broad fundamental basis required by the site-descriptive model. Thereby, they need to include essentially the same parameters as during the surface-based site investigations, with the addition of the need of also having to record the disturbances caused by construction. In addition to the general model scales used during the surface-based site investigations, modelling must also be able to use data for description of geoscientific conditions at more detailed scales.

The geoscientific information needs identified by SR-Site are mainly linked to the repository area and its surroundings, where the repository area includes all deposition areas. As a basis for future safety assessments, the results from detailed site investigations and modelling of other repository parts below the top seal are of particular interest. These repository parts include accesses and the central area and are located within the same rock domain as the deposition areas. Data for DFN modelling, rock mechanics and hydrogeochemistry are also of interest for rock volumes within the top seal (down to a depth of 370 m).

3.2 Information needs for adaptation of the repository to applicable technical design requirements related to safety after closure

Safety after closure related to the final repository is dependent on designing the repository facility adequately and adapting it to the properties and conditions of the rock. SKB has compiled a number of technical design requirements with a focus on safety after closure of the final repository (SKB 2009a). They include requirements on facility design, how the facility should be adapted to the properties and conditions of the bedrock, and how construction is allowed to affect the surrounding host rock, in all cases with respect to meeting the requirements on safety after closure. Some technical design requirements are linked directly to the barrier function of the rock, while others are formulated in order to ensure that the rock provides the conditions and geometry needed in order for the engineered barriers (canister, buffer, backfill and closure) to meet the stipulated requirements.

Subsequent to SKB's application for establishing the Repository for spent nuclear fuel in Forsmark was submitted to the regulatory authorities, SKB started working on an update of the technical design requirements, mainly based on the results of the underlying safety assessment SR-Site (SKB 2011a). This work has been carried out together with SKB's Finnish sister organisation Posiva, whereby the results from the Finnish safety assessment TURVA 2012 (Posiva 2012b) and subsequent regulatory review have also been taken into account. The work has resulted in a joint Posiva-SKB report (see Appendix and Posiva SKB 2017). The report will serve as a basis for the technical design requirements that will be formally presented to SSM in conjunction with the submission of the PSAR.

The technical design requirements that are linked to the repository host rock with associated underground openings and affect detailed site investigation components and performance are presented in the Appendix. It also describes the role of detailed site investigations in verifying compliance with the technical design requirements. Those technical design requirements that mainly affect the design of the detailed site investigation programme are presented below.

- **Repository depth**. Repository depth shall be within the range 400–700 metres. (Detailed site investigations will provide a basis for any refined adaptation of the repository depth relative to the rock stress situation and geological conditions and with regard to the presence of sub-horizontal deformation zones.)
- **Deposition areas – critical structures**. Deposition areas must not be placed within critical volumes of class 1. (For classification, see explanation below.)
- **Deposition areas – chemical conditions**. The deposition areas should be placed so that the salinity (TDS), pH and sulphide content are within the limits of their performance targets.
- **Deposition tunnels – critical structures**. Deposition tunnels must not be placed within critical volumes of class 1 and 2.
- **Deposition tunnels – orientation**. The deposition tunnels should be aligned according to the site-specific rock stresses in order to limit the volume of damaged rock around the tunnels.
- **Deposition tunnels – inflow.** Inflow to deposition tunnels shall be less than the limit to be determined in the design, to allow installation of the backfill and plug.
- **Deposition holes – critical structures**. Deposition holes must not be placed within critical volumes of class 1, 2 or 3.
- **Deposition holes – distance from a thermal point of view**. The minimum distance between deposition holes in a deposition tunnel and in relation to holes in adjacent tunnels shall be such that the temperature in the buffer is less than 100 °C.
- **Deposition holes – transmissivity**. The transmissivity in a pilot borehole for a deposition hole shall be less than the established limit. (Development and testing of the methodology for establishment of this limit is under way.)
- **Deposition holes – inflow**. The inflow to the deposition hole shall be less than the limit to be determined in the design, to allow installation of the buffer.
- **Deposition holes – geometry.** Geometrical parameters should be within limits to be determined in the design.
- **Entire repository – inflow**. Total groundwater inflow to the underground openings shall be less than the site-specific limit.
- **EDZ – deposition tunnel**. The specific capacity ($Q/\Delta p$) of the EDZ, measured from the pilot borehole for the deposition holes, shall be such that it corresponds to a transmissivity of 10^{-8} m^2/s at maximum.

Critical structures and volumes

Several of the technical design requirements above are handled by identifying, classifying and avoiding critical structures of different classes in various parts of the final repository. The critical structures will thus be crucial for the design/layout of the final repository.

Critical structures (CS) with associated critical volumes are geological structures that may have a negative impact on the safety after closure for a KBS-3 final repository (Munier and Mattila 2015). Examples of critical structures are deformation zones, which can be significant flow paths for groundwater, or structures where secondary shear movements may be triggered in conjunction with earthquakes and where the movements could be so large that they may damage a canister. The critical volume (CV) linked to critical structures essentially corresponds to the damaged zone developed on either side of the core of the structure.

Critical structures and volumes are classified according to their impact on repository layout. The following classification is applied:

- Critical structure/volume class 1 (in other documents denoted by the abbreviation CS1/CV1) has such properties that it cannot be accepted anywhere within the extent of the repository. These structures are crucial for the repository location and for delimiting its outer boundaries.
- Critical structure/volume class 2 (CS2/CV2) has such properties that it can be accepted between deposition areas but not in deposition tunnels. These structures are crucial for the repository layout and for the positioning and length of deposition tunnels.
- Critical structure/volume class 3 (CS3/CV3) has such properties that it cannot be allowed to intersect deposition holes. These structures are crucial for the positioning of deposition holes.

The classification is illustrated in Figure 3-1. Among other things, the classification methodology is used to determine whether a deformation zone will affect the location of a deposition tunnel, i.e. whether the deformation zone should be classified as a critical structure of class 1 or 2. Similar procedures are applied for class 1 structures that are not allowed to intersect the extent of the repository and class 3 structures that are not allowed to intersect deposition holes. During classification, the most important properties are considered: size, mechanical stability and importance for groundwater flow. The size of the structure is considered an indicator of its earthquake potential. During an analysis of mechanical stability, other aspects are also evaluated, such as the orientation in relation to present-day and future rock stress fields, geometry, friction, kinematics, etc. The structure's hydrogeological importance is based on investigations in boreholes and tunnels and, if necessary, modelling.

As seen in the text above, "critical structures" refer to a combination of technical design requirements regarding water-bearing structures and/or structures where secondary shear movements can take place in conjunction with earthquakes. The structure could be a deformation zone, a large fracture or a lithological contact.

A mechanically critical structure of class 3 with its associated critical volume must not intersect a deposition hole. Such a structure has mechanical properties and a geometric extent such that it may allow a shear movement of 5 cm or more. As mentioned above, its geometry, for example its orientation in relation to the rock stress field, must also be considered. A water-bearing structure can also constitute a critical structure of class 3 if it causes water inflow to a deposition hole that is so large during the time the deposition tunnel is open that the buffer could be eroded, or that the transmissivity near the hole is so large that the groundwater flow after closure (Darcy flux) will be too high, see Appendix.

A fracture/deformation zone that can be traced around the full tunnel perimeter is called FPI (*Full Perimeter Intersection*). Such a fracture/deformation zone may be a critical structure of class 3. The interpretation of FPIs is therefore an important basis for the classification of critical structures, as described above. If there are no data for classification according to the methodology described above, all FPIs that intersect a deposition hole are assumed to be critical structures of class 3. This criterion is called FPC, where C stands for *Criterion*. For critical structures that, due to their geometry, do not intersect the deposition tunnel, the criterion EFPC is applied, where deposition holes intersected by a structure that intersects five or more deposition holes will not be accepted, see Figure 3-2 (Munier 2010).

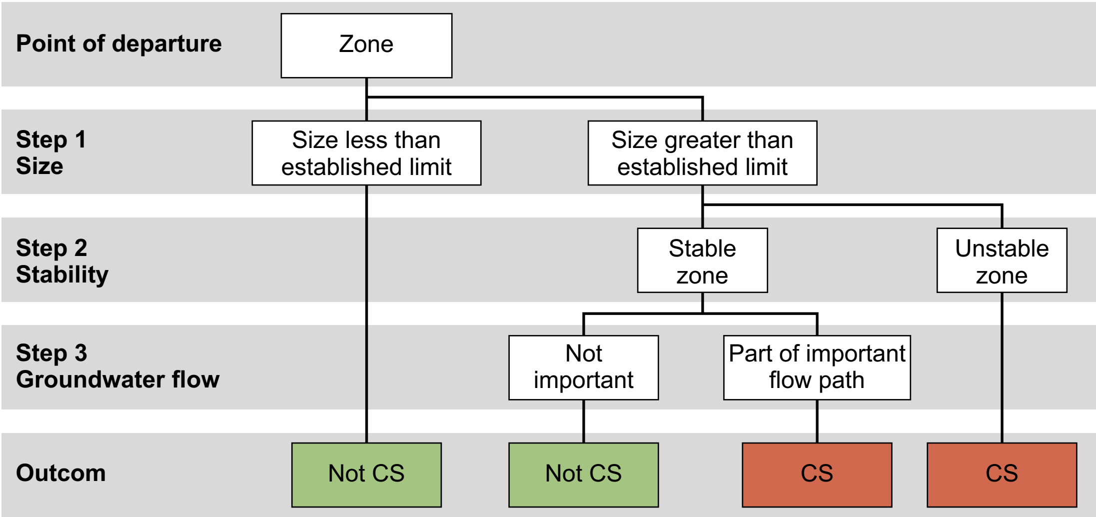

Figure 3-1. *Process chart for definition of critical structures (CS). This categorisation and sorting process is also applicable for "critical volumes" (CV) associated with the critical structures. The point of departure for the classification is a modelled structure based on tunnel mapping, borehole investigations and other investigation data. The first step is to assess the size of the structure (Step 1). For structures larger than the established limit, the stability of the structure is considered (Step 2) as well as its influence on groundwater flow (Step 3). The outcome of the process is a classification of the structure, either as a non-critical (green boxes) or as a critical (red boxes) structure/volume.*

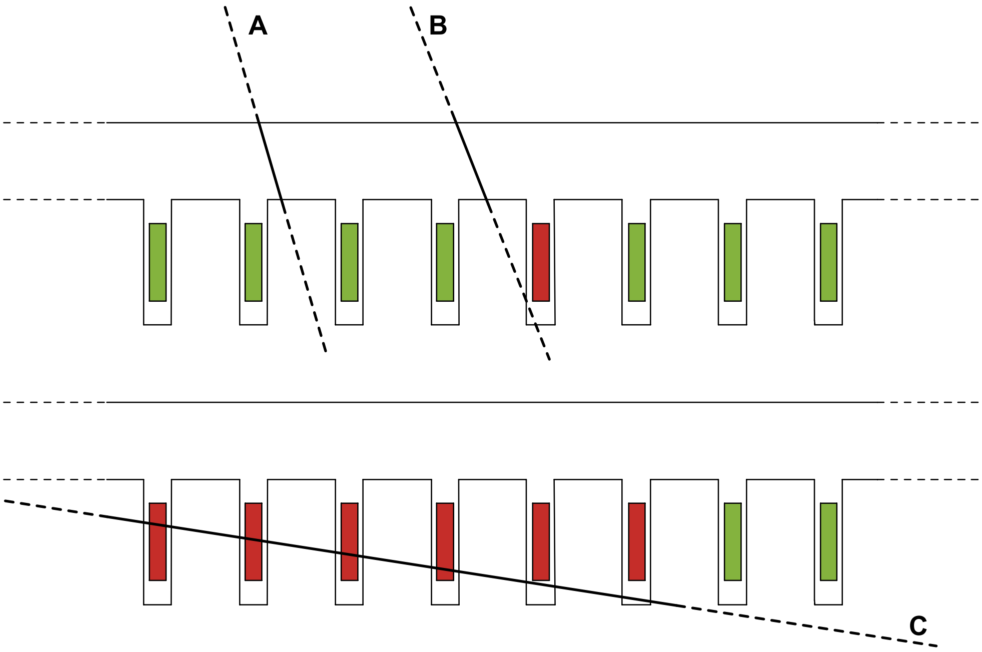

Figure 3-2. *Illustration of the FPI criteria. A and B are two structures that generate FPI objects in the deposition tunnel, of which A does not affect deposition while B prevents deposition, according to the FPC criterion. Object C intersects at least five deposition holes, which means that these positions may not be used for deposition according to the EFPC criterion.*

Compliance with technical design requirements

The fulfilment of technical design requirements is ensured by using methods that are specially designed for the construction and operation of the Repository for spent nuclear fuel and by verifying that the execution follows the method specifications. The detailed site investigations contribute to the fulfilment of technical design requirements in two ways. Collected data and updated models serve as a basis for adaptation of deposition tunnels and deposition holes to the rock conditions and thereby to design and construction, and investigation results are needed to quantitatively verify that the technical design requirements have been fulfilled.

It can be concluded that the verification of compliance with the technical design requirements requires extensive detailed site investigations in the deposition areas. Apart from limiting the inflow to the entire facility, there are technical design requirements concerning the excavation damaged zone (EDZ) for accesses below the top seal and the central area. For accesses within the top seal (down to a depth of 370 m), there are, besides the inflow limitation, no applicable technical design requirements with respect to safety after closure, which means that there are no particular information needs related to detailed site investigations based on this aspect.

3.3 Information needs for design, construction and operation

The report Underground design Forsmark, Layout D2 (SKB 2009b) describes the estimated information needs for design, construction and operation.

In general, the stability of underground openings is judged to be similar to corresponding openings built at corresponding depths in the Scandinavian Shield. There may be events of rock instabilitity, such as rock fallout or spalling, but the associated risk can be reduced by traditional rock support and by aligning the openings near parallel with the maximum horizontal stress. The highest frequency of open/water-bearing fractures will be found in accesses down to a depth of about 50 m. The rock mass at repository depth is expected to be relatively homogeneous with few water-bearing fractures. The average distance between such fractures is expected to be more than 100 m (SKB 2010b). Conventional grouting methods with cementitious grout will generally be sufficient. Silica-based grout may be needed locally at the repository level, especially in fractures of small aperture.

The risk of stress-induced spalling in tunnels and in deposition holes (before deposition) at repository depth is judged to be small, despite the uncertainty in rock stress magnitude. The risk is limited by aligning the deposition tunnels near parallel with the maximum horizontal rock stress. If necessary, the tunnel contour can be adjusted to mitigate spalling.

As in the case of other site investigations, there are uncertainties associated with the interpretation of information from the boreholes constructed during the surface-based site investigation. Some of the uncertainties may require a larger degree of flexibility in the design/layout and should be handled during future design steps and/or during construction of the repository accesses. In the summary of the report Underground design Forsmark, Layout D2 (SKB 2009b), the former uncertainties are listed as follows:

- The frequency and distribution of open water-bearing fractures and their potential impact on the drawdown in the vicinity of the shafts and ramp tunnel.
- In situ stress magnitudes and orientation at repository level.
- Spatial distribution of deformation zones that may impact repository layout.

The adaptation of the repository layout to deformation zones mainly concerns the deposition areas, in particular the positioning of deposition tunnels and deposition holes.

The Observational Method will be used when the geological uncertainties are of greater importance for design and construction. The method can be applied by measuring/observing rock stress/spalling during the advance and, if necessary, alter the excavation according to the alternative resolves developed in the detailed design. SKB used the Observational Method with respect to hydraulic conditions during the expansion of the Äspö HRL (Olofsson et al. 2014).

At the locations for the ramp and shafts, investigations are conducted to provide data for detailed design and the description of execution. In particular, information is needed concerning the location, frequency and hydraulic properties of gently dipping water-bearing fractures in the upper fracture domain FFM02.

For documentation of the facility (as-built documentation), tunnel locations and geometries and information on grouting and rock support measures are compiled with the geological mapping.

Conclusions for the detailed site investigation programme

During construction of repository accesses, the central area and deposition areas, investigations need to be conducted to study and resolve the uncertainties and information needs mentioned above.

3.4 Information needs for environmental monitoring

During construction of shafts, tunnels and rock caverns of the Repository for spent nuclear fuel, SKB will perform grouting in order to prevent inflow to underground openings and reduce withdrawal of inflowing groundwater, which could cause drawdown of groundwater levels that could have an impact on buildings, facilities, vegetation, wetlands or other bodies of surface water.

SKB will follow up on a number of environmental parameters during construction. A subset of these parameters is directly linked to the monitoring of parameters prescribed by the regulatory authority. This report is limited to the description of information needs for geoscientific parameters.

The geoscientific data required for environmental monitoring depend on the conditions and demands imposed on SKB when receiving a licence under the Environmental Code for the construction of the Repository for spent nuclear fuel. In the submitted application, SKB has committed to take steps, when the accesses are built and during the operational phase, to as far as is reasonable and possible prevent groundwater withdrawal that causes drawdown of groundwater levels that may significantly damage ponds and other wetlands with high natural values. This means that there exists a need to measure changes of the groundwater table in the soil layers, but also to some extent in the bedrock. When reviewing the environmental impact, monitoring of hydrogeochemical conditions in the underground facility and for pumped-up drainage water will also be of interest.

Other information needs for environmental monitoring regarding nature protection, noise etc. will be described in a special programme for environmental monitoring during the construction and operation of the final repository.

Conclusions for the detailed site investigation programme

The geoscientific information required for environmental monitoring consists of measurement of changes of the groundwater table in soil and rock as well as monitoring of hydrogeochemical conditions. This information should be provided by the current monitoring programme with subsequent and regular adjustments. Other geoscientific information (than groundwater table in soil and rock) may also be of interest for updating or verifying previous data that served as a basis for assessment of environmental impact. In the assessment of environmental impact and environmental monitoring, the results from model updates are also of interest.

3.5 Safeguards

In the future there also exists a need of information from detailed site investigations related to international nuclear safeguards. How the safeguards are to be implemented is not yet established. For detailed site investigations, it is most likely the monitoring programme, especially seismic monitoring, that will be relevant in connection with safeguards. (For verification that no rock excavation work is performed with the intention of removing nuclear material without authorisation). Because the requirements on investigations in conjunction with safeguards are not yet established, no such investigations are presented in this programme.

3.6 Summary of information needs

Since the framework programme for detailed site characterisation was published in 2010 (SKB 2010a/SKB 2011b), the safety assessment SR-Site has been concluded, along with system design and an updated design of the final repository. Furthermore, SKB and Posiva have updated the technical design requirements (Posiva SKB 2017) based on the conclusions in SR-Site and Posiva's equivalent TURVA 2012. These activities have confirmed that the detailed site investigations described in the framework programme are still adequate and no essential new information needs have been identified.

The current update of the detailed site investigation programme therefore focuses on describing how the investigations will contribute to the construction of underground openings for deposition that meet the technical design requirements regarding safety after closure. Furthermore, the programme describes other geoscientific information of interest for safety assessment, design and construction, environmental monitoring and updating of the SDM and how this should be carried out. More detailed descriptions of the practical execution of investigations and modelling during the construction of repository accesses, the central area and deposition areas will be presented in operational detailed site investigation programmes for each part of the facility.

3.7 Quality assurance

Quality assurance of the execution and results of the investigations will be carried out according to the management system established by SKB for the construction of the Repository for spent nuclear fuel. Because the detailed site investigations are carried out as an integrated part of the bedrock barrier system, quality assurance will be integrated at this level. At the routine level, the detailed site investigations will be governed by method and methodology descriptions with essentially the same role as in the surface-based site investigations. A complete revision will be made of these parts so that they meet the quality requirements for nuclear activities.

Fulfilment of safety after closure of the Repository for spent nuclear fuel is governed by the capacity of the engineered and natural barriers to contain the spent nuclear fuel and to prevent and delay radionuclide transport. Barrier properties are classified in terms of safety and quality based on their importance for maintaining the safety functions of the Repository for spent nuclear fuel. It should be noted that the rock properties and conditions are as such not classified in terms of quality as they are given by nature and cannot be controlled by SKB. The placement of underground openings and thereby the adaptation of them to the rock properties serve as a basis for the quality assurance of the construction of the Repository for spent nuclear fuel. Requirements in the form of technical design requirements have been compiled for how the underground openings shall be designed and constructed so that the safety functions of the final repository are fulfilled, as discussed in Section 3.2 and the Appendix. In this context, the purpose of detailed site investigations is to provide data for verification and approval that the underground openings have been located and designed so that the technical design requirements are met.

A point of departure for SKB's quality management system is that common principles and guidelines shall apply for the different subsystems of the Repository for spent nuclear fuel, namely the canister, buffer, backfill, closure, underground openings and deposition tunnel plugs. This is also clear from the report "Plan för implementering av kvalitetsstyrning och kontroll av KBS-3-förvaret" (Jonsson and Morén 2013), submitted by SKB to SSM in 2016 as a supplement to the ongoing review of the application. Another point of departure is that the quality management system will continue to be developed so that it corresponds to the needs in different phases. Based on these principles and guidelines, specific procedures and instructions are established for subsystem production and the activities included in production.

Detailed site investigations belong to the subsystem "Underground openings" and quality assurance relates to a nuclear facility already from the start of construction. During the construction phase, only a few specific requirements (technical design requirements) apply to the activities that are of relevance for safety after closure, while the construction of deposition areas and the excavation of deposition holes during the operational phase are controlled by a larger set of technical design requirements relevant for safety after closure, see further Section 3.2, the Appendix and Chapter 7.

The current report will not pre-empt the continued development of the quality management system that is under way for application in the construction and operational phases of the Repository for spent nuclear fuel. An important component is, however, to conduct product surveys and process mappings. This is done to identify the properties and related design parameters that are most important for repository safety and determine methods for characterisation, production and testing of these and decision points in the production line. During the process mappings and product surveys, the need for qualification (testing and approval) is also determined and if and when a third party needs to be engaged for monitoring and control.

Detailed site investigations, design and rock excavation work will constitute an integrated process to achieve the underground openings of the Repository for spent nuclear fuel. Examples of sub-processes are the construction of shafts, ramp and rooms of the central area and excavation and verification of the deposition areas and their deposition holes. Detailed site investigations of various types are part of these processes. Some detailed site investigations have the task to deliver rock data in order to build underground openings according to given technical design requirements. Other detailed site investigations are carried out to gain further knowledge and understanding of the site so that safety after closure of the Repository for spent nuclear fuel can be analysed and verified. Detailed site investigations thereby contribute to safety after closure by verifying by measurement that the technical design requirements are fulfilled, but also by providing material in the form of data and site models that are needed for safety assessment.

During the process mapping of the bedrock barrier system, production and detailed site investigation methods are identified, including systems and equipment, as well as those decision points that have the greatest importance for quality, based on the quality classification. Methods and tools to be qualified will then be identified based on the process mapping.

SKB has comprehensive and long-term knowledge and experience of investigations and modelling of the geosphere and the biosphere, not least from the surface-based site investigation phase. An important component for quality assurance of the execution and results of investigations was the so-called method descriptions. Even if the quality management system for the construction and operation of the Repository for spent nuclear fuel has not yet been fully developed, method descriptions are judged to have a corresponding role in the execution of detailed site investigations. They will be adapted to future activities, for example with respect to adaptation to rock excavation and underground construction, but also with respect to altered requirements on quality control and documentation. The corresponding discipline-specific methodology reports for site-descriptive modelling will undergo comprehensive updates.

4 Detailed site investigations during construction of accesses

4.1 Repository parts

The accesses consist of a ramp and four shafts, see Figure 4-1 and Section 2.2.2. The planned method for construction of the ramp is drill-and-blast. Prior to the start of excavation, curtain grouting will be carried out for the planned ramp section through the upper water-bearing parts of the bedrock.

