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Design Basis for DOPAS Plugs and Seals

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Executive Summary

Background to the DOPAS Project and WP2, and Report Objectives

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 the DOPAS Project. The Project is coordinated by Posiva Oy (Posiva) (Finland). A set of full-scale experiments, laboratory tests, and performance assessment studies of plugs and seals for geological repositories are being carried out in the course of the DOPAS Project.

Safe geological disposal of radioactive waste involves isolation and containment of the waste from the biosphere. Containment and isolation can be provided through a series of complementary barriers. Specific parts of a repository will have to be plugged and sealed as part of the backfilling and closure operations to ensure that the isolation and containment functions of the repository are not compromised. The specific purpose of plugs and seals depends on the disposal concept, the nature of the geological environment, and the inventory to be disposed of. For example: plugs and seals may be required during operations to isolate emplaced waste and other engineered barrier system components from the rest of the underground excavations; plugs and seals may be required following closure to limit groundwater flow and radionuclide migration; and plugs and seals may be required to prevent inadvertent or unauthorised human access.

The DOPAS Project aims to improve the industrial feasibility of full-scale plugs and seals, the measurement of their characteristics, the control of their behaviour in repository conditions, and their performance with respect to safety objectives. The Project is being carried out in seven Work Packages (WPs). WP1 includes project management and coordination and is coordinated by Posiva (Finland). WP2, WP3, WP4 and WP5 address, respectively, the design basis, construction, compliance testing, and performance assessment modelling of five full-scale experiments and laboratory tests. WP2, WP3, WP4 and WP5 are led by SKB (Sweden); Andra (France); RWM (United Kingdom); 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 led by Posiva.

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

- *Clay rocks*: the Full-scale Seal (FSS) experiment, being undertaken by Andra in a warehouse, which forms part of a surface facility at St Dizier, is an experiment of the construction of a drift and intermediate-level waste (ILW) disposal vault seal.
- *Crystalline rocks*: experiments related to plugs in horizontal tunnels, including the Experimental Pressure and Sealing Plug (EPSP) experiment being undertaken by SÚRAO and the Czech Technical University (CTU) at the Josef underground research centre (URC) and underground laboratory in the Czech Republic, the Dome Plug (DOMPLU) experiment being undertaken by SKB at the Äspö Hard Rock Laboratory (Äspö HRL) in Sweden, and the Posiva Plug (POPLU) experiment being undertaken by Posiva at the ONKALO Underground Rock Characterisation Facility (URCF) in Finland.

- *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 DBE TEC together with the Technical University of Freiburg and associated partners complemented by laboratory testing performed by GRS.

In the DOPAS Project, a distinction has been made between reference and experiment designs. The term "reference design" is used to denote the design of a plug/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/seal being tested, e.g., the designs of the plug/seal being tested at full scale in the DOPAS Project. Experiment designs are typically modified versions of reference designs, with the modifications made to investigate specific aspects of the design during the experiment. The differences are discussed throughout this report.

WP2 collates the design basis for plugs and seals considered in the DOPAS Project, it documents their reference designs and the experiment designs, and it describes the strategies used by WMOs to demonstrate the compliance of the reference designs to the design basis.

This report provides a synopsis of the work undertaken in WP2. The report describes the safety functions, the designs, and design basis of plugs and seals considered in the DOPAS Project. The report includes an analysis and discussion of the differences between the design bases for plugs and seals in different repository concepts, focusing on the safety functions performed by each plug and seal, and how these impact on the requirements placed on the plug/seal. This report also describes the learning from WP2 on the processes used to develop and structure the design basis for plugs and seals within the DOPAS Project, and uses that learning to provide guidance on the development of a design basis in the context of repository plugs and seals. In particular, lessons are drawn on the iterative development of the design basis for plugs and seals, in parallel with development of the design, as well as the use of hierarchical structures to describe the design basis.

The Design Basis of DOPAS Project Plugs and Seals

Andra's Drift and ILW Vault Seal

Drift and ILW Vault Seal Reference Design Basis

In Andra's Centre Industriel de Stockage Géologique (Cigéo) concept for disposal in a clay host rock, seals are defined as hydraulic components for closure of large diameter (several metres, up to 10 m) underground installations and infrastructure components. The safety functions of the drift and ILW vault seals are, following closure, to limit water flow between the underground installation and overlying formations through the access shafts/ramps, and to limit the groundwater velocity within the repository. 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 two concrete containment walls. The swelling clay core provides the required long-term performance of the seal, whereas the containment walls mechanically contain the clay core.

FSS Experiment Design Basis

FSS is a full-scale experiment of the reference drift and ILW disposal vault seal for the Cigéo repository concept. 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 such, the experiment is focused on the construction of the seal, and the materials will not be saturated or otherwise pressurised. Other experiments that investigate saturation phenomena (e.g., the REM experiment) are being undertaken by Andra in parallel with the FSS experiment.

FSS has been implemented in a specially constructed concrete box located in a surface facility. The box can be closed at each end to allow environmental conditions (e.g., temperature and relative humidity) to be representative of those of the underground. The seal itself consists of a cast concrete containment wall, a swelling clay core, and a shotcrete containment plug. The design also includes recesses that represent breakouts that may be generated by the removal of the concrete lining used to support drifts and vaults during operations of the repository; the linings are removed to ensure that the seal meets hydraulic requirements.

The design basis for FSS is derived from a functional analysis of the safety functions specified for the seal. The FSS design and construction is contracted to a consortium, and the design basis is captured in the technical specification produced by Andra in the tendering process for the experiment. The design basis contains requirements on each component of the experiment, and also on the site, on monitoring, and on procedures to be applied during implementation of the experiment.

SÚRAO's Tunnel Plug

Tunnel Plug Reference Design Basis

SÚRAO has developed a repository concept for crystalline rock based on the KBS-3H method, in which disposal drifts will be closed by an end plug. The safety functions of the plug are to separate the disposal container and the buffer from the rest of the repository, provide a safe environment for staff, and provide better stability of open tunnels.

The reference design for the tunnel plug in SÚRAO's repository concept is not highly developed. In the current concept, disposal drifts will be closed by a simple steel-concrete end plug, in which the concrete would be of low-pH.

EPSP Experiment Design Basis

EPSP is an experiment of a tunnel plug, with the focus of the experiment being on development of fundamental understanding of materials and technology, rather than testing of the reference design. This is because the Czech geological disposal programme is in a generic phase and designs are at the conceptual level. EPSP consists of a pressure chamber, an inner concrete plug, a bentonite zone, a filter, and an outer concrete plug. Concrete walls are used to facilitate emplacement of the experiment. The experiment is pressurised with air, water or slurry, and EPSP is designed so that the pressurisation can occur through the pressurisation chamber or through the filter. The primary sealing component is the inner concrete plug.

The design basis identifies requirements on each component of the experiment (including the host rock), plus general requirements on the experiment, on materials, on technology and on the pressurisation system. Key aspects of the experiment are to evaluate the use of glass fibre-reinforced sprayed concrete for the concrete plugs, and sprayed bentonite pellets composed of Czech bentonite for the bentonite zone.

SKB's Deposition Tunnel Plug

Deposition Tunnel Plug Reference Design Basis

In the KBS-3V method developed by SKB for disposal of spent fuel in crystalline host rock, deposition tunnels are closed with a deposition tunnel end plug. The main functions of the deposition tunnel plugs are to provide a barrier against water flow from the backfilled deposition tunnel and to confine the backfill in it during the operational period of the repository of at least 100 years. As such, they only have a “short-term” function.

The main components of the current SKB reference design for a deposition tunnel plug include a dome-shaped reinforced plug made of low-pH concrete, a bentonite watertight seal, a filter made of sand or gravel, and a backfill end zone (or transition zone) used to manage the swelling pressure loads on the plug. The plug also contains drainage, cooling and grouting pipes, as well as concrete beams to aid construction.

The function of the concrete dome is to resist deformation and to keep the watertight seal, filter and tunnel backfill in place. The function of the watertight seal is to seal water leakage pathways and to ensure an even pressure on the concrete. The function of the filter is to collect water draining from the deposition tunnel so that no water pressure is applied on the concrete dome before it has cured and gained full strength. The design basis for the deposition tunnel plugs are separated into requirements on the production (including construction and curing of the concrete), sealing and post-closure phases.

DOMPLU Experiment Design Basis

DOMPLU is a full-scale experiment of the reference deposition tunnel plug in SKB’s repository design. The DOMPLU experiment is part of an on-going testing and demonstration programme and will help to reduce uncertainties in the performance of deposition tunnel plugs, and to decrease uncertainties in the description of the initial state of the deposition tunnel plugs (i.e., the state of the plug when all components of the plug or seal have been constructed). Specific objectives for the experiment include further development of water tightness requirements on deposition tunnel plugs and plug production requirements. The main difference between DOMPLU and the reference deposition tunnel plug is the use of unreinforced low-pH concrete instead of reinforced low-pH concrete for the dome structure.

Posiva’s Deposition Tunnel Plug

Deposition Tunnel Plug Reference Design Basis

The spent fuel disposal concept in Posiva’s construction licence application for a repository in crystalline host rock located in Olkiluoto is based on KBS-3V, and, in this concept, deposition tunnel plugs will be placed at the entrance of deposition tunnels following emplacement of the spent fuel, buffer and backfill. In Posiva’s reference concept the deposition tunnel plug and backfill are considered together as *“sealing structures of deposition tunnels”*.

The reference design for deposition tunnel plugs in Posiva’s concept is the same as SKB’s (i.e., the dome-shaped design).

The design basis for the reference deposition tunnel plug has been captured in Posiva’s VAHA requirements management system (RMS) as a hierarchy of requirements. VAHA concentrates on post-closure requirements and, therefore, the majority of the requirements on deposition tunnel plugs focus on how the deposition tunnel plug contributes to post-closure safety, i.e., by keeping the backfill in place during the operational phase and ensuring that the plug does not significantly affect the post-closure performance of the backfill.

POPLU Experiment Design Basis

POPLU is a full-scale experiment of an alternative design of the deposition tunnel plug to that of the dome-shaped reference design, which could provide flexibility in both Posiva’s and SKB’s forward programmes. The POPLU design consists of a wedge-shaped reinforced concrete structure cast directly adjacent to a filter layer, which is positioned in front of a concrete tunnel backwall. The plug contains grouting tubes and bentonite circular strips at the rock-concrete interface to ensure water tightness.

The safety functions for POPLU are the same as those defined for the reference deposition tunnel plug in VAHA. An existing conceptual design for a wedge-shaped plug was used to define the requirements on POPLU.

German Shaft Seal Design Basis

Shaft Seal Reference Design Basis

The reference concept for disposal of spent fuel, high-level waste (HLW), ILW, graphite and depleted uranium in Germany is based on a repository design for the Gorleben salt dome. The Gorleben repository concept envisages two shaft seals, one in each shaft, and four drift seals. 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. Work in the DOPAS Project has focused on shaft seals.

At the current stage of the German programme, the design basis for the shaft seal is based on regulatory requirements, mining law, experience from the sealing of mine shafts, previous full-scale testing of shafts, and recent performance assessment studies. The design basis captures this understanding at a high level and groups requirements into those relating to the regulatory safety requirements of the Bundesministerium für Umwelt, Naturschutz and Reaktorsicherheit (BMU), safety and verification concepts (requirements related to the principal safety functions and performance of the seal), technical functional verification (requirements related to the design and demonstration of compliance with safety and verification concepts), site-specific boundary conditions, and other requirements.

The reference conceptual design for a shaft seal at Gorleben includes three sealing elements consisting of different materials to ensure that the performance of the seal system meets requirements. The design of these sealing elements takes into account the different kinds of salt solutions present in the host rock and the need to avoid chemical corrosion. These sealing elements are a seal located at the top of the salt rock and made of bentonite, a second seal made of salt concrete, and a third seal made of sorel concrete which is located directly above the disposal level. The sealing elements are designed to maintain their functionality until the backfill in the repository drifts, access ways and emplacement fields have sealed in response to compaction driven by host rock creep.

ELSA Design Basis

ELSA is a programme of laboratory tests and performance assessment studies that will be used to further develop the reference shaft seal design for the German reference disposal concepts for repositories in salt and clay host rocks.

Other Programmes

In addition to the five DOPAS Project experiments, information on the design basis for plugs and seals has been collected from the other programmes represented in the DOPAS Project (the Netherlands, Switzerland and the United Kingdom).

In the Dutch disposal concept, plugs and seals are not yet explicitly defined. However, the outline disposal concept for a clay host rock states: *"A plug is used to hydraulically seal off a disposal drift after emplacement of waste packages. Seals are used to seal the shafts and ramp when the facility is closed"*.

In the Swiss repository concept for disposal in a clay host rock, seals are defined as elements that hydraulically isolate parts of the repository system and/or the repository from the geosphere and biosphere. Seals are composed of a sealing element (e.g., bentonite) and mechanical supporting elements (e.g., concrete and gravel). Plugs are defined as temporary mechanical seals, and have no long-term safety functions.

Although the United Kingdom programme is in the generic phase, some work has been undertaken to identify generic safety functions of sealing plugs. These shall be designed to provide mechanical support to the backfill material in a disposal module, limit water flow from a disposal module to the access ways, and consider requirements on gas migration from a disposal module to the access ways. The United Kingdom has captured requirements on a geological disposal facility in a disposal system specification (DSS) document, and is in the process of developing its approach to the implementation of an electronic RMS that will help to ensure that the DSS provides a unified and comprehensive specification of requirements.

Factors Affecting the Design Basis

The safety functions of plugs and seals differ between waste management programmes depending on the geological environment, disposal concept, and approach to the safety case. Typical safety functions include confinement of the tunnel backfill and prevention of groundwater flow through disposal areas. In addition to the plugs and seals considered in the DOPAS Project, other safety functions for plugs and seals may be recognised, e.g., prevention of access to the repository after it is closed.

The type of host rock plays an important role in defining the design requirements for plugs and seals. For example, in clay host rocks, seals need to ensure that low hydraulic conductivities are achieved to match those of the clay until the host rock and backfill have re-established *in situ* hydraulic performance, which may be a period of thousands of years. Removal of host rock lining may be necessary to avoid flow along the interface between the lining and the rock. In crystalline rocks, plugging/sealing shafts and tunnels aims to achieve a low hydraulic conductivity, which requires, amongst other requirements, a good contact between the plug/seal material and the rock. Deposition tunnel plugs are generally required for the operational period of the repository (which may be of the order of ~100 years). For salt rocks, any sealing must be introduced in such a way that brine migration through the repository access ways to the waste canisters is avoided until the backfill is sufficiently compacted, which may be a period of hundreds of years.

