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Deliverable D2.2: Designs of Reference Concepts and DOPAS Experiments: DOPAS Reference Designs Report

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Executive Summary

The Full-Scale **D**emonstration **O**f **P**lugs **A**nd **S**eals (DOPAS) Project is a European Commission (EC) programme of work jointly funded by the Euratom Seventh Framework Programme and European nuclear waste management organisations (WMOs). A set of full-scale experiments, laboratory tests, and performance assessment studies of plugs and seals for geological repositories will be carried out in the course of the project.

The DOPAS Project focuses on tunnel, drift, vault and shaft plugs and seals for crystalline, clay and salt rocks. The project is coordinated by Posiva Oy, Finland. Work Package 2 (WP2) of the DOPAS Project is focusing on the design basis, reference designs and strategies used to demonstrate the compliance of the installed plugs and seals to the design basis. WP2 is coordinated by SKB, Sweden. This report is Deliverable D2.2 of DOPAS, and describes the reference and experiment designs for the full-scale plugs or seals being investigated within DOPAS:

- *Crystalline rocks*: experiments related to plugs in horizontal tunnels, including the Dome Plug (DOMPLU) experiment being undertaken by SKB at the Äspö Hard Rock Laboratory (ÄHRL) in Sweden, the Posiva Plug (POPLU) experiment being undertaken by Posiva at the ONKALO underground rock characterisation facility (URCF) in Finland, and the Experimental Pressure and Sealing Plug (EPSP) experiment being undertaken by SÚRAO and the Czech Technical University (CTU) at the Josef underground research laboratory (Josef URL) in the Czech Republic.
- *Clay rocks*: the Full-scale Seal (FSS) experiment being undertaken by Andra in a warehouse at St Dizier, which is an experiment of the construction of a drift and ILW disposal vault seal.
- *Salt rocks*: tests related to seals in vertical shafts under the banner of the Entwicklung von Schachtverschlusskonzepten (development of shaft closure concepts – ELSA) experiments, being undertaken by DBE TEC together with the Technical University of Freiberg and associated partners complemented by laboratory testing performed by GRS.

The host rock and disposal concept have a significant impact on the conceptual design of plugs and seals.

In crystalline rocks, the disposal concept places a high reliance on the engineered barrier system and the function of the plug is to hold the backfill in place during operations. This is achieved by providing a strong concrete plug. Owing to the potential for erosion of the backfilled bentonite, the groundwater flux across the plug has to be low, and this can be achieved through the use of a watertight seal or by using a massive concrete plug. In crystalline rocks, plugs may be keyed into the host rock (where an excavation damage zone is thought to be present) and contact grouted to avoid groundwater flow along the plug-rock interface.

In clay and salt host rocks, the creep properties of the host rock are taken into account in plug and seal design. The function of drift and shaft seals is to provide a sufficiently low hydraulic conductivity to limit radionuclide migration through the backfilled excavations (and, in the case of salt host rocks, brine inflow into the repository). In clay host rocks, swelling bentonite is suitable for use in providing this low hydraulic conductivity. In salt host rocks, a range of materials may be used, including salt concrete, sorel concrete and bentonite.

List of Acronyms

ÄHRL:	Äspö hard rock laboratory
BSK-3:	BrennStabKokille-3
Cigéo:	Centre Industriel de Stockage Géologique (Industrial Repository in France)
DOMPLU:	Dome Plug
DOPAS:	Full-scale Demonstration of Plugs and Seals
EBS:	Engineered barrier system
EC:	European Commission
EDZ:	Excavation damaged zone
ELSA:	Entwicklung von Schachtverschlusskonzepten (development of shaft closure concepts)
EPSP:	Experimental Pressure and Sealing Plug
FSS:	Full-scale Seal
HLW:	High-level waste
ILW:	Intermediate-level waste
KBS:	KärnBränsleSäkerhet (Nuclear Fuel Safety; the “3” in KBS-3 denotes the 3rd version, the “V” in KBS-3V denotes the vertical deposition mode and the “H” in KSB-3H refers to the horizontal deposition mode)
LECA:	Lightweight expanded clay/concrete aggregate
POPLU:	Posiva Plug
URCF:	Underground rock characterisation facility
URL:	Underground research laboratory
VAHA:	Vaatimusten hallintajärjestelmä (Posiva’s requirement management system)
VSG:	Vorläufige Sicherheitsanalyse Gorleben (Preliminary Safety Analysis for Gorleben)
WMO:	Waste management organisation
WP:	Work package

List of DOPAS Project Partners

The partners in the DOPAS Project are listed below. In the remainder of this report each partner is referred to as indicated:

Posiva	Posiva Oy	Finland
Andra	Agence nationale pour la gestion des déchets radioactifs	France
DBE TEC	DBE TECHNOLOGY GmbH	Germany
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit	Germany
Nagra	Die Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle	Switzerland
RWM	Radioactive Waste Management Limited	UK
SÚRAO	Správa Úložišť Radioaktivních Odpadu (Radioactive Waste Repository Authority – RAWRA)	Czech Republic
SKB	Svensk Kärnbränslehantering AB	Sweden
CTU	Czech Technical University	Czech Republic
NRG	Nuclear Research and Consultancy Group	Netherlands
GSL	Galson Sciences Limited	UK
BTECH	B+ Tech Oy	Finland
VTT	Valtion Teknillinen Tutkimuskeskus (Technical Research Centre of Finland)	Finland
UJV	Ustav Jaderneho Vyzkumu (Nuclear Research Institute)	Czech Republic

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1 Introduction

1.1 Background

The Full-Scale **D**emonstration **O**f **P**lugs **A**nd **S**eals (DOPAS) Project is a European Commission (EC) programme of work jointly funded by the Euratom Seventh Framework Programme and European nuclear waste management organisations (WMOs). The DOPAS Project is running in the period September 2012 – August 2016. Fourteen European WMOs and research and consultancy institutions from eight European countries are participating in DOPAS. The project is coordinated by Posiva Oy, Finland. A set of full-scale experiments, laboratory tests, and performance assessment studies of plugs and seals for geological repositories will be carried out in the course of the project.

DOPAS aims to improve the industrial feasibility of plugs and seals, the measurement of their characteristics, the control of their behaviour over time in repository conditions, and their performance with respect to safety objectives. The DOPAS Project is being carried out in seven Work Packages (WPs). WP1 includes project management and coordination. WP1 is coordinated by Posiva Oy, Finland. WP2, WP3, WP4 and WP5 address, respectively, the design basis, installation, compliance testing, and performance assessment modelling of the five full-scale experiments and laboratory tests. WP2, WP3, WP4 and WP5 are coordinated by SKB, Sweden; Andra, France; RWM, UK; and GRS, Germany, respectively. WP6 and WP7 address cross-cutting activities common to the whole project through review and integration of results, and their dissemination to other interested organisations in Europe and beyond. WP6 and WP7 are coordinated by Posiva Oy, Finland.

The DOPAS Project focuses on tunnel, drift, vault and shaft plugs and seals for crystalline, clay and salt rocks:

- *Crystalline rocks*: experiments related to plugs in horizontal tunnels, including the Dome Plug (DOMPLU) experiment being undertaken by SKB at the Äspö Hard Rock Laboratory (ÄHRL) in Sweden, the Posiva Plug (POPLU) experiment being undertaken by Posiva at the ONKALO underground rock characterisation facility (URCF) in Finland, and the Experimental Pressure and Sealing Plug (EPSP) experiment being undertaken by SÚRAO and the Czech Technical University (CTU) at the Josef underground research laboratory (Josef URL) in the Czech Republic.
- *Clay rocks*: the Full-scale Seal (FSS) experiment, being undertaken by Andra in a warehouse at St Dizier, is an experiment of the construction of a drift and intermediate-level waste (ILW) disposal vault seal.
- *Salt rocks*: tests related to seals in vertical shafts under the banner of the Entwicklung von Schachtverschlusskonzepten (development of shaft closure concepts – ELSA) experiment, being undertaken by GRS and DBE TEC.

Each experiment represents a different state of development. The Swedish experiment was started prior to the start of the DOPAS Project. The Finnish, Czech and French experiments are being designed and constructed during DOPAS. The German tests focus on the early stages of design basis development and on demonstration of the suitability of designs through performance assessment studies, and will feed into a full-scale experiment of some shaft seal components to be carried out after DOPAS.

WP2 addresses the design basis, reference designs and strategies used to demonstrate the compliance of the installed plugs and seals to the design basis. It is structured in four tasks:

- Task 2.1: Design Basis. Collation of the requirements and conditions for each individual experiment in DOPAS.
- Task 2.2: Reference Designs. Documentation of the designs in the reference concepts and the DOPAS experiments.
- Task 2.3: Strategies for Demonstrating Conformity of Design to Design Basis. Identification and description of the different strategies that will be adopted in the DOPAS experiments to demonstrate compliance of the designs to the design bases.
- Task 2.4: Final Reporting of WP2. In this task all of the WP2 results will be compiled in one final report.