The four shafts, skip, elevator and two ventilation shafts, are situated within the operational area. The skip shaft is constructed by shaft sinking in parallel with ramp excavation. The other shafts are constructed by raise boring, step by step between levels, as the ramp passes the locations for connections made between ramp and shafts. Curtain grouting is performed prior to the excavation of the skip shaft.

4.2 Information needs

For the construction of shafts and ramp, information on water-bearing fractures in the upper 50 m (fracture domain FFM02) of the bedrock is of particular importance. Below this level, the bedrock is judged to have such quality that there are no specific needs for information, more than what is provided by probe drilling, as a basis for decisions on grouting. Both the shafts and the ramp will be excavated through deformation zones. These are judged not to cause any extensive need of support but information from pilot boreholes could be warranted for some of them.

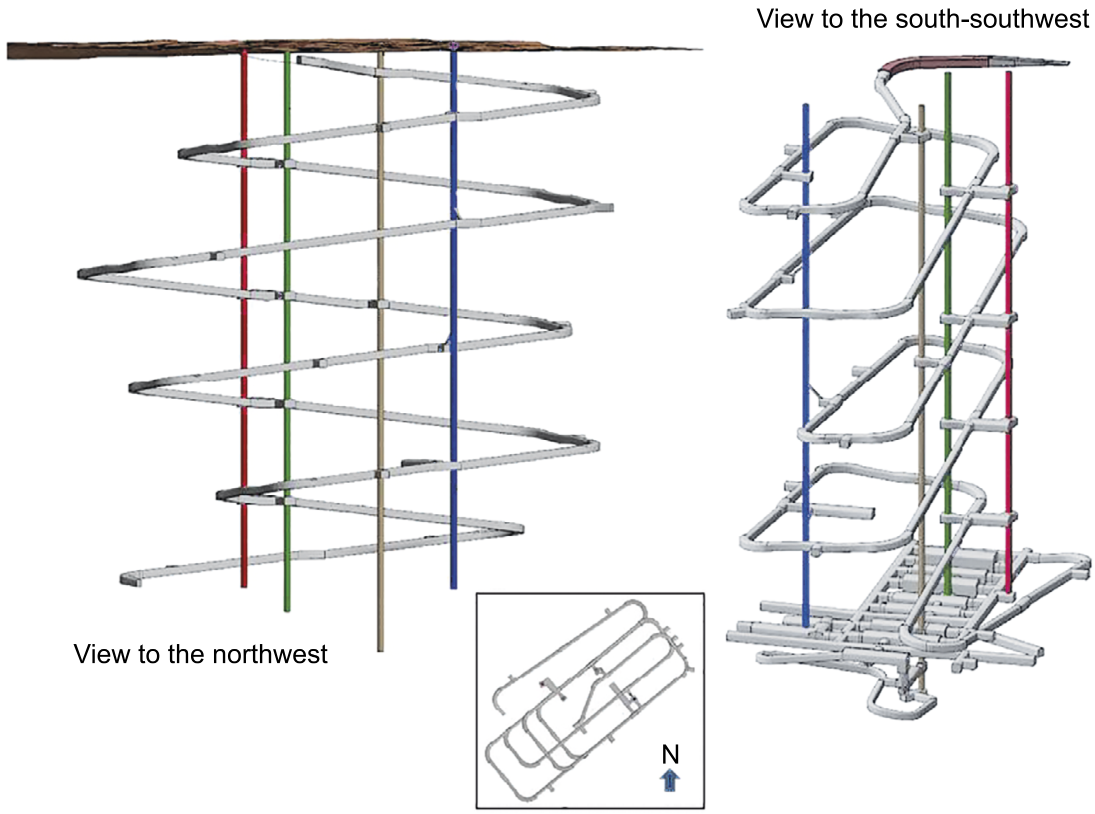

Figure 4-1. *View of accesses and central area.*

Given that the accesses are separated from the repository area, few technical design requirements must be fulfilled. The information that serves as a basis for assessment of whether the backfilling of shafts and ramp below 370 m (lower level of the top seal) will function as intended is of interest for the safety assessment. Primarily, information on the occurrence and extent of the excavation-damaged zone (EDZ) and inflows to underground openings is needed. At greater depths than 370 m, the repository accesses will be excavated in bedrock with similar properties and conditions as the repository area. As mentioned in Chapter 3, it is of interest for the safety assessment to in addition to EDZ increase the general understanding of the repository rock with regard to the presence and properties of fractures and deformation zones (for example for DFN analysis and identification of critical structures) as well as of rock mechanics (mainly rock stress) and hydrogeochemical conditions. Information from the skip shaft with preceding pilot boreholes will be used to establish and, if necessary, adjust the repository depth.

The upper part of the bedrock is more permeable than the lower part. When starting the construction of accesses, it is therefore important to already from the beginning note how the groundwater table is affected. The chemical composition of drainage water is also important to monitor. In the assessment of environmental impact and environmental monitoring, the results from model updates are also of interest. The programme for monitoring will be updated in conjunction with establishing an operational programme for repository accesses.

4.3 Activities

Detailed site investigations in conjunction with preparations and construction of accesses include the activities described below. A summary of and reasons for these activities are provided in Table 4-1. A slightly more detailed description of the activities follows after the table. In conjunction with the detailed design, operational programmes for detailed site investigations will be prepared for detailed steering of the execution of work.

- Geotechnical investigation of soil layers and bedrock.
- Pilot borehole for skip shaft.
- Continuous investigations during skip shaft excavation.
- Rock stress measurements during skip shaft excavation.
- Pilot boreholes for ramp excavation.
- Continuous investigations during ramp excavation.
- Rock stress measurements during ramp excavation.
- Investigations of the excavation-damaged zone, EDZ.
- Investigations in conjunction with excavation of ventilation and elevator shafts.
- Transport properties of the rock.
- Monitoring of inflow, groundwater pressure, hydrogeochemistry and hydrochemistry.
- Seismic monitoring.
- Modelling.

There must also be a preparedness for other elements of detailed site investigations, e.g. if structures or conditions that significantly deviate from the expected are found. This may entail new boreholes either from the ground surface or from the repository accesses. A decision on such drilling assumes a requisite safety evaluation. Other needs could be testing of detailed site investigation methods for later phases and training of personnel, but also specific characterisation efforts if the need arises.

Table 4-1. Geoscientific investigations during construction of accesses. Activities are for the most part presented in sequential order. Some activities, however, reoccur on two or more occasions. All pilot boreholes are cored boreholes.

Activity	Description	Reason
Geotechnical investigation of soil layers and bedrock	Probe holes and cored boreholes in the upper bedrock. Probing is carried out according to the geotechnical standard. Geological, geophysical and hydrogeological investigations in cored boreholes. A part of this has been carried out, including a 3-D seismic investigation.	A basis for: • Detailed design. • Shaft and ramp locations. • The occurrence of water-bearing fractures in the upper bedrock. • Programme for curtain grouting around ramp and shafts.
Pilot borehole for skip shaft	Pilot borehole in or adjacent to the shaft position from the ground surface down to the shaft bottom. Geological, geophysical and hydrogeological borehole investigations. Water sampling of water-bearing fractures where justified. The pilot borehole and borehole investigations are completed.	A basis for: • Detailed design. • Grouting and rock support needs. • Verification of modelled geoscientific conditions and update of the facility part model. • Possible adjustment of repository depth. • SDM-SAR.
Continuous investigations during skip shaft excavation	Geological/hydrogeological mapping of shaft wall. Data from probe holes and other construction-related information.	A basis for: • Grouting and rock support needs. • Verification of modelled geoscientific conditions and update of the facility part model. • Possible adjustment of repository depth. • SDM-SAR.
Rock stress measurements during skip shaft excavation	Overcoring measurements (LVDT method) are conducted at some levels in the skip shaft, complemented by convergence measurements. The measurement location is established in the operational programme.	A basis for: • Verification of modelled geoscientific conditions and update of the facility part model. • SDM-SAR. • Possible adjustment of repository depth. • Verification of deposition tunnel orientation and rock support needs.
Pilot boreholes for ramp excavation	Pilot boreholes through deformation zones that are judged to be significantly more permeable than the surrounding rock or could lead to increased needs of rock support. Pilot drilling below about 370 m in order to learn more about the repository rock, including additional data for DFN modelling. The scope is determined in operational programmes. Geological, geophysical and hydrogeological borehole investigations. Water sampling.	A basis for: • Grouting and rock support needs. • Verification of modelled geoscientific conditions and update of the facility part model. • SDM-SAR.
Continuous investigations during ramp excavation	Geological/hydrogeological mapping of rock walls. Data from probe holes and other construction-related information.	A basis for: • Grouting and rock support needs. • Verification of modelled geoscientific conditions and update of the facility part model. • SDM-SAR.

Activity	Description	Reason
Rock stress measurements during ramp excavation	As a complement to the rock stress measurements in the skip shaft, rock stress measurements are conducted at some ramp positions. The investigations include overcoring measurements (LVDT) and convergence measurements as well as mechanical parameters from drill core tests. The measurement locations are described in operational programmes.	A basis for: • Verification of modelled rock mechanical conditions and update of the facility part model. • SDM-SAR. • Verification of deposition tunnel orientation.
Investigations of the excavation-damaged zone, EDZ	Investigations of verification nature in a niche before the ramp reaches 370 m (including hydraulic tests). Geophysical and geological investigations in the ramp below 370 m.	A basis for: • Verification that the excavation damaged zone (EDZ) fulfils the technical design requirement for the ramp below the top seal.
Investigations in conjunction with excavation of ventilation and elevator shafts	Raise boring of shafts is carried out in steps and geological/hydrogeological mapping of the shaft wall is carried out after each step.	A basis for: • Verification of modelled geoscientific conditions and update of the facility part model. • SDM-SAR.
Transport properties of the rock	Sampling and laboratory experiments for determination of the diffusion and sorption properties of the rock.	A basis for: • Verification of retardation model. • SDM-SAR.
Monitoring of inflow, groundwater pressure, hydrogeochemistry and hydrochemistry	The ongoing monitoring programme continues. The scope is revised before construction begins. The monitoring will be gradually supplemented with monitoring of inflows to the ramp and shafts. Sampling for inspection of introduced and pumped-out water (chemical composition and concentration of added tracer). Follow-up of monitoring linked to SFR.	A basis for: • Environmental monitoring. • Verification of modelled geoscientific conditions and update of the facility part model. • SDM-SAR. • Understanding of the interaction between SFR and the Repository for spent nuclear fuel.
Seismic monitoring	The seismic monitoring is supplemented with a local measurement system well before the construction of repository accesses begins. Thus, seismic events with lower magnitudes are registered in the surrounding area. GNSS monitoring begins.	A basis for: • Assessment of the impact of tunnels/shafts on the surrounding bedrock. • SDM-SAR.
Modelling	Continuous updates of working models for the access area, mainly at the facility part scale and at the tunnel scale. Modelling satisfying the needs of rock construction. Modelling in preparation for the site-descriptive model update to SDM-SAR. Modelling for analyses of specific issues.	A basis for: • Adjustment of repository depth and the layout of the central area and the first deposition area. • Continuously updated programme for grouting and rock support. • Verification of modelled geoscientific conditions and update of the facility part model. • SDM-SAR.

Geotechnical investigations of soil layers and the shallow bedrock

Investigations made in preparation of construction are conducted before starting the construction of buildings and accesses. Geotechnical investigations are needed as a basis for determining the exact location of the shafts and ramp access, including the need of shaft excavation. The geotechnical investigations include soil-rock penetration tests at the start positions for shafts and ramp and in their immediate surroundings for determination of soil layer depth and stratification and the rock surface position and to provide a basis for foundation engineering and shaft excavation as well as for handling masses and establishment of mass balance.

Improvement of the knowledge concerning the occurrence of water-bearing fractures in the upper bedrock as observed along the initial parts of ramp route. This will serve as a basis for the curtain grouting that will be carried out from the ground surface before start of construction, and for the pre-grouting that will be carried out during the construction of the upper parts of the ramp. Data are also needed for curtain grouting and grouting prior to and during the construction of the skip shaft and the other shafts.

In order to obtain preliminary data related to the aforementioned issues, soil-rock penetration tests and short cored boreholes have already been carried out. A 3-D seismic investigation has been conducted in order to provide supplementary information on the rock along the planned ramp. Additional geotechnical investigations may be conducted prior to and during detailed design and before start of construction.

Pilot borehole for skip shaft

The investigations made in preparation of construction also include a pilot borehole at the planned location for the skip shaft. The purpose of the borehole is to provide data for the estimation of grouting and rock support needs in conjunction with shaft sinking. The frequency and distribution of open water-bearing fractures in fracture domain FFM02 are of particular interest for the assessment of grouting needs.

Geological, geophysical and hydrogeological investigations are conducted in the cored borehole. Water-bearing fractures are sampled for chemical analysis of the groundwater.

For establishment of the facility part model and as a basis for SDM-SAR, verification of modelled geological conditions is of general interest. Although the shaft is located adjacent to the repository area, the borehole at depth will supply knowledge concerning the conditions at repository depth. Of particular interest for the safety assessment are data on water-bearing fractures and hydrogeochemistry below a depth of about 370 m (lower limit of the top seal), as well as the location, orientation and properties of deformation zones, regardless of observation depth.

At the time of completion of the current report, the hole has been drilled while the investigation programme and modelling are in progress.

Continuous investigations during skip shaft excavation

During skip shaft excavation, geological mapping of the rock wall is conducted in conjunction with rock support work. The skip shaft will be lined with cement along its entire extent. Mapping is made with the RoCS system, which has been developed and tested at the Äspö HRL. The RoCS system, by means of photogrammetry, creates a geodetically correct map on which the geological parameters are entered. Application of the mapping methodology will be adapted so that it can be coordinated with the shaft sinking process. Prerequisites and conditions for mapping during shaft sinking will probably cause the mapping to be largely based on the indirect photogrammetric data.

Shaft sinking will generate data from rock excavation. Even if these data are part of the specific detailed site investigation, the data will be documented in a database as a basis for as-built documentation. Examples of such data are outflow data from probe holes, the amount of cement-based grout used, water consumption and pumped-out drainage water for different levels.

Rock stress measurements during skip shaft excavation

As noted in SR-Site, improved knowledge of rock stresses and other rock mechanics parameters are of interest. Rock stress measurements are conducted on several levels in the skip shaft. Overcoring measurements with the LVDT method are primarily used (Hakala et al. 2013) with convergence measurements as a complement. These methods have the best potential for measurements in shafts, especially since the complementary data that need to be supplemented concern horizontal stresses. For convergence measurements, measurement bolts are bored into the rock, after which shaft geometry changes caused by excavation in front of the measurement section and time-dependent deformations can be determined by measuring the bolts very carefully with laser technology. Data from deformation measurements and information on deformation properties (Young's modulus) can then be used to determine the magnitudes and orientations of the principal stresses at the relevant depth level.

Data from the lower part of the skip shaft will be of particular interest, since they serve as a basis for establishment or adjustment of the repository depth and as input to adjustment of the orientation of deposition tunnels. The depth levels at which the measurements will be conducted are established in the operational programme for accesses.

Pilot boreholes for ramp excavation

The existing knowledge of expected rock conditions in the rock volume involved in ramp excavation is deemed to be good. For rock excavation, the need of pilot boreholes is therefore mainly restricted to the upper fracture domain FFM02, where water-bearing fractures are common, and below it when passing through deformation zones that are judged to require specific grouting and rock support measures. The locations for drilling pilot boreholes are established in the operational programme and are thereafter adjusted in conjunction with modelling and updating of tunnel predictions.

For safety assessment, there is a need to update the DFN model with more high-resolution data from the rock at repository level and above. This need is met by drilling some pilot boreholes in the lower part of the ramp, below a depth of about 370 m. Data on water-bearing fractures, for example for DFN analyses, and information on hydrogeochemical conditions are of particular importance. The gently dipping inclination of the pilot boreholes provides a good picture of the lateral variability of various parameters in the repository rock. The occurrence, geometry and properties of permeable fractures are of main interest, since quantitative information on such fractures is difficult to obtain from regular tunnel mapping. This also applies for groundwater sampling. Although the primary point of departure is to obtain unaffected water samples, water samples that are affected by the ongoing construction of accesses can be helpful to better understand short-term changes in hydrogeochemistry, thereby also providing a better understanding of the hydrogeological situation. The number of pilot boreholes and the extent of borehole measurements and groundwater sampling are established in the operational programme. The location, geometry and properties of deformation zones, regardless of observation depth, are of interest for updating the facility part model, see Chapter 8, and as a basis for the SDM-SAR.

Continuous investigations during ramp excavation

During ramp excavation, data will be registered, e.g. the amount of cement-based grout used, water consumption and pumped-out drainage water. The bedrock and its fractures and inflows will be documented. This is done by geological overview mapping at the tunnel face mainly for observing structures of importance for predictions of excavation advance and measurement of the tunnel contour. Then follows detailed mapping with the RoCS system performed at larger distance behind the active driving face. When passing through deformation zones, use of shotcrete rock support may entail that the mapping needs to be partially based on photographs.

This heading also covers collection of data from the continuous probe drilling that will be carried out, covering some 4 to 5 blast rounds, see Figure 2-6, which provides a basis for decisions on pre-grouting, according to grouting classes established in advance. If necessary, flow and pressure build-up tests that allows transient evaluation of material properties can be carried out in the probe holes.

Rock stress measurements during ramp excavation

At some locations along the ramp, rock mechanics investigations will be carried out for establishing the magnitudes and orientations of the principal rock stresses, as a complement to the measurements in the skip shaft. The investigations include overcoring measurements (LVDT method) and convergence measurements as well as measurements of mechanical parameters on drill cores in the laboratory. The scope of the measurement programme and the measurement and sampling locations are established in the operational programme.

Investigations of the excavation-damaged zone, EDZ

Below a depth of 370 m, there are applicable technical design requirements regarding hydraulic characteristics of any developed and hydraulically connected EDZ. The possibilities to comply with the technical design requirements for EDZ are mainly dependent on the excavation technique and that the execution is quality assured. Methods for inspection of whether any hydraulically connected EDZ exists have been developed and tested in the Äspö HRL (Ericsson et al. 2015).

Mainly geophysical methods in combination with geological documentation are planned along the ramp when the methodology for rock excavation is tailored and tuned to comply with the EDZ requirement that applies below a depth of 370 m. Compliance of the blast design in the fulfilment of the hydraulic requirements on the excavation damaged zone will be demonstrated and documented in a separate niche in the ramp before it reaches a depth of 370 m. A further development of the characterisation methods, including hydraulic tests, which were used in the EDZ experiment at the Äspö HRL is applied for this purpose. If necessary, rock excavation is adapted so that the requirements on EDZ are met, after which continued follow-up is done with geophysical methods and geological documentation on a scale that will be finalised in the operational programme.

Investigations in connection with excavation of ventilation and elevator shafts

Ventilation and elevator shafts will be constructed by raise boring. Excavation is divided into several steps and is synchronised with the ramp construction. The understanding of the bedrock will be high at the time when these shafts are excavated and the information needs for rock excavation should be met by the pilot boreholes (not cored boreholes) that precede the stepwise raise boring. After the concluding excavation step, the geological mapping of the shaft wall will take place from the hoisting cage, or from pictures of the rock wall. The inflows to shaft sections are measured.

If necessary, a pilot borehole from the ground surface is core drilled at the shaft position. Investigations in the borehole are conducted in the same way as for the pilot borehole for the skip shaft.

Transport properties of the rock

A description of the diffusion and sorption properties of the rock was established in SDM-Site and resulted in a site descriptive model of the transport properties with an associated retardation model for Forsmark that was later used in SR-Site. Within the framework of the detailed site investigations, the rock is sampled, mainly below 370 m, for laboratory tests of verification nature. The results of the laboratory tests are a part of the primary data set for the preparation of the SDM-SAR and further analyses prior to the SAR.

Monitoring of inflow, groundwater pressure, hydrogeochemistry and hydrochemistry

Since the site investigation, extensive monitoring of meteorological, hydrological and hydrochemical parameters is under way in air and surface water in the Forsmark area. Monitoring also takes place in a large number of boreholes with respect to groundwater pressure, groundwater flow and hydrogeochemistry (SKB 2007). The monitoring programme has been evaluated with respect to the need for monitoring during the construction and operation of the Repository for spent nuclear fuel (Berglund and Lindborg 2018). These measurements will continue in all essential respects during repository construction and operation. Some adjustments may be made, depending on the conditions for the environmental monitoring. Monitoring is also in progress at the final repository for short-lived radioactive waste (SFR). This monitoring is carried out fully integrated with the monitoring for the Repository for spent nuclear fuel.

During construction of accesses, water-bearing parts of the bedrock will be grouted to create favourable conditions for rock excavation and operation. There is also a technical design requirement related to the amount of inflow to the entire final repository that can be accepted. Throughout the construction and operation of the Repository for spent nuclear fuel, measurements of groundwater leakage will be conducted, for different facility parts and depth levels and of the total amount of pumped-out groundwater. Monitoring stations are built in the repository accesses and monitoring is gradually extended as the construction of the facility progresses. The location of monitoring stations and other specifications concerning the measurements are described in the operational programme and are included in the monitoring programme, which is updated as new monitoring stations/boreholes are established. The groundwater chemical composition will also be analysed. Any additional investigation boreholes will be monitored.

Results from the monitoring are used within the framework of the environmental monitoring programme and serve as input data for modelling of groundwater flow and hydrogeochemistry.

All industrial water supplied to the facility should be marked with a stable non-reactive tracer. The reason is that it is then possible to check whether a given water sample collected in the facility for chemical analysis consist of unaffected groundwater or whether it is contaminated by industrial water introduced to the facility, and if so to what extent. In order to verify the chemistry of the supplied water, and that the concentration of tracer in introduced water is constant, regular water samples are collected and analysed.

Seismic monitoring

A seismic station was established in Forsmark during the surface-based site investigation and is now a part of the Swedish seismic network. Well before starting the construction of repository accesses, this station will be supplemented with a local seismic network with higher resolution so that seismic events of lower magnitude can also be registered (Berglund and Lindborg 2018). The measurements are expected to provide information on deformation of the rock mass as a result of tunnel/shaft excavation, which will contribute to improved knowledge of where such deformation occurs, thereby serving as a basis for determining the impact of tunnels/shafts on the surrounding bedrock. The expectation is that deformations in structures (fractures and deformation zones) will also be detected, which will be used for refining the structural geology model.

SKB has previously conducted GPS measurements in some measurement points to identify relative movements between rock blocks. A new monitoring programme with GPS or another GNSS (Global Navigation Satellite System) that includes around ten measurement points is under way to enable detection of any movements across selected major deformation zones in the Forsmark area. Information from seismic monitoring and GNSS monitoring is mainly used in support of descriptive geological models.

Modelling

Before the construction of accesses begins, the modelling predominantly involves development of a facility part model for the access area, see further Chapter 8. The model is based on SDM-Site (data and models) and its background reports, supplemented with data from investigations made in preparation of construction, including data from the pilot boreholes for the skip shaft and ramp drilled from the ground surface. Data from hydrogeological and hydrogeochemical monitoring are also used. During construction, the geological and hydrogeological models are updated at regular intervals, while updates of hydrogeochemical, rock mechanics and thermal conditions and transport properties of the rock are made less frequently. Rock mechanics modelling is mainly conducted to describe the rock stress situation and when there are new measurement data.