Strategies for Demonstrating Compliance of Designs to the Design Basis

The strategies and approaches used by WMOs to demonstrate compliance of the reference designs of plugs and seals to the design basis include:

- Full-scale Testing: Full-scale testing is the main strategy adopted by WMOs to compliance demonstration of plugs and seals. Full-scale experiments include demonstration of technical feasibility, tests of performance, and combined technical feasibility and performance tests.
- Quantitative Approaches to Compliance Demonstration: The German programme has developed a quantitative approach to compliance demonstration in which the loads on a structure are compared to the ability of a structure to perform under the induced loads, with uncertainty accounted for by the application of quantitative performance criteria modified to account for uncertainty and to provide an additional safety margin.
- Construction Procedures: WMOs have different approaches to describing the use of construction procedures for compliance demonstration. Some describe construction

procedures as an important element of compliance demonstrations, and others consider it to be part of quality control during repository implementation. In any case, the focus of quality control relies to a large extent on the practical experiences gained during "compliance demonstration".

- Monitoring: WMOs have different approaches to the use of monitoring as part of compliance demonstration strategies for plugs and seals. Some WMOs have not made firm decisions on how to monitor repository plugs and seals (e.g., SKB), while others are considering monitoring of repository plugs and seals (e.g., through instrumentation) to provide for compliance demonstration (e.g., Posiva).

DOPAS Design Basis Workflow

Work on the design basis in the DOPAS Project has allowed assessment of current practice with regard to both the process used to develop and describe the design basis and the content of the design basis of plugs and seals. The design basis is developed in an iterative fashion with inputs from regulations, technology transfer, tests and full-scale demonstrations, and performance and safety assessments. The learning provided by WP2 has been used to describe a generic process for development of the design basis for plugs and seals called the "DOPAS Design Basis Workflow" (Figure E.1). This workflow is structured to be consistent with three broad design stages:

- Conceptual Design: Conceptual designs describe the general layout of a repository structure, including the different repository components and how they are arranged, and the type of material used for each component (e.g., concrete, bentonite, gravel). In a conceptual design, the environmental conditions (including rock characteristics) are presented in generic terms, for example by describing the nature of the processes occurring rather than quantifying the processes. The performance of the components and the overall structure are described qualitatively.
- Basic Design: In a basic design, the components in the conceptual design are described in more detail with an approximate quantitative specification of geometry and material parameters. The properties of the environmental conditions are presented in detail, which requires characterisation of the site or elaboration of the assumptions underpinning the design. Performance is described quantitatively.
- Detailed Design: In a detailed design, the concept 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 DOPAS Design Basis Workflow is based on the design basis work undertaken for plugs and seals within the DOPAS Project. However, the Workflow is generic in nature, and could probably be applied to other repository design activities. The general applicability of the DOPAS Design Basis Workflow is considered as part of the wider DOPAS Project dissemination activities (WP7).

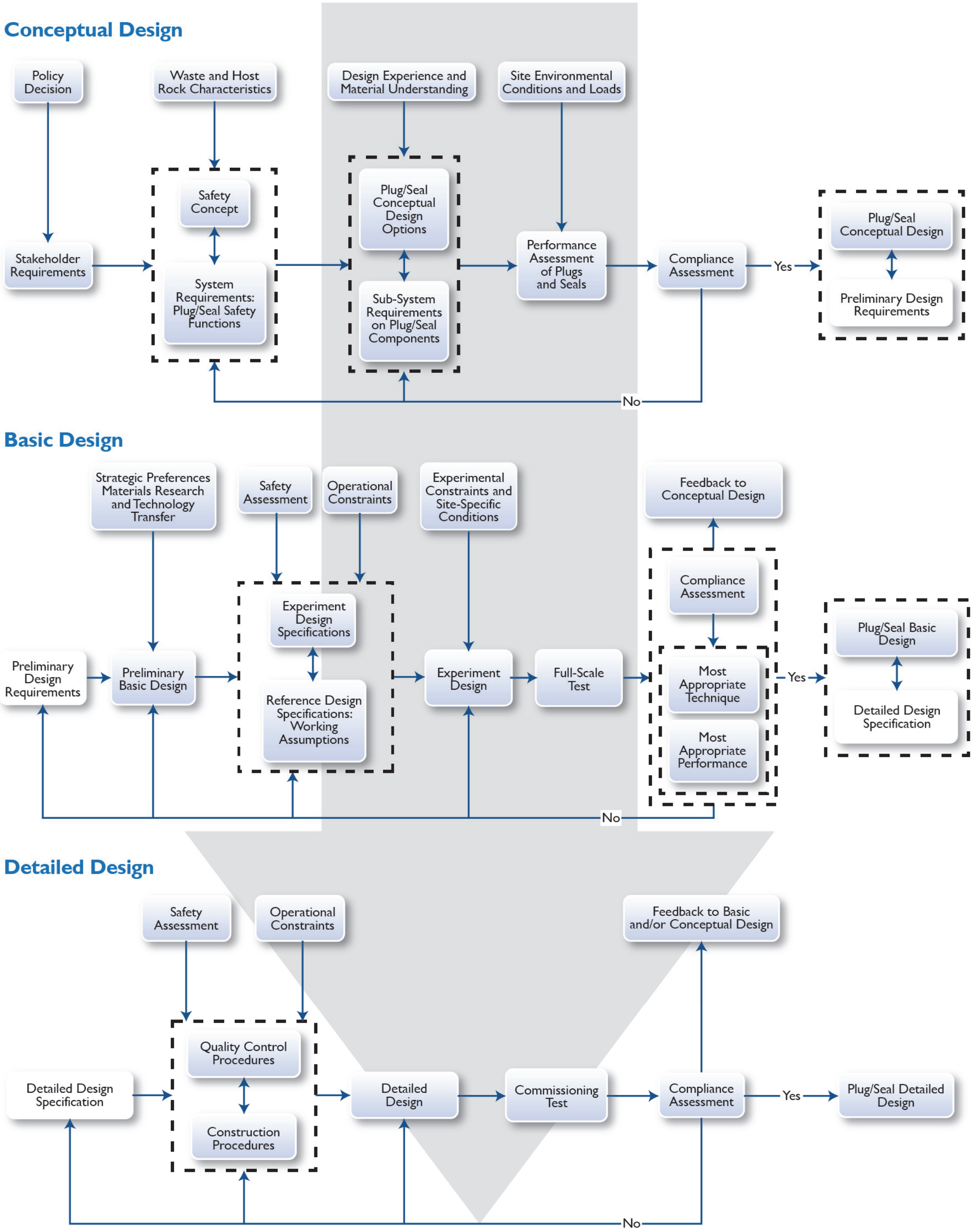

Figure E.1: The DOPAS Design Basis Workflow, which illustrates the iterative development of the design basis, undertaken in parallel with the development of conceptual, basic and detailed designs. Dashed boxes are used to show activities undertaken in parallel.

The design basis for a plug/seal conceptual design includes the stakeholder requirements that define the overall objectives of geological disposal (e.g., the safety criteria that must be met), safety functions for each of the components of the disposal system (e.g., for plugs and seals, this may include limiting groundwater flux through the repository), and the sub-system requirements on each of the components of a plug/seal (e.g., the role of a concrete dome or watertight seal and the plug lifetime). The safety functions are dependent on decisions made on the safety concept, and sub-system requirements are dependent on conceptual design options. Consideration of the site environmental conditions and loads acting on the structures allows conduct of a performance assessment, the results of which feed into a compliance assessment used to ascertain whether the system and sub-system requirements have been met by different conceptual design options. The outcome is selection of a conceptual design of a plug/seal, and elaboration of preliminary design requirements to be tested during development of the basic design.

Preliminary design requirements are used as the basis for developing preliminary basic designs. During the DOPAS Project, basic designs have been tested through full-scale tests. This has required the development of a set of working assumptions for the experiment design specifications, which are used to design the experiment and to assess its performance. The full-scale demonstration experiments undertaken in the DOPAS Project have addressed specific objectives, for example, technological feasibility (FSS), performance (DOMPLU), alternative design options (POPLU), and materials research in support of preliminary basic design (EPSP and ELSA). The results of full-scale tests provide further support to design decisions, especially optimisation issues such as the identification of design solutions that represent the most appropriate technique and the most appropriate performance. Compliance assessment at the basic design stage considers the extent to which the experiment results meet the experiment design specifications. Design requirements may be revised based on learning from the experiments, and the result of the compliance assessment can be used to revise the reference design requirements. In parallel, detailed design specifications are prepared based on working assumptions and experiment design specifications used as the basis for the full-scale test. The outcome of a satisfactory compliance assessment is selection of a basic design, and elaboration of detailed design specifications to be tested during development of the detailed design.

During detailed design, the detailed design specification, safety assessment and operational constraints are considered in order to establish quality control procedures and construction procedures. These allow development of a detailed design which is subject to a commissioning test. In contrast to demonstration testing, the commissioning test is a trial of the plug/seal as it is expected to be implemented in the repository. Consideration may be given to monitoring of these tests over long periods, for example Andra are planning an Industrial Pilot during the early stages of repository operation, which will run for as long as feasible, potentially decades. Compliance assessment of the commissioning test could lead to a revision of the design specifications, for example to write them in a manner that is amenable to checking using quality control or construction procedures. Compliance testing may also identify the need for revisions to the detailed design, which may, therefore, also lead to a need for further testing. Once the compliance assessment is acceptable, the plug/seal detailed design can be finalised and the detailed design specification accepted as the final design specification (subject to further revision based on learning during repository operation).

Key Messages from WP2 of the DOPAS Project

Key messages and learning points from WP2 of the DOPAS Project are summarised below.

Design Basis Development

The development of the design basis is generally undertaken in parallel with development of the design and development of the safety case rather than as a sequential process. For example, development of a disposal concept requires description of the components that make up the conceptual design at the same time as developing the statements regarding the functions that these components must provide (safety functions or system requirements using the terminology adopted in the DOPAS Design Basis Workflow). At a more detailed level of design development, designing a specific plug/seal component (e.g., defining the recipe for a concrete mixture) requires information on what the concrete recipe must achieve (e.g., strength, curing temperatures and hydraulic conductivity), but also leads to detailed design specifications (e.g., the acceptable range of constituents that can be used when mixing the concrete). These design specifications can be transferred into quality control statements and construction procedures for implementation during repository operation.

The processes used by WMOs to develop requirements and design specifications that form part of the design basis are expressed in different ways using different terminology. However, these processes are largely comparable to each other and are consistent with the DOPAS Design Basis Workflow. Some commonalities that have been identified include:

- Using the experience gained from previous tests and experiments on plugs and seals and/or from underground mining activities.
- Using an iterative process involving the design basis, performance assessment and safety evaluation to fine tune the design basis for the final plug/seal system, paying due consideration to the constructability and durability of these complex structures.
- Performing critical reviews periodically to assess the results, verify their compliance with the design basis, and identify possible modifications to the design basis.

All of the work undertaken to develop the design basis needs to be reflected in the safety case, and integrated with work undertaken on development and management of the safety case.

The design basis for a reference design and an experiment are usually different because the design basis for an experiment needs to respond to experimental constraints and site-specific environmental conditions (e.g., the location of the experiment and limited duration of the experiment). The design basis for experiments might represent a preliminary design basis for a detailed design.

Design Basis Content

The design basis incorporates both requirements and the conditions under which the requirements must be met. Significant work has been done on requirements; future development of the design basis for plugs and seals should also concentrate on the way conditions are expressed in the design basis. Conditions that are important to include in the design basis include the outcomes of safety assessments, the loads on a structure, and the nature of the underground environment, which, using the terminology adopted in the DOPAS Design Basis Workflow, includes the host rock characteristics (e.g., creep rate, heterogeneity, thermal conductivity, and fracture distribution).

The design basis should include requirements on the performance of the plug/seal (e.g., water leakage rate) and requirements on the methods that are suitable for its installation.

Performance requirements should reflect both the long-term (post-closure) requirements and short-term requirements. Short-term requirements include factors that are required for successful implementation of a plug/seal (e.g., management of the stresses acting on a concrete dome during curing, robustness, durability, and cost-effectiveness), and factors related to human activities (e.g., health and safety, choice of construction methods, and the operational constraints such as the time and space available for undertaking specific activities). All of these different types of requirements should be recognised within the design basis. The design basis requirements at the specifications level should be worded so that they can be readily implemented during construction and their compliance assessed, i.e., they should include appropriate ranges for material properties and be measurable during the practical operation of the repository.

The Structure of the Design Basis

Some WMOs use hierarchies to describe and present the design basis. For example, Posiva and SKB use a five-level requirements hierarchy based on the V-Model to structure requirements. This hierarchy, an adaptation of which has been used in the DOPAS Design Basis Workflow, is considered appropriate for describing the design basis of plugs and seals. The principal safety functions of a plug or seal can be specified and stabilised once the repository concept has been specified and the national regulations developed. More detailed requirements are developed through an iterative process in parallel with specific design activities, including materials research and full-scale testing. There is a need to identify and describe change management processes to respond to design basis revisions to operate alongside these processes. Further updates may be needed as the design work proceeds since the design work may imply that some overall design requirements may be hard to meet/verify and then a valid question is whether the design requirement based on the simplifications made in the safety assessment are justified – or could be altered without jeopardising overall safety.

A hierarchical and structured design basis can be used as part of a structured approach for demonstrating to the regulator the manner in which safety functions are met, and how this will be ensured during implementation. Compliance assessment during development of a design basis can be part of structured methods for developing comprehensive construction and quality control procedures.

Glossary of Terms in the DOPAS Design Basis Workflow

The learning provided by WP2 has been used to develop and describe a generic process for development of the design basis for plugs and seals called the “DOPAS Design Basis Workflow”. The Workflow contains a number of terms, for which specific definitions have been developed as part of the DOPAS Project WP2 activities. These terms are described in this report. In addition, we have provided this glossary for easy reference to the Workflow terminology.