This report is Deliverable D2.2 of DOPAS, and describes the outcome from Task 2.2. It presents the reference and experiment designs for the full-scale plugs or seals being investigated within DOPAS.

1.2 Objectives

The objectives of this report are to document the reference and experiment conceptual designs of the five plugs and seals considered in DOPAS and to identify the influence of the design basis, including host rock characteristics, on the designs.

1.3 Scope and Terminology

In this report, we focus on the conceptual designs of plugs and seals. Conceptual designs are part of a hierarchy of increasingly detailed designs, as follows:

- Conceptual Design: Conceptual designs describe the general layout of a repository structure including the different components and how they are arranged, the type of material used for each component (e.g. concrete, bentonite and sand). In a conceptual design, the properties of rock are presented in generic terms, and the performance of the components and the overall structure is described in qualitative terms.
- Basic Design: In a basic design, the components in the conceptual design are described in more detail with a quantitative specification of geometry and material parameters. The properties of the rock are presented in detail, which requires characterisation of the site or elaboration of the assumptions underpinning the design. Performance is described in quantitative terms.
- Detailed design: In a detailed design, the concept, in the case of DOPAS the plug or seal, is presented in such detail that it can be constructed, i.e. it provides precise information on all aspects of the structure's components.

The experiments in DOPAS are investigating specific aspects of reference plug or seal designs. There are differences between the design basis for the reference design for the plug or seal tested in DOPAS, and the design basis for the experiment. These differences are the consequence of several considerations in development of test-specific objectives, for example to test alternative designs and compare the performance with the reference designs (e.g. POPLU), and to test planned modifications in the reference design (e.g. DOMPLU).

Therefore, a distinction is made between reference and experiment designs:

- The term "reference design" is used to denote the design of a plug or seal within a disposal concept, i.e. the design used to underpin the safety case or licence application.
- The term "experiment design" is used to indicate the design of the plug or seal that is being tested at full-scale in DOPAS.

A range of plugs and seals are envisaged in repository concepts. The types of plugs and seals, and their functions, have been summarised in (White *et al*., 2014). The descriptions of the designs of plugs and seals in this report focus on their components and function.

1.4 Approach

Information on the reference and experiment designs being carried out in DOPAS was compiled by Galson Sciences Limited (GSL) using the following methods:

- Through a questionnaire that was completed by WMO partners. The questionnaire contained a series of questions regarding the reference and experiment designs. For the preparation of this report, partners were asked to complete sections WP2.0, WP2.1 and WP2.2 (Waste Management Programme Context, General Repository Plugs and Seals in Waste Management Programmes: Design Bases and Criteria, and DOPAS Experiments: Reference Designs respectively).
- Referring to published documents supplied by partner organisations.
- Discussions at project meetings.

1.5 Report Structure

The remainder of this report is set out as follows:

- Section 2 describes the reference design of the SKB's deposition tunnel plug and the experiment design of DOMPLU.
- Section 3 describes the reference design of the Posiva's deposition tunnel plug and the experiment design of POPLU.
- Section 4 describes the reference design of the Czech deposition tunnel plug and the experiment design of EPSP.
- Section 5 describes the reference design of the Andra's drift / ILW disposal vault seal and the experiment design of FSS.
- Section 6 describes the reference design of the German shaft seal and the experiment design of ELSA.
- Section 7 provides a discussion on the factors influencing the design of plugs and seals, in particular the influence of host rock characteristics are considered.
- Section 8 lists the references used in this report.

2 DOMPLU Conceptual Design

In this section, SKB's designs for deposition tunnel plugs are described. In Section 2.1, the conceptual design of the reference deposition tunnel plug is described. This includes a description of the main safety functions of deposition tunnel plugs and how they are met by the conceptual design on a component-by-component basis. In Section 2.2, the modifications to the conceptual design in DOMPLU are described. In Section 2.3, a discussion of the conceptual design is provided including, limitations and the planned initial state.

2.1 Deposition Tunnel Plug Reference Design

The KBS-3V method is proposed by SKB for the disposal of spent fuel packaged in copper canisters with cast iron inserts in a crystalline host rock. The long-term safety principles are based on isolation and containment of radioactive waste through the choice of a stable geological environment at depth and the use of a multi-barrier system consisting of engineered barriers (canister, buffer, backfill, and closure) and the host rock. The canisters are emplaced in vertical holes, containing pre-compacted blocks of bentonite buffer, below horizontal deposition tunnels. The deposition tunnels are backfilled with bentonite blocks and pellets, and closed with a deposition tunnel plug (see Figure 2.1).

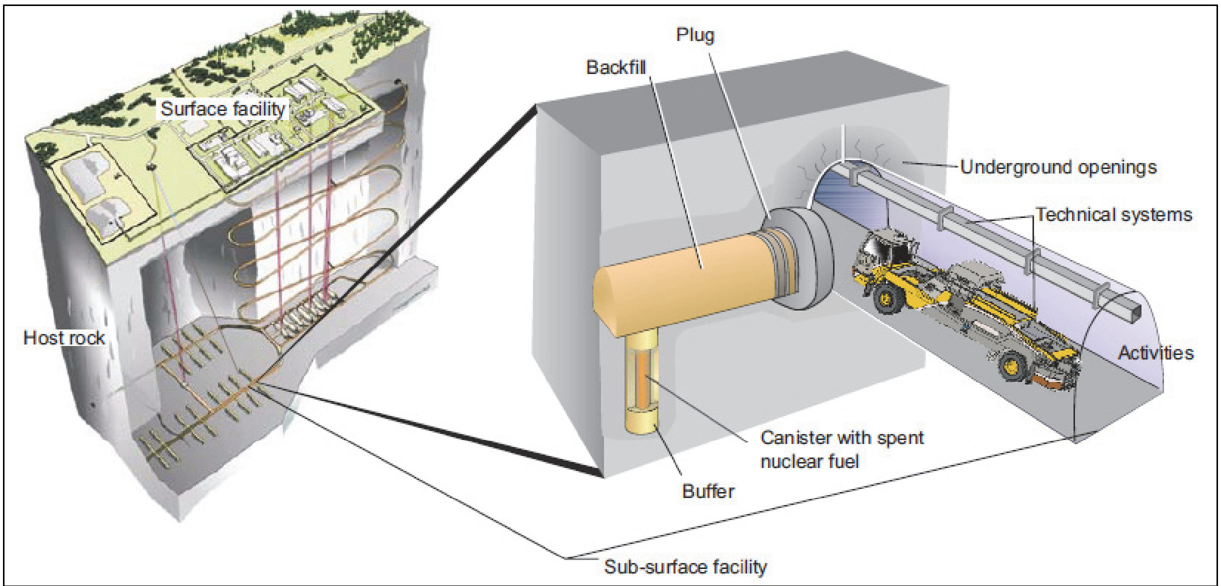

Figure 2.1: The KBS-3V repository and the location of the deposition tunnel plug (SKB, 2010a).

Deposition tunnel plugs in the Swedish repository have temporary functions with the objective of supporting the performance of other safety barriers. Their functions during the operational period of the repository are to:

- Confine the backfill in the deposition tunnel.
- Support saturation of the backfill.
- Provide a barrier against water flow that may cause harmful erosion of the bentonite in buffer and backfill.