Priority tasks for modelling before the start of construction are:

- Presenting an updated model of deformation zones at the facility part scale of the rock volumes affected by the accesses.
- Preparing a detailed prediction for sections along the ramp and shafts that may be associated with stability problems and/or high inflows. In particular for inflows, the prediction will be uncertain, although valuable information is obtained from curtain grouting in the upper bedrock. The excavation of tunnels/shafts is therefore preceded by systematic drilling of probe holes from tunnels/shafts to assess the need and extent of the grouting.
- Providing a basis (predictions) for assessment of shaft and ramp excavation impact on the surrounding environment.

As mentioned previously, it is of interest for the safety assessment to in addition to EDZ increase the general understanding of the repository rock with regard to the presence and properties of fractures and deformation zones (for DFN analysis and identification of critical structures) as well as of rock mechanics (mainly rock stress) and hydrogeochemical conditions.

Priority tasks for modelling during the construction of accesses are:

- Describing the rock stress situation, which together with the existence of subhorizontal zones is a basis for determining the repository depth.
- Providing a basis for any adjustment of the layout of the central area and the first deposition area.
- Providing a basis for continuously updated predictions of rock support needs and the need for drilling of pilot boreholes.
- Providing a basis for any specific measures, for example in support of analyses of the EDZ characterisation work during excavation of the repository accesses.
- Verifying and elaborating the conditions described in SDM-Site concerning the repository rock properties by means of data from the lower parts of the accesses.

The content and scope of the modelling work will be specified in operational programmes based on the methodology described in the updated methodology reports (for discipline-specific and integrated modelling).

The modelling, which will be carried out step by step during construction, includes single-hole interpretation of pilot boreholes and updating of working models at the tunnel scale that describe parts of the ramp and shafts based on mapping results and construction-related data. These results are thereafter integrated through an update of the facility part model. Integration of models on different scales, as well as between the different accesses, is strategic for modelling of the entire access volume and updating of the predictions during construction. Given that the construction of the central area will begin before the accesses are completed, the initial facility part model of accesses will be enlarged to also include the central area.

Examples of studies of specific issues are modelling of drawdown of the groundwater table in sensitive environments at the ground surface and analysis of the occurrence and extent of episyenite (vuggy rock) and its importance for groundwater flow.

A more extensive update of the site descriptive model, from SDM-Site to SDM-SAR, will be made towards the end of the construction phase, see Chapter 6. This update serves as a basis for the safety analysis report (SAR), which in turn will serve as a basis for the application for trial operation. With a modelling process that already from the start of construction continuously includes results from the investigations during construction in working models, the site-descriptive modelling to be included in SDM-SAR will be well prepared, see Chapter 8.

5 Detailed site investigations during construction of the central area

5.1 Repository parts

The central area contains the functions and processes for operation and maintenance that must be located close to the repository area, see Figure 5-1. The area is divided into a number of separate rock caverns, denoted rooms, and tunnel systems below and above the level of the floor of the rooms, intended for various functions. Most halls are similarly designed with the width 15 m, the height 10 m and the length 65 m.

Tunnels around the central area connect the rooms with each other and with the repository area and the ramp. Tunnels between rooms and shafts are used for transport, communications, technical systems, evacuation etc. In addition, there is a tunnel connecting the various levels of the rock loading station.

The construction of the central area begins when the skip shaft has reached repository depth and thus initially takes place at the same time as the construction of the deeper parts of the ramp. Tunnel excavation towards the first deposition area and the execution of integration and commissioning tests are also carried out in simultaneously with the construction of the central area. How the excavation of the mentioned repository parts will proceed in detail will be determined in the detailed design with a description of detailed site investigations in the operational programmes.

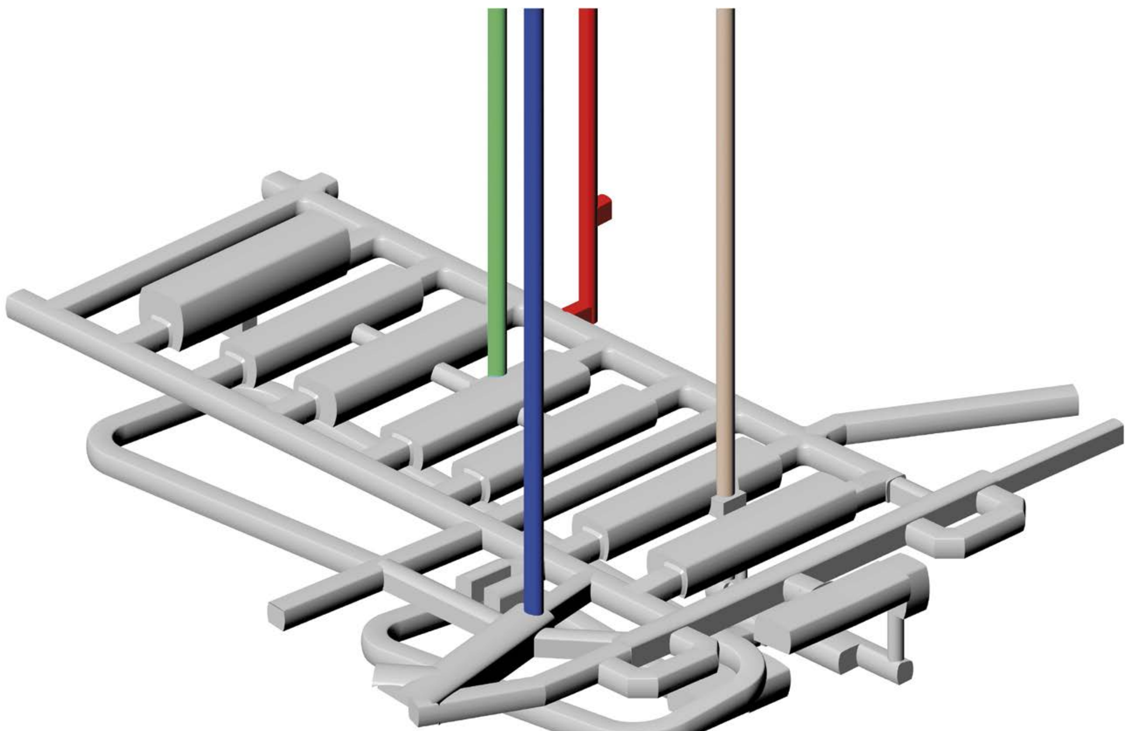

Figure 5-1. *Perspective view of the central area with the lower parts of the ramp and shafts. Blue represents fresh air shaft, red is exhaust air shaft, green the elevator shaft and brown the skip shaft.*

5.2 Information needs

Detailed site investigations in the central area should provide the necessary rock engineering data as a basis for the construction of the central area. Collected primary data and established models have no crucial importance for meeting technical design requirements regarding safety after closure.

Even though the investigations are not primarily focused on verifying that the technical design requirements are met, they need to provide data for verification of repository rock properties and conditions since the central area is located in the same bedrock as nearby repository parts. They should also provide data for the site model update and for the detailed design of nearby repository parts. The data are later used for updating the assessment of safety after closure that is included in the safety analysis report (SAR) prior to the application for trial operation, see Chapter 6. Important investigations concern rock mechanics properties and conditions, the occurrence of potential critical structures, other information on fracture geometries, the presence of water-bearing fractures and groundwater chemical composition. Information on the behaviour and heterogeneity of bedrock with low thermal conductivity (mainly amphibolite) is also important, as well as any occurrence of episyenite (vuggy rock).

The geometry of the central area provides opportunities for testing strategies and methods for detailed site investigations in deposition areas, including identification and characterisation of potential critical structures.

The detailed site investigations in the central area will be specified in an operational programme. The activities described below are based on current knowledge and the information needs of design/construction and safety assessment.

5.3 Activities

Detailed site investigations in conjunction with construction of the central area include the following activities. A summary of and reasons for these activities are provided in Table 5-1. A description of the activities follows after the table. In conjunction with the detailed design, operational programmes for detailed site investigations will be prepared for detailed control of their execution.

- Pilot boreholes for rooms and tunnels.
- Continuous investigations during excavation of rooms and tunnels.
- Testing of the methodology for identification and characterisation of critical structures for deposition positions.
- Testing of the methodology concerning the occurrence and spatial extent of amphibolite.
- Geometries and properties of deformation zones.
- Rock mechanics conditions.
- Transport properties of the rock.
- Monitoring of inflow, groundwater pressure, hydrogeochemistry and hydrochemistry.
- Seismic monitoring.
- Modelling.

There must also be a preparedness for targeted detailed site investigations, if structures or other conditions are encountered that significantly deviate from the expected outcome.

Table 5-1. Geoscientific investigations during construction of the central area. Activities are for the most part presented in sequential order. Some activities, however, reoccur on two or more occasions. All pilot boreholes are cored boreholes.

Activity	Description	Reason
Pilot boreholes for rooms and tunnels	Pilot boreholes through deformation zones that are judged to be significantly more permeable than the surrounding rock or could entail increased needs of rock support. Pilot boreholes for certain tunnels and rooms to increase the understanding of the repository host rock, including more data for DFN modelling. The extent of the pilot borehole drilling is established in the operational programme. Geological, geophysical and hydro-geological borehole investigations. Water sampling.	A basis for: • Grouting and rock support needs. • Excavation sequences. • Verification of modelled geoscientific conditions and update of the facility part model. • Test of methodology for identification of critical structures. • SDM-SAR.
Continuous investigations during excavation of rooms and tunnels	Geological/hydrogeological mapping of rock walls. Data from probe holes and other construction-related information.	A basis for: • Grouting and rock support needs. • Verification of modelled geoscientific conditions and update of the facility part model. • SDM-SAR. • Documentation of geometric and geological conditions.
Testing of the methodology for identification and characterisation of critical structures for deposition positions	Mapping of FPIs (indicators of critical structures) intersecting one or more tunnels and rooms as well as geophysical and hydrogeological methodology for determining their extent in the surrounding rock. The mapping provides initial information for accumulation of site-specific knowledge concerning the occurrence of potential critical structures in the repository rock. The parallel rooms of the central area, with an orientation similar to the deposition tunnels, offer opportunities to test the methodology prior to the planned verification of methodology that will be carried out within the framework of integration and commissioning tests (Chapter 6).	Testing of the methodology that will be used in deposition tunnels when choosing and approving canister positions. A basis for: • Verification of modelled geoscientific conditions and update of the facility part model. • SDM-SAR. • Basis for estimating the loss of canister positions in nearby deposition areas.
Testing of the methodology concerning the occurrence and spatial extent of amphibolite	Mapping the occurrence of amphibolite and other basic rocks with low thermal conductivity. Testing geological and geophysical methods for determining their distribution and spatial extent.	Testing of the methodology that will be used in deposition tunnels when choosing and approving deposition hole positions. A basis for: • Verification of modelled geoscientific conditions and update of the facility part model. • SDM-SAR. • Basis for estimating the loss of canister positions in nearby deposition areas.
Geometries and properties of deformation zones	Mapping of deformation zones in pilot boreholes, tunnels and halls. Borehole measurements of hydrogeological and other properties. If water-bearing fractures are encountered, water samples are taken. During pilot drilling, the pressure responses in other boreholes are registered. Scope according to the operational investigation programme.	A basis for: • Grouting and rock support needs. • Verification of modelled geoscientific conditions and update of the facility part model. • Any adjustment and successive adaptation of the central area layout. • SDM-SAR.

Activity	Description	Reason
Rock mechanics conditions	Borehole/drill core, tunnels and rooms are inspected for possible spalling and other instabilities. If necessary, determination of rock mechanics parameters on drill cores and rock stress measurements. The scope is described in the operational programme.	A basis for: • Verification of modelled rock mechanics conditions and update of the facility part model. • SDM-SAR.
Transport properties of the rock	Sampling and laboratory tests for determination of the diffusion and sorption properties of the rock.	A basis for: • Verification of retardation model. • SDM-SAR.
Monitoring of inflow, groundwater pressure, hydrogeochemistry and hydrochemistry	Continued monitoring in boreholes from the ground surface and any additional investigation boreholes. During construction of the central area, new monitoring points are generated for inflows at measuring weirs in individual tunnels and rooms, and of the total amount of pumped-out drainage water and its chemical composition. Sampling for inspection of introduced industrial water (chemical composition and concentration of added tracer). Follow-up of monitoring linked to SFR.	A basis for: • Environmental monitoring. • Verification of modelled geoscientific conditions and update of the facility part model. • SDM-SAR. • Understanding of the interaction between SFR and the Repository for spent nuclear fuel.
Seismic monitoring	Continued monitoring of the national and local seismic network for registration of seismic events. GNSS monitoring continues.	A basis for: – Assessment of the impact of tunnels/shafts on the surrounding bedrock. – SDM-SAR.
Modelling	Continuous updates of working models covering the access and central area, mainly at the tunnel scale and at the facility part scale. Modelling to satisfy the needs of rock excavation. Modelling in preparation for the site model update to SDM-SAR. Modelling for investigation of specific issues. The modelling is largely integrated with the modelling for accesses and the initial modelling of the first deposition area. Analysis of interaction between repository parts where simultaneous activities are planned and assessment of the implications of these activities.	A basis for: • Adjustment and successive adaptation of the central area layout. • Continuously updating programme for grouting and rock support. • Verification of modelled geoscientific conditions and update of the facility part model. • SDM-SAR. • Support for investigations of critical structures.

Pilot boreholes for rooms and tunnels

Excavation of some tunnels and rooms will be preceded by pilot boreholes. The extent will be specified in the operational programme. When the latter programme is established, there will be more extensive information from the construction of repository accesses, which will affect both the location and the extent of the pilot boreholes. Investigations of deformation zones will be important for design/construction and for verification and update of the SDM.

Some deformation zones could be potential critical structures. In addition to the possibility of testing methodology for identification and characterisation of such structures in the central area, information on their presence can be used for estimating the loss of canister positions in nearby deposition areas. From this aspect, data from pilot boreholes that can be used to identify potential critical structures are of particular interest. In addition, fracture data, particularly data on water-bearing fractures, are used for updating DFN models, see Section 4.3. Drill core samples are taken for determination of geophysical and rock mechanics parameters. If water-bearing fractures are encountered, water samples for chemical analyses are collected after an assessment of the need and relevance.

Continuous investigations during excavation of rooms and tunnels

As described earlier, the excavation of tunnels and rooms will generate data, such as outflow data from probe boreholes, the amount of cement-based grout used, water consumption and pumped-out drainage water, which must be continuously documented in a database. If necessary, flow and pressure build-up tests that allow transient evaluation are carried out in the probe boreholes. The bedrock with its main rock types, and the presence of important subordinate rock types, is documented using the RoCS system, as are observed fractures and inflows. The scope and level of detail of the mapping for different rooms and tunnels are described in the operational programme.

Testing the methodology for identification and characterisation of critical structures for deposition positions

The central area tunnels and halls can provide an opportunity to test the methodology for identification and classification of critical structures, as described in Section 3.2. The methodology can be tested in repository host rock in the central area and then verified during integration and commissioning tests in the first deposition area. Regardless of the results of the methodology tests, the most important aspect with respect to critical structures is judged to be the site-specific knowledge that is gradually assembled during the operational phase of the final repository and then successively integrated into increased site understanding and models at different scales.

The deterministic knowledge (the database) on critical structures may initially be built up through systematic mapping of FPIs as indicators of critical structures in the tunnels and rooms of the central area, including interpretation of structure indications that can be connected, thereby providing an indication of extent. Geological and hydraulic information from pilot boreholes contributes to this end. The rooms of the central area have a favourable geometry in relation to the deposition tunnels of the repository area. Understanding of the interpreted size of structures provides supplementary site-specific knowledge. With respect to shear along a critical structure, not only the geometric size is decisive but the investigations also need to provide information on the structure's surface properties (governing friction) and its geometry in relation to rock stresses. Information on surface properties are included in the data collection for these structures, while rock stresses are assumed sufficiently known in this respect, but will be measured further for other reasons.

Detailed fracture mapping of the rooms, which have larger dimensions than the deposition tunnels, provides a good basis for determination of the fracture size distribution when updating the DFN models, which serve as a basis for predictions of the occurrence of critical structures in future deposition areas. At the same time, an empirical database is assembled and a better understanding is achieved of the occurrence, attributes and properties of critical structures, and of decisive investigation methods.

Testing the methodology concerning the occurrence and spatial extent of amphibolite

Amphibolite and other basic inclusions have lower thermal conductivity than the quartz-rich metagranite, which is the main host rock type in the repository volume. If larger inclusions of amphibolite would occur, it could affect the canister spacing and thereby lead to a loss of canister positions.

In SDM-Site, the occurrence of amphibolite is described statistically. Geological and geophysical surveys in the central area with its rooms and the tunnels above and below the rooms will therefore be used to shed light on the size distribution and spatial extent of existing amphibolite bodies. The results are used for estimations of amphibolite occurrence in nearby deposition areas and thereby serve as a basis for assessing the loss of canister positions and more generally in conjunction with the update of SDM-Site.

Geometries and properties of deformation zones

Deformation zones in the central area are investigated with respect to geometry (location, orientation, thickness and extent) and properties as a basis for grouting and rock support measures during construction of the central area and for identification of potential critical structures and for SDM-Site updates. Before the central area is built, investigations in the repository accesses are expected to have further specified the geometries of some of the relevant deformation zones.

The investigations that are continuously conducted during the construction of the central area, combined with pilot boreholes through potential deformation zones, are expected to provide the required data. During pilot drilling, the pressure responses in other boreholes are registered, including any parallel instrumented pilot boreholes nearby. If one or more of the deformation zones are water-bearing, hydraulic interference tests, in addition to verification of hydraulic connections and the extent of deformation zones between boreholes, can also provide detailed knowledge of their hydraulic material properties. Water samples are taken for chemical analyses. The need and the actual possibilities in relation to the central area construction determine the scope of such investigations, which will be presented in the operational investigation programme.

Rock mechanics conditions

During excavation of rooms and tunnels, the rock walls will be inspected and rock support introduced where instabilities, in the form of spalling, are observed or can be expected to occur. Such observations are documented and may govern where additional rock mechanics studies are conducted. This could entail drill core sampling for determination of rock mechanics parameters and supplementary rock stress measurements.

Transport properties of the rock

The rock is sampled for laboratory tests of verification nature where the results serve as input data for the preparation of SDM-SAR and further analyses in SAR.

Monitoring of inflow, groundwater pressure, hydrogeochemistry and hydrochemistry

During construction of the central area, monitoring continues in the same way as during the construction of repository accesses, see Section 4.3, and may be supplemented with monitoring in additional (temporary) investigation boreholes underground.

In addition to the hydrogeological and hydrogeochemical monitoring in existing boreholes from the surface-based site investigation, monitoring will be done in measuring weirs for documentation of inflowing groundwater to various rooms and tunnel sections. The measuring weirs are built successively as described in the operational programme. The amount of pumped-out drainage water is measured constantly and water samples are taken regularly for chemical analyses. The water supplied to the facility is also analysed and inspected with respect to the concentration of tracer used to tag the water.

Seismic monitoring

During the construction of the central area, seismic monitoring continues, using both the national seismic network and the local seismic network. The local seismic network is gradually extended with new monitoring stations. GNSS monitoring will continue to detect any movements along selected major deformation zones in the Forsmark area. The information is mainly used in descriptive geological modelling.

Seismic monitoring can also provide information on rock mass deformation due to tunnel excavation. This contributes to greater knowledge of where such deformation occurs, thereby serving as a basis for determining how great the impact of tunnel excavation is on the surrounding bedrock. Deformation along structures (fractures and deformation zones) could also be detected.

Modelling

During the construction of accesses, the investigations resulted in working models of mainly geological and hydrogeological conditions at the tunnel and facility part scale. Modelling of the central area is partly integrated with modelling of repository accesses and the first deposition area in an integrated facility part model, given that these parts are constructed partly in parallel. Such an integrated model also provides an opportunity to analyse the effects of simultaneously ongoing activities in the different facility parts. The modelling results serve as a basis for any adjustment and adaptation of the layout of the different parts of the central area.

Some activities may require special modelling efforts, especially as training before the first deposition area and for development and testing of investigation and modelling methodology for deposition tunnels. This mainly concerns the occurrence and spatial extent of amphibolite, DFN modelling, methodology for identification, characterisation and classification of critical structures and geometries and properties of deformation zones. At the occurrence of episyenite (vuggy rock), there may be a need for modelling of its extent and importance for groundwater flow.

Given that rock excavation is at this time carried out at repository depth, modelling of hydrogeochemical, rock mechanical and thermal conditions and of the transport properties of the rock will also be carried out, partly in preparation for the update of the site model to SDM-SAR, see Chapter 6.

6 Detailed site investigations during integration and commissioning tests and delineation of the first deposition area

This chapter describes the detailed site investigations that are carried out in the first deposition area before the deposition of spent nuclear fuel begins. These detailed site investigations are mainly related to two tunnels for integration and commissioning tests that are designed in the same way as for the future deposition tunnels. The execution is described in Section 6.3.1. Before the operational phase begins, the first tunnel loop is completed whereby detailed site investigations are also carried out to determine the outer boundaries of the first deposition area, see description in Section 6.3.2. It should be noted that the construction of these parts takes place while the construction of the central area is still under way.

The purpose of integration and commissioning tests is to verify that the processes for rock excavation and deposition in the Forsmark host rock can be carried out while ensuring safety after closure. The integration tests consist of two parts, an integration test for underground construction and an integration test for deposition. Tests are made of all activities that are relevant for construction of underground openings and deposition of spent nuclear fuel canisters. A third tunnel may be built to meet future needs of more long-term demonstration of processes of importance for safety after closure. The needs for the latter tests are currently being studied, including identification of what demonstrations should be carried out. In the current report, it is assumed that such a tunnel is built.

The integration test for construction involves testing and approval of the strategies and methods for detailed site investigations that will be used when selecting the locations of deposition tunnels and deposition holes and when verifying that the applicable technical design requirements are fulfilled. This implies for the construction integration tests, that the constructed deposition holes can be used for the integration test for deposition and for commissioning tests. The integration test for deposition correspondingly verifies the deposition process employing dummy canisters (no spent nuclear fuel is used), buffer and backfill and plugging of the deposition tunnel. This is repeated during the commissioning tests, but then all infrastructure and functions for deposition are in place so that the entire deposition process can be verified. The tunnels for integration and commissioning tests may also be used for various demonstrations with the purpose of site-specifically studying the evolution of the barriers after completed deposition. During such experiments, canisters with built-in heaters may also be used to create an environment that resembles the environment around a canister with spent fuel.

After the commissioning tests, permission for a licence to commence trial operation is requested. In the application, an updated site descriptive model will be presented, called SDM-SAR, which is a part of the basis for the safety assessment (SAR) that is included in the application. A planning premise for the report is that only results from the detailed site investigations in and between pilot boreholes for the deposition tunnels for integration and commissioning tests are included in the basis for SDM-SAR. The results from other detailed site investigations in the tunnels, until verification that the technical design requirements for deposition holes are fulfilled, constitute supplementary material for the application for trial operation.

6.1 Repository parts

Integration and commissioning tests are carried out in tunnels that are excavated from the first (northerly) main tunnel, which will be used for the development of the first deposition area. These tunnels are designed as short deposition tunnels and are used for verification of methodology. They start from a main tunnel, which together with the outer transport tunnel and a second main tunnel constitutes the first tunnel loop, see Figure 6-1. Construction of the first tunnel loop starts from the central area. At this time, continued rock excavation and installations in the central area are still under way.