Compliance assessment: Evaluation to determine whether the design meets the requirements.

Commissioning test: A final test of the plug/seal design ahead of repository operation based on the design expected to be implemented in the repository. The test may be used to check and adapt the initial parameters used in long-term estimations specifically linked to the repository, and to provide demonstration that the design is fit-for-purpose.

Construction procedures: Development of methods and description of how the installation of a plug/seal shall be undertaken according to the method(s).

Design basis: The set of requirements and conditions taken into account in design. The design basis specifies the required performance of a repository and its sub-systems, and the conditions under which the required performance has to be provided.

Design experience: Knowledge from other plugs and seals or other plug/seal experiments taken into consideration in the identification of conceptual design options for a particular plug/seal.

Design requirements: Qualitative statements describing the qualities or performance objectives for plug/seal components.

Design specifications: The quantitative requirements on the design components.

Detailed design: A design of a plug/seal based on detailed design specifications and used as an input to a commissioning test of the detailed design.

Detailed design specifications: A list of quantitative statements describing the plug/seal components (e.g., how they should be emplaced, the dimensions of the components, the materials to be used and the acceptable tolerances), prepared as a basis for development of the detailed design.

Experiment design: A description of the plug/seal to be tested in sufficient detail that it can be constructed, i.e., it provides precise information/technical drawings on all aspects of the experiment’s components.

Experiment design specifications: The quantitative requirements on the experiment design components. These may be different to the design specifications on the reference design to allow for testing of specific components or because of the constraints on the experiment.

Experimental constraints: Considerations taken into account when planning an experiment, including, for example, the time and space available for undertaking the work and operational safety concerns.

Full-scale test: Experiments at 1:1 scale, used to evaluate the performance of a plug/seal design, and/or to evaluate if it is technically feasible for the structure to be constructed to meet the requirements in the preliminary design specification. Full-scale tests would be undertaken in an environment that provided an adequate representation of the expected conditions in the repository (e.g., this would represent relevant environment testing).

Host rock characteristics: The features of the host rock and the processes occurring within it. These include the rock type and a description of the geological structure, hydrogeological regime and groundwater chemistry.

Loads: The conversion of environmental conditions at the plug/seal location into a quantitative expression of the processes acting on the plug/seal during its design life (e.g., mechanical loads, hydraulic loads, thermal loads).

Materials research: Investigation of the substances used in the construction of plugs and seals (e.g., testing of candidate concrete recipes), with the specific purpose of identifying those substances meeting or exceeding the design requirements for materials.

Material understanding: Generic knowledge of the qualities and behaviour of the different types of materials that could be used to construct plugs and seals such as clay, concrete and gravel.

Most appropriate performance: The situation where the design considered is judged to provide the most suitable solution for meeting the design requirements associated with the performance of the plug/seal.

Most appropriate technique: The situation where the design considered is judged to provide the most suitable method for constructing the plug/seal, that takes into account a range of factors, including safety as the first concern, but also cost, schedule, boundary conditions, and techniques (i.e., both the technology used and the way in which the structure is designed, built, maintained, operated and decommissioned).

Operational constraints: Factors that restrict and affect how the plug/seal must be constructed and installed, taking into account any applicable requirements of national legislation or company policies from the operational or post-closure safety points of view (e.g., the time needed to complete plug/seal installation, the number of workers present at the site, and permissions to use specific materials).

Performance assessment of plugs and seals: An appraisal of the manner in which a plug/seal and the sub-systems within the plug/seal function with respect to the safety functions assigned to the structure. This could include evaluation of material behaviour under expected loads supported by a programme of laboratory testing and computer modelling.

Plug/seal basic design: Quantitative information on the geometrical and material parameters of the plug/seal, and details on the composition of the materials used to construct it. Dimensions are approximate, for example metre-scale dimensions such as tunnel cross-sections or component lengths might be expressed to the nearest centimetre or decimetre, with a similar level of precision used for other components.

Plug/seal components: The different structures making up the whole plug/seal sub-system. This may include, for example, a concrete structure, a bentonite layer and a filter.

Plug/seal conceptual design options: A set of alternative designs for a plug/seal reference conceptual design.

Plug/seal detailed design: A description of the plug/seal in sufficient detail that it can be constructed, i.e., it provides precise information/technical drawings on all aspects of the structure's components. A detailed design might be undertaken in two stages: first, prior to the excavation of the rock in which the plug/seal will be located; second, following excavation based on the as-built site-specific conditions.

Plug/seal conceptual design: A qualitative description of the plug/seal components and how they are arranged with respect to each other. The conceptual design includes identification of the type of material used for each component (e.g., concrete, bentonite).

Plug/seal safety functions: A qualitative statement describing how a plug/seal contributes to the safe operation, to the safe evolution of other components, and/or to post-closure safety of a disposal system.

Policy decision: A high-level resolution, typically made by Government, e.g., a decision to select geological disposal as the preferred waste management option; a policy decision represents a top-level stakeholder requirement.

Preliminary basic design: An initial design based on preliminary design requirements used as an input to full-scale testing.

Preliminary design requirements: An initial list of qualitative statements describing the qualities or performance objectives for plug/seal components, and developed as a basis for an iterative development of the basic design.

Quality control procedures: A description of the manner in which the implementer will ensure that the plug/seal meets the design specifications during construction of a plug/seal. This includes listing of the standards, and guidance on materials, dimensions and methods (including documentation of the implementation of the procedures) that will be followed during construction.

Reference design: The design of a plug/seal within a disposal concept, i.e., the design used to underpin the safety case or licence application.

Reference design specifications: working assumptions: A set of design specifications developed in parallel with experiment design specifications and used as a basis for elaboration of the preliminary reference design specifications following the iterative development of the plug/seal basic design. These working assumptions are expectations of the design specifications that would be adopted as preliminary design specifications if the full-scale testing and compliance testing supported further development of the proposed design.

Requirement: A statement that the design needs to comply with.

Repository: The series of complementary barriers e.g., the wasteform, waste containers, buffer and backfill materials, plugs and seals, and the host geology, each of which will be effective over different timescales that provide safe geological disposal of radioactive waste through isolation and containment of the waste from the biosphere.

Safety function: A certain performance that a sub-system must provide (see also: Plug/seal safety functions).

Site environmental conditions: The characteristics of the location where the plug/seal will be constructed (e.g., relative humidity, temperature and rock characteristics). These conditions could have representative (i.e., generic) values for use in safety analyses rather than actual values in the specific plug location. The generic nature of these environmental conditions reflects the status when no specific site has yet been identified.

Site-specific conditions: Characteristics of the location of the plug (e.g., relative humidity, temperature and rock characteristics), taken into account when planning an experiment.

These conditions could have specific values obtained from the plug location and wider environment.

Safety assessment: The process of systematically analysing the hazards associated with a facility and the ability of the site and designs to provide the safety functions and meet design requirements.

Safety concept: A description of how a series of engineered and natural barriers provide safe disposal of radioactive waste in a particular host rock environment consistent with top-level stakeholder requirements.

Stakeholder requirements: Stakeholder requirements are the top-level statements on, and description of, what must be achieved by a waste management programme and elaboration of specific approaches that must be considered in the repository design

Sub-system: A component of the whole repository system (e.g., plug/seal, waste package, or buffer).

Sub-system requirements on plug/seal components: A list of the functions that the sub-structures that comprise the plug/seal must provide and the qualities that the sub-structures must have.

Strategic preferences: Choices made during design as a result of general considerations, for example, a choice to use locally-sourced bentonite or to use a particular construction technique.

System: The overall repository "system" including all its components.

System requirements: The requirements on the disposal system, i.e., the safety functions provide by the components that comprise the disposal system. For plugs and seals, therefore, system requirements are the safety functions provided by plugs/seals.

Technology transfer: Adoption of approaches from other industries or other countries where a similar challenge has already been addressed.

Waste characteristics: The features of the material to be disposed of that need to be taken into account when developing the safety concept and designing the disposal system.

List of the 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	Nationale Genossenschaft für die Lagerung radioaktiver Abfälle (National Cooperative for the Disposal of Radioactive Waste)	Switzerland
RWM	Radioactive Waste Management Limited	United Kingdom
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	United Kingdom
BTECH	B+ Tech Oy	Finland
VTT	Teknologian tutkimuskeskus VTT Oy (VTT Technical Research Centre of Finland Ltd)	Finland
UJV	Ustav Jaderneho Vyzkumu (Nuclear Research Institute)	Czech Republic

List of Acronyms

ASN:	Autorité de Sûreté Nucléaire (Nuclear Safety Authority in France)
BMU:	Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety in Germany)
Cigéo:	Centre Industriel de Stockage Géologique (Industrial Repository in France)
CNE:	Commission Nationale d'Evaluation (National Review Board in France)
CoRWM:	Committee on Radioactive Waste Management
DAC:	Demande d'Autorisation de Construction
DOMPLU:	Dome Plug
DOPAS:	Full-scale Demonstration of Plugs and Seals
DSS:	Disposal system specification
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
FISST:	Full-scale *In Situ* System Test
FSS:	Full-scale Seal
GME:	Groupement Momentané d'Entreprises (FSS General Contractor)
HLW:	High-level waste
HRL:	Hard Rock Laboratory
ILW:	Intermediate-level waste
IRSN:	Institut de Radioprotection et de Sûreté Nucléaire (Radioprotection and nuclear safety institute in France)
KBS:	Kärnbränsle Säkerhet (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)
LASA:	"**La**ngzeitsicherer **S**chachtverschluß im S**a**linar" – a set of experiments on shaft sealing concepts in Germany focusing on mechanical-hydraulic issues
LAVA:	"**La**ngzeitsicherer Schacht**v**erschluß im S**a**linar" – a set of experiment on shaft sealing concepts in Germany focusing on chemical-hydraulic issues
LECA®:	Light-weight expanded clay/concrete aggregate
LLW:	Low-level waste
POPLU:	Posiva Plug
R&D:	Research and development

RMS:	Requirement management system
SCC:	Self-compacting concrete
SFRC:	Steel-fibre-reinforced concrete
THMCGR:	Thermal, hydraulic, mechanical, chemical, gas and radionuclide transport
TSX:	Tunnel sealing experiment
TURVA:	TURVA is Finnish for safety; TURVA-2012 is Posiva's safety case supporting the construction licence application submitted in 2012 for the Olkiluoto spent fuel disposal facility
URC:	Underground research centre
URCF:	Underground Rock Characterisation Facility
URL:	Underground research laboratory
VAHA:	Vaatimusten hallintajärjestelmä (Posiva's requirement management system)
VOP:	Vaatimuksia Ohjaava Päätös (Decisions Guiding Requirements)
VSG:	Vorläufige Sicherheitsanalyse Gorleben (Preliminary Safety Analysis for Gorleben)
WMO:	Waste management organisation
WP:	Work package
YVL:	YVL-ohje (Nuclear regulatory guides in Finland)

Table of Contents

1 Introduction

1.1 Background to the DOPAS Project

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 the DOPAS Project. The Project is coordinated by Posiva Oy (Posiva) (Finland). A set of full-scale experiments, laboratory tests, and performance assessment studies of plugs and seals for geological repositories are being carried out in the course of the project.

The DOPAS Project aims to improve the industrial feasibility of full-scale plugs and seals, the measurement of their characteristics, the control of their behaviour in repository conditions, and their performance with respect to safety objectives. The Project is being carried out in seven Work Packages (WPs). WP1 includes project management and coordination and is coordinated by Posiva, Finland. WP2, WP3, WP4 and WP5 address, respectively, the design basis, construction, compliance testing, and performance assessment modelling of five full-scale experiments and laboratory tests. WP2, WP3, WP4 and WP5 are led by SKB (Sweden); Andra (France); RWM (United Kingdom); 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 led by Posiva.

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

- *Clay rocks*: the Full-scale Seal (FSS) experiment, being undertaken by Andra in a in a surface facility at St Dizier, is an experiment of the construction of a drift and intermediate-level waste (ILW) disposal vault seal.
- *Crystalline rocks*: experiments related to plugs in disposal tunnels, including the Experimental Pressure and Sealing Plug (EPSP) experiment being undertaken by SÚRAO and the Czech Technical University (CTU) at the Josef underground research centre (URC) and underground laboratory in the Czech Republic, the Dome Plug (DOMPLU) experiment being undertaken by SKB and Posiva at the Äspö Hard Rock Laboratory (Äspö HRL) in Sweden, and the Posiva Plug (POPLU) experiment being undertaken by Posiva, SKB, VTT and BTECH at the ONKALO Underground Rock Characterisation Facility (URCF) in Finland.
- *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 DBE TEC together with the Technical University of Freiburg and associated partners complemented by laboratory testing performed by GRS and co-funded by the German Federal Ministry for Economic Affairs and Energy (BMWi).

Each experiment represents a different state of development. The French, Czech and Finnish experiments are being designed and constructed during the Project. The Swedish experiment was started prior to the start of the DOPAS Project. 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 laboratory testing, and will feed into a full-scale experiment of prototype shaft seal components to be carried out after DOPAS.

1.2 Work Package 2

WP2 addresses the design basis for plugs and seals, their reference designs, and the strategies used to demonstrate the compliance of the designs of 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 the DOPAS Project (White *et al.*, 2014).
- Task 2.2: Reference Designs. Documentation of the designs in the reference concepts and the DOPAS Project experiments (White and Doudou, 2014).
- Task 2.3: Strategies for demonstrating conformity of reference designs to the design basis. Identification and description of the different strategies that are adopted by WMOs carrying out the DOPAS Project experiments to demonstrate compliance of the reference designs to the design bases (White and Doudou, 2015).
- Task 2.4: Final Reporting of WP2. In this task all of the WP2 results are compiled in one final report.

This report is Deliverable D2.4 of the DOPAS Project, and describes the outcomes from WP2.

1.3 Report Objectives and Intended Audience

The objectives of this report are to compile and analyse the results from WP2 of the DOPAS Project.

The report describes the safety functions, the designs, and design basis of plugs and seals considered in the Project. The report includes an analysis and discussion of the differences between the design bases for plugs and seals in different repository concepts, focusing on the safety functions performed by each plug and seal, and how these impact on the requirements placed on the plug/seal.