The current SKB reference conceptual design for a deposition tunnel plug is described in SKB's *Design, production and initial state of the backfill and plug in deposition tunnels* report (SKB, 2010b), and includes the following components (see Figure 2.2):

- Concrete Plug: The concrete plug is a dome-shaped structure made of low-pH reinforced concrete. It contains pipes for auxiliary equipment such as air ventilation pipes, cooling pipes, and grouting tubes. The cooling pipes are used to avoid internal cracking due to cement hydration and to pe-stress the concrete dome before contact grouting. The function of the concrete plug is to resist deformation and to keep the watertight seal, filter and backfill in place.
- Watertight Seal: The watertight seal is made of bentonite blocks and pellets in a similar configuration to the backfill. It is 710-mm thick. The functions of the watertight seal are:
  - To seal water leakage paths through small cracks in the concrete plug or between the concrete and the rock surface
  - To reduce the water pressure acting on the concrete dome so that no unfavourable water pressure is applied in the interface between the rock and the concrete, and so that the water pressure within the backfilled deposition tunnel is equalised.
- Backfill End Zone: The part of the backfill closest to the plug in which the density is reduced to manage the swelling pressure loads on the plug.
- Filter: The filter is made of sand or gravel. Its function is to collect groundwater leaking from the backfilled deposition tunnel and if required drain it to the drainage pipes, so that no water pressure is applied on the concrete plug before it has cured and gained full strength. The filter will also facilitate saturation of the bentonite seal.
- Concrete beams (Delimiters): The beams are made of low-pH reinforced concrete. Their function is to facilitate the construction works. The outer beams (towards the concrete plug) are covered with a thin layer of shotcrete to prevent the concrete slurry from mixing with the bentonite during casting of the concrete plug. The function of the outer beams is to keep the watertight seal in place during installation, i.e. acting as an inner formwork for the concrete dome. The inner beams (towards the deposition tunnel) shall keep the backfill in place during installation. The middle beams shall keep the filter in place during installation and are designed to withstand the development of the pressure during swelling of the watertight seal and/or backfill.
- Drainage pipes: The drainage pipes need to operate throughout operations (up to 100 years), and are made of steel or titanium. They are required to drain the water collected in the filter and transport it out of the deposition tunnel, which will prevent water pressure being applied on the concrete plug before it has cured and gained full strength.
- Grouting pipes: The grouting pipes are made of steel and may be isolated by geotextile to prevent blocking during pouring. They shall be grouted when the concrete has reached a certain level of strength and shrinkage. The grout shall tighten the contact area between the concrete plug and rock and contribute to keeping the concrete plug under compression.

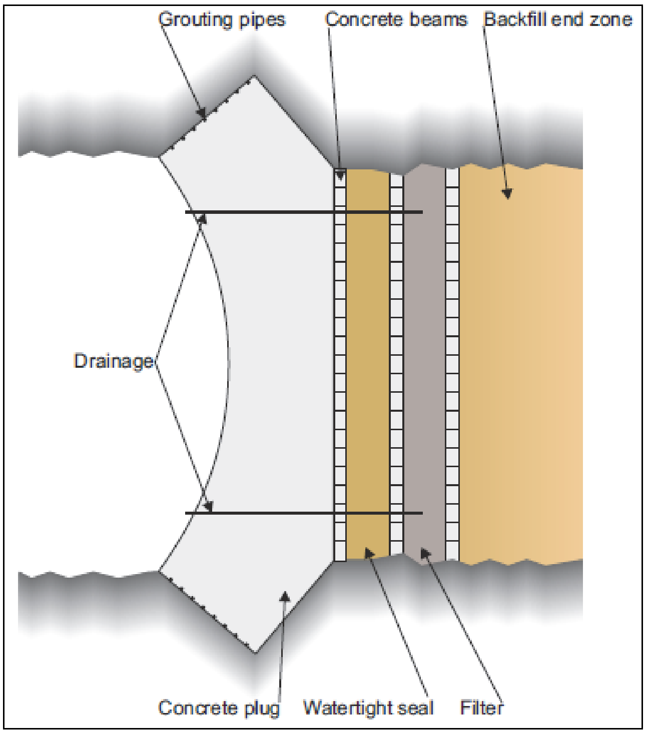

Figure 2.2: Schematic of the deposition tunnel plug SKB conceptual design (SKB, 2010b).

2.2 DOMPLU Conceptual Design

DOMPLU represents a detailed iteration of the reference design rather than a fundamental change. A schematic illustration of DOMPLU is provided in Figure 2.3. The current SKB reference design and DOMPLU design are broadly similar, with the exception of a few modifications intended to test the performance of new materials planned to be introduced as the reference design in the future, or to facilitate experiment implementation. Such modifications include:

- The use of unreinforced concrete instead of reinforced concrete for the concrete dome.
- In DOMPLU, the backfill end zone is redefined as a backfill transition zone where the swelling pressure from backfill is reduced to a level that is similar to the resulting swelling pressure of the bentonite seal (about 2 MPa). The purpose of introducing a transition zone is to reduce the displacement of the plug system components.
- In DOMPLU, the innermost delimiter is considered to be part of the filter. Instead of concrete beams, porous LECA beams and gravel with high permeability are used. The filter thickness is 600 mm, made up of 300 mm of gravel (with a particle size of 2-4 mm) and 300 mm of LECA beams, compared to a thickness of 700 mm, which is specified in the reference design for the filter.
- The middle delimiter between the filter and the watertight seal is composed of a geotextile instead of concrete beams.
- The outer delimiter is composed of low-pH concrete beams as for the reference design. There is also a double geotextile layer between this delimiter and the concrete dome to prevent adhesion of the delimiter to the concrete dome, and therefore avoid potential cracking of the concrete dome during shrinkage.

- Cooling pipes are made of copper.
- Grouting tubes are made of cross-cut 50 mm plastic drainage tubes.
- The thickness of the watertight seal is 500 mm in DOMPLU, which is considered sufficient for the timescales of the experiment.
- The filter installed dry density is 1,400 kg/m^3 in DOMPLU. A value of 1,900 kg/m^3 is considered in the reference design.

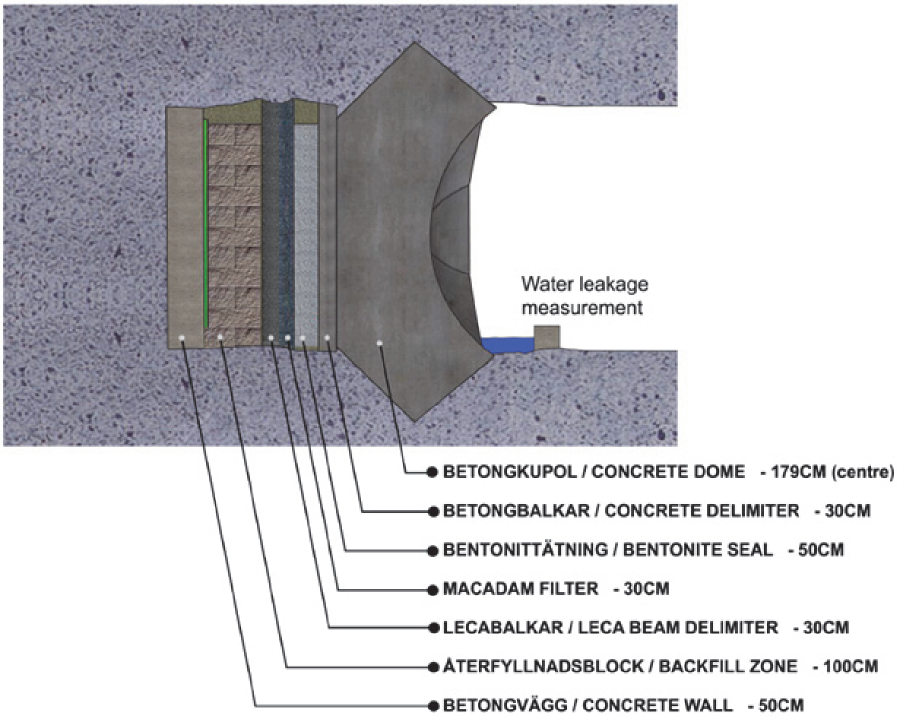

Figure 2.3: Schematic of the DOMPLU design (Palmer, 2011).

2.3 Discussion of DOMPLU Conceptual Design

The reference design of the plug will be updated and modified based on DOMPLU outcomes. This may include consideration of the materials and installation processes for each component of the plug. The update on the new design is required to capture any learning from the DOMPLU experiment. There are two driving forces for the demonstration of plugging and sealing technology in SKB's programme: to decrease uncertainties in the description of the initial state of the deposition tunnel plugs, and to decrease uncertainties in the long-term performance of deposition tunnel plugs.

The design basis for both the reference plug and experiment designs have been documented in White *et al*. (2014). One main purpose of the DOMPLU design is to fully correspond to the KBS-3V reference plug design and to demonstrate that it is possible to fulfil requirements stated in the application for the spent fuel repository to be built in Forsmark.

DOMPLU is a demonstration of the initial state of the deposition tunnel plug. This initial state is the starting point for safety analysis. Consequently, verification of the plug structure's conformity to the design basis is vital for the accuracy of the safety case.

DOMPLU addresses the "short term" period and, thus, addresses requirements applicable to the design and construction phases of the deposition tunnel plug. DOMPLU also tests the initial operation and performance of the plug under the full hydrostatic pressure and the backfill swelling pressure. The plan for the experiment was to pressurise the filter to 7 MPa of water pressure, but reassessment of the system during testing has reduced this to 4 MPa. Just before dismantling testing will be made with 10 MPa water pressure.

The main uncertainty in the DOMPLU design is that a requirement on the water leakage rate through the plug has not been defined. The results of DOMPLU will be used to quantify such a rate for application to the leakage rates through the plug during the operational period of the final repository.