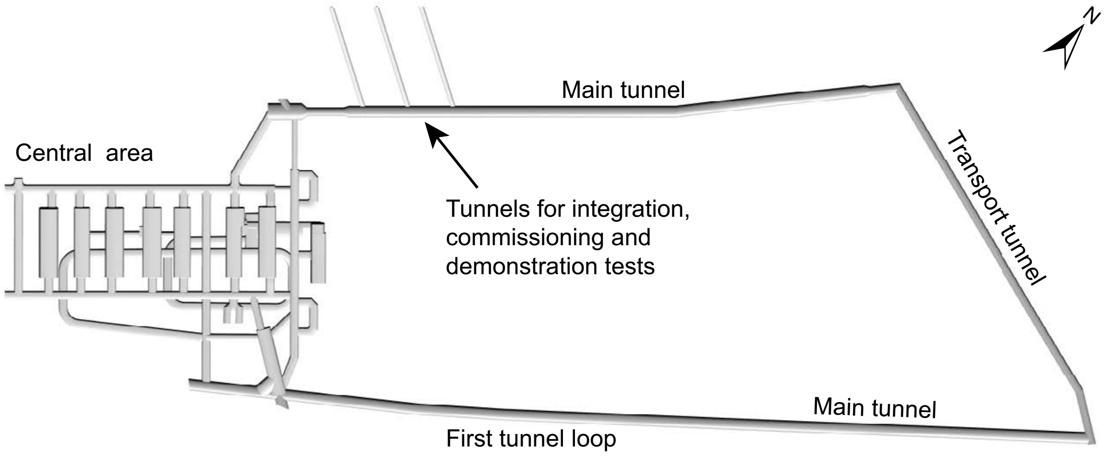

Figure 6-1. Planned locations at the beginning of the first tunnel loop for two tunnels for integration and commissioning tests and a possible third tunnel for demonstration of processes of importance for safety after closure. The central area and the location of the first tunnel loop in relation to the repository area are illustrated by Figure 2-3.

Tunnel construction for the first tunnel loop will continue while the construction integration test is in progress. The possibility to do this while avoiding mutual interference is assessed by means of the integrated facility part model, which includes the facility parts concerned. Since the construction integration test includes a couple of deposition tunnels in the repository host rock, experience from the investigations in and construction of the first tunnel can be used in the construction of the next tunnel. The accumulated experience from the construction integration test regarding the steps that are linked to bedrock conditions will be evaluated. This will lead to qualification of methodology and procedures for siting, excavation and detailed site investigations prior to and during the construction of the deposition areas that are of importance for the qualification of repository safety.

6.2 Information needs

Excavation of the main and transport tunnels that are part of the first tunnel loop requires information for assessment of grouting and rock support needs. Depending on the state of knowledge at the time, additional cored boreholes may be needed for determining the boundaries of the first deposition area. Information for decisions on construction, design and approval of deposition tunnels and deposition holes is described in Chapter 7, but are verified in the construction integration test described in this chapter.

The integration test for construction includes activities that will be implemented in the deposition areas during the operational phase. The activities thereby include all investigations and modelling required, from decisions regarding the location and length of deposition tunnels to decisions regarding approval of deposition holes. The rock excavation technique needs to be verified so that it fulfils the technical design requirements for the EDZ.

During the integration tests, the investigation and modelling methodology for deposition tunnels and deposition holes is applied systematically for the first time in deposition tunnels in Forsmark. This means that there must be time for fine-tuning/adjustment of the methodology, training of personnel and establishment of procedures for all steps.

6.3 Activities

Section 6.3.1 describes investigations in conjunction with the construction integration test for verification of methodology for adaptation of deposition tunnels to local rock conditions and compliance with the technical design requirements for deposition tunnels and deposition holes. Section 6.3.2 describes investigations for defining the boundaries of the first deposition area.

6.3.1 Integration test for underground construction

A summary of the detailed site investigation activities during the construction integration test, with motivations, is presented in Table 6-1. The activities are described in more detail after the table. Note that pilot drilling with investigations is carried out first for all three tunnels. Subsequently, the first tunnel with its deposition holes are excavated during which verification tests of detailed site investigation methods are carried out. Thereafter, evaluation and possible improvement of technology and methodology is performed before an updated construction and excavation process, including investigations, is applied in the next tunnel.

The detailed site investigations provide data for verification of the following steps and decisions:

- The choice of locations for experimental deposition tunnels and deposition holes.
- Excavation of deposition tunnels and drilling of deposition holes.
- Approval that deposition tunnels and deposition holes conform to the applicable technical design requirements.

The investigation activities that are conducted in these steps are:

- Pilot boreholes with associated investigations for main and transport tunnels.
- Continuous investigations during excavation of main and transport tunnels.
- Pilot boreholes with associated investigations for deposition tunnels.
- Hydraulic interference tests and geophysical cross-hole measurements.
- Continuous investigations during deposition tunnel excavation.
- Pilot boreholes with associated investigations for deposition holes at designated deposition positions.
- Investigations regarding the technical design requirement for critical structures in deposition holes.
- Mapping and measurement of deposition holes.
- Rock stress measurements and inspection of mechanical stability.
- Investigations of the excavation-damaged zone, EDZ.
- Transport properties of the rock.
- Monitoring of deposition tunnel(-s) and deposition holes.
- Monitoring of inflow, groundwater pressure, hydrogeochemistry and hydrochemistry.
- Seismic monitoring.
- Modelling.

Table 6-1. Geoscientific investigations during construction of the first tunnel loop and the integration test for underground construction. Activities are primarily presented in sequential order. Some activities, however, reoccur on two or more occasions. All pilot boreholes are cored boreholes.

Activity	Description	Reason
Pilot boreholes for main and transport tunnels	Continuous pilot drilling is applied in main and transport tunnels. For investigations in pilot boreholes in deposition areas, a standard for geological, geophysical, hydro-geological and hydrogeochemical borehole investigations will be applied, for establishment in the operational phase.	Application, verification and further development of methodology for detailed site investigations with regard to: • Verification of compliance with technical design requirements. • Preliminary choice of locations for deposition tunnels. A basis for: • Grouting and rock support needs. • Verification of modelled geoscientific conditions and update of the facility part model. • SDM-SAR.
Continuous investigations during excavation of main and transport tunnels	Data from probe holes and other construction-related information. Geological/hydrogeological mapping of rock walls. Geometric documentation of tunnels.	Application, verification and further development of methodology for detailed site investigations with regard to: • Verification of compliance with technical design requirements. • Choice of locations for deposition tunnels. A basis for: • Grouting and rock support. • Verification of modelled geoscientific conditions and update of the facility part model. • SDM-SAR.
Pilot boreholes for deposition tunnels (Decisions on locations and orientation are based on an updated working model with data from pilot boreholes and investigations in the main tunnel, including rock stress data and thermal properties.)	Pilot boreholes for the three tunnels are excavated in direct sequence. Finished pilot boreholes are instrumented for monitoring of pressure responses when additional pilot boreholes are drilled. An investigation programme is carried out in and between pilot boreholes.	Application, verification and further development of methodology for detailed site investigations with regard to: • Verification of compliance with technical design requirements. • Decision on construction of deposition tunnel and preliminary choice of canister positions. A basis for: • Grouting and rock support needs. • Verification of modelled geoscientific conditions and update of the facility part model. • SDM-SAR.
Hydraulic interference tests and geophysical cross-hole measurements	If water-bearing fractures are encountered in pilot boreholes for deposition tunnels, and if drilling gives rise to pressure responses between boreholes, hydraulic interference tests and geophysical (mainly electrical) cross-hole measurements are performed to study hydraulic and physical connections, which may indicate the occurrence of potential critical structures in future deposition hole positions. In-depth characterisation of the hydraulic material properties of investigated structures.	Application, verification and further development of methodology for detailed site investigations with regard to: • Verification of compliance with technical design requirements. • Choice of deposition positions. A basis for: • Verification of modelled geoscientific conditions and update of the facility part model. • SDM-SAR.

Activity	Description	Reason
Continuous investigations during deposition tunnel excavation	Data from probe holes and other construction-related information. Geological/hydrogeological mapping of tunnel wall and floor. Geometric documentation of tunnel.	Application, verification and further development of methodology for detailed site investigations with regard to: • Verification of compliance with technical design requirements. • Choice of deposition positions, including data for thermal optimisation of the deposition hole spacing. A basis for: • Grouting and rock support. • Verification of modelled geoscientific conditions and update of the facility part model. Supplementary material for the application for trial operation.
Pilot boreholes for deposition holes at deposition positions (Decisions on locations for pilot drilling are based on an updated working model at the tunnel scale with data from pilot boreholes, investigations in main and deposition tunnels, completed grouting, including assessment of thermal properties.)	Pilot drilling at selected locations for deposition positions. Continued testing and development of characterisation methodology for pilot boreholes for deposition holes. Drill core mapping and hydraulic measurements.	Application, verification and further development of methodology for detailed site investigations with regard to: • Identification of potential critical structures in pilot boreholes for deposition holes. • Decisions on drilling of deposition holes. A basis for: • Verification of modelled geoscientific conditions and update of the facility part model. • Verification of the methodology for approval of deposition holes. Supplementary material for the application for trial operation.
Investigations regarding the technical design requirement related to critical structures in deposition holes (see Section 3.2)	Mapping and modelling (in several steps) of minor deformation zones and individual persistent fractures in and between the main tunnel, pilot boreholes, deposition tunnels and deposition holes. Borehole and tunnel measurements of geological, geophysical, hydrogeological and other properties.In the main and deposition tunnels, mapping of FPIs as indicators of critical structures is a basal effort.	Application, verification and further development of methodology for detailed site investigations with regard to: • Identification of critical structures in deposition holes. • Choice of deposition positions and review of the methodology for approval of deposition holes. A basis for: • Verification of modelled geoscientific conditions and update of the facility part model. • Verification of the methodology for approval of deposition holes. Supplementary material for the application for trial operation.
After drilling of deposition holes: Mapping and measurements in deposition holes.	Geological and rock mechanics mapping. Hydraulic measurements. Geometric documentation.	Application, verification and further development of methodology for detailed site investigations with regard to: • Identification of critical structures in deposition holes, according to a combined assessment of applicable technical design requirements (risk of shear and hydraulic properties). • Verification that deposition holes meet geometric requirements. • Choice and approval of deposition holes. A basis for: • Verification of modelled geoscientific conditions and update of the facility part model. • Verification of the methodology for approval of deposition holes. Supplementary material for the application for trial operation.

Activity	Description	Reason
Rock stress measurements • Main tunnel • Deposition tunnels Inspection of mechanical stability	Measurements in the main tunnel are conducted with the LVDT method, possibly supplemented with convergence measurements, for orientation of the principal stresses, stress magnitudes. In the deposition tunnel, verification measurements are conducted with the SLITS method in a selection of deposition positions. Pilot borehole/drill core, deposition tunnels, deposition holes and main and transport tunnels are inspected for observations of spalling and other instabilities. Mechanical parameters are obtained from tests on drill cores from the pilot boreholes.	Application, verification and further development of methodology for detailed site investigations with regard to: • Establishment of and decision on deposition tunnel orientation. A basis for: • Verification of modelled geoscientific conditions and update of the facility part model. • Verification of the methodology for approval of deposition holes. • SDM-SAR (measurements in the main tunnel). Supplementary material for the application for trial operation.
Investigations of the excavation-damaged zone, EDZ	Geophysical and geological investigations in main, transport and deposition tunnels, with different requirements for different tunnels. For deposition tunnels, there is a proposed methodology for hydro-geological characterisation of the EDZ with utilisation of data from hydraulic measurements in pilot boreholes for deposition holes.	Application, verification and further development of methodology for detailed site investigations with regard to: • Verification that the excavation damaged zone (EDZ) fulfils the technical design requirements for tunnels in the deposition area. • Possible adjustment of the rock excavation technique. • SDM-SAR (measurements in transport and main tunnel). Supplementary material for the application for trial operation.
Transport properties of the rock	Sampling and laboratory tests for determination of the diffusion and sorption properties of the rock.	A basis for: • Verification of the retardation model SDM-Site. • SDM-SAR (pilot boreholes for the deposition tunnels).
Monitoring of deposition tunnel and deposition holes	Measurements of inflow into the deposition tunnel and provisionally approved deposition holes.	Application, verification and further development of methodology for detailed site investigations with regard to: • Verification of compliance with technical design requirements. A basis for: • Verification of modelled geoscientific conditions and update of the facility part model. • Verification of the methodology for approval of deposition holes. Supplementary material for the application for trial operation.
Monitoring of inflow, groundwater pressure, hydrogeochemistry and hydrochemistry	Continued monitoring of groundwater pressure, flow and chemistry in boreholes from the ground surface and in the underground facility. During the construction of the first tunnel loop (transport and main tunnels), new monitoring points are added for inflows at measuring weirs in individual tunnels. Sampling for inspection of introduced industrial water and inflowing ground-water (chemical composition and tracer content). Follow-up of monitoring linked to the SFR.	A basis for: • Environmental monitoring. • Verification of modelled geoscientific conditions and update of the facility part model. • Understanding of the interaction between different parts of the Repository for spent nuclear fuel. • Understanding of the interaction between the SFR and the Repository for spent nuclear fuel. • SDM-SAR. Supplementary material for the application for trial operation.

Activity	Description	Reason
Seismic monitoring	Continued monitoring using the national and local seismic networks for registration of seismic events. GNSS monitoring continues.	A basis for: • Assessment of the impact of tunnels/shafts on the surrounding bedrock. • SDM-SAR. Supplementary material for the application for trial operation.
Modelling	Continuous updating of working models primarily at the tunnel scale and integrated at the facility part scale, covering the accesses and the central area, the first tunnel loop and the area for integration and commissioning tests. Modelling for analysis of the interaction between the central area, construction of the first tunnel loop and the area for integration and commissioning tests. Integrated analysis used in support for verification of the applicable technical design requirements. Modelling for decisions regarding the location, construction and approval of deposition tunnels, deposition holes and plugs involved in the integration and commissioning tests. Modelling of rock excavation needs. Update of the site model to SDM-SAR.	Verification of the methodology for decisions related to construction and approval of deposition tunnels and deposition holes. A basis for a continuously updated programme for grouting and rock support needs. A basis for verification of the modelled geoscientific conditions and update of the site model to SDM-SAR, as a basis for the safety assessment, SAR. A basis for continued update of the SDM as a basis for detailed design of continued development and periodic overall assessment of safety after closure, at least every ten years.

Pilot boreholes for main and transport tunnels

Excavation of all main and transport tunnels will be preceded by cored pilot boreholes. Investigations in these boreholes, along with the mapping of the first main tunnel, provide data for adaptation of the location of the experimental deposition tunnel for integration and commissioning tests to ambient local bedrock conditions. The pilot boreholes are expected to provide knowledge of value for decisions regarding the location and construction of the tunnels primarily by investigations of the hydraulic properties of deformation zones and other hydraulic properties of the rock.

Hydraulic tests and geophysical measurements are performed in the pilot boreholes. If water-bearing fractures are encountered, an assessment is made of whether water samples should be taken for chemical analyses. The drill core is mapped and geophysical and rock mechanics parameters are determined on drilling samples. The scope of borehole investigations is established in the operational programme.

Continuous investigations during excavation of main and transport tunnels

The main tunnel, from which the tunnels for integration and commissioning tests start, is investigated according to the plans for main and transport tunnels. Excavation of the tunnel will generate outflow data from probe holes, the amount of cement-based grout used, water consumption and the amount of pumped-out drainage water and other data from excavation. If necessary, flow and pressure build-up tests that permit transient evaluation can be carried out in probe holes. The bedrock with its rock types, fractures and inflows will be documented with the RoCS system. The locations of measurement weirs are described in the operational programme. All data are documented continuously in a database.

Pilot boreholes for deposition tunnels

Tunnel excavation made as part of the integration test for underground construction will be preceded by three pilot boreholes drilled within the contour of the future tunnels, respectively. The pilot boreholes are bored in direct sequence and then investigated in a joint effort. In order to verify the detailed site investigation methodology for characterisation of the rock volume around deposition tunnels that will later be used in deposition areas (Chapter 7), three pilot boreholes are judged to be adequate, even though the investigations will normally include a batch of five pilot boreholes when applied in the deposition areas. The pilot boreholes are successively provided with packer systems for registration of pressure responses during drilling, which provides data for a preliminary interpretation of hydraulically connected structures and for planning of more advanced hydraulic and geophysical (mainly electrical) cross-hole measurements.

The pilot boreholes also provide data for estimating needs of rock support and assessment of the need for pre-grouting of any specific deformation zone or water-bearing section. During the integration test for construction, the methodology for modelling and choice of preliminary locations of canister positions is verified based on information from the pilot borehole. Indications of potential critical structures are of particular interest, as well as the presence of important subordinate rock types (amphibolite and episyenite (vuggy rock)). If a rock type with lower thermal conductivity occurs to a sufficiently large extent, the methodology for thermal optimisation of deposition hole spacing is applied. Geological, geophysical and hydrogeological borehole investigations are conducted in pilot boreholes, including determination of geophysical, thermal and rock mechanics parameters on drilling samples. If water-bearing fractures are encountered, an assessment is made of whether water samples should be taken for chemical analyses.

Hydraulic interference tests and geophysical cross-hole measurements

If the pilot boreholes for the deposition tunnels show hydraulically conductive structures or indication of critical structures, hydraulic interference tests and geophysical cross-hole measurements are conducted. Primarily, the electrical method called mise-a-la-masse is used, which can be used between boreholes and tunnels or between tunnels, but other geophysical methods may also be relevant. The purpose is to demonstrate hydraulic and physical connections that may indicate a possible occurrence of critical structures and to quantify their (hydraulic) material properties. Similarly, cross-hole measurements can be used for investigation of episyenite (vuggy rock), if encountered.

Continuous investigations during deposition tunnel excavation

Excavation of deposition tunnels will generate construction-related data, such as outflow data from probe holes, the amount of cement-based grout used in conjunction with passage of minor deformation zones, water consumption and pumped-out drainage water and other data from the excavation. If necessary, flow and pressure build-up tests that allow transient evaluation can be carried out in probe holes. The bedrock with its rock types, fractures and inflows will be mapped on tunnel walls using the RoCS system. Of particular interest is the existence and extent of rock types with low thermal conductivity, such as amphibolite, as a basis for decisions regarding the distance between deposition holes. The methodology is verified and procedures adjusted if necessary. All data are documented continuously in a database.

Pilot boreholes at deposition hole positions

During the integration test for underground construction, the methodology for selection of deposition hole locations is verified. The selection is based on an updated working model at the tunnel scale with data from pilot boreholes and investigations in the deposition tunnel, including thermal properties. The methodology for pilot drilling and associated investigations is verified for selected deposition hole positions. During drilling, the completed pilot boreholes are progressively equipped with packers and registration of pressure responses during drilling of subsequent pilot boreholes is used as an indicator of axial hydraulic connectivity along the deposition tunnel between possible positions for deposition holes. Drill cores from the pilot boreholes at the proposed deposition hole positions are mapped. If necessary, the thermal properties of the drill core are determined. Water inflow to the borehole is measured. This procedure is carried out until all pilot boreholes are drilled.

Strategies and methods are verified in the integration test for underground construction. In pilot boreholes, verification is made of the methodology for determination of inflow to pilot boreholes along with determination of transmissivity, which is thereafter used for verification that hydraulic technical design requirements for approval of the deposition hole (inflow and transmissivity) have been fulfilled. In cooperation with Posiva, strategies for hydraulic tests in pilot boreholes for deposition holes have been tested (Hjerne et al. 2016). Modelling in support of the choice of hydraulic acceptance criteria, where the mentioned pilot borehole transmissivity data are used, is in progress (Baxter et al. 2017). Hydraulic tests in pilot boreholes also serve as a basis for inspection of the properties and axial extent of the excavation-damaged zone (EDZ) along the deposition tunnel, see below.

Investigations regarding the technical design requirement for critical structures in deposition holes

In deposition tunnels for integration tests, methods for identification, investigation and modelling of combined technical design requirements for critical structures and for classification are verified, the latter as described in Section 3.2. Fundamental FPI criteria are applied and verification is made of whether detailed site investigations can be used to better determine or delimit the real size of the structures and determine other essential properties for assessing the risk of shear (fracture surface properties and structure orientation in relation to the rock stress field) and hydraulic properties (connectivity and transmissivity). Identification and characterisation of critical structures are carried out in a step-wise manner during the construction of a deposition area by pilot drilling, mapping, hydraulic and geophysical measurements with associated modelling. In this way unnecessary drilling of deposition holes in positions where such critical structures have been identified is avoided. At the same time, an empirical database is established and a better understanding is achieved of the occurrence, attributes and properties of critical structures, and of applicable investigation methods for their identification and quantification.

Data for identification of the geometries and properties of critical structures are obtained from investigations in pilot boreholes and from the mapping made in the tunnels and later in the deposition holes, where modelling is instrumental in the integration of results. In conjunction with tunnel mapping, special emphasis is placed on identifying FPIs, as an indicator of critical structures of class 3. Mapping is supplemented with information collected during drilling and the hydraulic interference tests and geophysical cross-hole measurements mentioned above. Depending on what structures are encountered, other geophysical surveys, mainly ground-penetrating radar (GPR), may be needed for identification of critical structures in the immediate vicinity of the deposition tunnels, especially below the tunnel floor, and for determining their extent. Levelling of the tunnel floor is expected to provide better prospects for ground-penetrating radar measurements. A final inspection with respect to critical structures should be made of all completed deposition holes before they are approved for deposition.

Chapter 5 describes tests of characterisation methodology in the central area and site-specific accumulation of knowledge regarding the repository host rock in Forsmark. The experience from these tests is used in the verification and further development carried out within the framework of the integration tests for underground construction, and in the continued knowledge accumulation (the database) concerning the occurrence of interpreted FPIs and associated surface properties and hydraulic properties regarding the repository host rock in Forsmark.

Mapping and measurements in deposition holes

If the pilot borehole indicates that the technical design requirements will be met, the deposition hole is drilled to its full diameter and depth. Subsequently the methodology for mapping of the wall and bottom of the deposition hole with the RoCS method is verified. Indications of large fractures and water-bearing fractures are of particular interest, as well as the presence of amphibolite and indications of spalling.

The deposition hole nominal geometry is specified with high tolerance requirements for emplacement of canisters and to enable the buffer to work according to given technical design requirements. Geodetic measurement of the deposition hole geometry is planned to be carried out by laser technology or photogrammetry, and will be verified during the integration test for underground construction, for establishment of techniques to be employed during the operational phase.

The methodology for control of the hydraulic technical design requirement applicable to deposition holes (inflow/buffer erosion) is verified with inflow measurements. If the deposition holes are shown to meet the stipulated requirements, methodology for final verification of the inflow criteria linked to buffer stability will be tested by monitoring of inflows during the period up to deposition. (In the case described here, it applies to the period up to the integration test for deposition and commissioning tests.)

Rock stress measurements and inspection of mechanical stability

The tunnels will be inspected and rock support installed where instabilities, such as spalling, are observed or are to be expected. Such observations and measures are documented. The occurrence of spalling in deposition boreholes is also documented.

As a supplementary basis for establishment of the optimal orientation of deposition tunnels in relation to rock stress conditions, rock stress measurements are conducted in the main tunnel. The measurements are primarily carried out by means of the overcoring method LVDT, if necessary supplemented with convergence measurements.

In the deposition tunnels, the SLITS method is used for verifying measurements in a selection of deposition positions. When applying the SLITS method in a deposition position, a short borehole is drilled before the deposition hole is fully drilled. A heater is installed in the hole and during a couple of weeks heating will provide an additional load, which leads to spalling. Since the rock stress situation determines how the spalling is formed in the hole, the method provides verifying data on the orientation of the largest principal stress. Because the short measurement hole is placed in the deposition position, it is eliminated when the deposition hole is drilled to its full diameter. The SLITS method described in Hakami (2011) is judged to have potential for this type of verification measurements. After completing the rock stress programme in the tunnels for integration and commissioning tests, the methodology for application in the future deposition of spent nuclear fuel canisters will be established.