This report also describes the learning from WP2 on the processes used to develop and structure the design basis for plugs and seals within the DOPAS Project, and uses that learning to provide guidance on the development of a design basis in the context of repository plugs and seals. In particular, lessons are drawn on the iterative development of the design basis for plugs and seals, in parallel with development of the design, as well as the use of hierarchical structures to describe the design basis.

This report also outlines the strategies used by WMOs to demonstrate compliance of the reference designs with the design basis, and in particular with the safety functions captured in the design basis.

The intended audiences of this report are technical staff and technical management of WMOs, and the report has been written primarily for this audience. The report is also expected to be of interest to regulators.

1.4 Plugs and Seals in Repository Concepts

Safe geological disposal of radioactive waste involves isolation and containment of the waste from the biosphere. Containment and isolation can be provided through a series of complementary barriers, e.g., the wasteform itself, waste containers, buffer and backfill materials, plugs and seals, and the host geology, each of which will be effective over different timescales. The depth of disposal and the characteristics of the host geological environment provide isolation from the biosphere and retardation of migrating radionuclides, and reduce the likelihood of inadvertent or unauthorised human intrusion.

Specific parts of a repository will have to be plugged and sealed as part of the backfilling and closure operations to ensure that the isolation and containment functions of the repository are not compromised. The number and specific purpose (function) of plugs and seals depends on the disposal concept, the nature of the geological environment, and the inventory to be disposed of. For example:

- Plugs and seals may be required during operations to isolate emplaced waste and other engineered barrier system (EBS) components from the rest of the underground excavations.
- Plugs and seals may be required following closure to limit groundwater flow and radionuclide migration.
- Plugs and seals may be required to prevent inadvertent or unauthorised human access.
- Plugs will be required for sealing of investigation boreholes, in particular to intersect and isolate water-conducting fractures.

1.5 Scope and Terminology

1.5.1 The Design Basis of Plugs and Seals

In general terms, a design basis can be defined as the set of requirements and conditions taken into account in design. The design basis specifies the required performance of a repository and its sub-systems, and the conditions under which the required performance has to be provided. It includes requirements derived from regulations, and safety functions that plugs and seals have to fulfil as part of the overall safety objective of a disposal system. Requirements are statements on what the design has to do (the performance) and what it must be like (the characteristics). For a plug/seal, this could be, for example, the strength and the hydraulic conductivity of the materials making up the plug/seal. Conditions are the loads and constraints imposed on the design, for example, the underground environment (dimensions, air temperature, humidity, etc.) or controls on the manner in which the design is implemented (e.g., the time available for construction).

The requirements in the design basis form a hierarchy of increasing detail, which is developed in parallel with decisions on the design. At each stage in the design development process, the requirements are used as the basis for more detailed designs. Therefore, although there is a transition from problem specification to solution during design development, requirements are defined at each stage in the process as the basis upon which more detailed designs are developed.

Consistent with an iterative approach to development of a design basis hierarchy, the requirements discussed in this report are still under development and are subject to change.

The design basis is developed and described differently in each WMO programme, and this report describes the process used to develop the design basis and the specific approaches adopted by the WMO partners conducting the five full-scale experiments and laboratory tests within the DOPAS Project. This includes previous development of plugs and seals design bases, and the methods used to develop, record, and communicate the design basis by

WMOs. As such, there are general conclusions to be drawn that are relevant to the design basis for other aspects of repository design as well as lessons specific to plugs and seals.

1.5.2 Reference and Experiment Designs and Compliance with the Design Basis

In the DOPAS Project, a distinction has been made between reference and experiment designs:

- The term "reference design" is used to denote the design of a plug/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/seal being tested, e.g., the designs of the plug/seal being tested at full scale in the DOPAS Project.

Experiment designs are typically modified versions of reference designs, with the modifications made to investigate specific aspects of the design during the experiment. In particular, there are differences in the boundary conditions between the experiment designs and reference designs. These include the number of plugs and seals in the actual repository (just one plug/seal for the experiments compared to many tens of plugs/seals for the repository) and the impact on the construction of these plugs and seals (for example cost constraints), and the acceptability, for experiments, to use monitoring instrumentation within the plug/seal structure. Other differences generally arise as a result of experiment-specific objectives, for example to test alternative designs and compare the performance with the reference designs (e.g., POPLU is a test of an alternative conceptual design for the deposition tunnel plug in the KBS-3V concept), or to test planned modifications in the reference design (e.g., DOMPLU, one aspect of which is testing the use of concrete without reinforcement).

Both reference and experiment designs are presented in this report for the full-scale plugs and seals being investigated within the DOPAS Project. The focus is on the conceptual designs of plugs and seals. Conceptual designs are part of a hierarchy of increasingly detailed designs (IAEA, 2001), as follows:

- Conceptual Design: Conceptual designs describe the general layout of a repository structure, including the different components and how they are arranged, and the type of material used for each component (e.g., concrete, bentonite and sand). In a conceptual design, the properties of the rock are presented in generic terms (e.g., by describing the nature of the processes occurring rather than quantifying the processes), 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 a DOPAS plug/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.

1.5.3 Other DOPAS Project Summary Reports

This report is part of a series of WP-level summary reports describing the integrated outcomes of the technical work in the DOPAS Project. The reports were produced partly sequentially and partly in parallel, but represent an integrated suite of documents describing the outcomes from the DOPAS Project from the perspective of each WP. As such, there are cross-references between each report, which reflect the position at the end of the project when all of the reports are complete and published. the other WP-level summary reports are:

- D3.30, the WP3 Final Summary Report (DOPAS, 2016a), summarises the work undertaken and the lessons learned from the detailed design and construction of the experiments. D3.30 summarises the experiences from the DOPAS Project experiments, including the design work and construction activities. These include the full-scale demonstrators, laboratory work and its upscaling, and the learning provided by the practical experience in constructing the experiments.
- D4.4, the WP4 Integrated Report (DOPAS., 2016b), summarises what has been learnt with respect to the reference designs for plugs and seals. The report also considers alternatives to the reference designs (e.g., the wedge-type plug investigated by Posiva). It considers what can be concluded from the experiments conducted in the DOPAS Project with respect to the technical feasibility of installing the reference designs, the performance of the reference designs with respect to the safety functions listed in the design basis, and identifies and summarises achievements of WP2, WP3 and WP4 of the DOPAS Project at the time of writing. D4.4 also considers the feedback from the work to the design basis.
- D5.10, the WP5 Final Integrated Report (DOPAS, 2016c), describes the conceptualisation of plugs and seals in performance and safety assessments and the expected evolution of plugs and seals. This includes a description of the evidence that the materials used in plugs and seals will maintain their required performance for the period specified in the design basis.

1.6 Approach

Information on the plug/seal reference and experiment designs, the design basis of each experiment being carried out in the DOPAS Project, and the strategies for demonstrating compliance of the reference designs with the design basis was compiled 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 and design bases, the management of requirements, and compliance strategies. The questionnaire was completed by staff from Andra, DBE TEC/GRS, Nagra, NRG, Posiva, RWM, SKB and SÚRAO.
- Referring to published documents supplied by partner organisations.
- Holding face-to-face discussions with representatives of the organisations undertaking the experiments. Meetings were held with:
    - The Andra WP2 representative, FSS experiment leader and other Andra staff.
    - The SÚRAO WP2 representative, the CTU EPSP experiment leader and other SÚRAO staff
    - The DOMPLU experiment leader.

- The Posiva WP2 representative and the POPLU experiment leader.

These meetings allowed the collection of more detailed information and development of a more detailed understanding of each experiment design basis than the information provided in the questionnaires. These meetings were also used to agree a way of presenting the design basis for each experiment, and to discuss the process and approach employed by each WMO to develop the design basis. A meeting was not held with GRS and DBE TEC owing to the preliminary nature of the design basis for the shaft seal in the German programme. Therefore, information on the design basis for ELSA presented in this report is based on the questionnaire response and published information only.

Throughout this work, no specific approach to design basis development was used to frame the discussions and collation of information. This allowed specific approaches adopted by WMOs to be considered, and an evaluation of the similarities and differences between different WMO approaches to be identified and described. The knowledge gained from the work in WP2 and the understanding of specific approaches used by each WMO have been used to develop a general process for design basis development. This is referred to as the "DOPAS Design Basis Workflow". The Workflow and the overall conclusions and key messages from the work in WP2 focus on generic lessons that could be applied more widely through consideration of specific WMO approaches.

1.7 Report Structure

The remainder of this report is set out as follows:

- Section 2 describes the reference and experiment design bases and designs for the five plugs and seals considered in the DOPAS Project, plus the disposal programmes represented in the Project.
- Section 3 provides a discussion of the content of design bases for plugs and seals. This includes the influence of host rock type on the design basis of plugs and seals, a discussion of thermal, hydraulic, mechanical, chemical, gas and radionuclide transport (THMCGR) requirements, and an analysis and discussion of the differences between the design bases for plugs and seals in different repository concepts, focusing on the different safety functions performed by each plug and seal, and how this impacts on the requirements placed on the structure.
- Section 4 provides a discussion of compliance strategies adopted or planned by WMOs to demonstrate compliance of the plug and seal reference designs to the design bases.
- Section 5 provides a discussion of the learning from WP2 on the processes used to develop and structure the design basis, and uses that knowledge to develop a general process for development of the design basis.
- Section 6 provides the conclusions from WP2 of the DOPAS Project.
- Section 7 lists the references used in this report.

2 Design Basis for the DOPAS Project Plugs and Seals

In this section, the design basis and the design for each of the five DOPAS Project plugs and seals are presented. The discussion of each plug/seal is presented in five sub-sections: the safety functions of the plug/seal, the process used to develop the reference design basis, the reference conceptual design of the plug/seal, the DOPAS Project experiment design, and the DOPAS Project experiment design basis. The design basis for plugs and seals in other disposal programmes represented by the DOPAS Project partners are also summarised.

More detail on the design bases discussed in this section is provided in the WP2 Task 2.1 report (White *et al.*, 2014). Additional information on the conceptual reference designs and experiment designs of plugs and seals discussed in this section is provided in the WP2 Task 2.2 report (White and Doudou, 2014).

Information on the design basis of plugs and seals presented in this section was compiled through responses to a questionnaire that was completed by WMO partners, through published reports by partner organisations, and through face-to-face discussions with representatives of the organisations undertaking the experiments in the DOPAS Project, as described in Section 1.6.

2.1 Andra's Drift and ILW Vault Design Basis

2.1.1 Drift and ILW Vault Seal Safety Functions

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 on the containment of radionuclides.

In Andra's concept, seals are defined as hydraulic components for closure of large-diameter (several metres, upto 10 m) underground installations and infrastructure components. 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 groundwater velocity within the repository.

2.1.2 Process used by Andra to Develop the Drift and ILW Vault Design Basis

Safety objectives for the Cigéo are defined in the safety guide produced by the French Nuclear Safety Authority (ASN) (ASN, 2008). In order to meet these safety objectives, Andra assigns safety functions to all repository components that have a significant role in providing safety, including the host formation, the waste packages and the EBS. Plugs and seals are considered to be part of the EBS. Each safety function is then broken down into sub-functions, to a level of detail that the designer considers sufficient – this process is termed 'functional analysis' (Andra, 2005). The functional analysis outputs are used to develop the more detailed design requirements and technical specifications on each repository component.

For seals, the designer asks the following questions to help develop the specifications from the safety functions (and any sub-functions):

- Based on various performance evaluations, what is the required performance of the seal?
- Considering the thermal, hydraulic, chemical and mechanical contexts, what is the phenomenological environment?
- Considering technical feasibility and demonstration capacity, what influence do the design elements have on hydraulic performance?

After developing the design requirements and specifications, an iterative process is used to update and develop these design specifications and requirements further as more knowledge is acquired (e.g., through scientific knowledge on the host rock and repository materials, and through knowledge gained from design studies), and a more detailed understanding of the post-closure performance is gained by conducting safety assessments and demonstrator experiments. The high-level safety functions are kept unchanged throughout the process, whereas the sub-functions, and design specifications and requirements evolve as more knowledge is gained. As a consequence, sub-functions and design specifications will become more detailed and specific through time. The iterative process used to update the design basis is illustrated in Figure 2.1.

Many divisions within Andra are responsible for maintaining the definitions and traceability of specifications. The Cigéo Project Division coordinates this work in close collaboration with:

- The Risk Assessment Division: this division develops safety principles, and operational and post-closure safety assessments.
- The Research and Development Division: this division develops scientific and technological knowledge, in particular scientific knowledge on the long-term behaviour of the repository system.
- The Engineering Division: this division develops the approach to industrial implementation of disposal, in particular development of engineering materials used in designs.

Regular meetings are organised between these divisions to discuss and assess the work carried out and its results, to identify potential issues, to verify compliance of designs with requirements, and to propose modifications to the requirements and design basis in order to support a demonstration of safety. There is no formalised process for change management of requirements in Andra's programme. The meetings (and the related minutes) with the different divisions are seen as a way of providing a critical approach to what has been achieved and carrying out a gap analysis.

Discussions between Andra, and ASN and ASN's scientific and technical expert support organisation the Institut de Radioprotection et de Sûreté Nucléaire (IRSN), and between Andra and the National Review Board (CNE), also contribute to the development of the design basis.