3 POPLU Conceptual Design

In this section, Posiva's designs for deposition tunnel plugs are described. In Section 3.1, the conceptual design of the reference deposition tunnel plug is described. This includes a description of the main safety functions of deposition tunnel plugs and how they are met by the conceptual design on a component-by-component basis. In Section 3.2, the conceptual design of POPLU is described. In Section 3.3, a discussion of the conceptual design is provided, including limitations and the planned initial state.

3.1 Deposition Tunnel Plug Reference Design

The spent fuel disposal concept of Posiva Oy is based on KBS-3V, the same as the SKB method described in Section 2.1. The long-term safety principles are based on the use of a multi-barrier system consisting of engineered barriers and the host rock. The engineered barrier system (EBS) consists of canisters, buffer, backfill, deposition tunnel plug, and the closure for other tunnels, shafts and for the access drift. The EBS components provide the primary containment against the release of radionuclides from spent fuel.

Materials that will be used to fill openings (e.g. deposition tunnels, other tunnels and shafts) created during the emplacement of waste canisters and buffer are called "sealing structures". The sealing structures of deposition tunnels consist of the backfill and plugs. Plugs will be placed at the entrance of deposition tunnels. These plugs are referred to as "deposition tunnel plugs" or "deposition tunnel end plugs". The safety functions of the sealing structures (backfill and plug) are to:

- Contribute to favourable and predictable mechanical, geochemical and hydrogeological conditions for the buffer and canisters.
- Limit and retard radionuclide releases in the possible event of canister failure.
- Contribute to the mechanical stability of the rock adjacent to the deposition tunnels.

Of the above safety functions, the plug is not required to limit and retard releases, but the plug design should be such that it does not reduce the performance of the backfill.

The reference design for the Posiva deposition tunnel plug is the same as that described for the reference SKB deposition tunnel plug (Section 2.1, Figure 2.1) (Posiva, 2012). However, there will be two variations for deposition tunnel heights depending on the origin of the spent fuel being disposed in the Posiva repository, which results in two different plug dimensions being used.

3.2 POPLU Conceptual Design

The POPLU design is based on a different concept for meeting the safety functions compared to the dome-shaped reference deposition tunnel plug. The differences to the reference design arise from a desire to demonstrate performance of a simpler plug design that can be used in a drier tunnel without high water inflows; such conditions are found in ONKALO. POPLU will be a wedge-shaped low-pH reinforced concrete structure that is cast in place into a slot that has been notched into the excavation damaged zone (EDZ) (Haaramo and Lehtonen, 2009). The current conceptual design of the POPLU wedge plug is illustrated in Figure 3.1. The design consists of a wedge-shaped concrete structure containing grouting tubes and bentonite circular strips at the rock-concrete interface to ensure water tightness.

By providing evidence that a simpler concrete structure with less components (e.g. no filter and sealing layers as in the reference concept) will perform as required, the plugging process could become more straightforward to implement. A design with fewer components should be easier to construct and to model, and it may be possible to argue in the safety case that there is a better understanding of the evolution of the plug. Should the POPLU experiment be successful, there may be two options for the deposition tunnel plug available during the implementation stage, and, possibly, the wedge design might replace the dome design as the reference design.

The safety functions of the POPLU plug are the same as those defined for the reference design (Posiva, 2012), because the POPLU design is made to comply with the long-term safety requirements in Posiva's VAHA requirements management system.

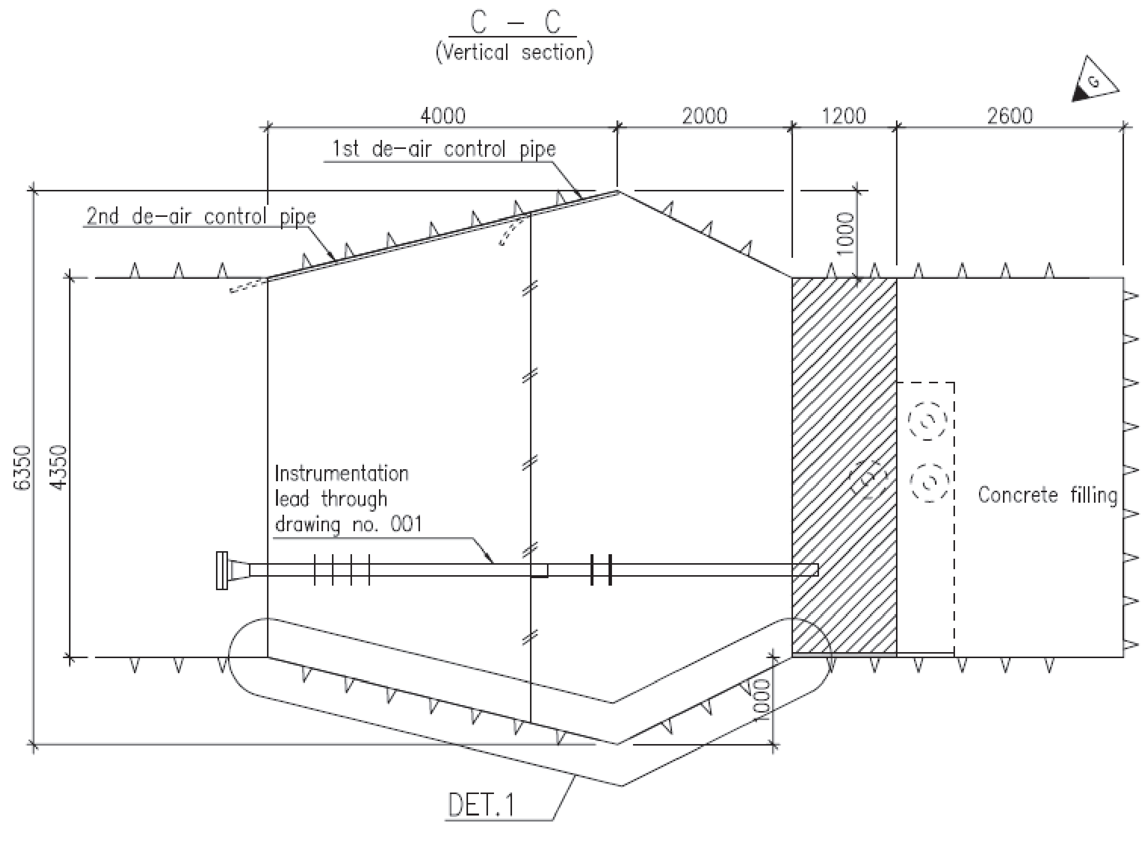

Figure 3.1: Schematic of the POPLU deposition tunnel plug preliminary design. Dimensions are in mm.

3.3 Discussion of POPLU Conceptual Design

The POPLU experiment aims to comply with the requirements in the design basis as described in White *et al.* (2014). However, due to experimentation needs, there are deviations from the final operational plug requirements in the following areas:

- Amount and types of stray materials: more stray materials are allowed in POPLU than will be allowed in the repository plugs and seals as POPLU will be dismantled.

- Use of sensors and wires for monitoring: currently, there are no monitoring sensors foreseen in the final plugs, but monitoring will be undertaken of POPLU to collect data on the performance of the plug.

The design selected for POPLU was based on the desire to demonstrate water-tightness, higher mechanical capacity and potentially easier construction (and lower cost) of the wedge design compared to Posiva's reference design. SKB's DOMPLU experiment implements the dome design and the two plug demonstrations (DOMPLU and POPLU) can therefore be compared within DOPAS.

The major uncertainties about the POPLU design and the expected performance of the plug relate to the following:

- Iteration of plug requirements in VAHA.
- Use of stray materials.
- Operational requirements.
- Interaction requirements for the whole system (tunnel excavation, host rock, backfill, and plug).
- The final duration of the experiment design is yet to be defined.

The pressurisation of POPLU will follow the plans for DOMPLU so that the performance of the two different plugs can be compared.

4 EPSP Conceptual Design

In this section, the designs of deposition tunnel plugs in the Czech Republic are described. In Section 4.1, the conceptual design of the reference deposition tunnel plug is described. This includes a description of the main safety functions of deposition tunnel plugs and how they are met by the conceptual design. In Section 4.2, the conceptual design of EPSP is described. In Section 4.3, a discussion of the conceptual design is provided, including limitations and the planned initial state.

4.1 Reference Design of Plugs in the Czech Disposal Concept

The first assessment of disposal of spent fuel and HLW in the Czech Republic considered a generic reference concept based on KBS-3V. However, subsequent studies have focused on the horizontal variant of that concept – KBS-3H, where the waste packages will be emplaced axially in disposal drifts within supercontainers in a crystalline host rock. Inside the supercontainers, the waste, packaged in steel canisters, is surrounded by compacted bentonite with a steel handling overpack. This concept was the basis for a generic safety assessment in 2011 (SÚRAO, 2011). Although KBS-3H is now regarded as the reference concept in the Czech Republic, both KBS-3H and KBS-3V are being further developed in parallel.