Investigations of the excavation-damaged zone, EDZ

Testing of the methodology for verification of the technical design requirements for the excavation damaged zone (EDZ) is carried out in deposition, main and transport tunnels. Primarily, geophysical methods in combination with geological documentation will be used for verification that the conditions are adequate (i.e. limited blast damage) for fulfilling the hydraulic technical design requirement. Testing and demonstration that the blasting design fulfils the hydraulic requirements on the EDZ has previously been performed in a separate niche in the ramp, see Chapter 4.

The methodology is applied and further developed for approval in the experimental deposition tunnels for integration and commissioning tests. In addition to geological and geophysical characterisation, hydraulic investigations in and between pilot boreholes for deposition holes are included, in the same way as planned for deposition areas (i.e. determination of EDZ transmissivity and characterisation of its hydraulic continuity). The overall results are used to control that no hydraulically connected EDZ is developed along the floor of the relevant deposition tunnels, and to establish the necessary relationships between geological/geophysical and hydraulic signatures of the EDZ. These relationships can subsequently be used for assessing compliance with the technical design requirement for EDZ in main and transport tunnels, where only geological and geophysical detailed site investigations are performed.

It is possible to change the applied procedures and blasting plan for rock excavation for the next deposition tunnel in case the requirement is not fulfilled for the first deposition tunnel.

Transport properties of the rock

The rock is sampled for laboratory tests of verification nature, where the results serve as input data for the preparation of SDM-SAR and further analyses in SAR.

Monitoring of deposition tunnel and deposition holes

Regarding the compliance with technical design requirements with regard to the maximum allowed inflow to deposition tunnels and deposition holes, the following applies. The inflow to deposition holes is measured in conjunction with the characterisation, for preliminary verification that the hydraulic technical design requirement is met, as described above. For final acceptance, approved deposition holes need to be monitored continuously up to canister deposition. The methodology is verified within the framework of the integration test for underground construction.

The inflow to deposition tunnels is measured at the measuring weir close to the main tunnel. This methodology is also verified within the framework of the integration test.

Monitoring of inflow, groundwater pressure, hydrogeochemistry and hydrochemistry

During construction of the first tunnel loop and the tunnels for integration and commissioning tests, monitoring continues in the same way as during the construction of repository accesses and the central area, see Section 4.3, and may be supplemented with monitoring in additional (temporary) investigation boreholes underground. The number of monitoring points is extended successively. The locations are described in the operational programme. A follow-up is made of the interaction between simultaneously ongoing activities in different parts of the repository.

The amount of pumped-out drainage water is measured constantly and water samples are taken regularly for chemical analyses. The water supplied to the facility is also analysed and inspected with respect to the concentration of tracer content.

Seismic monitoring

During the integration and commissioning tests, seismic monitoring continues, with both the national seismic network and the local seismic network. GNSS monitoring will continue to detect any movements along selected major deformation zones in the Forsmark area. The information is mainly used for descriptive geological modelling.

The seismic monitoring can also provide information on deformation of the rock mass as a result of tunnel excavation, which contributes to an improved understanding of where such deformation occurs, thereby serving as a basis for determining how great the impact of tunnel excavation is on the surrounding bedrock. Deformation in structures (fractures and deformation zones) could also be detected.

Modelling

As a basis for determining the location of deposition tunnels and deposition holes and as a test of the verification of technical design requirements, detailed modelling is carried out, mainly geological and hydrogeological modelling at the tunnel scale. Modelling is also carried out to analyse the interaction between the different parts of the repository, primarily between the area for integration and commissioning tests and the simultaneously ongoing construction of the first tunnel loop and the central area. This is in order to ensure that experimental activities in the area for integration and commissioning tests do not stand risk of being adversely affected.

During the integration test for underground construction, the modelling methodology is verified as well as the level of ambition and scope of modelling required. The focus will be on modelling of the rock types in the bedrock, mineralogical composition and thermal properties, stress situation, deterministic description of deformation zones and critical structures and statistical description of the mechanical stability and hydraulic properties of the rock mass based on the description of discrete fracture networks (DFN). The occurrence of hydraulically connected structures (fractures and deformation zones) and their properties are therefore of special interest, as well as hydraulic conditions in general in the bedrock close to the deposition tunnels and deposition holes (including analysis of continuity and properties of any EDZ).

The proposed modelling methodology and strategies for its application in deposition tunnels with preceding pilot boreholes are verified and procedures are established regarding the data, models, model results and other documentation needed for decisions on construction, execution and approval of deposition tunnels and deposition holes.

The utilisation of investigation and modelling results from the area for integration and commissioning tests in SDM-SAR is described in Section 6.3.2.

6.3.2 Delineation of the first deposition area

The current facility layout for the first deposition area, with locations for main, transport and deposition tunnels, is based on SDM-Site. During the construction of repository accesses and the central area, the design may be adjusted based on data from modelling results from the detailed site investigations.

When the first tunnel loop is excavated, new knowledge for determining the outer boundaries of the deposition area is accumulated, especially in relation to the margin of the tectonic lens to the north-east, but also towards the north-west. These data consist of information from pilot hole drilling and investigations in the main tunnels, and any supplementary exploratory drilling. The data are also used to establish the location of the intermediate transport tunnel, see Figure 6-1 and Figure 2-3. In order to utilise the space in the repository bedrock optimally, the transport tunnel may be located in the marginal zone. Information from investigations in pilot boreholes for tunnels for integration and commissioning tests serves as a supplementary basis for the delineation. The decision process for determining the locations of deposition tunnels is described in Chapter 7.

Investigations in the marginal zone also serve as a basis for the updated site description SDM-SAR.

A summary of the activities involved in the delineation of the first deposition area and associated motivations is presented in Table 6-2. The investigations carried out during the excavation of main and transport tunnels during the development of the deposition area are described in Section 6.3.1 and in Chapter 7. A more detailed description of the activities follows after the table.

Table 6-2. Geoscientific investigations for delineation of the first deposition area. All pilot boreholes are cored boreholes.

Activity	Description	Reason
Conditions in the marginal zone of the tectonic lens and delineation of the first deposition area	Investigations of the margin of the tectonic lens towards the north-east and delineation of the first deposition area towards the north-east and north-west. Pilot boreholes employed during excavation of main tunnels and any investigation boreholes from these. Possible extension of a pilot borehole for the tunnel for integration tests. Pilot boreholes for excavation of deposition tunnels. Geological, geophysical and hydrogeological borehole investigations. Water sampling. Geological and geophysical investigations in/from tunnels. Depending on the conditions in the marginal zone, rock stress measurements may be carried out if the transport tunnel is to be located there.	A basis for: • Grouting and rock support needs. • Verification of modelled geoscientific conditions and update of the facility part model. • Delineation of the deposition area. • Transport tunnel positioning. • SDM-SAR. Rock stress measurements provide data for the site-specific rock mechanics model.
Modelling	Update of the facility part model and the model at facility scale (the facility model). Completion of SDM-SAR.	A basis for determining the outer boundaries of the deposition area and possible adjustment/adaptation of the layout of the first deposition area. Verification of modelled geoscientific conditions and update of the facility part model. Verification of modelled geoscientific conditions and update of the site model to SDM-SAR, as a basis for the safety assessment, SAR. Subsequently, continued update of the SDM as a basis for detailed design of continued development and periodic overall assessment of safety after closure, at least every ten years.

Conditions in the marginal zone and delineation of the first deposition area

The outer boundaries of the tectonic lens are not sharply defined in relation to the surrounding bedrock. More detailed information may be needed on the properties and conditions of the marginal zone in order to determine where the possibilities to meet the technical design requirements decrease, which thereby defines the boundaries of the deposition area. Depending on the boundaries of the deposition area, the transport tunnel may be located in the marginal zone, which entails a need for investigations for assessment of grouting and rock support needs.

To increase the understanding of conditions and properties in the marginal zone, including the occurrence of major deformation zones, pilot hole drilling for main tunnels and continuous investigations will be carried out during tunnel excavation. There may also be a need for special investigation boreholes. A decision on such drilling assumes a requisite safety evaluation. Depending on the knowledge at the time, geophysical investigations in tunnels may be needed combined with cored boreholes that investigate the properties of the marginal zone from main tunnels. This also applies to rock stress measurements, if the transport tunnel is located there.

In order to obtain more data for determining the boundaries of the first deposition area towards the north-west, it may be necessary to extend one of the pilot boreholes made for the tunnels for integration and commissioning tests. The need for investigations is studied in the successive modelling work and is described in operational programmes.

Modelling

The facility part model is extended to also include the first deposition area. The models are updated regularly, including analysis of the mutual hydraulic impacts between the different parts of the Repository for spent nuclear fuel and in relation to SFR, see Chapter 8. During construction of the first tunnel loop, information from pilot boreholes in main and transport tunnels and any boreholes investigating the deposition area boundaries is used. Depending on what is at the time known about the conditions in the marginal zone towards the north-east and the tectonic lens continuation towards the north-west, modelling can identify and analyse uncertainties of importance for the boundaries and layout of the first deposition area and thereby where the transport tunnel will be located.

Modelling during this phase results in the model version SDM-SAR. The basis for SDM-SAR consists of SDM-Site with associated data, investigations and models established during the construction of accesses and the central area (see Chapter 4 and 5), characterisation results from pilot boreholes for the tunnels for integration and commissioning tests (see Section 6.3.1) and the accumulated body of data linked to the construction of the first tunnel loop and the delineation of the first deposition area, as described in this section (6.3.2). The continued detailed site investigations in the tunnels, up to verification that the technical design requirements for deposition holes are fulfilled, constitute supplementary material for the subsequent application for trial operation. Results from these investigations with associated modelling will be cross-checked against descriptions in SDM-SAR. They are thereafter included as supporting material for the future SDMs during the operational period.

Models at the tunnel and facility part scale for the first deposition area are subsequently updated continuously with information from mapping and other investigations and experiments in the tunnels for integration and commissioning tests, as described in Section 6.3.1.

7 Detailed site investigations during development of deposition areas

In contrast to the preceding chapter, which describes how the methodology for detailed site investigations is verified in the integration test for construction, this chapter describes the application of established methodology and investigation methods in the successive development of deposition areas. The description of individual activities is, therefore, similar to the preceding chapter. What differs is the overall investigation strategy applied for development of a new deposition area, including the specific information that is needed from detailed site investigations as a basis for various decisions.

7.1 Repository parts

The construction of the repository area takes place successively, one deposition area at a time. For each deposition area, a tunnel loop from the central transport tunnel is completed first, see Figure 2-3. The main tunnel of the preceding deposition area is normally included in this loop, which is why the first step of the development includes a new main tunnel. The size of the deposition area is determined using the investigations described in Chapter 6 for the first deposition area and thereby the length of the main tunnels and the position of the outer transport tunnel are also determined. A general prerequisite is that all elements of tunnel excavation in the repository area are preceded by pilot drilling. The development of each deposition area will be carried out in a number of construction steps, where each step comprises a number of deposition tunnels, typically 4 to 5 tunnels per year. Modelling is initially done at the tunnel scale and gradually integrated in a facility part model for the deposition area in question. The facility part model is thereafter integrated in a comprehensive facility model. Figure 7-1 shows a fully built-out repository based on present-day knowledge of rock conditions and need of deposition tunnels.

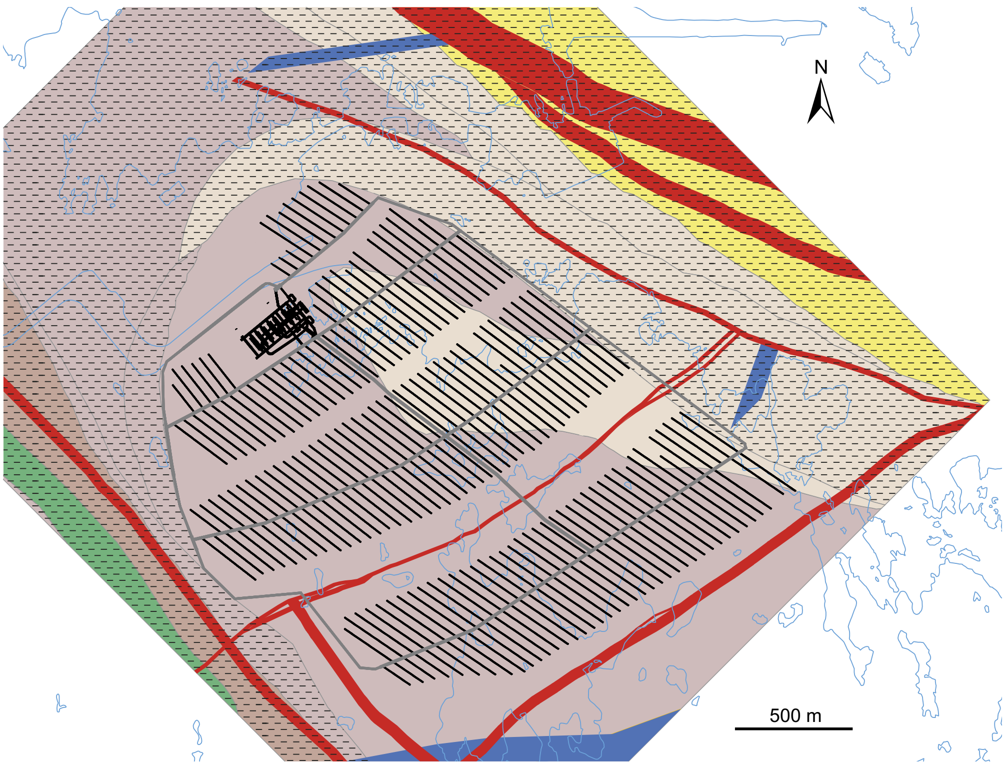

Figure 7-1. Proposed layout of the Repository for spent nuclear fuel at repository depth, with geology according to SDM-Site (SKB 2008). The deposition areas are located within the tectonic lens in the rock domains RFM029 and RFM045. Other rock domains are marked by dotted lines. The layout is affected by the interpreted major deformation zones (red).

The requirement on physical separation between simultaneous rock construction and deposition is met by installing a partition wall in the main tunnel, which prevents contact between the two work areas. The above-mentioned transport and main tunnel loop is then a prerequisite for transports to and from each area.

Figure 7-2 illustrates the state of the facility during construction of the second deposition area. The same sequence with tunnel loop construction followed by construction of deposition tunnels will be employed in other deposition areas.

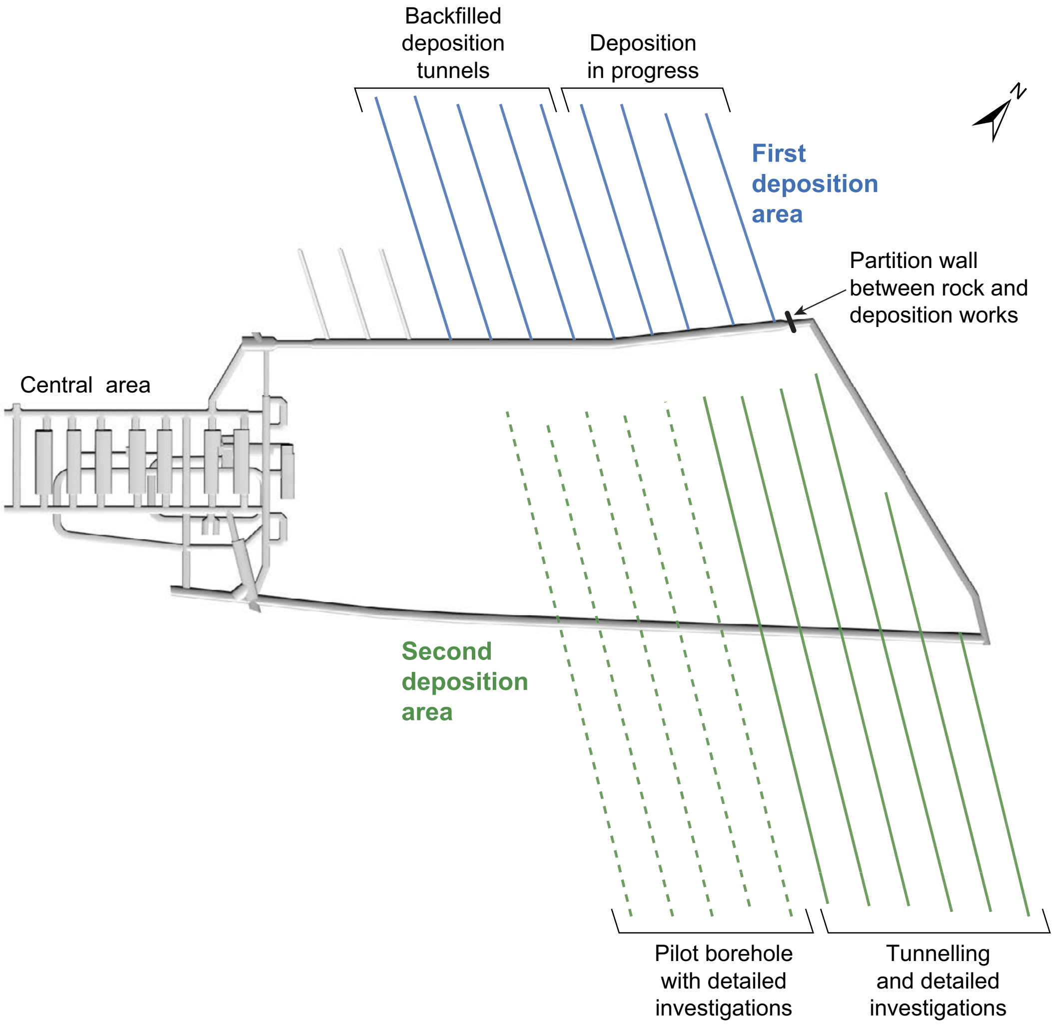

Figure 7-2. *Illustration of operations during development of the second deposition area while deposition is under way in the first.*

7.2 Information needs

During development of deposition areas, adaptation of deposition tunnels and deposition holes to local bedrock conditions is in focus. Detailed site investigations should provide the data required for this, as well as data for verification that this adaptation results in deposition tunnels and deposition holes that fulfil the stipulated requirements. The requirements are formulated as technical design requirements. They are described in general terms in Section 3.2 and in more detail in the Appendix.

The technical design requirements entail that detailed site investigations need to deliver the following information for approval of deposition holes and of other underground openings:

- Geometric information. For requirements related to the function of the buffer and backfill in deposition holes, deposition tunnels and other underground openings, respectively.
- Chemical analyses of groundwater samples. For control of chemically favourable conditions.
- Spatial extent of rock types with different thermal properties. For calculations of maximum temperature in the buffer at different deposition hole spacings (and/or deposition tunnel spacing).
- Rock stress orientation and magnitude. For optimal orientation of deposition tunnels.
- The occurrence of critical structures of class 2 (see Section 3.2), which can be accepted between deposition areas but not in deposition tunnels. No critical structures of class 1 may occur anywhere within the extent of the repository.
- The occurrence of critical structures of class 3, which cannot be accepted in deposition holes. They could be fractures with a potential for shear and/or with high transmissivities.
- Inflows to deposition holes, deposition tunnels and other underground openings. For compliance with the requirement on maximum inflow rates.
- Hydraulic transmissivity for pilot boreholes for deposition holes. The transmissivity in a pilot borehole for deposition shall be less than the established limit. (Development and testing of the methodology for establishment of the limit is under way.)
- Properties of the EDZ (excavation damaged zone) in deposition tunnels and other underground openings. For compliance with the requirement on maximum specific capacity.
- Data for the placement of plugs near the deposition tunnel entrance from the main tunnel. The requirements state that the plugs must not be placed within critical volumes of class 1, 2 and 3 and that the distance between plug and main tunnel must be larger than a specified distance to avoid mechanical disturbances on the plug.
- Data for determining the distance between existing investigation boreholes from the ground surface to various types of underground openings.

For additional boreholes outside the tunnel contour, with various purposes, the requirements state that they must be justified and safety-evaluated and that drilling sites must be restricted to tunnels not used for deposition and the boreholes must be sealed after use.

In addition to the aforementioned information needs, tunnel excavation requires data to estimate grouting and rock support needs. Detailed site investigations will also provide data for verification of the modelled geoscientific conditions and for update of the facility part model.

An additional task for the detailed site investigations is to document the facility and its initial state. The initial state is not only dependent on bedrock material properties and rock state variables (e.g. groundwater pressure and rock stresses), but also how they are changed by the excavation and how they change over time.

7.3 Decision sequence for deposition area development

The need for adaptation of deposition tunnels and deposition holes and verification of the technical design requirements requires that the detailed site investigations provide a basis for decisions during deposition area development. The decision sequence includes determining the initial outer boundaries of the deposition area, transport and main tunnel positioning, deposition tunnel locations, deposition tunnel orientations and length and deposition hole locations. The investigations also need to provide a basis for formal approval of deposition tunnels and deposition holes. A general process scheme for deposition area development is shown in Figure 7-3. Table 7-1 provides a relative overview of when the technical design requirements are handled in each investigation step.

Decision on deposition area boundaries

Detailed site investigations need to provide information to define suitable outer boundaries for the deposition area. The investigations are conducted during the excavation of main and transport tunnels. Supplementary investigation boreholes from these tunnels may also be required in addition to the pilot boreholes.

Figure 7-1 shows a subdivision of the repository area into a number of deposition areas based on SDM-Site. The main factor determining the outer boundaries of these areas to the south-west and north-east is the extent of the tectonic lens with the associated rock domains RFM029 and RFM045. The governing factor for deposition area boundaries of the Repository for spent nuclear fuel is, apart from factors relating to technical handling, critical structures of class 2 and their critical volumes. For the exact determination of boundaries with respect to such structures, detailed site investigations are required in and from tunnels.

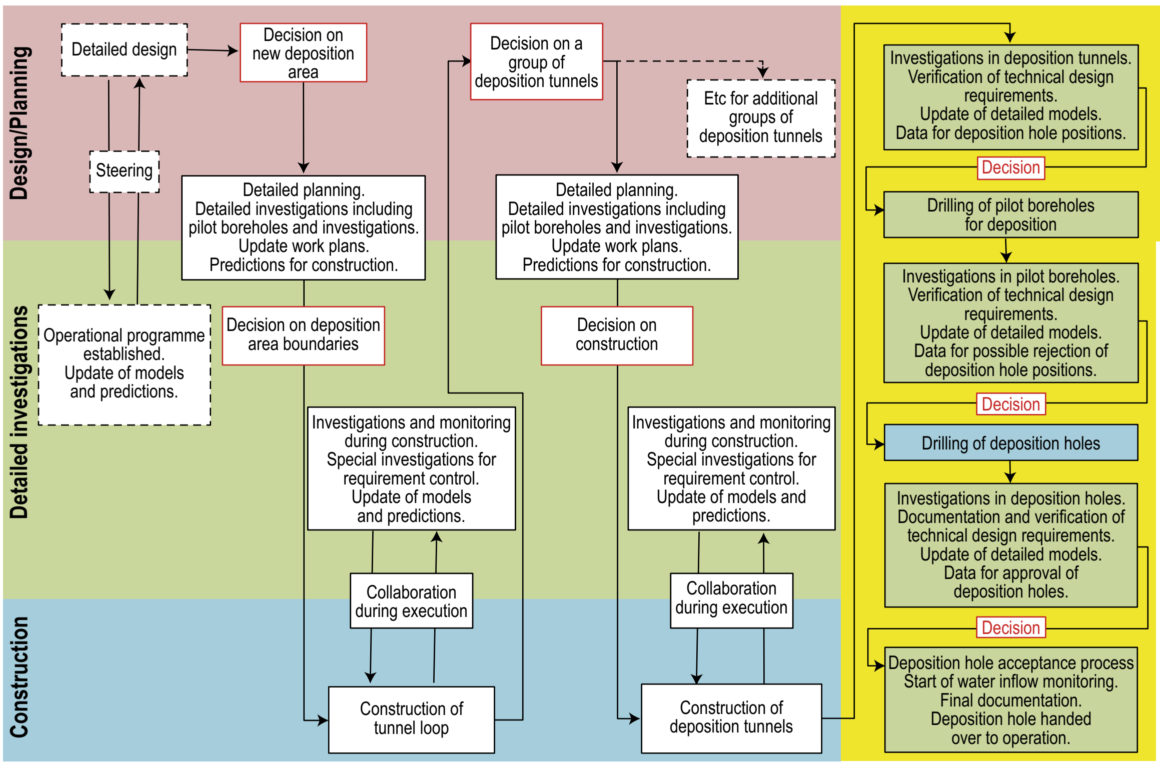

Figure 7-3. *General scheme for decisions on and construction of deposition areas, deposition tunnels and deposition holes.*

Table 7-1. Detailed site investigations for verification of compliance with requirements during different steps in the investigation and decision process.