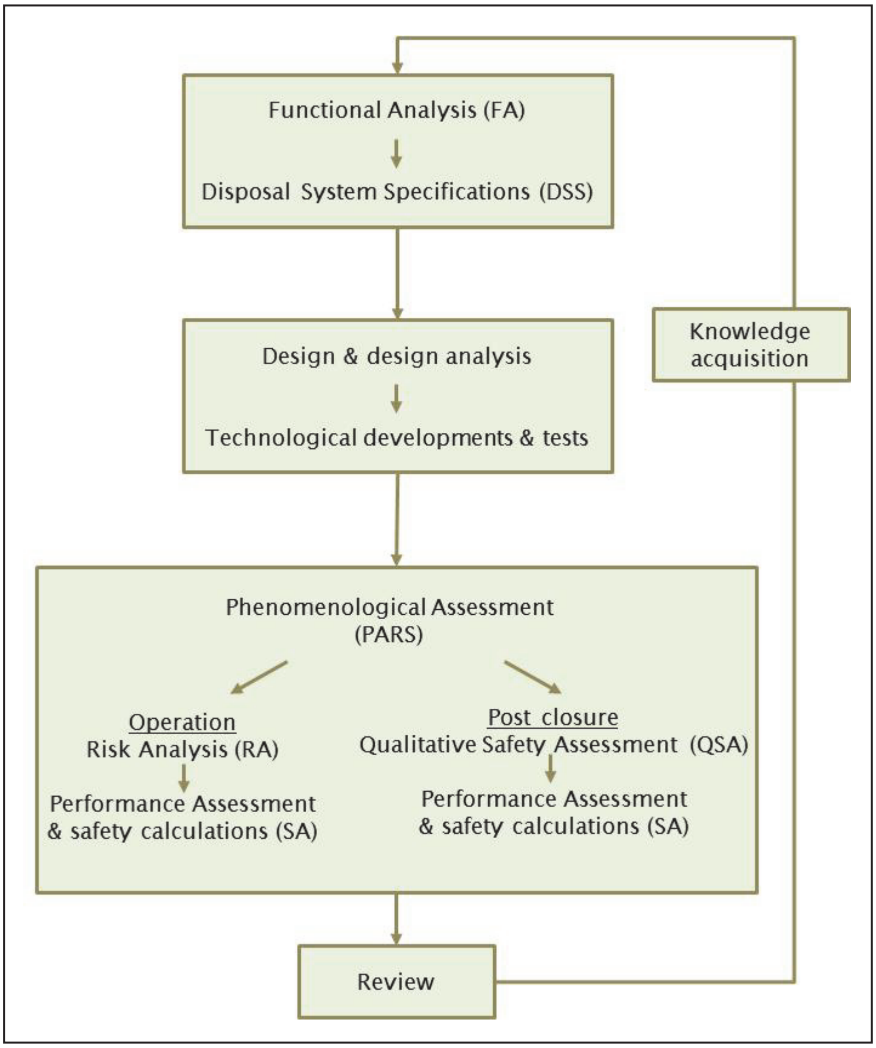

Figure 2.1: Iterative process used to update the design basis in Andra's concept. Provided by Andra.

At the current stage of Andra's programme, which is focused on developing a construction licence application referred to as the Demande d'Autorisation de Construction (DAC) by mid-2018, specifications for the drift seal are intended to demonstrate the feasibility of "reasonable" sealing performance. In this context, *reasonable* refers to a design that meets current requirements; further research and development (R&D) (e.g., further tests, studies and/or experiments related to seals phenomenology, and technical improvements in the seal construction process) could be undertaken to improve the design and performance. Specifications are intended to become increasingly more precise after consideration of feedback from these R&D activities.

The term '*design basis*' is not used by Andra in its programme. Historically, Andra has not employed a systems engineering approach for the seal concept nor has it used structured databases featuring hierarchies of requirements. However, the functional analysis process that is used to define the requirements and specifications on seal design is consistent with the approach used in other programmes, as discussed in Section 5. Currently, the "ISO 10006, RG AERO 000-40" (AFNOR, 1999) is the reference standard that is now being used by Andra for the system engineering approach of the studies currently implemented for the basic and detailed design of Cigéo.

2.1.3 Drift and ILW Vault Seal Reference Conceptual Design

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 two concrete containment walls (Figure 2.2). The swelling clay core provides the required long-term performance of the seal, whereas the containment walls are included to mechanically contain the clay core. The conceptual design of drift and ILW disposal vault seals is the same.

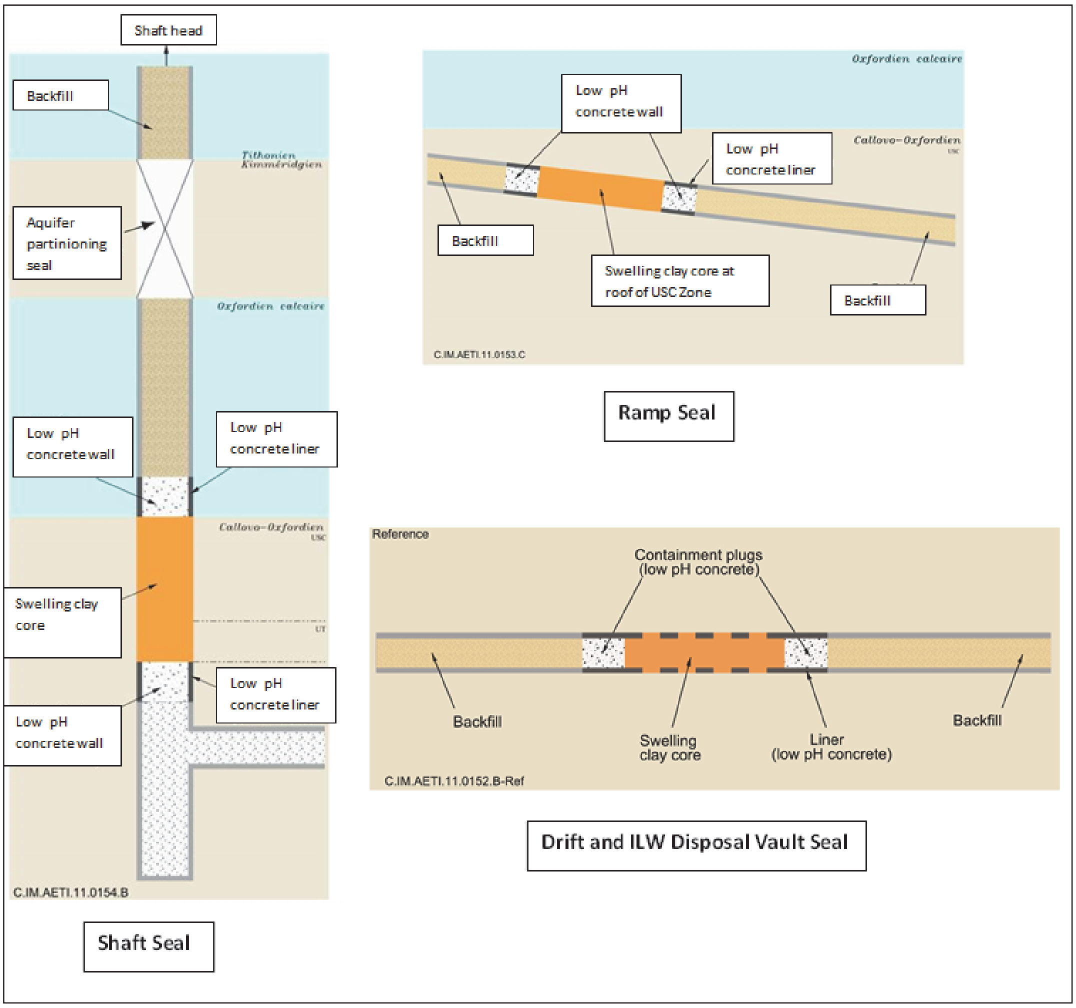

Figure 2.2: Schematic illustration of the conceptual designs for shaft, ramp, and drift and ILW disposal vault seals for the Cigéo reference disposal concept. From Wendling *et al*. (2015).

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 host rock, which is more competent than the lower part 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.

2.1.4 FSS Experiment 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, which has less limitations than undertaking the experiment underground. 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 which may be 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 (the REM experiment, which is part of WP5 of the DOPAS Project, 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 at a metric scale) and the global performance after resaturation (NSC half-scale *in-situ* seal test in the Meuse/Haute-Marne underground research laboratory (URL)). The conceptual design of the FSS experiment is illustrated in Figure 2.3.

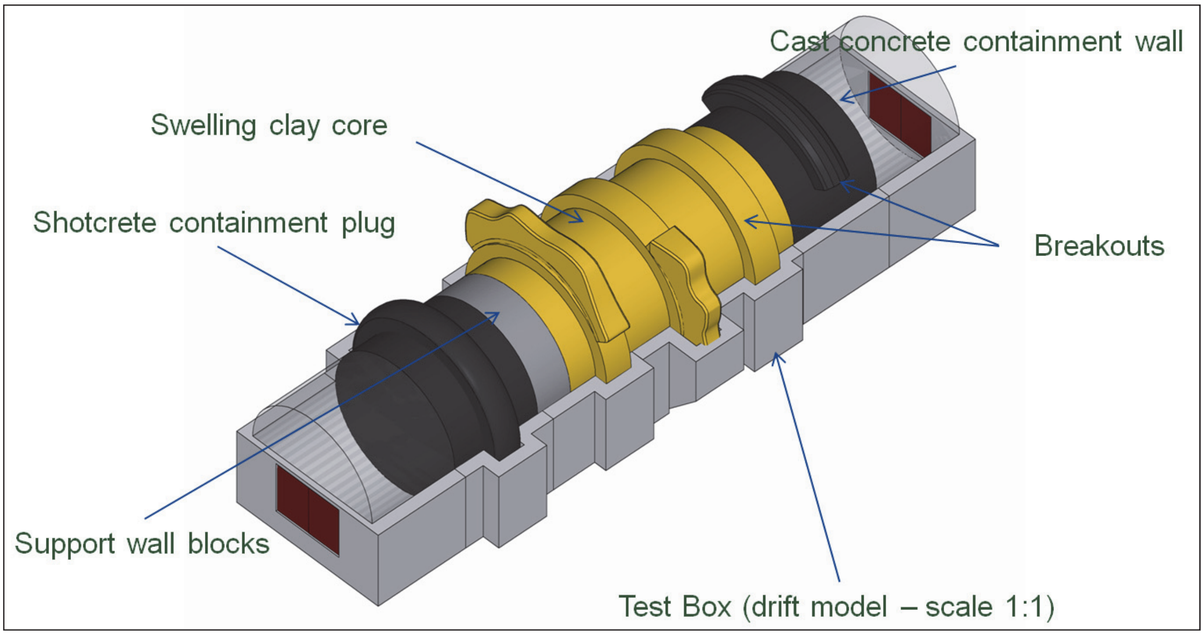

Figure 2.3: Schematic illustration of the FSS experiment design. From Bosgiraud and Foin, (2013).

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 2.3); one self-compacting and one emplaced as shotcrete, to allow the preferred method to be selected and incorporated into the reference concept.

2.1.5 FSS Experiment Design Basis

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 hydraulic conductivity, plasticity, swelling pressure, etc.) to support the long-term hydraulic performance of the seal. As already noted, no hydraulic performance of the FSS is being carried out in the DOPAS Project. Instead, the hydraulic performance is 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.

With regard to the management of the design basis for the FSS experiment, the FSS design and construction is contracted to a consortium of four companies (known as the Groupement Momentané d'Entreprises (GME) consortium), and the contract for the design and construction includes a set of technical specifications detailing the requirements on the experiment. Andra's experiment leader scrutinises the results obtained by the consortium at each step of the work and checks their compliance with the pre-established requirements. Detailed specifications for the FSS experiment are documented in Andra (2012), which is the technical specification document used in the tendering process for the experiment. The main design specifications relate to the following topics:

- Context of the experiment: the experiment will be carried out as if it were implemented 500 m underground by taking account of underground construction regulations, underground temperature and humidity, and the distance and time over which materials are transported following their manufacture.
- Upstream concrete containment wall: specifications on the dimensions of this wall and the requirement on the use of low-pH concrete. This wall has no hydraulic function.
- Clay core: the dimensions of the core and the form of the breakout sections.
- Downstream concrete support wall: the composition of the support wall of low-pH concrete blocks. This wall has no hydraulic function. It is progressively constructed as the swelling clay core is emplaced.
- Downstream concrete containment wall: specifications on the dimensions of this wall and the requirement on using low-pH shotcrete. This wall has no hydraulic function.
- Material requirements include:
    - Low-pH concrete: specifications on concrete formulations to be used, including use of aggregates and other materials, and specifications on the temperature of the concrete and shotcrete and minimisation of cracking. The specification to have a pH of 10.5 to 11 at 28 days was found to be quite optimistic in the initial tests. This requirement should now be fulfilled at 90 days.
    - Swelling clay: requirements on the swelling clay materials mainly specify a swelling pressure and hydraulic conductivity to be achieved. These are 7 MPa and 10^{-11} m/s, respectively. There is no requirement for a specific dry density value; however, a value is specified during material testing. This dry density value is measured in the monitoring stage to ensure that the swelling pressure and hydraulic conductivity requirements are met. Bentonite pellets of different sizes and powder can be used in the swelling clay core.

- Procedures for box filling: particular attention is given to the feasibility of filling the recesses to ensure adequate contact with the box lining.
- Compliance and monitoring: requirements on the methods and measures that need to be in place in order to verify the compliance of the construction methods, the box dimensions, the filling operations, and the concrete and clay formulations to the specifications.
- Interface with the REM experiment: the same filling materials used in FSS will be used for the REM experiment box.

2.2 SÚRAO Tunnel Plug Design Basis

2.2.1 Tunnel Plug Safety Functions

The first assessment for disposal of spent fuel and high-level waste (HLW) in the Czech Republic considered a generic reference concept based on KBS-3V in a crystalline host rock. However, subsequent studies have focused on a concept based 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 2012 (SÚRAO, 2012). Although the KBS-3H-based concept is now regarded as the reference concept in the Czech Republic, both the horizontal and vertical container emplacement concepts 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 safety functions of the plug are to:

- Separate the disposal container and the buffer from the rest of the repository.
- Provide a safe environment for workers.
- Provide better stability of open tunnels.

The aim of SÚRAO in the DOPAS Project is not to test the design or performance of the reference deposition tunnel plug, but to test the materials and technology considered for plugs and seals. At this early stage in the Czech geological disposal programme, with around 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.

2.2.2 Process used by SÚRAO and CTU to Develop the Tunnel Plug Design Basis

The Czech plug design basis has been developed from experience gained through installation of the plugs at the Háje underground gas storage facility (Hilar and Pruška, 2011). The Háje facility, located near Příbram in the Czech Republic, consists of a network of interconnected 3.5-m diameter tunnels at a depth of 950 m below the surface. The storage facility is located completely outside the production zone of a former uranium-ore mine. Four concrete plugs were used to separate the gas storage spaces from the uranium production zone. Each concrete plug is 10-m long. The plugs were constructed using steel-fibre-reinforced concrete (SFRC) and incorporate extensive grouting of the host rock. The plug construction and testing techniques were verified underground on trial plugs. The plugs were built using wet-process sprayed SFRC with a high fibre content. A similar spray technique to that used at Háje has been used in the EPSP experiment.