In the Czech reference concept, a plug is defined as a structure for closure of tunnels in the repository. The 2011 KBS-3H study disposal drifts will be closed by a steel-concrete end plug (Figure 4.1), in which the concrete would be of a low-pH type.

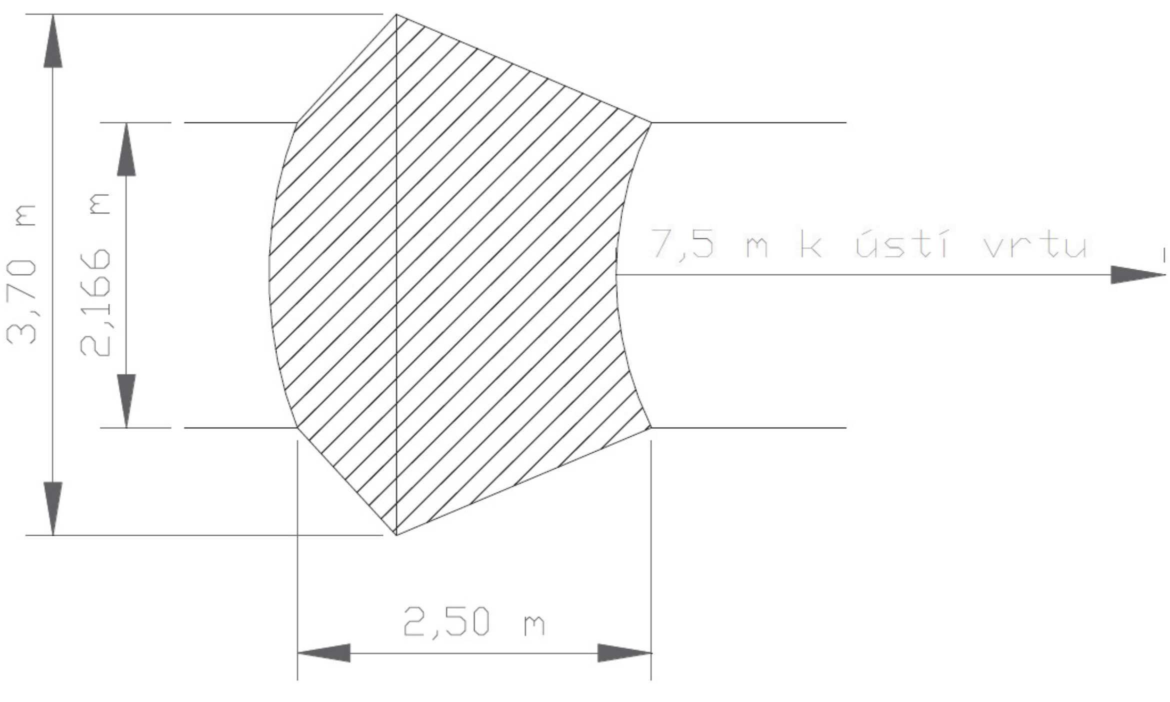

Figure 4.1: Schematic of the Czech deposition tunnel.

4.2 EPSP Conceptual Design

The EPSP test is not an experiment of a specific plug or seal, but is undertaken at a similar scale to a disposal drift plug, and will contribute specifically to the development of the reference design for these structures.

The EPSP experiment is the first time that SÚRAO has carried out any detailed work on plugs and seals. The conceptual design for EPSP includes the following components (see Figure 4.2):

- Pressure Chamber: The pressure chamber (or injection chamber) is an open area that can be used to pressurise the inner concrete plug. The chamber contains an inlet valve and a drain valve that can be used to fill the chamber with air (gas), water or bentonite slurry. The chamber will be as small as possible to allow the pressure to be readily controlled. The pressure chamber will be sealed with a membrane.
- Concrete Walls: Concrete walls (or blocks) will be used to facilitate construction of EPSP. Three concrete walls will be built: one between the pressure chamber and the inner concrete plug, one between the bentonite and the filter, and one between the filter and the outer concrete plug.
- Inner Concrete Plug: The inner concrete plug will be one of the sealing components in EPSP and will be constructed using sprayed fibre concrete. It is anticipated that there will be no need for contact grouting of the plug, but this will be determined by measurements taken during the experiment. The fibre concrete will be of relatively low pH, although the recipe and pH values are to be determined during the detailed design stage.
- Sprayed Bentonite Pellets: The bentonite pellet zone will be comprised of B75 bentonite, a natural and high-smectite content Ca-Mg bentonite with notably high iron content in the octahedral layer of the smectite. The purpose of the bentonite is to seal and absorb/adsorb any water that leaks across the inner concrete plug. The bentonite zone will be 2-m long.
- Filter: The filter will collect any water that is not absorbed by the bentonite. This is most likely to occur if the leakage rate across the inner concrete plug is sufficient for piping and erosion of the bentonite to occur. The filter may also be used to reverse the direction of pressurisation of EPSP.
- Outer Concrete Wall: The outer concrete plug is designed to hold the other components of EPSP in place. However, should the direction of pressurisation of EPSP be reversed, the outer concrete plug will have to perform as well as the inner concrete plug, and, therefore, the requirements on the outer concrete plug are the same as the requirements on the inner concrete plug.

A pressure test will be carried out on the inner concrete plug before bentonite is emplaced to test the quality of this plug and to decide, after inspection, whether grouting around the plug is required. This initial pressurisation will be carried out using air and water.

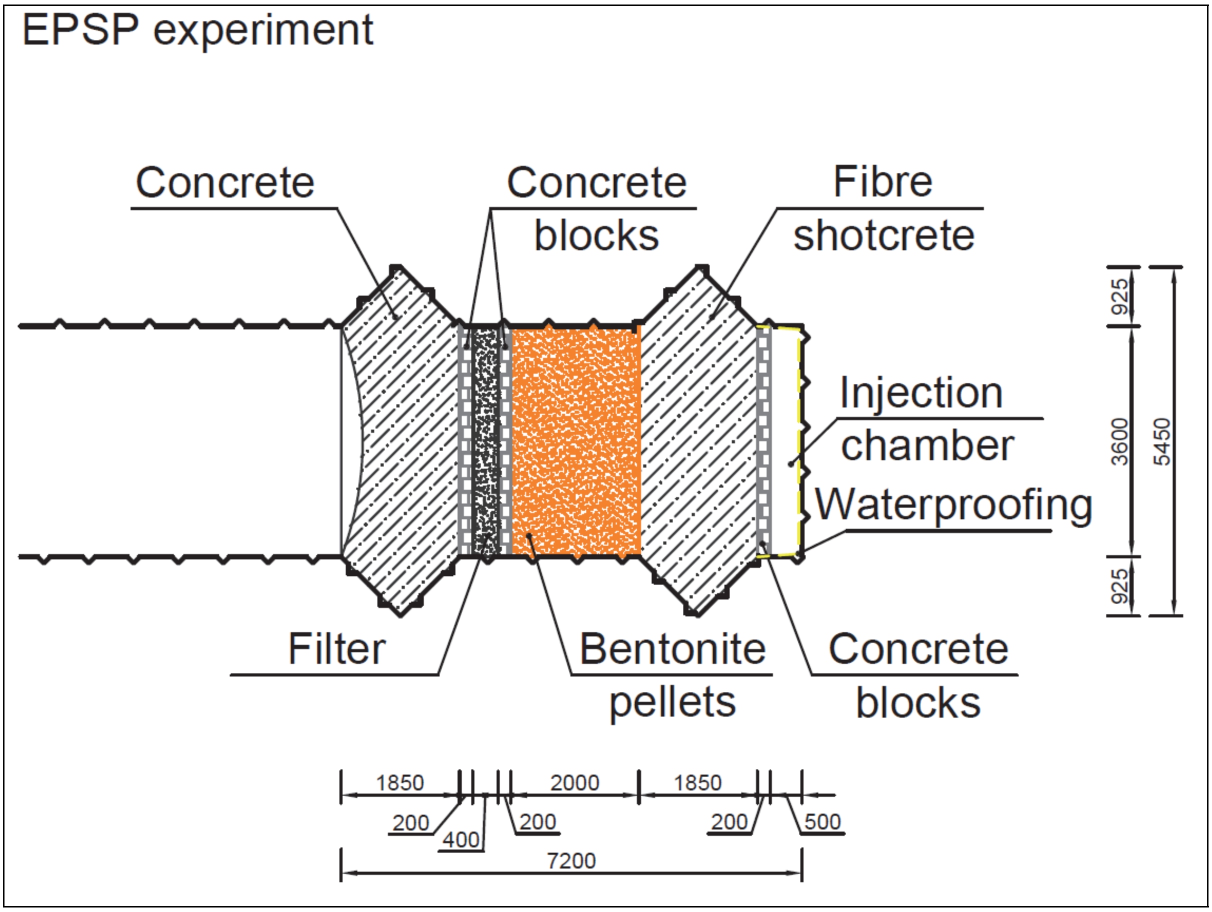

Figure 4.2: Schematic of the EPSP conceptual design. Dimensions are in mm.