Technical design requirement (with reference to Appendix)	**Detailed site investigations during construction of repository accesses and the central area**	**Investigations in main and transport tunnels including preceding pilot boreholes.** *A basis for decisions on the delineation and development of a deposition area.*	**Investigations in and between pilot boreholes for deposition tunnels.** *A basis for decisions on deposition tunnel construction.*	**Investigations in deposition tunnels during and after construction.** *A basis for decisions on deposition hole positions in deposition tunnels.*	**Investigations in and between pilot boreholes for deposition holes.** *A basis for decisions on deposition hole excavation.*	**Investigations in deposition holes.** *A basis for decisions on approval of deposition holes for canister deposition.*
Repository depth	(X)	–	–	–	–	–
Deposition areas – critical structures class 1	X	X	–	–	–	–
Deposition areas – chemical conditions	X	X	X	–	–	–
Deposition tunnels – critical structures class 2	(X)	X	X	(X)	–	–
Deposition tunnels – Inflow	–	–	(X)	X	–	–
Deposition tunnels – orientation	(X)	X	X	–	–	–
Deposition tunnels – separation from a mechanical point of view	–	(X)	X	X	–	–
Deposition tunnels – geometry	–	–	–	X	–	–
Deposition tunnels – plugs (critical structures)	–	–	(X)	X	–	–
Deposition tunnels – plugs (rock mechanics)	–	–	X	X	–	–
Deposition holes – critical structures class 3	(X)	X	X	X	X	X
Deposition holes – transmissivity	–	–	(X)	(X)	X	(X)
Deposition holes – inflow	–	–	(X)	(X)	X	X
Deposition holes – separation from a mechanical point of view	–	(X)	(X)	(X)	X	X
Deposition holes – separation from a thermal point of view	–	(X)	(X)	X	X	X
Deposition holes – geometry	–	–	–	–	–	X
Deposition holes – location in relation to remaining engineering materials	–	–	(X)	X	X	X
Entire repository – inflow	X	X	–	X	–	–
EDZ – other openings than deposition tunnels and deposition holes	X	X	–	(X)	(X)	–
EDZ – deposition tunnel	(X)	–	–	X	–	–
Distance between existing investigation boreholes and tunnels/shafts	X	X	X	X	–	–
Distance between deposition tunnels and other underground openings	–	–	(X)	X	–	–
Distance between deposition tunnels and areas where rock construction is under way	–	–	(X)	X	–	–

X = Information for adaptation of design or verification of compliance with requirements
(X) = Indicative/supporting information

Decision on the location and construction of deposition tunnels

According to the current layout, deposition tunnels are spaced with a c/c distance of 40 m and are oriented to the north-west. The current layout will be confirmed or adjusted depending on the properties of the rock. Tunnel orientation must be confirmed for the entire deposition area. Decisions on the location of individual deposition tunnels (about five are included in each construction step) in a first step include the choice of locations for pilot boreholes for deposition tunnels. The basis for this choice is results from pilot boreholes that precede the construction of the main tunnel, tunnel mapping and rock stress measurements in the main tunnel and geological, geological-structural, hydrogeological, thermal and rock mechanics modelling.

Results from the investigations in pilot boreholes for the deposition tunnels, including modelling, are a basis for decisions on construction of deposition tunnels. The investigations include pilot boreholes for the entire construction step in an integrated sequence to characterise rock volumes between the deposition tunnels, mainly with respect to the presence of critical structures. The investigation results can affect the decision on deposition tunnel length.

The pilot borehole and investigation data from the deposition tunnel are used in modelling prior to decisions on the location of plugs at the entrance of the deposition tunnel from the main tunnel.

Decision on deposition hole positions in deposition tunnels

A basis for decisions on the location of provisional deposition hole positions are investigations from the pilot borehole that preceded deposition tunnel construction, investigations in the constructed tunnel and geological and hydrogeological modelling based on these investigation results. A determining factor is the occurrence of critical structures of class 3 (regarding mechanical stability and groundwater flow). Furthermore, the occurrence of amphibolite and other thermally low-conductive rock types can reject a given deposition hole position or affect the deposition hole spacing, which according to the current layout is 6.0 or 6.8 m, respectively, for the two principal rock domains in the repository area.

After construction of a deposition tunnel, decisions should be taken on pilot drilling and investigations regarding deposition hole positions for the entire deposition tunnel. Furthermore, the investigations in the pilot boreholes should be carried out in the entire deposition tunnel before drilling of deposition holes begin.

Decision on deposition hole construction

A decision on what deposition positions will result in drilling of full size deposition holes is based on investigation results from pilot boreholes and updated modelling, cross-checked against the technical design requirements. Identification of any subhorizontal critical structure of class 3 situated beneath the tunnel floor is an important task, as well as the possible occurrence of important subordinate rock types.

Decision on approval of deposition holes for canister deposition

A decision on approval of deposition holes concern both purely geometric requirements and geological and hydrogeological requirements related to buffer stability and safety after closure. Decisions are based on geological, hydrogeological and rock mechanical investigations and geometric measurements of verification nature in the deposition hole.

For deposition holes that initially meet the requirements, follow-up observations and monitoring of inflows are carried out until canister deposition (within 5 years from their excavation). The concluding measurements provide a final basis for the decision to approve an individual deposition hole.

7.4 Activities

Investigations in conjunction with deposition area development are described below. The design and scope of the investigations may be adjusted based on experience from integration and commissioning tests, uncertainties presented in SDM-SAR and experience from construction of preceding deposition areas. Results from the assessment of safety after closure included in SAR prior to trial operation, modified technical design requirements and conditions associated with the licence for trial operation and routine operation of the final repository may also affect the design and scope of the detailed site investigations.

A summary of the activities with motivations are presented in Table 7-2. A more detailed description of the activities is presented after the table. In conjunction with the detailed design of deposition areas, operational detailed site investigation programmes will be prepared for detailed control and steering of the execution.

- Pilot boreholes with associated investigations during main tunnel excavation.
- Pilot boreholes with associated investigations during transport tunnel excavation.
- Continuous investigations during excavation of main and transport tunnels.
- Conditions in marginal zones of the deposition area.
- Geometries and properties of major deformation zones.
- Pilot boreholes with associated investigations for deposition tunnels.
- Hydraulic interference tests and geophysical cross-hole measurements.
- Continuous investigations during deposition tunnel excavation.
- Pilot boreholes with associated investigations for deposition holes at deposition hole positions.
- Investigations regarding critical structures in deposition holes.
- Mapping and measurements in deposition holes.
- Rock stress measurements and control of mechanical stability.
- Investigations of the excavation-damaged zone, EDZ.
- Transport properties of the rock.
- Monitoring of inflow, groundwater pressure, hydrogeochemistry and hydrochemistry.
- Seismic monitoring.
- Modelling.

There must also be a preparedness for detailed site investigations if structures or conditions are encountered that significantly deviate from the expected outcome, but also specific characterisation efforts if additional need arises.

Table 7-2. Geoscientific investigations employed during deposition area development. Activities are primarily presented in sequential order. Some activities, however, reoccur on two or more occasions. All pilot boreholes are cored boreholes.

Activity	Description	Reason
Pilot boreholes during main tunnel excavation	Continuous pilot drilling. Borehole investigations with water sampling.	A basis for: • Verification of compliance with technical design requirements. • Grouting and rock support needs. • Verification of modelled geoscientific conditions and update of the facility part model. • Delineation of the deposition area. • Transport tunnel location. Preliminary choice of locations for deposition tunnels. • Updated safety assessment at least every 10 years.
Pilot boreholes during transport tunnel excavation	Continuous pilot drilling. Borehole investigations with water sampling.	A basis for: • Verification of compliance with technical design requirements. • Grouting and rock support needs. • Verification of modelled geoscientific conditions and update of tunnel and facility part scale models. • Updated safety assessment at least every 10 years.
Continuous investigations during excavation of main and transport tunnels	Data from probe holes and other construction-related information. Geological/hydrogeological mapping of tunnel walls. Geometric documentation of tunnels.	A basis for: • Verification of compliance with technical design requirements. • Choice of locations for deposition tunnels. • Grouting and rock support. • Verification of modelled geoscientific conditions and update of tunnel and facility part scale models. • Updated safety assessment at least every 10 years.
Conditions in marginal zones	Investigations of the margins of the tectonic lens for determining deposition area boundaries. Pilot boreholes with investigations according to the above are supplemented with investigation boreholes from main and transport tunnels, if necessary. Borehole measurements and geological/geophysical investigations from tunnels are established in the operational investigation programme. Rock stress measurements. Investigation boreholes outside the deposition area can be used for hydrogeological and hydrogeochemical monitoring.	A basis for: • Determination of the boundaries of the deposition area. • Grouting and rock support needs. • Verification of modelled geoscientific conditions and update of tunnel and facility part scale models. • Updated safety assessment at least every 10 years. Rock stress measurements provide data for the rock mechanical site-specific model.
Geometries and properties of major deformation zones	Mapping of deformation zones in pilot boreholes and tunnels. Borehole measurements of hydrogeological and other properties. Sampling for determination of geophysical and rock mechanics parameters. If water-bearing fractures are encountered, water samples are taken for chemical analyses. If necessary, hydraulic interference tests and geophysical measurements are conducted between pilot boreholes and tunnels. Classification with respect to critical structures of class 1 and 2 and their critical volumes.	A basis for: • Verification of compliance with technical design requirements. • Grouting and rock support. • Verification of modelled geoscientific conditions and update of tunnel and facility part scale models. • Determining the available space for the deposition area and deposition tunnels. • Updated safety assessment at least every 10 years.

Activity	Description	Reason
Pilot boreholes for deposition tunnels	Pilot boreholes for deposition tunnels are excavated in batches of about five and in sequence. In completed packed-off pilot boreholes, pressure responses are monitored when new holes are drilled, as a basis for understanding hydraulic connectivity. Investigations in the boreholes are carried out according to the standard procedure for pilot boreholes in deposition areas, which is developed during integration tests and presented in the operational investigation programme. Identification of rock types with reduced thermal conductivity. Boreholes are successively equipped with packers.	A basis for: • Detailed planning of any hydraulic interference tests and geophysical cross-hole measurements. • Verification of compliance with technical design requirements. • Decision on construction of deposition tunnel and preliminary choice of deposition hole positions. • Plug position at the deposition tunnel entrance. • Grouting and rock support needs. • Verification of modelled geoscientific conditions and update of tunnel and facility part scale models. • Updated safety assessment at least every 10 years.
Hydraulic interference tests and geophysical cross-hole measurements	If water-bearing fractures are encountered in pilot boreholes for deposition tunnels, and if drilling gives rise to pressure responses between boreholes, hydraulic interference tests and geophysical (mainly electrical) cross-hole measurements are performed to quantify hydraulic and physical connections, which may indicate the occurrence of potential critical structures in future deposition hole positions. In-depth evaluation of the hydraulic material properties of investigated structures.	A basis for: • Verification of compliance with technical design requirements. • Choice of deposition hole positions. • Grouting and rock support needs. • Verification of modelled geoscientific conditions and update of tunnel and facility part scale models. • Updated safety assessment at least every 10 years.
Continuous investigations during deposition tunnel excavation	Data from probe holes and other construction-related information. Geological/hydrogeological mapping of tunnel walls and floors. Follow-up of rock types with reduced thermal conductivity. Geometric documentation of tunnels.	A basis for: • Verification of compliance with technical design requirements. • Choice of deposition hole positions, including data for thermal optimisation of the separation between deposition holes. • Grouting and rock support needs. • Plug position at the entrance of the tunnel . • Verification of modelled geoscientific conditions and update of tunnel and facility part scale models. • Updated safety assessment at least every 10 years.
Pilot boreholes at designated deposition hole positions (Decisions on locations for pilot drilling are based on an updated working model at the tunnel scale with underlying data from pilot boreholes and investigations in the deposition tunnel, including consideration of thermal properties.)	Pilot drilling at designated locations for deposition positions. Pressure registration in packed-off pilot boreholes during drilling, covering 5–10 boreholes. Drill core mapping. Hydraulic measurements. Identification of rock types with reduced thermal conductivity.	A basis for: • Identification of potential critical structures in pilot boreholes for deposition holes. • Decisions on drilling of deposition holes. • Verification of modelled geoscientific conditions and update of tunnel and facility part scale models. • Updated safety assessment at least every 10 years.
Investigations regarding critical structures in deposition holes	Investigations (including monitoring of pressure responses between boreholes) of minor deformation zones and persistent individual fractures in and between pilot boreholes, deposition tunnels and deposition holes. Measurements of geological, geophysical, hydrogeological and other properties in boreholes and tunnels. FPIs (indicators of critical structures of class 3) are mapped in the deposition tunnel.	A basis for: • Identification of critical structures of class 3 in deposition holes. • Choice of deposition positions and approval of deposition holes. • Verification of modelled geoscientific conditions and update of tunnel and facility part scale models. • Updated safety assessment at least every 10 years.

Activity	Description	Reason
After drilling of deposition holes: Mapping and measurement of deposition holes.	Geological and rock mechanics mapping. Hydraulic measurements. Geometric documentation.	A basis for verification of compliance with technical design requirements: • Critical structures in deposition holes. • Inflow to deposition holes. • Geometric requirements on deposition holes. A basis for: • Choice and approval of deposition holes. • Verification of modelled geoscientific conditions and update of tunnel and facility part scale models. • Updated safety assessment at least every 10 years.
Rock stress measurements Inspection of mechanical stability	Measurements in the main tunnel with the LVDT method, possibly supplemented with convergence measurements, for magnitude and orientation of the principal stresses. In the deposition tunnel, verification measurements with the SLITS method in a selection of deposition hole positions. Pilot borehole/drill core, deposition tunnels, deposition boreholes and main and transport tunnels are inspected with respect to spalling and other instabilities. Mechanical parameters are obtained from tests on drill cores from the pilot boreholes.	A basis for: • Establishment of orientation of deposition tunnels. • Assessment of rock support needs. • Verification of modelled rock mechanics conditions and update of the facility part model. • Inspection of deposition hole geometry. • Updated safety assessment at least every 10 years.
Investigations of the excavation damaged zone, EDZ	Geophysical and geological investigations in deposition tunnels, main and transport tunnels. In addition, hydrogeological investigations in deposition tunnels for determination of EDZ transmissivity and hydraulic continuity.	A basis for: • Verification that the excavation damaged zone (EDZ) fulfils the technical design requirements for tunnels in the deposition area. • Updated safety assessment at least every 10 years.
Transport properties of the rock	Laboratory tests for determination of diffusion and sorption properties of the rock.	A basis for: • Verification of the retardation model SDM-SAR. • Updated safety assessment at least every 10 years.
Monitoring of inflow, groundwater pressure, hydrogeochemistry and hydrochemistry	Continued monitoring of groundwater pressure, flow and chemistry in boreholes from the ground surface and in the underground facility. New monitoring points for inflow are added regularly in deposition areas at measuring weirs in individual tunnels. Monitoring of inflow into the deposition tunnel and provisionally approved deposition holes. Hydrogeological monitoring at the deposition tunnel plugs. Sampling for inspection of supplied and inflowing water (chemical composition and tracer content). Follow-up of monitoring linked to SFR.	A basis for: • Environmental monitoring. • Verification of compliance with technical design requirements. • Decision on approval of deposition holes. • Verification of modelled geoscientific conditions and update of the facility part model. • Updated safety assessment at least every 10 years. • Understanding of the interaction between SFR and the Repository for spent nuclear fuel.
Seismic monitoring	Continued monitoring using the national and local seismic network for registration of seismic events. GNSS monitoring continues.	A basis for: • Assessment of the impact of tunnels/shafts on the surrounding bedrock. • Updated safety assessment at least every 10 years.

Activity	Description	Reason
Modelling	Continuous update of working models for deposition areas (and parts of deposition areas) mainly at tunnel scale and facility part scales. Modelling of thermal conductivity (using underlying stochastic model of lithological heterogeneity). Modelling in support of verification of technical design requirements. Modelling for decisions on the location and construction of deposition tunnels, deposition holes and plugs near the deposition tunnel entrance from the main tunnel, for example by applying thermal optimisation. Modelling as a basis for a decision on approval of deposition tunnels, deposition holes and deposition tunnel plug. Modelling of rock excavation needs.	A basis for an updated programme for grouting and rock support needs. A basis for verification of the modelled geoscientific conditions and updated safety assessments. A basis for the positioning of deposition tunnels, deposition holes and plugs, including local adaptation of deposition hole positions A basis for decisions on: • Deposition area boundaries. • Main tunnel construction. • Transport tunnel construction. • Positioning and construction of deposition tunnels. • Deposition hole positions and construction of deposition holes in deposition tunnels. • Approval of deposition holes for canister deposition. A basis for updating the SDM, at least every 10 years for updated safety assessments, see Chapter 8.

Pilot boreholes during main tunnel excavation

The understanding of rock conditions in future deposition areas is generally considered to be good. Information from the construction of repository accesses, the central area, the first tunnel loop, with associated investigations will be analysed and described in SDM-SAR as a basis for the application for trial operation. Prior to the development of each new deposition area, all available information is compiled and analysed.

The construction begins with a main tunnel with continuous pilot drilling. Investigations in pilot boreholes, together with the results of main tunnel mapping, serve as a basis for adaptation of the locations of deposition tunnels to local conditions in the bedrock. The pilot borehole provides knowledge for decisions on the locations of deposition tunnels primarily by investigations of the hydraulic properties of deformation zones (potential critical structures) and by data for updating the hydrogeological properties of the DFN model.

Hydraulic tests and geophysical measurements are performed in the pilot boreholes. The drill core is mapped and geophysical and rock mechanics parameters are determined on drill core samples. In case water-bearing fractures are encountered, an assessment is made of whether water samples should be collected for chemical analyses. For investigations, a standard procedure for pilot boreholes in deposition areas will be prepared during the integration tests and presented in operational investigation programmes.

Pilot boreholes during transport tunnel excavation

The position of the outer transport tunnel has been determined based on data from main tunnels. Continuous pilot drilling is used during construction. Investigations are essentially the same as in the pilot holes of main tunnels.

Continuous investigations during excavation of main and transport tunnels

As described earlier, excavation of tunnels will generate data, such as outflow data from probe holes, the amount of cement-based grout used, water consumption and pumped-out drainage water and other data from excavation. If necessary, flow and pressure build-up tests that allow transient evaluation can be carried out in probe holes. All data are documented continuously in a database. The bedrock with its rock types, fractures and inflows will be documented with the RoCS system. Of particular interest is the extent of rock types with low thermal conductivity, such as amphibolite, as a basis for a final decision on the deposition tunnel spacing.

Measurement weirs are installed with measurement systems for water inflow monitoring. The strategy and investigations to determine where they are positioned are described in operational programmes.

Conditions in marginal zones

The outer boundaries of the tectonic lens are not sharply defined in relation to the surrounding bedrock. In order to make optimal use of the favourable properties of the rock domains, their individual boundaries need to be successively established as the deposition areas are constructed. Transport tunnels may be located in the surrounding bedrock (i.e. outside the boundaries of the tectonic lens, but in its close proximity) if geological conditions so permit. To increase the understanding of conditions and properties in marginal zones, including the occurrence of major deformation zones, cored boreholes that investigate the properties of the marginal zones from main and transport tunnels may be needed, in addition to pilot hole drilling and continuous investigations in tunnels. Hydrogeological and geophysical investigations in and between boreholes and tunnels, along with sampling and chemical analysis of groundwater, provide an indication of the conditions in the given rock volume. The need for further investigations is continuously addressed in the ongoing modelling work and is described in operational programmes. This also applies to the need of rock stress measurements if the transport tunnel is located there, see the activity rock stress measurements below. Possible investigation holes that are not pilot boreholes for tunnels can, if necessary, be used for hydrogeological and hydrogeochemical monitoring for a shorter or longer period. The boreholes should be sealed when they are no longer in use.

Geometries and properties of major deformation zones

Depending on their geometries and properties, major deformation zones delimit the extent of deposition areas and deposition tunnels (critical structures and their volumes, see Chapter 3). In addition to the characterisation conducted during pilot drilling and continuous investigations in tunnels, uncertainties with respect to the presence, location and properties of these zones may lead to further investigations. This could include geophysical investigations in and between tunnels and boreholes, possibly combined with cored boreholes from main or transport tunnels according to the above.

In order to determine the extent and properties of deformation zones, geological characterisation and geophysical investigations from the ground or rock surface and drilling from the ground surface may also be required. Such investigations may also need to be carried out if previously unknown deformation zones are encountered during construction, if they could be potential critical structures or are important in other respects for design/construction and/or safety assessment. In order to determine whether a deformation zone (or another geological structure such as a rock contact) should be classified as a critical structure, modelling is required. The need for investigations is studied in the modelling work, which is carried out continuously during the construction and described in operational programmes.

Pilot boreholes for deposition tunnels

Excavation of deposition tunnels will be preceded by a batch of about five pilot boreholes (for the same number of potential deposition tunnels) drilled within the contour of the future tunnels. The pilot boreholes are bored in direct sequence and then investigated in a joint effort. The boreholes are successively equipped with packers to enable registration of pressure responses during drilling, which provides a basis for preliminary interpretation of hydraulically connected structures and for planning of more advanced hydraulic and geophysical cross-hole measurements (interference tests). The pilot boreholes also provide data for rock support estimation and for the assessment of need for pre-grouting of any specific deformation zone or water-bearing section. They also provide data for preliminary positions of deposition holes. Indications of critical structures and the presence of amphibolite and episyenite (vuggy rock) are of particular interest. Pilot boreholes are investigated according to the standard procedure for pilot boreholes that will be established during the integration tests, including hydraulic tests and determination of geophysical, thermal and rock mechanics parameters on drill core samples. If water-bearing fractures are encountered, an assessment is made of whether water samples should be collected for chemical analyses.

Hydraulic interference tests and geophysical cross-hole measurements

If the pilot boreholes for deposition tunnels intersect hydraulically conductive structures, these and other monitored boreholes can be used for in-depth characterisation using hydraulic interference tests. This also applies to episyenite (vuggy rock) if this rock type is encountered and is shown to have significant extent. The scope of the investigations is based on experience from the integration tests for construction and may also include geophysical (mainly electrical) cross-hole measurements. The latter method can be used between boreholes and tunnels or between tunnels. The overall purpose is to demonstrate the existence of any hydraulic and physical connections, which may indicate the occurrence of critical structures. These may affect the choice of deposition hole positions and provide an improved understanding of the (hydraulic) material properties of the investigated structures.