Experience from other organisations (e.g., SKB and Posiva) has also been used to develop the plug design. No requirements management system has yet been developed and no formal processes exist for developing and managing requirements.

2.2.3 Tunnel Plug Reference Conceptual Design

Consistent with the conceptual approach taken in the 2012 study in which the concept based on KBS-3H was adopted, the reference design for the tunnel plug in the repository concept is not highly developed and specific requirements on the reference plug are yet to be specified.

In the 2012 study, it was assumed that disposal drifts would be closed by a steel-reinforced concrete end plug, in which the concrete would have a low pH (Figure 2.4).

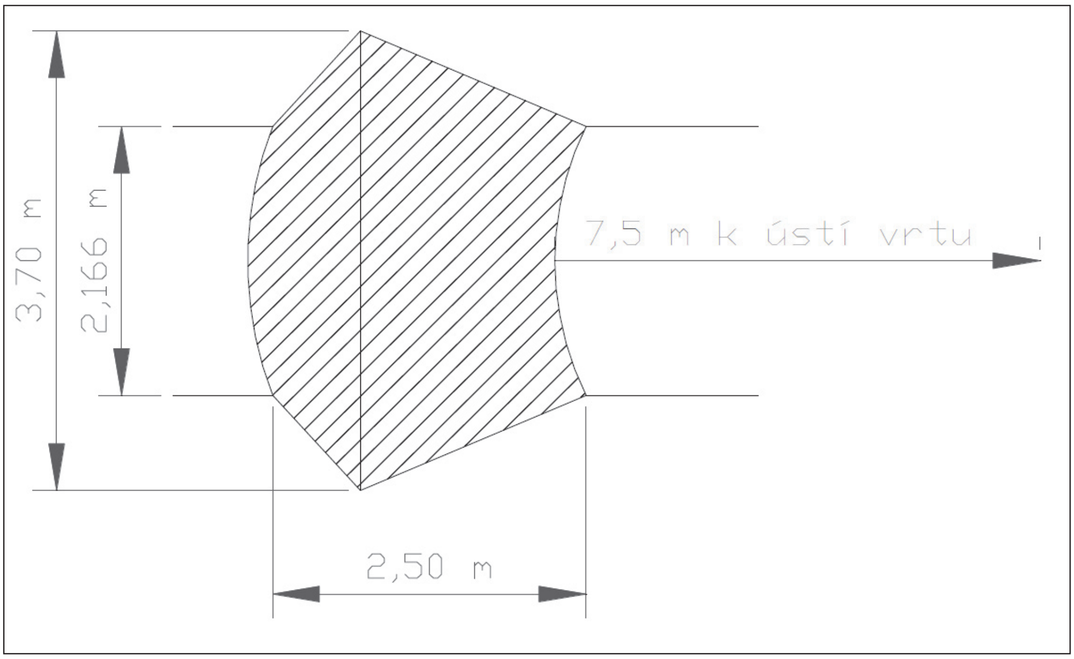

Figure 2.4: Schematic illustration of the Czech deposition tunnel steel-concrete plug (SÚRAO, 2012).

2.2.4 EPSP Experiment 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 2.5):

- 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 is built to be as small as possible to allow the pressure to be readily controlled. The pressure chamber is sealed with a membrane.
- Concrete Walls: Concrete walls (or blocks) are used to facilitate construction of EPSP. Three concrete walls are 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 is one of the sealing components in EPSP and is constructed using sprayed glass fibre concrete. Measurements and observations during the experiment demonstrated that contact grouting was necessary. The fibre concrete is of relatively low pH, although the recipe and pH values are to be determined during the detailed design stage.
- The fibre concrete used for the plug is of relatively low pH and contains glass fibre.

- Sprayed Bentonite Pellets: The bentonite pellet zone is 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 is 2-m long.
- Filter: The filter collects 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 similar to the inner plug (i.e., made using sprayed glass fibre concrete) and 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.

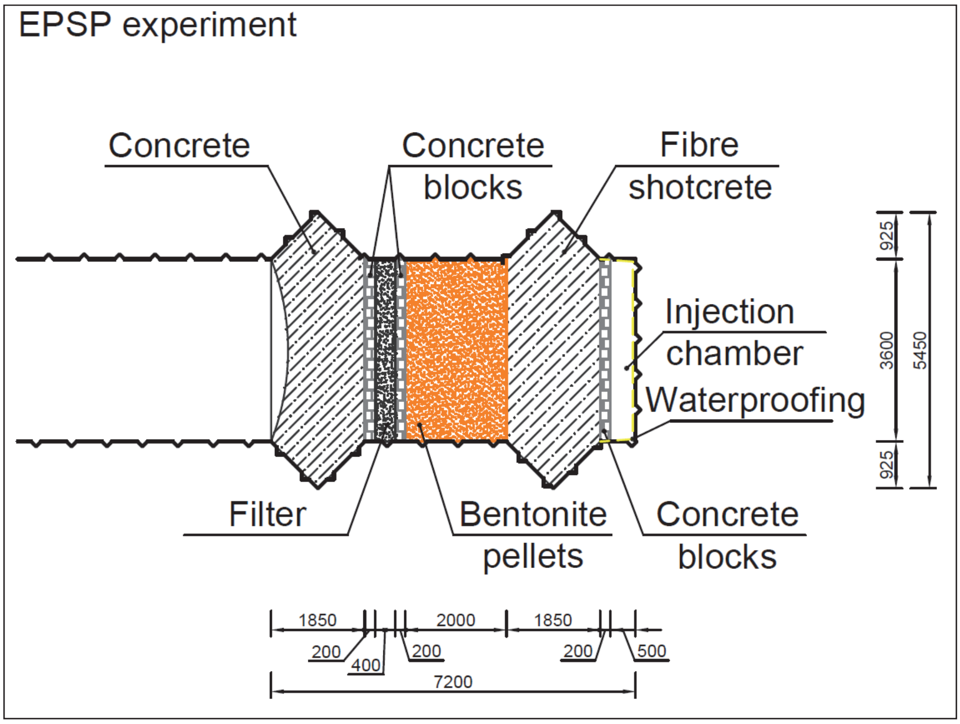

Figure 2.5: Schematic illustration of the EPSP experiment design. Dimensions are in mm. Provided by CTU.

2.2.5 EPSP Experiment Design Basis

The design basis of EPSP is flexible in order to allow the contractor responsible for implementation to respond to experience gained throughout the experiment. Specific issues for investigation are related to requirements such as achievement of target bentonite density, concrete quality (lack of voidage, homogeneity), strength, shrinkage and absence of cracking, and how these can be demonstrated. The experiment must also be carried out in a manner that complies with national mining and environmental safety regulations (White *et al.* 2014).

Some of the more significant requirements on EPSP are:

- The strength of EPSP shall be consistent with withstanding a pressure of 7 MPa to simulate the maximum pressure expected to be developed by the groundwater and the bentonite buffer in the deposition tunnels.
- The temperature in the concrete plugs during the cement curing shall be controlled in order to limit shrinkage and crack formation.
- The design life of the components of EPSP is 150 years, as the reference deposition tunnel plugs must function through the operational period of the repository.
- The bentonite zone shall use Czech bentonite (Bentonite B75) as this is the candidate buffer material in the reference concept.
- A concrete recipe with a relatively low pH shall be used for all the concrete and shotcrete components to develop further understanding of these materials.
- Fibre shotcrete shall be used for the inner and outer concrete plugs to limit crack formation and to improve the strength of these structures without using pre-emplaced reinforcement.

2.3 SKB's Deposition Tunnel Plug Design Basis

2.3.1 SKB's Deposition Tunnel Plug Safety Functions

The KBS-3V method is proposed by SKB in their application for a construction licence for the disposal of spent fuel packaged in copper canisters with cast iron inserts in a crystalline host rock. The post-closure safety principles are based on isolation and containment of radioactive waste through the choice of a stable geological environment at depth and through the use of a multi-barrier system consisting of engineered barriers (canister, buffer, backfill, and plugs and seals) and the host rock. The canisters are emplaced in vertical deposition 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 2.6).

Deposition tunnel plugs in the SKB repository have several 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 the buffer and backfill.

SKB's design basis for deposition tunnel plugs is still under development, and this list represents the status at the start of the DOMPLU experiment.

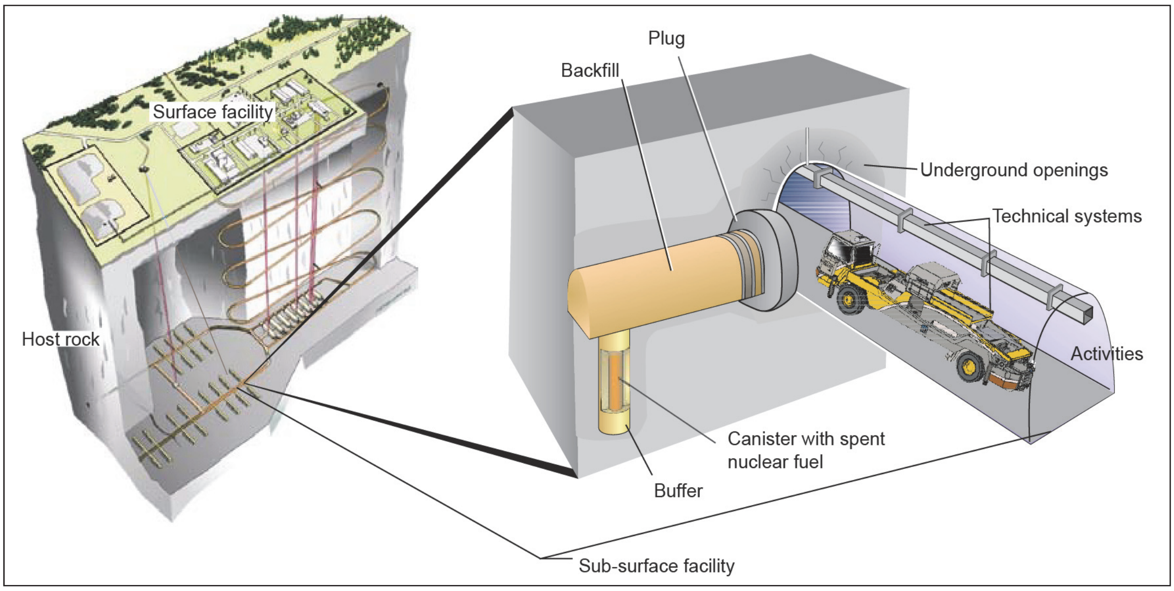

Figure 2.6: The KBS-3V repository and the location of the deposition tunnel plug (SKB, 2010a).

2.3.2 Process used by SKB to Develop the Deposition Tunnel Plug Design Basis

The design basis for deposition tunnel plugs has been in development for many decades, driven by the learning gained from more detailed knowledge on the repository site conditions and from full-scale experiments and laboratory tests in Sweden and elsewhere. These experiments have been undertaken in collaboration with Posiva (Finland) and have also fed in to the development of the reference deposition tunnel plug in the Posiva disposal concept.

The need for a plug at the entrance of a deposition tunnel was recognised at an early stage of the Swedish programme as a means of maintaining the backfill in place and having a compartment which has a higher water head than the open galleries in the repository. Different designs have been tested in previous full-scale experiments, including:

- The Stripa mine tunnel plugging experiment in the 1980s (Gray, 1993).
- The Äspö Backfill and Plug Test in the 1990s (SKB, 2005).
- The Äspö Prototype Repository in the 2000s (SKB, 2005).
- A compartment plug test for the horizontal emplacement concept, KBS-3H, in 2005 (SKB, 2012).

A simple design of a plug was tested in the Stripa mine in Sweden as part of the Tunnel Plugging Experiment in the 1980s. An O-ring of bentonite was introduced into the design after this experiment, and was tested in the Backfill and Plug Test at the Äspö HRL in the late 1990s and early 2000s. The O-ring did not perform as intended, as leakage of water was found to be quite high. Subsequent to these experiments, the Prototype Repository, incorporating two plugs, was built at the Äspö HRL, beginning in 2001. Unlike previous experiments, both concrete plugs were cast with self-compacting concrete (SCC). As part of the EC ESDRED Project (Alonso *et al.*, 2008), a low-pH shotcrete plug was tested for horizontal emplacement of disposal containers. Significant water leakage was observed at the bottom of the plug. Another experiment from which valuable experience was gained is the Canadian Tunnel Seal Experiment (TSX) (Martino *et al.*, 2007). Very small seepages of water through the concrete plug and bentonite seal were measured in this experiment.

SKB manages requirements using a hierarchical system based on the V-model. General Principles govern how requirements are developed and managed by SKB. They include national laws and regulations governing disposal of spent fuel, stakeholder requirements, and the host rock conditions and constraints. The safety functions of a deposition tunnel plug are then defined to comply with these requirements before more detailed design specifications are developed.

The requirements are stored in an electronic database or requirements management system (RMS). One SKB staff member is responsible for managing the database and its structure. The responsibility for the database content lies with staff members responsible for engineering and safety analysis. A series of Production Reports that provide design premises for the licence application have been produced by SKB. These reports present how the Swedish repository based on the KBS-3V method is designed and constructed (e.g., SKB, 2010a).

2.3.3 Deposition Tunnel Plug Reference Conceptual Design

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 2.7):

- Concrete Plug: The reference concrete plug is a dome-shaped structure made of low-pH reinforced concrete. The term "low-pH concrete" is used by SKB to refer to concrete generating leachate with a pH of less than 11 (see Section 3.2.4 for information on how other WMOs define the term low pH). 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 pre-stress the concrete dome before contact grouting. The function of the concrete dome 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. 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 function throughout the operational period (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.