4.3 Discussion of EPSP Conceptual Design

The objective of the EPSP experiment is to test the materials and technology for implementation, not to test the design or performance of the reference disposal drift plug. At this early stage in the Czech geological disposal programme, with more than 50 years before operations are scheduled to begin, it is considered more important to build knowledge and experience than refine designs for implementation in an, as yet, unidentified site with unknown mechanical, hydrogeological and chemical characteristics.

5 FSS Conceptual Design

In this section, the designs of drift and ILW disposal vault seals in France are described. In Section 5.1, the conceptual design of the reference drift and ILW disposal vault seal is described. This includes a description of the main safety functions of drift and ILW disposal vault seals and how they are met by the conceptual design. In Section 5.2, the conceptual design and the planned initial state of FSS is described. In Section 5.3, a discussion of the conceptual design is provided, including uncertainties.

5.1 Drift and ILW Vault Seals Reference Design

In France, HLW and ILW will be disposed of in a repository referred to as the Centre Industriel de Stockage Géologique (Cigéo). The repository is located in a clay host rock in the Meuse and Haute Marne Departments of Eastern France. The repository's primary function is to isolate the waste from activities at the surface and its second function is to confine radioactive substances and control the transfer pathways which may in the long term bring radionuclides into contact with humans and the environment (Andra, 2013). The principal contribution of the seals in Andra's concept is to the second function.

In Andra's concept, seals are defined as hydraulic components for closure of large diameter (several meters) underground installations and infrastructure components. There are three types of seals envisaged in the French reference disposal concept: shaft seals, ramp seals, and drift and ILW disposal vault seals. Each seal consists of a swelling clay core and concrete containment walls (see Figure 5.1). The swelling clay core provides the required long-term performance of the seal; whereas the containment walls are included to mechanically contain the clay. The conceptual design of drift and ILW disposal vault seals is the same.

The safety functions of the drift and ILW vault seals are:

- To limit water flow between the underground installation and overlying formations through the access shafts/ramps.
- To limit the water flow speed within the repository.

The primary difference between the different types of seal (shaft, ramp, and drift / ILW disposal vault) is the extent to which the concrete lining is removed before installation of the swelling clay core. Shaft and ramp seals will be located in the upper part of the Callovo-Oxfordian Clay, which is more competent as it contains more carbonates and, therefore, will generate less damage of the rock during construction. As a consequence, complete removal of the lining prior to installation of the swelling clay core can be considered as a reference for shaft and ramp seals; this ensures a good contact between the clay core and the rock, and so a better hydraulic performance. For the drift and ILW disposal vault seals only partial removal of the lining is envisaged.

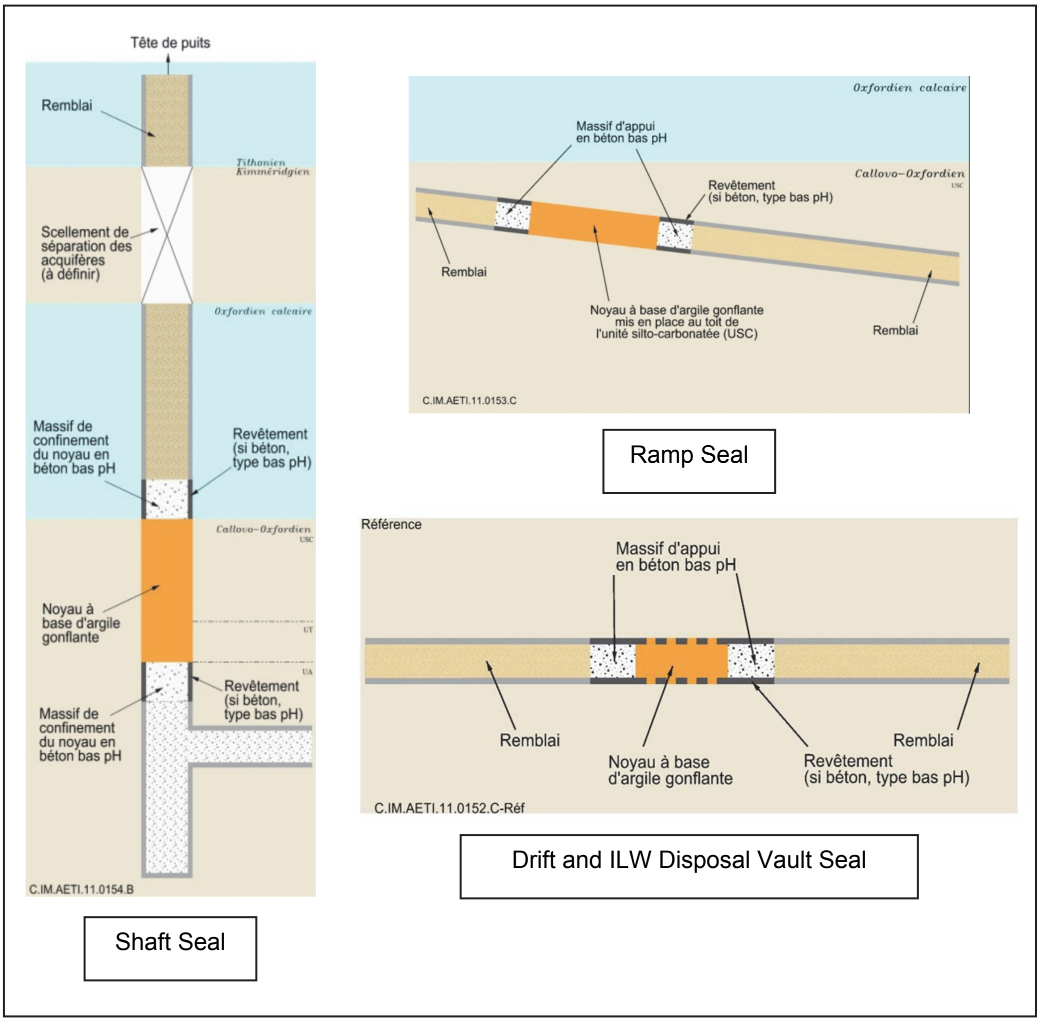

Figure 5.1: Conceptual designs for shaft, ramp, and drift and ILW disposal vault seals for the Cigéo reference disposal concept.

5.2 FSS Conceptual Design

The main objective of the FSS experiment is to develop confidence in, and to demonstrate, the technical feasibility of constructing a full-scale drift or ILW disposal vault seal. As the focus of the experiment is on the technical feasibility of seal installation, and not on long-term performance, it can be undertaken in a surface facility. The experiment is housed in a concrete test box, and the environment is controlled such that it mimics the underground environment. Technical feasibility includes demonstrating the ability of the approach used to emplace the clay to be suitable for filling recesses in the clay host rock, i.e. any potential breakouts generated during the removal of the concrete support lining. Therefore, the concrete test box includes recesses that mimic breakouts. As the experiment is focused on the construction and installation of the seal, the materials will not be saturated or otherwise pressurised; complementary experiments are designed to investigate the resaturation process (REM, part of DOPAS WP5, consists of an "as close as possible to *in-situ* conditions" resaturation test undertaken in a surface laboratory with the same pellets/powder mixture as used in FSS) and the global performance after resaturation (NSC half-scale *in-situ* seal test in the Meuse/Haute-Marne URL). The conceptual design of the FSS experiment is illustrated in Figure 5.2.

The main difference between the reference and FSS designs for the Andra drift and ILW vault seal is the length of the seal. The real seal underground will be longer than the seal considered in FSS. The FSS experiment will investigate two types of low-pH containment wall (Figure 5.2); one self-compacting and one emplaced as shotcrete, to allow the preferred method to be selected and incorporated into the reference concept.