Continuous investigations during deposition tunnel excavation

As described previously, excavation of tunnels will generate construction-related data, such as outflow data from probe holes, the amount of cement-based grout used in minor deformation zones, water consumption and pumped-out drainage water and other data from excavation. If necessary, flow and pressure build-up tests that allow transient evaluation can be carried out in probe holes. All data are documented continuously in a database. The bedrock with its rock types, fractures and inflows will be documented using the RoCS system. Of particular interest is the existence and extent of rock types with low thermal conductivity, such as amphibolite, as a basis for decisions regarding the distance between deposition hole positions.

Measurement weirs are installed with measurement systems for monitoring. Their design and location are described in operational programmes.

Pilot boreholes at deposition hole positions

At selected deposition hole positions, a pilot borehole is core-drilled within the contour of the future deposition hole. (This pilot borehole is an investigation borehole that is not used as a pilot for the drilling of the full-size deposition hole.) The selection is based on an updated working model at the tunnel scale with data from the pilot borehole for the deposition tunnel and investigations in the deposition tunnel, including thermal properties. In case a significant inflow is noted during drilling of the pilot borehole, the borehole is equipped with packers for registration of pressure responses when subsequent pilot boreholes for deposition holes are drilled. The drilling is carried out step-wise.

The drill core from the pilot borehole is mapped and hydraulic investigations are performed. If necessary, the thermal properties of the drill core are determined. Results from inflow measurements provide data for an indirect verification of the hydraulic technical design requirement related to inflow to deposition holes (regarding installation of buffer). Transmissivity is determined using hydraulic tests in the pilot borehole, which according to the technical design requirement on transmissivity enables verification of compliance, see Appendix. The hydraulic tests in the pilot holes also constitute a basis for determination of the hydraulic material properties of the excavation-damaged zone (EDZ) and of hydraulic continuity along the floor of the deposition tunnel. Strategies for evaluation, including associated modelling, and for prediction of whether the hydraulic technical design requirements will be met are developed in cooperation with Posiva. These strategies will also be verified within the framework of integration tests, for laying firm the methodology to be employed during the operational phase.

Investigations regarding critical structures in deposition holes

Critical structures must not intersect deposition holes. Identification of potential critical structures is achieved in several steps and using different methods, in pilot boreholes for tunnels and deposition holes, in the excavated tunnels and in deposition holes. Strategies and methodology will be updated when the investigation and modelling methods have been tested in the integration tests for construction, see Section 6.3.1. If critical structures can be verified at an early stage, it is possible to avoid unnecessary drilling of pilot boreholes for deposition holes in positions where such structures have been identified.

Data for identification and classification of the geometries and properties of critical structures are obtained from investigations in pilot boreholes and from the mapping made in tunnels and later in deposition holes, employing modelling as atool for integration, see Section 3.2. In conjunction with tunnel mapping, special emphasis is placed on identifying FPIs, as indicators of potentially critical structures. The mapping is supplemented with the previously mentioned hydraulic interference tests and geophysical, mainly electrical, cross-hole measurements. Depending on what structures are encountered, other geophysical surveys, mainly ground-penetrating radar, may be needed for identification of critical structures in the immediate area of the deposition tunnels, especially beneath the tunnel floor, and for assessing their extent. Levelling of the tunnel floor is expected to provide better prospects for ground-penetrating radar measurements. A final inspection with respect to the occurrence of critical structures should be made of all completed deposition holes before they are approved for deposition.

With the methodology for classification of critical structures described in Section 3.2, there is potential to use a greater number of deposition positions than permitted by the FPI criteria. This presumes that it is possible to determine or define the maximum size of the potentially critical structures and determine other essential properties for assessment of the risk of shear (surface properties and orientation in relation to the rock stress field). This will probably not be the case during the start of the operational phase, but as the methodology, knowledge base and understanding of the behaviour and properties of potential critical structures in the repository area are assembled, it will be possible, to a greater extent, to identify certain structures as being non-critical.

Deposition hole mapping and measurements

Verification of compliance with the technical design requirements is done according to the following:

- Requirements on the inflow to deposition holes are verified by inflow measurements and follow-up monitoring.
- Geometric requirements on the deposition hole are verified by geodetic measurements.
- For critical structures in deposition holes, seethe activity "Investigations regarding critical structures in deposition holes", as described above.

Verification of compliance with the requirement on maximum transmissivity is done in accordance with the technical design requirement formulation regarding pilot boreholes for deposition holes, see above.

For pilot boreholes where site investigations indicate that the technical design requirements will be met, a deposition hole is drilled to its full diameter. The wall and bottom of the deposition hole are mapped with the RoCS method. Indications of large fractures and water-bearing fractures are of particular interest, as well as the presence of amphibolite and episyenite (vuggy rock) and indications of spalling.

The deposition hole geometry is specified with high tolerance requirements for emplacement of canisters and to enable the buffer to work according to given technical design requirements. Geodetic measurements of the deposition hole geometry are planned to be conducted with the methodology that is laid firm after completed integration tests.

The methodology for inflow measurements and the need for any follow-up verification of the requirement on maximum transmissivity in deposition holes will be established after completed integration tests.

Rock stress measurements and inspection of mechanical stability

As a basis for decisions on possible adjustment of deposition tunnel orientation in a deposition area, rock mechanics investigations are carried out at some positions in the main tunnels for establishment of the principal stress orientation. If a transport tunnel is located in the tectonic lens margin, rock stress measurements are performed there as well since stress conditions may deviate from the conditions within the lens. The investigations include overcoring measurements (LVDT method) and convergence measurements. If necessary, verification measurements with the SLITS method are carried out in the deposition tunnels. The design of the rock stress measurement programme will be established when strategies and methods have been tested in the tunnels for integration and commissioning tests (Section 6.3.1), hereby being verified to be adequate for their purpose. Mechanical parameters of the rock are obtained from drill core tests. The location of measurements and the extent of the investigations to be performed are described in operational programmes.

In the aforementioned tunnels, as well as in deposition tunnels, the tunnel rock walls will be inspected and rock support installed where instabilities, such as spalling, are observed or are to be expected. Such observations are documented and may govern where additional rock mechanics studies are conducted. The occurrence of spalling and its possible time dependency are also documented in deposition holes.

Investigations of the excavationdamaged zone, EDZ

Verification that the hydraulic technical design requirements related to the EDZ are fulfilled in tunnels is carried out with the methodology that has been tested in the ramp and in tunnels for integration tests, see Chapter 6. After approval for application, it is used in the repository area tunnels. If the requirement is not fulfilled, the investigations provide data for adjustment of the excavation technique.

Transport properties of the rock

The drill cores from pilot boreholes for tunnels in the deposition areas (mainly deposition tunnels) and from pilot boreholes for deposition holes are sampled for laboratory tests. The results serve as a basis for verification of the retardation model SDM-SAR, which serves as input data to the SDM updates prior to the updated SAR. The scope of these laboratory tests depends on the confidence in the existing model and the degree of homogeneity in the matrix rock lithology and fracture mineralogy of the rock and fracture domains of interest.

Monitoring of inflow, groundwater pressure, hydrogeochemistry and hydrochemistry

Throughout the operational phase, monitoring of meteorological, hydrological and hydrochemical parameters related to air and surface water continue in the Forsmark area. The hydrogeological and hydrogeochemical monitoring also continue in boreholes from the ground surface and in any additional (temporary) investigation boreholes underground. The same applies to the monitoring that is conducted in the underground facility at measurement weirs for quantification of inflowing groundwater to different repository parts and tunnel sections.

New monitoring points are added regularly in deposition areas as the successive development progresses. This mainly refers to monitoring of inflows to deposition tunnels and deposition holes, for verification of technical design requirements. The inspections are intended to ensure that the inflows to deposition tunnels and deposition holes can be accepted with respect to installation methods for buffer and backfill. The inflow to deposition holes is measured first in conjunction with the characterisation for a provisional verification of the hydraulic technical design requirement. For final acceptance, approved deposition holes need to be monitored continuously up to canister deposition. Monitoring of inflow, groundwater pressure, hydrogeochemistry and hydrochemistry in the deposition tunnel is concluded when the deposition tunnels are backfilled and plugged.

The amount of pumped-out drainage water is measured constantly and water samples are collected regularly for chemical analyses. The water supplied to the facility is also analysed and inspected with respect to constant concentration of tracer.

Seismic monitoring

During the entire operational phase, seismic monitoring continues, using both the national seismic network and the local seismic network. The number of measurement points for the local network will be increased when necessary. GNSS monitoring will also continue in order to detect any movements across selected major deformation zones in the Forsmark area. The information is mainly used for descriptive geological modelling.

Seismic monitoring can also provide information on deformation of the rock mass as a result of tunnel excavation, which contributes to an improved understanding of where such deformation occurs, thereby serving as a basis for determining how great the impact of tunnel excavation is on the surrounding bedrock. Deformation in individual fractures and deformation zones could also be detected.

Modelling

The updating of working models at different scales continues (mainly at the tunnel and facility part scale for deposition areas and integrated at a larger scale for the entire repository at the facility scale). This includes results from investigations performed in conjunction with the construction of main, transport and deposition tunnels, as well as in and between pilot boreholes for deposition tunnels and any additional cored investigation boreholes. For deposition tunnels (or batches of deposition tunnels), models are created at a more detailed scale (mainly the tunnel scale) addressing factors important for the demonstration of compliance with the technical design requirements, for example stress conditions, mechanical stability and thermal properties. The geological and hydrogeological modelling, employing statistical description of discrete fracture networks and deterministic description of deformation zones and individual fractures, has a specific goal to identify and quantify possible critical structures, see also Table 7-2. The modelling must also consider the need of estimating the grouting and rock support needs for rock excavation. The working models are successively integrated at the facility part scale and subsequently serve as a basis for updating a comprehensive site descriptive model, which in turn constitutes a basis for the periodic overall assessments and safety assessments that need to be carried out at least every 10 years, see Section 8.4.

Some activities will require special modelling efforts. For example, the occurrence of episyenite (vuggy rock) may require special efforts if this subordinate rock type is encountered to such an extent that its occurrence, extent and properties are of importance for the description and quantification of groundwater flow and transport of solutes.

Integrated updating of the geological and hydrogeological submodels takes place continuously while updating of other discipline-specific models takes place when necessary.

8 Modelling

The site descriptive model from the site investigation, SDM-Site, including the results from supplementary investigations carried out prior to the start of construction, constitutes the essential basis for the continued modelling work during the construction and operation of the repository. While the site investigation mainly established site descriptive models at the local and regional scale, models for different purposes and in other more detailed scales will now be created. Working models of different kinds, volumetric extent and scales will be the most significant new elements in the modelling work. Prior to the application for trial operation, an updated site description (SDM-SAR) will be prepared. In this context, it can be noted that the Nuclear Activities Act imposes requirements on periodic overall assessments of safety and radiation protection every 10 years for nuclear facilities in operation, preceded by an associated update of the SDM.

Models are used for different purposes, for example for descriptions, predictions or quantitative assessments, or a combination of these. The close mutual coupling between the different model volumes/scales is typical for the modelling, see Section 8.1. For example, if uncertainties in a prediction (expectation model) at a larger scale elicit a need for detailed site investigations (such as pilot boreholes), work models at the tunnel scale are used for interpreting the measurement results, which in turn provides feedback to the prediction established in the larger scale model. This chapter provides a general description of the various modelling components and modelling procedures employed during construction, in conjunction with construction and operation and for the site descriptive modelling for SDM-SAR. Brief descriptions of modelling applications can also be found under the various construction and operation steps that are presented in Chapters 4 through 7.

The main scales of the working models are the tunnel scale and the facility part scale. The tunnel scale describes individual underground openings (tunnels, shafts and rooms) or models based on preceding pilot boreholes. For continuous follow-up, results from these detailed models must be integrated in the models that describe the conditions in larger rock volumes and that include the parts of the repository being developed. Facility part models therefore need to handle both deterministic and stochastic information from tunnels and boreholes while being practically manageable in the relevant computer systems. The current working model therefore needs to be limited to the rock volume that is included in the facility parts where activities are under way and/or where continuous follow-up is required at any given time.

The first facility part model comprises the bedrock volume affected during construction of the repository accesses, and is successively extended to also include the central area and the first deposition area. During operation of the final repository, the facility part models will typically comprise individual deposition areas.

Models are also needed at other scales. Both more detailed models for individual underground openings, such as deposition tunnels with associated deposition holes where data for verification of compliance with technical design requirements are in focus, and more tentative models at the facility scale for the entire final repository as well as more large-scale models to describe processes that can affect the repository in the long term, for example effects of a future glaciation.

The modelling methodology will be described in updated discipline-specific methodology reports for site descriptive modelling. The updates are based on the methodology reports established prior to the surface-based site investigation and do not in any way imply a paradigm shift, the fundamental elements in the modelling methodologies established at the time still remain. New elements are information from near horizontal pilot and investigation boreholes, the possibility to establish a close link between mapped tunnels and preceding pilot boreholes and the exposure of large and extensive rock surfaces at relevant depths. In addition, experience from the site modelling in Forsmark and Laxemar has been taken into account. Experience from the Äspö HRL and Posiva's work in Olkiluoto is also incorporated. Updated methodology reports for site-descriptive modelling during detailed site investigations (under development) are shown in Table 8-1, see also Figure 8-3.

Table 8-1. Ongoing further development of methodology for site descriptive modelling.

Discipline	General title (Methodology for ….)
Geology	site descriptive geological modelling
Rock mechanics/Thermal properties	site descriptive rock mechanical and thermal modelling
Hydrogeology (including flows in the surface system)	site descriptive hydrogeological modelling
Hydrogeochemistry	site descriptive hydrogeochemical modelling
Transport properties of the rock	site descriptive transport modelling
Integrated modelling	integrated site descriptive modelling

8.1 Modelling scales and modelling processes

Model scale in this context incorporates a combination of the physical size of the rock volume represented by the model and the resolution of the objects described therein, under the assumption that the volume in question is completely filled. Resolution refers to the minimum size of a geoscientific object at the current model scale. Based on experience from the site investigations (SKB 2008 and SKB 2011), including fundamental work by Munier et al. (2003), different model scales are planned to be used during construction and operation of the Repository for spent nuclear fuel in accordance with Figure 8-1.

Stochastic DFN models are preferably created at the facility part scale and the facility scale with data collected from boreholes and tunnels. This work uses methodology developed in cooperation with Posiva for conditioning on fracture and hydraulic information. For quantitative hydrogeological models, boundary conditions are transferred from models on a larger scale to more detailed and high-resolution embedded small-scale models. In the following, the description of the modelling is elaborated in more detail.

Tunnel scale modelling

Modelling at the tunnel scale in a first step incorporates investigation data from pilot boreholes and in a second step data from the associated tunnel. In addition, all available interpretation and models are used, not just in the facility part scale, but also integrated at a larger scale (the facility scale and the local scale). The type and scope of detailed site investigation methods and associated data for the different construction and operational phases are presented in Chapters 4 through 7.

Hydraulic information from the drilling of pilot boreholes for a tunnel section and a general geological mapping of the drill core serve as a basis for an initial rough update of the model (with associated predictions) of the corresponding tunnel section based on a simplified single-hole interpretation. Where possible, the model also considers information from opposite/nearby ramp sections/shafts or nearby tunnels. It is emphasised that close collaboration between the in-situ investigation and modelling teams is essential for the basic modelling at the tunnel scale. In the ideal case, members of the investigation team are therefore closely involved in the modelling process. Conversely, it is also important that the modelling team is involved in the planning of further investigation efforts.

The continued investigations in the pilot borehole and subsequent single hole interpretation (SHI) and mapping of rock types, fractures, deformation zones and water inflow into the tunnel, constitute a basis for the single tunnel interpretation (STI). The latter identifies rock domains and improves the description of deformation zones and discrete fractures, which subsequently serves as a basis for 3D modelling at the facility part scale. The tunnel scale is also used for the integration of information from a number of deposition tunnels based on the construction steps including the batch of five deposition tunnels that are expected to be excavated per year and prior to that based on the preceding corresponding pilot boreholes.

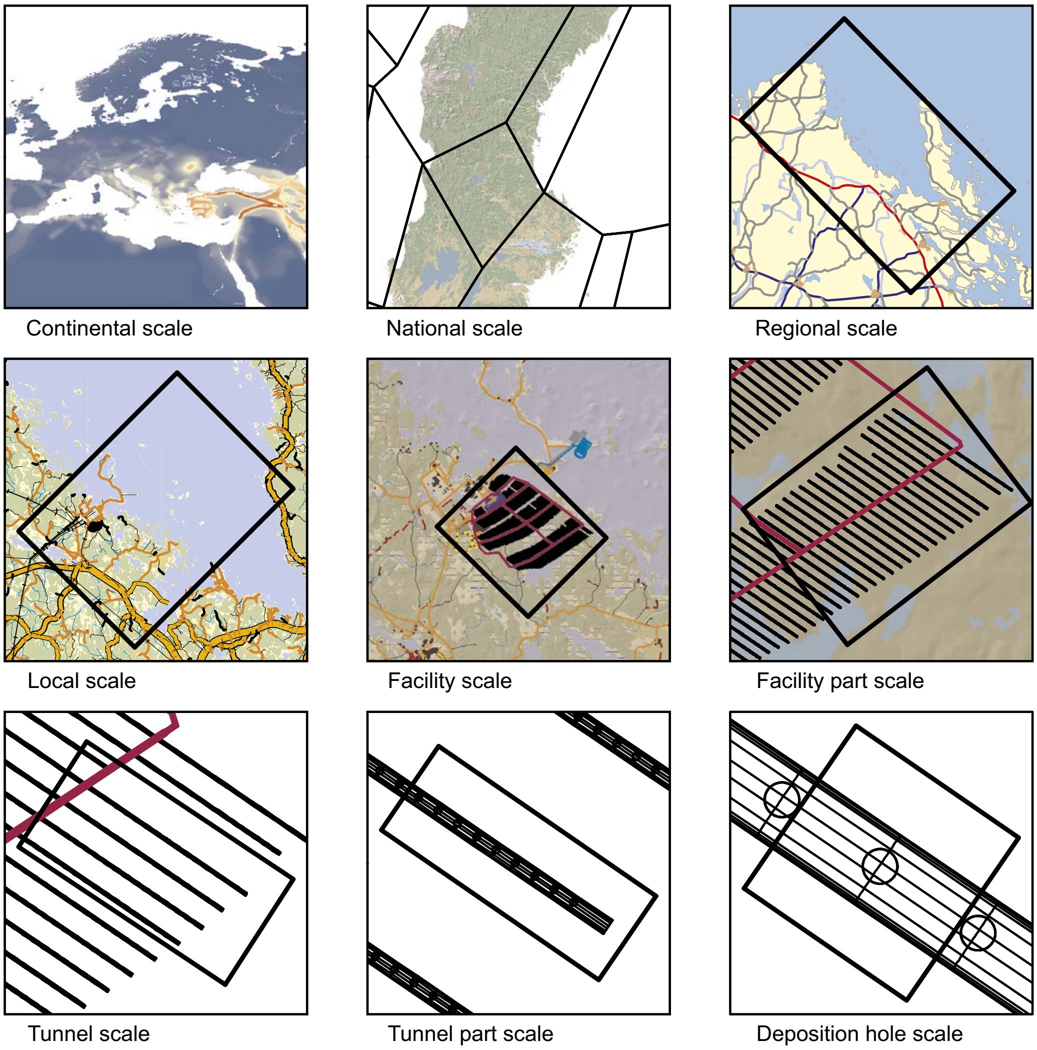

Figure 8-1. *Illustration of the model scales that can be employed during the construction and operation of the final repository and during development of the SDM. Note that the designations of the following scales differ from SDM-Site: Repository scale (area ~ 7 km^2, depth 1.2 km) is denoted "Local scale" in SDM-Site, Local scale (area ~ 165 km^2, depth 2.1 km) is denoted "Regional scale" in SDM-Site and Regional scale (area ~ 1500 km^2, depth 2.1 km) is denoted "Super-regional scale" in SDM-Site. The size of models at the facility part scale varies depending on the facility part in question. A tunnel part scale and deposition hole scale have been defined for possible future use. The latter scales are currently covered by models at the "tunnel scale".*

Facility part scale modelling

This scale gradually integrates the local 3D information modelled at the tunnel scale with application of necessary upscaling of modelled components and thus comprises the principal integration scale for the descriptive/conceptual and integrated modelling. Examples of such an application of integration with upscaling is the description of rock types with low thermal conductivity (e.g. amphibolite), originally established at the tunnel scale.

The first model at the facility part scale initially includes repository accesses and the central area, subsequently extended or supplemented with the area covering the first tunnel loop and parts of the tectonic lens margin (for determining the boundaries of the first deposition area), see Figure 8-2. This model can also be used as a basis for analysing and quantifying the possible impact of simultaneously ongoing activities in current repository parts, for example the impact of the development of the central area on the execution of integration tests.

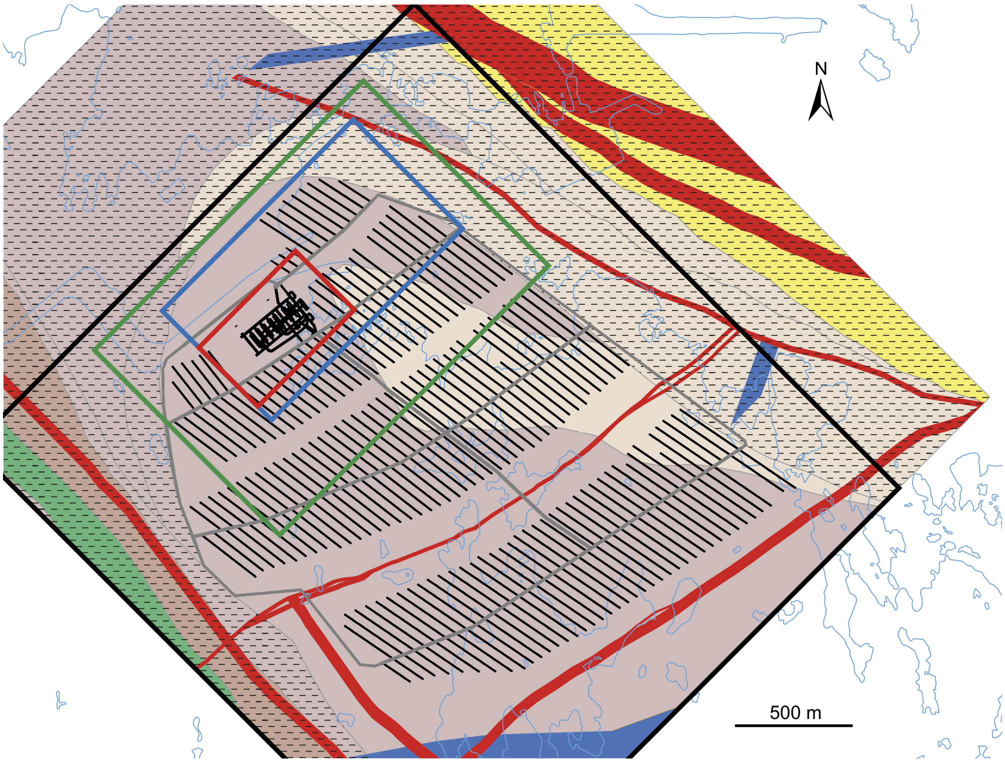

Figure 8-2. Examples of the extent of different models, based on Figure 7-1. The large black box refers to the facility model. The red box refers to the first facility part model applied during the construction of accesses and the central area. The blue box refers to the facility part model applied when integration tests are performed and during development of the first deposition area, whereas the green box exemplifies a possible model area at a stage. The extent of model areas is preliminary and will be established in operational programmes.