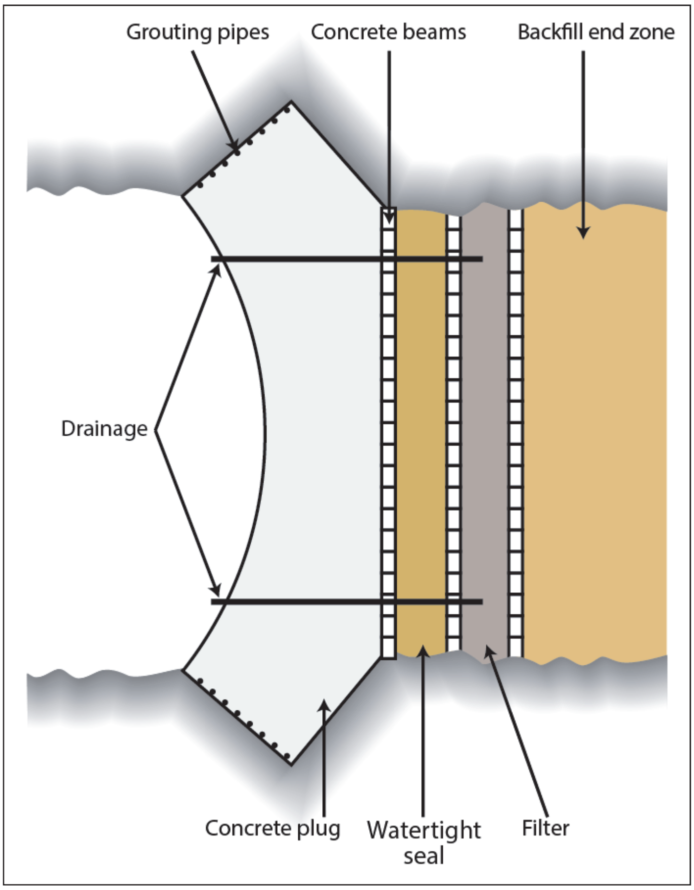

Figure 2.7: Schematic illustration of the deposition tunnel plug components in SKB's reference conceptual design (SKB, 2010b). There are three concrete beams in the conceptual design; these are sometimes referred to as the inner, middle and outer concrete beams or delimiters, with the inner concrete beam being adjacent to the backfill end zone.

2.3.4 DOMPLU Experiment Design

A schematic illustration of DOMPLU is provided in Figure 2.8. DOMPLU represents a detailed iteration of the reference design 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 low-pH concrete instead of reinforced low-pH concrete for the concrete dome. The use of an unreinforced structure was proposed in Malm (2012). The reason for using unreinforced concrete in DOMPLU is to test whether this solution can be adopted in the reference design. Malm (2012) concluded that the dome plug is strong enough without reinforcement, that reinforcement has some undesirable properties (e.g., potential for cracking due to autogenous shrinkage and the corrosion of the reinforcement), and cost and time implications during construction of the 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 (towards the backfill) delimiter is considered to be part of the filter. Instead of concrete beams, porous light-weight expanded concrete aggregate (LECA®) beams and gravel with high hydraulic conductivity 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 as this is considered sufficient for the planned lifetime of DOMPLU (710 mm is used in the reference design).
- 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. In the reference design, compaction of the filter was presumed, but this turned out to be impractical and not useful for the grading chosen for the filter material. The result is of course a larger compression of the filter by the swelling pressure, which has to be taken into account in the design of the transition zone.

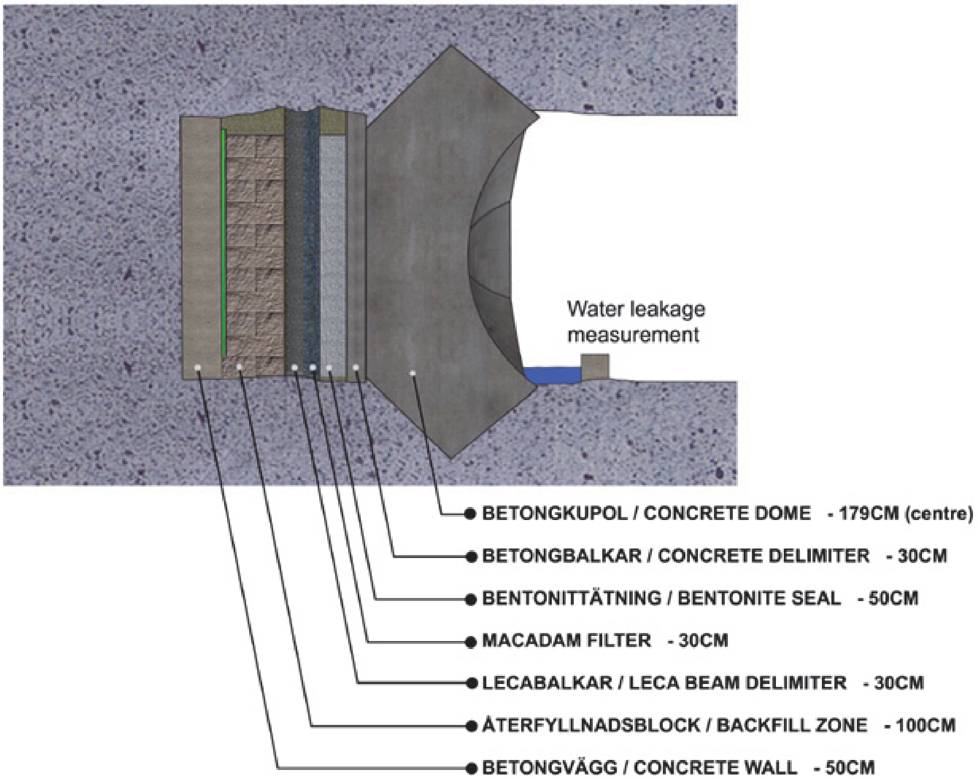

Figure 2.8: Schematic illustration of the DOMPLU experiment design (Malm *et al.*, 2014).

2.3.5 DOMPLU Experiment Design Basis

In the initial stages of the DOMPLU Project, a sub-project was formed to manage requirements on the plug by analysing basic knowledge and the current reference design. Specific requirements to be used for the DOMPLU set-up were then prescribed in two internal memos – a memo with requirements for the plug location and a memo describing design criteria for the DOMPLU plug structure (Palmer, 2011). These requirement memos were reviewed and approved before the go-ahead was given for the project to start. The development of the DOMPLU design took approximately one year and involved knowledge sharing and coordination between cross-functional areas (rock, concrete, clay, etc.).

Development of the DOMPLU design basis has been driven by the need to determine and define water tightness and plug production requirements. In addition to this, material specifications have been modified with respect to requirements driven by the needs of post-closure safety, e.g., the exclusion of steel reinforcement. None of the previous full-scale concrete plugs have been subjected to the expected hydraulic pressure of water and swelling pressure of bentonite expected in real repository conditions. The requirements of the plug system have changed over time and this has meant that previous experiments used different materials to the ones currently envisaged in the DOMPLU design.

The design basis for the reference deposition tunnel plug in the Swedish concept is divided into three phases:

- The Production Phase, including Construction and Curing: This phase comprises the installation and the period until the plug has gained full strength. The main installation considerations in this phase are for the plug to be prepared and installed with high reliability, at the prescribed rate, using well–tried and tested techniques, and in a cost-effective manner. In the curing period, the design of the deposition tunnel plug must ensure that the full pressure against the concrete plug does not appear until it has fully cured and gained sufficient strength. This is achieved by provision of the drainage pipes.

- The Sealing Phase: This phase refers to the period from the end of the production phase until the time when the adjacent main tunnel to the plug is filled and saturated. The functions of the plug during this phase are to resist the hydrostatic pressure and swelling pressure of the backfill until the main tunnel is filled, to limit water flow until the main tunnel is filled and saturated, and to be durable. The function of the plug during operation is necessary to ensure the post-closure safety functions of the backfill and the buffer are met. This especially relates to the hydraulic tightness requirements of the plug. Further, it may take a long time before the outer part of the tunnel saturates after closure (of the order of 100 years), and the plug must remain tight during this period also.

- The Post-closure Phase: This is the phase after installation of the closure when the plug is left in the closed repository. Deposition tunnel plugs have no post-closure safety function in the Swedish repository, but they must not significantly impair the barrier functions of the other engineered barriers or host rock. This requires the use of low-pH concrete in the dome, that there is not a significant reduction in volume, and that materials that can be harmful to the engineered barriers are not introduced in significant quantities.

The design basis for DOMPLU is established around the design basis for the reference deposition tunnel plugs. As DOMPLU has been constructed, it can be presented in a more detailed fashion than the reference plug design. For example, there is no quantitative requirement on the rate of water leakage through the plug in the reference design basis. However, the results of DOMPLU will be used to define a leakage rate for application during the operational period of the repository. Recent analyses have proposed a maximum leakage of <0.1 l/min past the plug (Börgesson *et al.*, 2015). The DOMPLU design requirements and specifications (also called design criteria, Palmer 2011) are grouped as follows:

- Experiment site and how to choose the specific plug location (characterisation): the strength and properties of the rock in the area of the recess with the concrete dome have to be suitable for construction. This means that long fractures should not be present at the plug location to prevent leakage of water.
- Rock excavation method: this requires that the rock surfaces connecting the concrete dome abutment to be free from excavation damaged zone (EDZ) and smooth. The rock excavation method recommended is wire-sawing. This is an example of using a design solution as part of the design basis.
- Functional requirements: this includes a requirement for small leakage of water through the plug, although no specific value for the rate of water leakage has been assigned. Another important functional requirement is the use of a transition backfill zone so that the backfill swelling pressure is reduced from ~6-10 MPa to ~2 MPa.
- Geometrical requirements: these include requirements on the tunnel dimensions, concrete dome geometry, and the shape of the excavated slot.
- Material properties for all plug components: including the filter material, bentonite seal, the delimiters, concrete dome, drainage pipes, cooling pipes, and grouting pipes. Low-pH concrete based on the B200 recipe (Vogt *et al.*, 2009) is used for the concrete dome.
- Load cases: a nominal design value of 5 MPa for water pressure and 2 MPa from backfill transition zone is assumed[1].
- Design of the experimental set-up including the control programme and data to be recorded.

The requirements in the DOMPLU design basis deal mostly with scientific and technical considerations, but other requirements, such as the constructability (the ability and ease to construct in a constrained environment), robustness, durability, cost-effectiveness of the structures, the construction methods deployed underground, and the overall repository conditions, are also included.

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[1] One of the objectives of the DOMPLU experiment was to test the plug at the reference load case value of 7 MPa. Since the development of a full swelling pressure in the seal is predicted to take many years, the plan was to achieve this load for DOMPLU by injecting water from the pressurisation system. However, the full water pressure of 7 MPa could never be reached due to conditions of the surrounding rock at the experimental site. Soon after the pressure of the injected water exceeded the groundwater pressure at the experimental site (approximately 3 MPa), a main water escape was discovered in a fracture by-passing the plug to the main tunnel. Despite the promising results from the hydro-tests in the pilot-borehole of the experiment tunnel, water escaping into the rock had been recognized as one major project risk since the rock at Äspö HRL is significantly fractured. Owing to the water flow through the fracture, it was decided to limit the water pressure in the plug to 4 MPa and perform continuous measurements of the observed leakages at this level.

2.4 Posiva's Deposition Tunnel Plug Design Basis

2.4.1 Posiva's Deposition Tunnel Plug Safety Functions

The spent fuel disposal concept in Posiva Oy's construction licence application is based on KBS-3V, the same as the SKB method described in Section 2.3.1. The post-closure safety principles are based on the use of a multi-barrier system consisting of engineered barriers and the host rock. The 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 isolation and containment against the release of radionuclides from spent fuel.

In Posiva's facility description, materials that will be used to fill underground openings (e.g., deposition tunnels, other tunnels and shafts) created during the excavation of the underground disposal facility belong to the backfill and closure systems. The backfill sub-system consists of the backfill and plugs in deposition tunnels. 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 term "deposition tunnel plug" is used in this report for consistency with the terminology used for the DOMPLU experiment).

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 deposition tunnel 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.

2.4.2 Process used by Posiva to Develop the Deposition Tunnel Plug Design Basis

The development of the design basis for Posiva's deposition tunnel plug has used the regulations for final disposal of spent nuclear fuel as a starting point. These regulations are based on the need to secure post-closure safety, operational safety, environmental aspects and national interests.

As mentioned in Section 2.3.2, a great deal of learning has been gained from large-scale experiments carried out as part of the cooperation between Posiva and SKB. The experience gained has been used to further develop and improve the design basis of deposition tunnel plugs in both Sweden and Finland.

The Posiva reference conceptual design of the deposition tunnel plugs has been based on a wedge-shaped structure since 1999 (Haaramo, 1999). Further consideration of the design basis, and the advantages and disadvantages of five types of plug design were provided in a study reported in 2009 (Haaramo and Lehtonen, 2009). The types of plugs considered were a straight plug, a butt-shaped plug, an irregular-shaped plug, a wedge-shaped plug, and a dome-shaped plug (Figure 2.9).

Haaramo and Lehtonen (2009) concluded that the wedge-shaped and dome-shaped plug designs were preferred over the other types of plug designs for the following reasons:

- The straight plug and the butt plug require a lot of construction materials relative to wedge-shaped and dome-shaped plugs.
- The butt plug closes the central tunnel preventing further operations being conducted there.
- The irregular plug requires significantly more reinforcement than the other types of plug, and results in an extra curve in the deposition tunnel.

Overall, the wedge-shaped plug was considered to be less technically-challenging than the dome-shaped plug and was therefore adopted as the reference at that time. However, in developing the construction licence application for the Olkiluoto repository, Posiva decided to adopt a dome-shaped plug as the reference because dome-shaped plugs had been successfully tested in the Äspö HRL, whereas no full-scale demonstration of the wedge-shaped plug had been undertaken.

It is expected that further analysis of deposition tunnel plugs will be undertaken during the development of the operating licence application for the spent fuel repository. This analysis will comprise an iterative process involving the design basis, performance assessment, and evaluation of safety to ensure that these aspects of the repository system are updated so that technical feasibility and post-closure safety of the disposal system are demonstrated (see Figure 2.10).