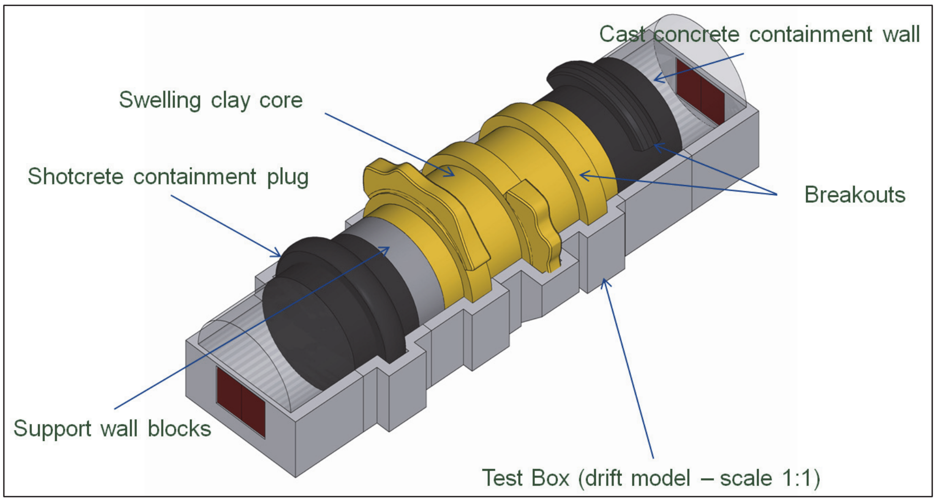

Figure 5.2: Conceptual design for the Andra FSS experiment.

5.3 Discussion of FSS Conceptual Design

The FSS design adheres to all of the requirements specified in its design basis (White *et al.*, 2014). The safety functions are fulfilled by the use of a swelling clay core with specific properties (low permeability, plasticity, swelling pressure, etc.) to support the long term hydraulic performance of the seal, although no hydraulic performance of the FSS will be carried out within DOPAS. Instead, the hydraulic performance will be demonstrated by emplacing the clay material at a sufficient density to achieve the required hydraulic conductivity. This density value has been previously investigated and is further tested in the REM metric-scale experiment.

The FSS design addresses material requirements through the use of a mixture of bentonite pellets and powder for the swelling clay core to guarantee a perfect filling of the core volume, including voids created by potential break-outs of the clay host rock.

The use of low-pH concrete in FSS for the containment walls and the support wall ensures that interactions between the concrete and bentonite core are limited, and that the wall and clay core properties are preserved.

The main uncertainties in the FSS design implementation concern the following:

- Good homogeneity of the swelling clay core at emplacement and the capability to emplace bentonite pellets and powder at the required density and within specified voids such as break-outs of the clay host rock. Design of the test includes several methods of estimating this homogeneity (e.g. 3D scan, time-domain reflectometry, and gamma-gamma density logging) and the outcomes of FSS will be used to develop a suitable filling procedure in the future.
- The homogeneity and overall resistance of the concrete monoliths, the quality of bonding with the drift concrete liner, the limitation of curing temperature and shrinkage.

6 ELSA Conceptual Design

In this section, the designs of shaft seals in Germany are described. In Section 6.1, the conceptual design of the reference shaft seal is described. This includes a description of the main safety functions of shaft seals and how they are met by the conceptual design. In Section 6.2, the conceptual design of ELSA is described. In Section 6.3, a discussion of the conceptual design is provided, including uncertainties and the planned initial state.

The future strategies for site selection and licensing for a repository for HLW and spent fuel in Germany are currently under discussion. Therefore, information provided below is based on previous proposals for a repository located at Gorleben in a salt dome.

6.1 Shaft Seal Reference Design

The reference concept for disposal of spent fuel, HLW, ILW, graphite and depleted uranium is based on a repository design for the Gorleben salt dome. A site-specific research project, the Preliminary Safety Analysis for Gorleben (VSG), was conducted between July 2010 and March 2013. The repository concept considered in the VSG assumed disposal at a depth of 870 m, in a series of twelve emplacement fields. Two emplacement concepts have been considered for spent fuel: horizontal drift disposal of Pollux casks and vertical borehole emplacement of BrennStabKokille-3 (BSK-3) containers.

The main transport drifts are backfilled with crushed salt, with a water content of 0.6% by weight, to accelerate the compaction process. There are two types of seals – shaft seals and drift seals. Drift seals are located close to the infrastructure area in the vicinity of the two shafts. Each drift seal consists of two 50-m-long sealing elements made of MgO-based concrete and three support elements. The total length of a drift seal is about 150 m. The infrastructure area is backfilled with non-compactible serpentine gravel to allow potential brines and gases to accumulate. The shafts are both backfilled and sealed over a length of nearly 600 m with a sequence of three sealing elements and multiple static abutments.

The Gorleben repository concept envisages two shaft seals, one in each shaft, and four drift seals. In order to meet the requirements laid down in the repository regulations and mining law, the primary safety function for shaft and drift seals is to provide a sufficiently low hydraulic conductivity to avoid brine paths into the repository and the movement of radionuclides out of it.

The reference conceptual design for a shaft seal in the German repository programme, which is developed for the site-specific conditions at Gorleben, includes three short-term sealing elements (see Figure 6.1) designed to maintain their functionality until the backfill in the repository drifts, access ways and emplacement fields has sealed in response to compaction driven by host rock creep:

- The first sealing element is located at the top of the salt rock and is made of bentonite. The material properties are similar to those of the salt clay at the top of the salt rock. It has a high cation exchange capacity. The swelling pressure of the bentonite supports closure of the EDZ at shallow depths. This makes it suitable for use in the upper sealing element, which only needs to function for a short period.
- The second sealing element is made of salt concrete. Salt concrete is stable against the expected brines and creates an alternative approach to meeting the safety functions to the bentonite.

- Directly above the disposal level, a third sealing element made of sorel concrete is located. The sorel concrete consists of magnesium oxide as adhesive cement and crushed salt as aggregate. In the lower part of the shaft, potash salt could change the composition of the brines. Compared with salt concrete, sorel concrete is stable against Mg-rich brines. Both types of concrete create sufficiently low permeabilities, and the convergence of the salt closes the EDZ.

In addition to the three short-term sealing elements, there is a long-term sealing element made of crushed salt. This salt layer compacts and reaches a hydraulic conductivity that is similar to the hydraulic conductivity of the host rock (Müller-Hoeppe *et al.*, 2012).