Before construction begins, the geoscientific conditions described by the facility part scale model are based on SDM-Site and its underlying data and data from investigations made in preparation of construction. The facility part model shows where deformation zones and large water inflows are expected to occur in accesses and other repository parts and what other conditions are expected during construction. During construction, recurrent updates of this model are carried out with results from detailed site investigations at the tunnel scale. For the geological and hydrogeological models (and in combination), this is done regularly and well integrated. It is done more rarely for the rock mechanics, thermal and hydrogeochemical models.

Facility scale modelling

Models at this scale include all parts of the repository included in the rock volume from the ground surface down to a level well below the repository level. Geometric structures such as rock type boundaries and deformation zones are scaled up from the basic description in the facility part models. Modelling at the facility scale mainly includes geological modelling (of rock domains/fracture domains and deformation zones) and associated descriptive hydrogeological and hydrogeochemical models as well as quantitative hydrogeological models. The latter can for example be used in the quantification of effects of the successive development of the accesses within the framework of the assessment of environmental impact and environmental monitoring, possibly embedded in the local scale model, with the possibility of full inclusion and description of the hydrogeology and hydrology of the surface system. For special needs, a model of the repository area and the central area (i.e. all facility parts with a more pronounced 2D coverage at repository depth) can be established.

Local scale modelling

This scale is primarily used for quantitative analysis of the hydrogeological descriptive models described above, but also for the quantification of hydrological/hydrogeological interaction between the surface system and the bedrock at greater depths, as well as for possible supplementary paleo analyses of the hydrogeochemical evolution. In the latter case, new ways to also include the effects of chemical reactions along the flow paths can be utilised. Models at this scale are used, together with supporting modelling at more detailed scales, for site descriptive modelling (SDM) reported at specifically selected occasions. The local model area also includes the SFR facility. Quantitative flow models at this scale are also used to analyse the possible interactions between SFR and the Repository for spent nuclear fuel.

Regional scale modelling

This scale is primarily used for hydrogeological/surface ecological analyses including one or more catchment areas and for analyses of hydrogeochemical evolution.

National and continental scale modelling

An example of modelling at the national scale is seismic zonation, which provides data for assessment of the seismic risk for surface facilities. Evaluation of seismic risk linked to tunnels, rock caverns and utilised deposition positions may also be needed. An example of modelling at the continental scale is the analyses of the impact of ice sheet propagation included in the assessment of repository safety after closure. In addition, large-scale models can provide boundary conditions for smaller-scale models.

8.2 Modelling during construction

Repository construction includes development of repository accesses and shafts, the central area, tunnels for integration and commissioning tests and associated transport and main tunnels. Based on current planning, the skip shaft will reach the repository area well before the ramp. Construction of the central area starts from the skip shaft. Simultaneously with the construction of the central area, tunnel excavation to the first deposition area begins, see Chapter 6. Thereby, information from different depths and parallel excavation fronts is obtained on a continuous basis.

For individual tunnels, rooms and shafts, tunnel scale modelling will be carried out continuously during construction, including the preparation of construction-related predictions for design/construction. The facility part model is updated regularly and in an integrated manner for the disciplines geology and hydrogeology. When some clear milestones are reached, it is appropriate to also produce a more comprehensive report where modelling related to all disciplines (possibly with the exception of transport properties) is performed and reported. These milestones are established in the operational programme before the start of construction. Tentatively, the milestones could occur when the first ramp loop has been built (all known extensive vertical deformation zones affecting the accesses have then been intersected), when the skip shaft has reached repository depth and when the central area is fully excavated and investigated. This type of comprehensive report should be structured in a similar manner as SDM-SAR (see Section 8.4), although not with the same scope.

During construction of the accesses, no additional information is expected on bedrock conditions outside the rock volume affected by the constructed repository parts. An exception is seismic, hydrogeological and hydrogeochemical data from monitoring in boreholes or on the ground surface. During construction, data concerning drawdown of the groundwater table (groundwater pressure) and inflow comprise the primary basis for calibration (and conditioning) of hydrogeological models with respect to the distribution of hydraulic material properties. Furthermore, the impact of groundwater drawdown on the surface system can be analysed, as well as the impact of countermeasures to prevent unacceptable effects on the environment. The collected information from accesses (mainly from the skip shaft with associated pilot borehole) and initial underground work at repository level is used to verify the chosen repository depth and, if necessary, make necessary adjustment.

In addition to the recurring updates of discipline-specific models at the facility part scale that are carried out during construction, other types of modelling may be needed. Tunnel scale modelling will be needed to investigate certain issues, for example the spatial extent of occurring amphibolite bodies (related to thermal conductivity), the occurrence of critical structures, the occurrence of episyenite (vuggy rock) and initial DFN modelling at repository level. More detailed modelling could also be undertaken if the construction shows conditions different to those predicted by the facility part model.

8.3 Modelling during development of a deposition area

During the development of deposition areas, modelling is carried out continuously at the tunnel and facility part scales in order to successively integrate results from the detailed site investigations. The modelling takes into account the successive extension and is carried out for individual deposition areas. In addition to continued modelling for the rock excavation predictions, as a basis for assessment of grouting and rock support needs, the modelling will mainly be focused on providing data for the succession of decisions described in Section 7.3. Initially, the focus will be on layout-determining structures (critical structures of class 1 and 2 with associated critical volumes, see Section 3.2), which, where they occur, provide a basis for determining the boundaries of the repository area and associated deposition areas. This is followed by modelling that provides a basis for adaptation of the positioning and orientation of deposition tunnels to local bedrock conditions, including rock stresses, and modelling in support of demonstration of compliance with technical design requirements for selecting deposition hole locations and subsequent approval of deposition holes for deposition.

Delineation, adaptation and compliance with the technical design requirements require that the modelling considers varying requirements on resolution, geometries and parameters for different issues and decisions. Those related to the development of a deposition area are mainly handled at the facility part scale. Those related to individual deposition tunnels or groups of deposition tunnels are mainly handled at the tunnel scale. Those related to compliance with the technical design requirements for deposition holes are handled at the tunnel scale and, if necessary, at more detailed scales, see Figure 8-1.

8.4 Modelling for SDM-SAR

At giventimes during construction and operation of the repository, there is a need for a complete update of the integrated site descriptive model SDM. These occasions are primarily linked to formal regulatory requirements (licensing issues and requirements on updated safety analysis reports during operation), but may also be initiated by SKB. All previous data and models serve as a basis for the SDM updates. The data are specified in the form of a database at a data freeze, well-defined in time.

While the integration and commissioning tests are conducted, the updating of SDM-Site to a new integrated site model called SDM-SAR is completed. The latter serves as a basis for a decision on whether the current detailed design of repository parts needs to be adjusted and is an important basis for the safety analysis report SAR, which will be included in the application for trial operation.

The data underlying the site-descriptive model update consist of SDM-Site with supporting material, as well as results from all preceding investigations during construction, including investigation results from the first tunnel loop and from pilot boreholes for tunnels for the integration and commissioning tests. It also includes information from any cored boreholes, which in accordance with Section 6.3.2 may be drilled to define the repository area boundaries in relation to the tectonic lens margin to the north-east. The background material consists of primary data and working models at different scales, as described previously in this chapter.

Another essential source of information for modelling is the time series of various parameters generated by the extensive monitoring that has been conducted continuously since the completion of the site investigations, not only in conjunction with the area of the Repository for spent nuclear fuel, but also adjacent to the SFR facility and in the local and regional model areas.

As mentioned above, the discipline-specific models at the facility part scale are updated regularly during the construction. At defined information-related milestones, cross-checks between disciplines will be carried out for analyses of mutual consistency between the models. In case of deviations, possible causes are investigated and measures are taken in order to investigate discrepancies, which could entail a need for further investigations.

When the data freeze for the integrated site description SDM-SAR is established, updates and analyses of models have been in progress since the construction of accesses started. A substantial part of the modelling, analyses and descriptions that are to be included in SDM-SAR should thus be essentially completed and well established and the concluding work can primarily focus on consolidation, analysis of consistency between disciplines, confidence building and analysis of consistency in relation to SDM-Site at scales covering the entire repository and the local model area. For facilities in operation, the Nuclear Activities Act imposes requirements on periodic overall assessments of safety and radiation protection every ten years. The site descriptive model (SDM) will consequently be updated as a basis for these reports.

In practice, the basic elements of the strategy for development of an integrated SDM, according to Andersson (2003) and described by Andersson et al. (2013), are also applicable for detailed site investigations underground. The main difference is that primary data from detailed site investigations underground are derived from pilot boreholes and corresponding tunnels and are successively integrated into the working models that are established at a more detailed scale than that used during the surface-based site investigation. These working models, and integration of these into more tentative model scales, serve as a basis for SDM-SAR.

Figure 8-3 shows the logical links that serve as a basis for the work with SDM-SAR, where particularly the hydrostructural framework is established by close integration between geology and hydrogeology. The latter is established successively in the construction process at the tunnel scale and at facility part scale during the successive development of the repository.

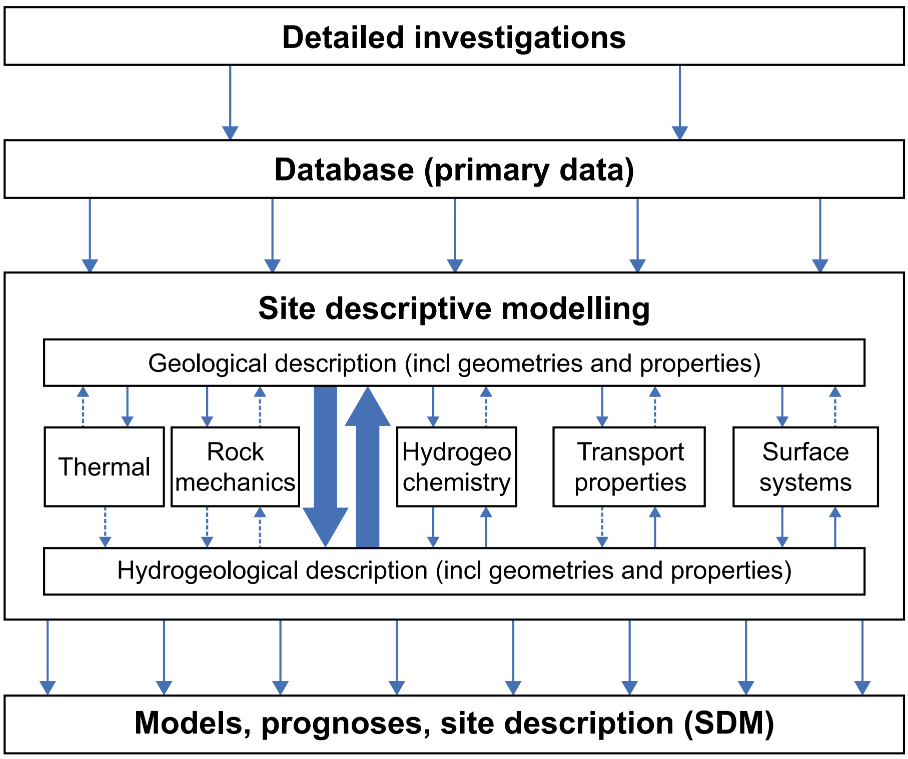

Figure 8-3. *The discipline-specific descriptions are unified by a number of recurrent feedback loops where the hydrostructural framework established by close integration between geology and hydrogeology is emphasised and constitutes a platform for other modelling.*

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SKBdoc documents will be submitted upon request to document@skb.se.

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Appendix

The role of detailed site investigations in attaining compliance with technical design requirements

A fundamental principle for the Repository for spent nuclear fuel is that the nuclear waste shall be kept isolated from the biosphere. Safety is based on the so-called principle of multiple barriers, consisting of the natural barrier (the host rock) and engineered barriers (canister, buffer, backfill, closure) that mutually contribute to contain, prevent and retard radionuclides from reaching human beings. The repository rock shall contribute

- mechanically stable conditions,
- favourable thermal conditions,
- favourable chemical conditions,
- favourable hydrogeological conditions with limited transport of solutes.

The construction of the final repository with its different underground openings must not in an undesired way disturb or alter the properties of the rock as a barrier. In addition, the engineered barriers and the reliability of their installation impose requirements on the design of the underground openings.

SKB and Posiva are collaborating to establish a bilateral consensus regarding design principles and technical design requirements, which in an optimal way takes into account the limitations and opportunities provided by identified similarities, in terms of types of spent nuclear fuel, available technology and technical solutions and the chosen repository sites in each country. The common technical design requirements for a complete final repository system according to KBS-3 are presented in Posiva SKB (2017).

The following table presents the common technical design requirements that are applicable to the repository rock and associated underground openings, and describes the role of detailed site investigations in the fulfilment of these requirements. The technical design requirements are direct transcripts as presented in Section 8.3 in Posiva SKB (2017).

Technical design requirement (transcript from Posiva SKB 2017)	The role of detailed site investigations in attaining compliance with requirements	Comment
Repository depth 400 m < repository depth < 700 m.	The proposed repository depth is based on results from the surface-based site investigations. Refined adaptation of locations of repository parts at depth may take place on the basis of additional information from the detailed site investigations, for example concerning possible subhorizontal structures with large extent and prevailing rock stress conditions.	
Deposition areas – critical structures Deposition areas must not be placed within critical volumes of class 1.	The surface-based site investigations are assumed to have identified critical structures of class 1, which cannot be accepted anywhere within the extent of the repository. In the modelling for the SDM (or large-scale modelling) the location and extent of these structures (with associated critical volume) are verified.	Critical volumes of class 1 are linked to critical structures of class 1, see Section 3.2.
Deposition areas – chemical conditions The deposition areas should be placed so that the salinity (TDS), pH and sulphide content of the groundwater are within the limits of their performance targets.	Basic compliance with requirements has been demonstrated by the surface-based site investigations. The parameters linked to the requirements are well established and can be measured with conventional methods. The opportunity to obtain undisturbed samples during detailed site investigations is, however, a complication that needs to be considered in the operational investigation programmes.	Building of a knowledge base is in progress with regards to sulphide and the dynamics of the evolution of sulphide concentrations over time.

Technical design requirement (transcript from Posiva SKB 2017)	The role of detailed site investigations in attaining compliance with requirements	Comment
Deposition tunnels – critical structures Deposition tunnels must not be placed within critical volumes of class 1 and 2.	This technical design requirement is of crucial importance for detailed site investigations, when the approach is developed from a geometric default value (respect distance) to the use of actual mapped site-specific conditions and coupled modelling and description. In general, however, based on the surface-based site investigations, the confidence in the modelled location and geometry of critical structures of class 1 and 2 is considered to be good. By way of investigations and modelling, the information on the location and geometry of these structures within the repository area is supplemented and improved, for example by pilot hole drilling and investigations in and from main and transport tunnels.	Critical volumes of class 1 and 2 are linked to critical structures of class 1 and 2.
Deposition tunnels – orientation The deposition tunnels should be aligned according to the site-specific rock stresses to limit damaged rock volume around the tunnel.	A fundamental understanding of the geometry of the rock stress field and the magnitudes of the maximum and minimum horizontal rock stresses was established in the repository area during the surface-based site investigations. This understanding will be improved at an early stage by the planned measurement programme in the ramp and skip shaft. Repeated rock stress measurements in the deposition areas are used to verify and improve the description of the rock stress situation and, if necessary, adapt the tunnel orientation in individual deposition areas.	
Deposition tunnel – plugs (critical structures) The deposition tunnel plugs shall not be placed within critical volumes of class 1, 2 or 3.	The detailed site investigations provide the data that are needed to demonstrate the absence of structures of class 3 at plug positions.	See "Deposition holes – critical structures" below.
Distance between central or main tunnel and plug in deposition tunnels Larger than *site-specific limit to be determined in the design* to avoid mechanical influence.	The detailed site investigations provide data for the rock mechanics analyses that are needed to determine this minimum distance.	
Deposition holes – critical structures Deposition holes must not be placed within critical volumes of class 1, 2 or 3.	One of the main tasks for detailed site investigations is the identification and quantification/delineation of critical structures of class 3. The detailed site investigation programme describes the strategy and methodology for investigations and modelling. The empirical knowledge base acquired successively will constitute an important component in the continued work. In the absence of other information, the positioning of deposition holes in relation to critical structures of class 3 can be made according to FPI criteria.	Critical volumes of class 1, 2 and 3 are linked to critical structures of class 1, 2 and 3. A field test of methods and methodology for identification and quantification of critical structures of class 3 has been carried out at Äspö.

Technical design requirement (transcript from Posiva SKB 2017)	The role of detailed site investigations in attaining compliance with requirements	Comment
Deposition holes – transmissivity Deposition holes shall be placed where the transmissivity of the pilot borehole drilled in deposition hole position is less than *limit under development*.	The transmissivity is measured in pilot boreholes for deposition holes by well-established methods (transient injection tests).	Development of the methodology for establishing a limiting transmissivity is under way and has been tested on conditions experienced in Posiva's ONKALO facility, within the framework of a Posiva-SKB cooperation (Baxter et al. 2017). The basis for establishment of the limit includes simulated injection tests at open repository conditions and simulated Darcy fluxes at the corresponding deposition hole positions during backfilled and saturated conditions. The limit for measured transmissivity in the pilot borehole is provided by a limiting Darcy flux, assuming a linear relationship between pilot borehole transmissivity and Darcy flux. Methods and methodology for determination of transmissivity in pilot boreholes have been tested by Posiva and SKB in ONKALO (Hjerne et al. 2016).
Inflow to deposition hole Less than *limit to be determined in the design* to allow installation of the buffer.	The methodology for measurement of inflow to the deposition hole is developed for open deposition holes and is in practice independent of the chosen limit for inflow.	
Deposition tunnels – separation from a mechanical point of view The distance between the deposition tunnels shall be at least *site-specific distance* to avoid mechanical influence between tunnels.	The detailed site investigations provide the data required for the rock mechanics analyses that are needed to determine this minimum distance.	
Deposition holes – separation from a thermal point of view The minimum distance between deposition holes within a deposition tunnel and to holes in adjacent tunnels shall be such that the temperature in the buffer < 100 °C.	Based on data collected during the site investigation and calculations in SDM-Site, basic design has been specified for the deposition tunnel spacing (L = 40 m) and the spacing between deposition holes along the deposition tunnel (6.0 m in rock domain RFM029 and 6.8 m in rock domain RFM045 (SKB 2009c)). The detailed site investigations will provide data for verification of the design, including possible occurrence of thermally anomalous rock types and, if necessary, associated adjusted thermal optimisation of deposition positions.	
Deposition holes – separation from a mechanical point of view The distance between the deposition holes shall be at least *site-specific distance* to avoid mechanical influence between holes.	The detailed site investigations provide sufficient data for the rock mechanics analyses that are needed to determine this minimum distance.	

Technical design requirement (transcript from Posiva SKB 2017)	The role of detailed site investigations in attaining compliance with requirements	Comment
Spacing between existing investigation boreholes and tunnels/shafts The distance between investigation holes connected to the surface and shafts or tunnels other than deposition tunnels shall be at least *site-specific distance to be determined in the design*. The distance between investigation holes connected to the surface and deposition tunnels shall be at least *site-specific distance to be determined in the design.* The distance between investigation holes connected to the surface and deposition holes shall be at least *site-specific distance in the design*.	These technical design requirements impose quality requirements on the geodetic measurement of underground openings and boreholes in order to take into account site-specific factors related to existing investigation holes and their possible role and interaction with the hydrostructural network (as provided by established models). In addition, there may be additional requirements on establishing borehole locations and geometry, employing indirect methods from tunnels in order to ensure that stipulated design requirements are fulfilled.	Where opportunities are provided, surface boreholes should be remeasured with modern technology and methods in order to reduce uncertainties in the description of the borehole geometry in 3D space.
Distance between deposition tunnels and other underground openings The distance between deposition tunnels where canisters have been emplaced and other underground openings shall be at least *site-specific distance to be determined in the design*.	This requirement has no direct implications on the detailed site investigations more than quality requirements on the geodetic measurement of underground openings and boreholes.	
Distance between deposition tunnels and areas where rock construction is under way The distance between deposition tunnels where canisters have been emplaced and rock construction shall be at least *site-specific distance to be determined in the design*.	This requirement has no direct implications on the detailed site investigations more than quality requirements on the geodetic measurement of underground openings and boreholes.	
Entire repository – Inflow Total groundwater inflow to the underground openings shall be less than *site-specific limit*.	The requirement has no direct implications on the detailed site investigations apart from the monitoring of inflows in established sumps.	Pressure drawdown is monitored in existing packed-off boreholes and is utilised for environmental monitoring and calibration/conditioning of numerical flow models.
Inflow to deposition tunnel Less than *limit to be determined in the design* to allow installation of the backfill and plug.	Registration of inflow in measurement weir located near the entrance of the deposition tunnel.	
EDZ – deposition tunnel The specific capacity ($Q/\Delta p$) of the EDZ, measured from the pilot borehole for the deposition holes, shall be such that it corresponds to a transmissivity of 10^{-8} m^2/s at maximum.	The results of detailed site investigations are crucial for approval of properties and characteristics of the EDZ in deposition tunnels from the perspective of safety after closure. The results have implications for the excavation method used and any subsequent levelling of deposition tunnel floors.	Technology for determination of specific capacity in boreholes close to tunnel floors exists and has been demonstrated in situ (Ericsson et al. 2015, Hjerne et al. 2016). Problems related to effects of hydraulic boundary and the selection of evaluation model remain. Development of methodology and technology is under way. In addition, the current technical design requirement will be developed to better account for the hydraulic connectivity and effective material properties of the EDZ along deposition tunnels.

Technical design requirement (transcript from Posiva SKB 2017)	The role of detailed site investigations in attaining compliance with requirements	Comment
EDZ – other openings than deposition tunnels and deposition holes The specific capacity (Q/Δp) of the EDZ, that needs to be shown to be achievable with the excavation technique to be applied, shall be such that it corresponds to a transmissivity *to be determined* at maximum.	Demonstration and documentation that the excavation technique fulfils the technical design requirement will be made before the excavation of the ramp reaches a depth of 370 m, using a separate niche along the ramp. If necessary, the rock excavation technique is adapted so that the requirements on EDZ are fulfilled. Continued follow-up of the EDZ is carried out regularly using geophysical methods in combination with geological documentation.	
Geometry of deposition tunnel *Geometrical parameters within limits to be determined in the design*.	This requirement has no direct implications on the detailed site investigations more than quality requirements on the geodetic measurement of underground openings and boreholes.	
Geometry of deposition hole *Geometrical parameters within limits to be determined in the design*.	There are requirements on high quality verifying measurements of the geometry of the completed deposition hole. Parameters of importance are radius/diameter, straightness (undulation), length, volume and inclination of the bottom surface.	Technology development is under way.
Geometry of other underground openings *Geometrical parameters within limits to be determined in the design*.	This requirement has no direct implications on the detailed site investigations more than quality requirements on the geodetic measurement of underground openings and boreholes.	
Remaining engineering materials – chemical composition Only low pH grouting materials yielding a pH < 11 in deposition tunnels are allowed.	This is a material requirement and has no direct implications for detailed site investigations.	
Positioning and approval of deposition holes in relation to remaining engineering materials There shall be no grouting of deposition holes. Deposition holes shall not be emplaced along tunnel sections where grouting or other measures to control inflow are applied, if these measures may even locally impair the backfill performance above the deposition hole. Tunnel sections with grouting holes outside the tunnel perimeter shall not be used for deposition holes, if the holes may create a connection to a critical volume of class CV1, CV2 or CV3.	The two first technical design requirements are met by documentation of the rock excavation work. For the third technical design requirement, the detailed site investigations need to identify the occurrence of critical structures.	

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SKB is responsible for managing spent nuclear fuel and radioactive waste produced by the Swedish nuclear power plants such that man and the environment are protected in the near and distant future.

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