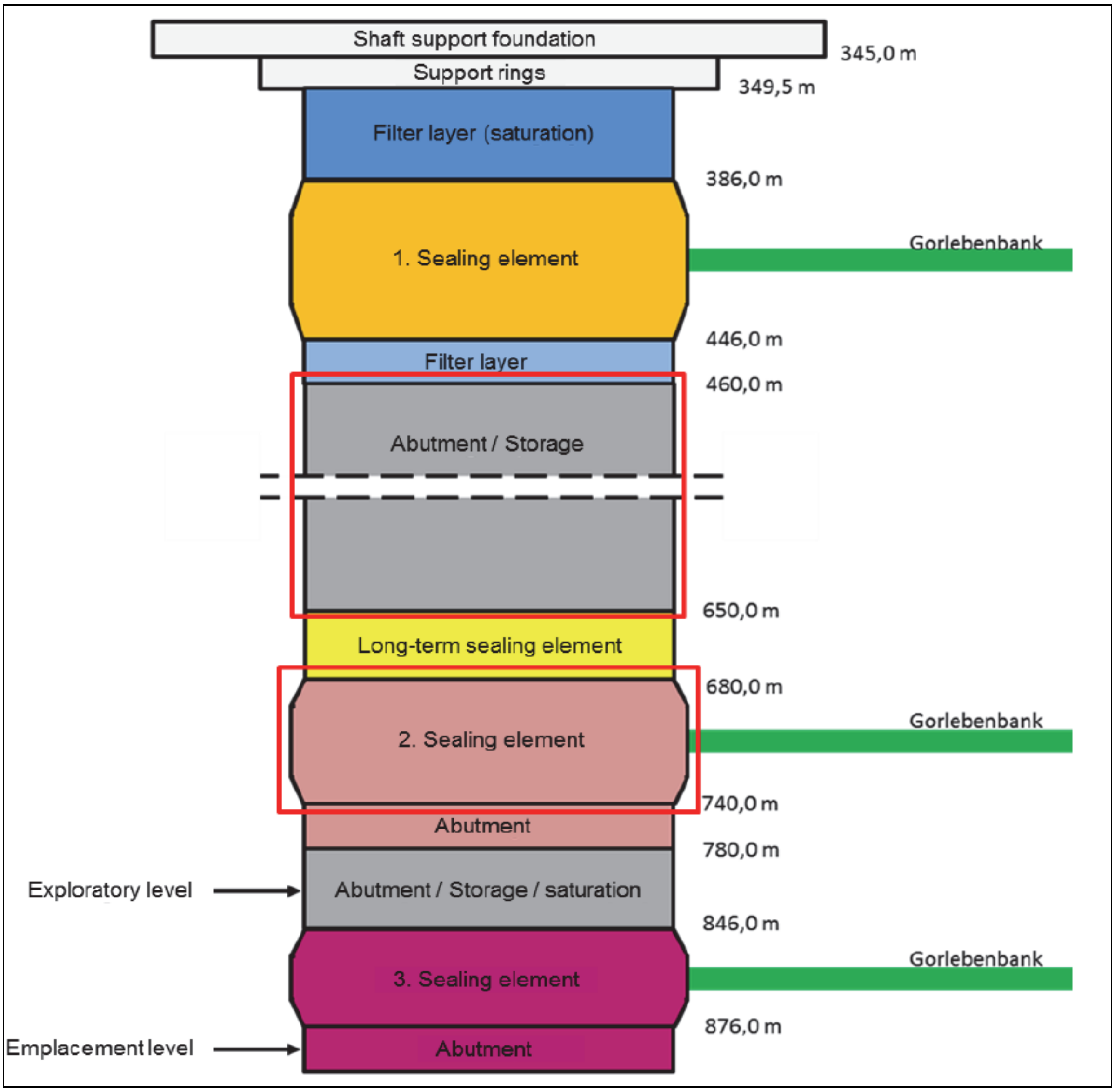

Figure 6.1: Reference conceptual design for the German shaft seal. The elements considered in the safety assessment are framed in red (Müller-Hoeppe *et al.*, 2012). The Gorlebenbank is a folded anhydrite layer in the rock salt.

6.2 ELSA Conceptual Design

The aims of the ELSA project are to develop generic design concepts for shaft seals in salt and clay host rocks that comply with the requirements for a repository for HLW (Jobmann, 2013) and to carry out the necessary preparatory work. Therefore, it is not intended to implement a full-scale demonstration of the reference conceptual design of the shaft seal, but to test prototypes of the different sealing elements on a large scale. The experiment design will have be adapted to the geological and geometrical conditions to be found at the actual testing site which has not yet been decided.

6.3 Discussion of ELSA Conceptual Design

The ELSA experiment design will be directly based on the safety assessment concept and the material selection with regard to the achievable properties when implemented.

The main uncertainty in the shaft seal design concerns the contact zone between the sealing elements and the rock. During the shaft sealing experiment at Salzdetfurth (see Appendix B of White *et al*. (2014)), a special implementation procedure had to be applied to tighten the contact zone. This procedure has to be improved to assure a proper implementation.

Another uncertainty concerns the homogeneity of permeability in the sealing elements and the possible presence of local inhomogeneity in permeability.

7 Discussion: Factors Influencing Choice of Designs

In this section, the principal factors affecting the choice of designs are discussed. These include the type of host rock, the disposal concept and choices regarding operational procedures. The discussion is structured in relation to the different types of host rock considered in DOPAS: crystalline rocks (Section 7.1), clay (Section 0) and salt (Section 7.3).

7.1 Crystalline Host Rocks

The three plug designs presented in this report concern sealing of the EBS in crystalline host rocks in Sweden (DOMPLU), Finland (POPLU) and the Czech Republic (EPSP). The KBS-3 method is the reference disposal concept in all of these countries. DOMPLU and POPLU are testing designs of deposition tunnel plugs, whereas EPSP is a test of materials and implementation technology.

The KBS-3 method, in particular, places a high reliance on containment by the canister and the key function of the buffer and the deposition tunnel backfill is to protect the canister. In KBS-3, the EBS components provide the primary containment against the release of radionuclides. The principal role of the deposition tunnel plug is to hold the backfill and buffer in place during operations; this is achieved through use of a strong concrete plug. In order to limit deleterious effects caused by interactions between alkaline leachates from the concrete plug and bentonite materials used in the plug, the deposition tunnel backfill and the deposition holes, the concrete is composed of low-pH concrete.

Owing to the potential for water flow to erode the bentonite backfill in the deposition tunnel, the water flux across the plug must be low. The method for providing a low hydraulic conductivity across the deposition tunnel plug can depend on the specific rock conditions. In the DOMPLU test undertaken in Äspö HRL, it is judged necessary to introduce a watertight seal composed of swelling bentonite. In ONKALO, the POPLU experiment is testing the ability for a massive concrete plug to provide the required performance.

Crystalline rocks are relatively strong and do not creep to the same extent as clay or salt rocks. Water conducting fractures may be present and may facilitate groundwater flow. Plugs should provide a hydraulic conductivity comparable to that of the rock mass while ensuring a good contact is established between the plug or seal material and the rock. In competent crystalline rocks, achieving a low hydraulic conductivity across the plug therefore requires grouting of the interface between the concrete and the rock, following curing and shrinking of the concrete. In POPLU, bentonite strips are included in the conceptual design to help meet the hydraulic conductivity requirements. Successful grouting can be supported by cooling of the concrete (e.g. in DOMPLU).

In crystalline rocks there is a potential for both the host rock and the EDZ to provide groundwater flow paths that could short-circuit the plug. Therefore, the plugs must be keyed into the host rock, and criteria to determine the suitability of the plug location must be established in advance of the decision on plug location.

Depending on the rate of groundwater flow and, therefore, the timescale for saturation and swelling of the watertight seal, it may be necessary to introduce a filter layer for drainage to delay the pressurisation of the plug until the concrete has cured and developed sufficient strength.

As the function of deposition tunnel plugs is related to operational activities, the design life of the structures is 100 years in Sweden and Finland and 150 years in the Czech reference concept.

7.2 Clay Host Rocks

The drift and ILW disposal vault seal design presented in this report concerns a clay host rock in France. Clay rocks generally have very low permeabilities, and can be plastic and soft. The plasticity and self-healing properties of most clay rocks contribute to the self-healing of any cracks that may develop during the construction and operation of the repository. Underground openings in clay rocks may require lining or mechanical stabilisation; this lining may need to be removed in the plug or seal location to ensure a tight rock-plug/seal interface. The objective of plugs and seals in clay rocks is to limit the flux of groundwater by ensuring that low permeabilities are reached. This is achieved through use of a bentonite-based swelling clay core, with concrete containment walls provided to keep the clay core in place.

In clay host rocks, the repository access ways represent a possible short circuit to the geosphere containment function. Therefore, the key function for seals in these systems is to seal the repository such that groundwater flow into and out of the repository is restricted. This function is expected to last until the host rock and backfill have re-established *in situ* hydraulic performance, which may be a period of thousands of years in a clay rock.

The design of seals in sedimentary rocks needs to take account of variations in mineralogy, which may have an impact on the competency of the rock. For example, it is envisaged that seals emplaced in the ramp and shaft of the French Cigéo repository will be located in the more competent carbonaceous units of the Callovo-Oxfordian Clay, and will therefore allow full removal of the tunnel lining, rather than partial removal envisaged for the drift and ILW vault seals.

In Andra's drift seal design, a swelling clay core was selected for its chemical compatibility with the clay host rock chemistry. Low-pH concrete was chosen for the containment walls to limit the alkaline plume effect on the swelling clay and the near field clay host rock that may jeopardise their required performance. In France, the main feature of the clay host rock that influences the design of the drift seal concerns host rock creep. This property has the following positive and negative effects:

- Negative effects: the concrete support removal operations may result in rock fall, due to creep, and compromise the safety of workers. The length of the concrete support to be removed can also represent some technical difficulties.
- Positive effects: Self-sealing of the near field host rock (i.e. EDZ) increases the hydraulic performance of the seals over time. In addition, development of shear stresses between the near field host rock, concrete containment walls and the clay core of the seal, due to radial stresses from the host rock, helps to balance the swelling pressure of the clay core and contributes to the overall mechanical stability of the seal over time.

7.3 Salt Host Rocks

The shaft seal design presented in this report concerns a salt dome in Germany. Salt rocks are characterised by an extremely low hydraulic conductivity, and creep properties that can contribute to the closure of a repository. Some salt host rocks also have extremely low water/brine content. Therefore, any openings within the salt rock may have to be backfilled in such a way that this rock's containment function is not compromised due to fracture initiation and growth. The main safety function of seals in a salt host rock is to avoid brine migration through the underground openings to the waste canisters. This function is expected to last until the host rock and backfill have re-established *in situ* hydraulic performance, which may be a period of hundreds of years in a salt rock; the design life of the shaft seal considered in ELSA is 50,000 years.

Materials used in seals in salt host rocks require chemical compatibility with the host rock over the timescales that they must function. Materials such as salt concrete and sorel concrete are envisaged. Other materials that may be affected by chemical interaction with the salt can be used, for example bentonite, as long as the period over which alteration of the bentonite is longer than the period over which its swelling properties are required.

In salt domes, layers within the salt host rock may be highly folded by the process of diapirism. This may lead to a requirement for multiple sealing elements within a seal, especially within vertical shaft seals.

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