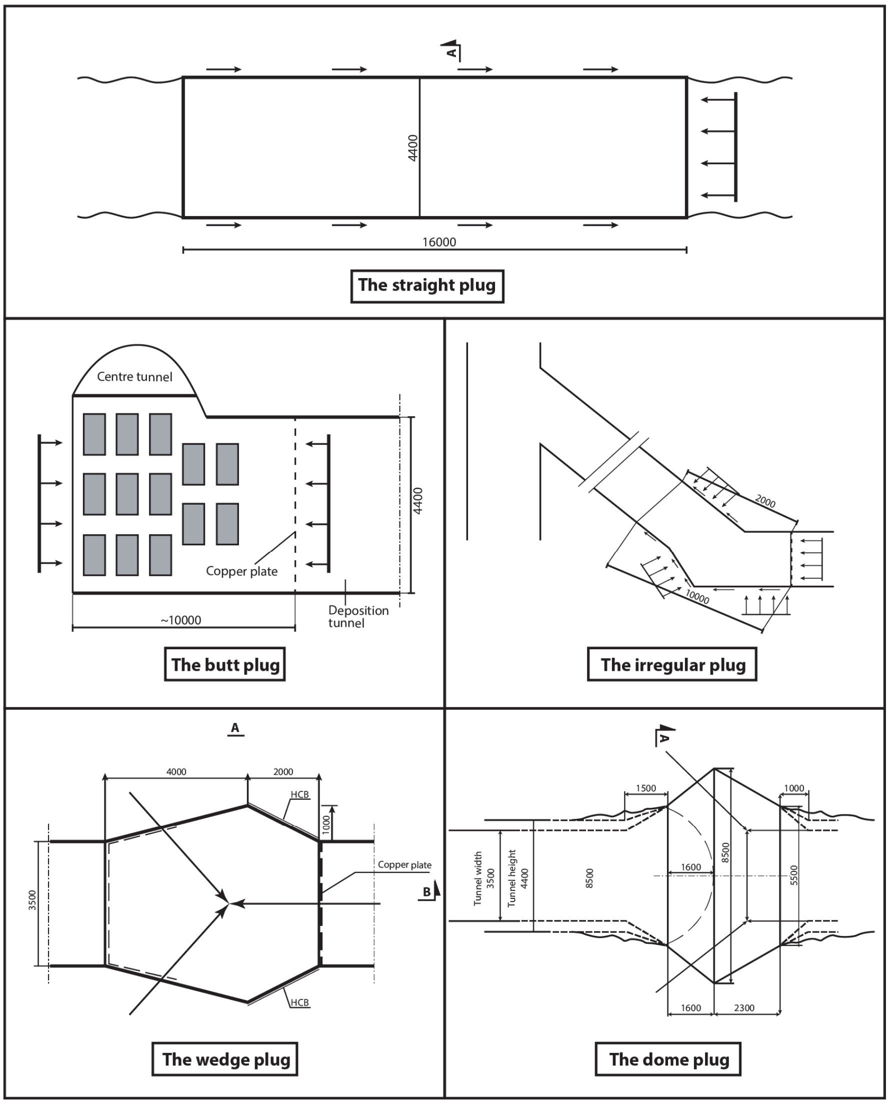

Figure 2.9: The five plug types studied in Haaramo and Lehtonen (2009).

Posiva has worked collaboratively with SKB in the development of an approach to requirements management based on the V-model, and, therefore, has a similar way of structuring requirements. Posiva uses a formal requirements management system (this is referred to in Finnish as Vaatimusten hallintajärjestelmä (VAHA)) to capture and manage requirements related to geological disposal on spent nuclear fuel in Finland. The VAHA system provides a rigorous and traceable method of translating the safety principles and concept to a set of safety functions, performance requirements and design specifications for the various barriers in the disposal system. The design basis of the spent fuel repository is described in Posiva, (2012a).

VAHA requirements have been formulated as a group effort in Posiva with the responsible persons for sub-system development having a large role. Changes to VAHA can be applied by making a “decision guiding requirements” (this is referred to in Finnish as Vaatimuksia ohjaava päätös (VOP)). A VOP application is made using a template that presents the current requirement, suggestions for changes and the rationale for the change. VOPs are presented to the Posiva Technical Group for acceptance. Design personnel take part in the updating of requirements and the change management procedure, and, therefore, requirements management is undertaken in parallel with design development.

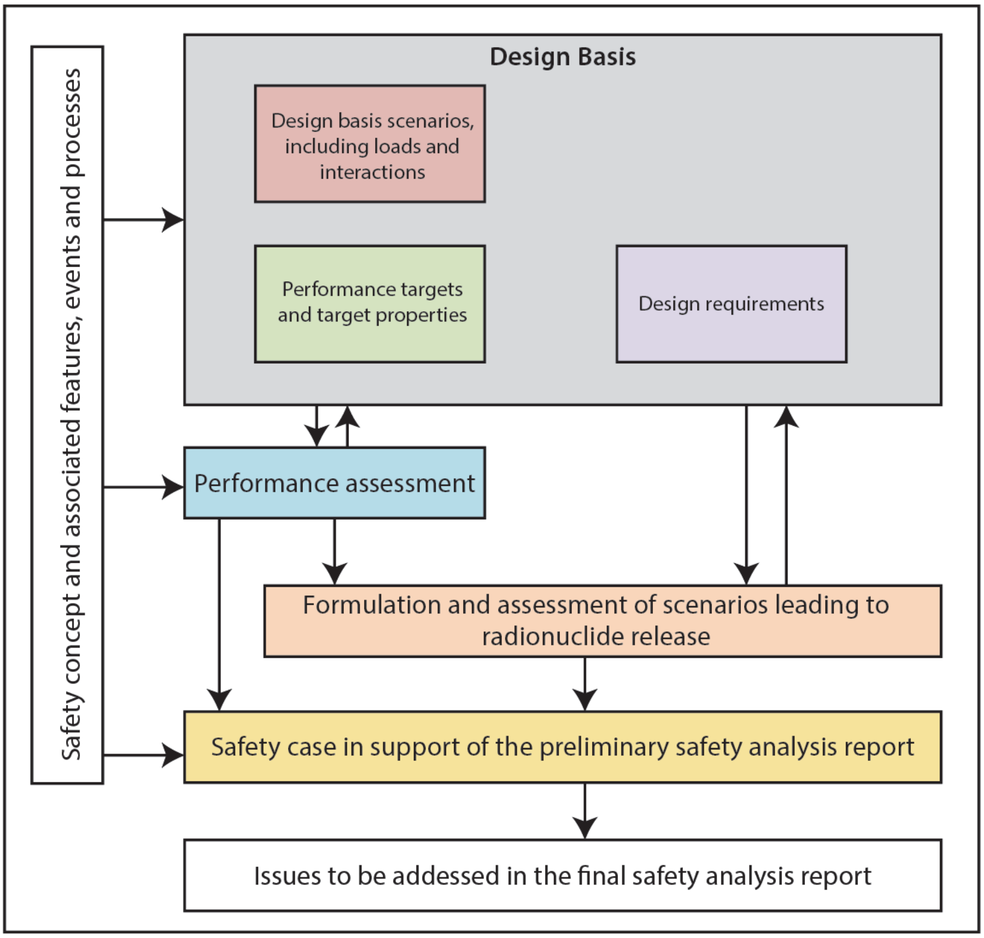

Figure 2.10: Disposal system development in an iterative manner involving performance assessment, evaluation of safety and design basis. Adapted from Posiva, (2012a).

2.4.3 Deposition Tunnel Plug Reference Conceptual Design

The current reference design for the Posiva deposition tunnel plug is the same as that described for the reference SKB deposition tunnel plug (Section 2.3.3 and Figure 2.7) (Posiva, 2012b). However, there will be two variations for deposition tunnel heights depending on the origin of the spent fuel being disposed of in the Posiva repository, which results in two different plug dimensions being used.

The deposition tunnel plug reference design is affected by the requirements set in response to consideration of post-closure safety. Stray materials, water inflow, EDZ and investigation boreholes have been identified by Posiva as features and processes that can have an impact on safety-critical functions. Of these, the presence of stray materials, EDZ, or high rates of water inflow can have direct consequences on the plug design. Plug materials will be approved according to Posiva's guidelines on stray materials. All materials introduced to ONKALO and into the repository will need to be pre-approved and added to a material handbook. Any host rock in which a significant EDZ is present will be removed from the plug site. In the plug locations, any rock support introduced will not use rock bolts, but will, instead use other methods, such as shotcrete or wire mesh.

Design requirements for the deposition tunnel plug state that “the plugs shall be designed to maintain their hydraulic isolation capacity at least as long as the central tunnels are open”, and design specifications state that “the plug shall maintain its hydraulic isolation capacity for at least 100 years”. These requirements are related to plug operational lifetime and technical feasibility. After the deterioration of the concrete, the plug is considered to be part of the backfill, and the safety functions of the backfill provide for the post-closure safety.

Unlike SKB, who plan to implement a water leakage requirement into the design basis of the reference deposition tunnel plug design with the learning gained from DOMPLU, Posiva has no value specified for a water leakage rate through the plug in the VAHA requirements. Posiva considers that it is generally hard to predict an exact leakage rate through the plug and providing the correct value at this stage is not possible. It is also argued that a specific value may be hard to verify practically after installation, especially given the large structure of the concrete plug. A water leakage rate is likely to be set by Posiva in the future.

In POPLU and Posiva's repository concrete structures must be constructed from low-pH materials. However, no specific pH value requirement has been defined for the cementitious materials of the reference plug. Instead, the calcium to silica content ratio is used[2]. Further studies on the impacts of low-pH materials are on-going.

In addition to plug-specific requirements, the VAHA system also includes requirements on the rock where the plug will be located. These requirements focus on ensuring that there is no continuous EDZ fractures present at the plug location and that hydraulically conductive fractures do not intersect the whole length of the plug.

2.4.4 POPLU Experiment Design

The POPLU design is based on a different concept to that of the dome-shaped reference deposition tunnel plug. POPLU is a wedge-shaped low-pH reinforced concrete structure that is cast in place into a slot that has been notched into the EDZ (Haaramo and Lehtonen, 2009). The differences to the reference design arise from a desire to demonstrate performance of a potentially simpler plug design that can be used in a drier tunnel without high water inflows; such conditions are found in ONKALO (or the Olkiluoto repository). The test is designed to establish whether a potentially simpler design without the bentonite watertight seal is able to fulfil the same requirements as the design applied in the DOMPLU test. The current conceptual design of the POPLU wedge plug is illustrated in Figure 2.11. The design consists of a wedge-shaped concrete structure cast directly adjacent to a filter layer in front of a concrete tunnel backwall. The plug contains grouting tubes and bentonite circular strips at the rock-concrete interface to ensure water tightness.

By providing evidence that a concrete structure with fewer components (e.g., no 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. 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.

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[2] The exact ratio in the current design basis is currently being investigated and is subject to change.

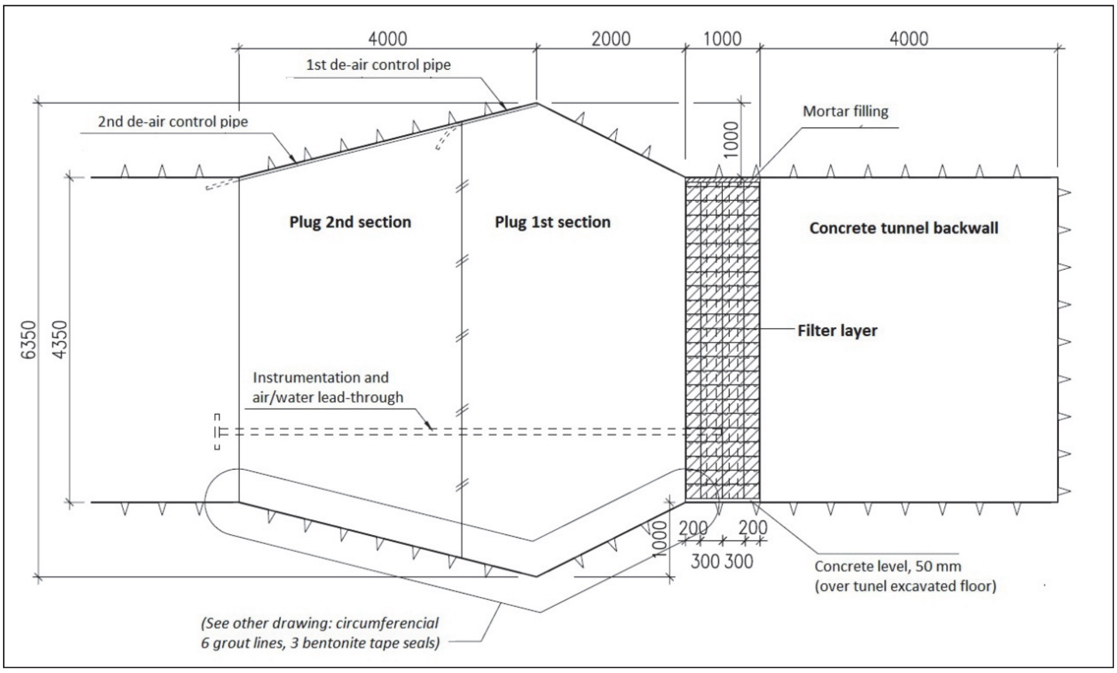

Figure 2.11: Schematic illustration of the POPLU experiment design. Dimensions are in mm (Holt *et al.*, 2016).

2.4.5 POPLU Experiment Design Basis

POPLU designers used information from previous Posiva reports on the wedge plug and the VAHA requirements to develop the POPLU design. The design basis for POPLU is in principle the same as that for the reference deposition tunnel plug. For example, the safety functions of the POPLU plug are the same as those defined for the reference design (Posiva, 2012b), because the POPLU design is made to comply with the post-closure safety requirements in Posiva's VAHA requirements management system. However, there are some significant differences between the POPLU design basis and that of the reference deposition tunnel plug because POPLU is an experiment of an alternative design rather than an implementation of the reference design. Such differences include:

- Amount and types of stray materials (defined as materials introduced into the repository that are not part of the engineered barriers, rock materials or groundwater (Posiva, 2011)): 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 of POPLU will be undertaken to collect data on the performance of the plug.

In addition, part of the design basis of POPLU is to have a similar performance monitoring programme and pressurisation approach as DOMPLU.

Performance assessment also plays a role in the development of the design basis for POPLU. A specific illustration of this role is provided in Figure 2.12. It shows the interaction between performance assessment, requirements and "decision guiding documents" or VOPs (referred to in Finnish as Vaatimuksia ohjaava päätös). VOPs are produced in order to apply changes to requirements in Posiva's VAHA RMS. Figure 2.12 is not a complete illustration of the entire process including all aspects of requirements management, but points out the most important factors affecting the POPLU Project. Although the plug does not have a long-term requirement concerning radionuclide containment, the long-term evolution of the plug could affect the performance of other EBS components and, therefore, requirements on post-closure performance of the plug are included in the design basis.

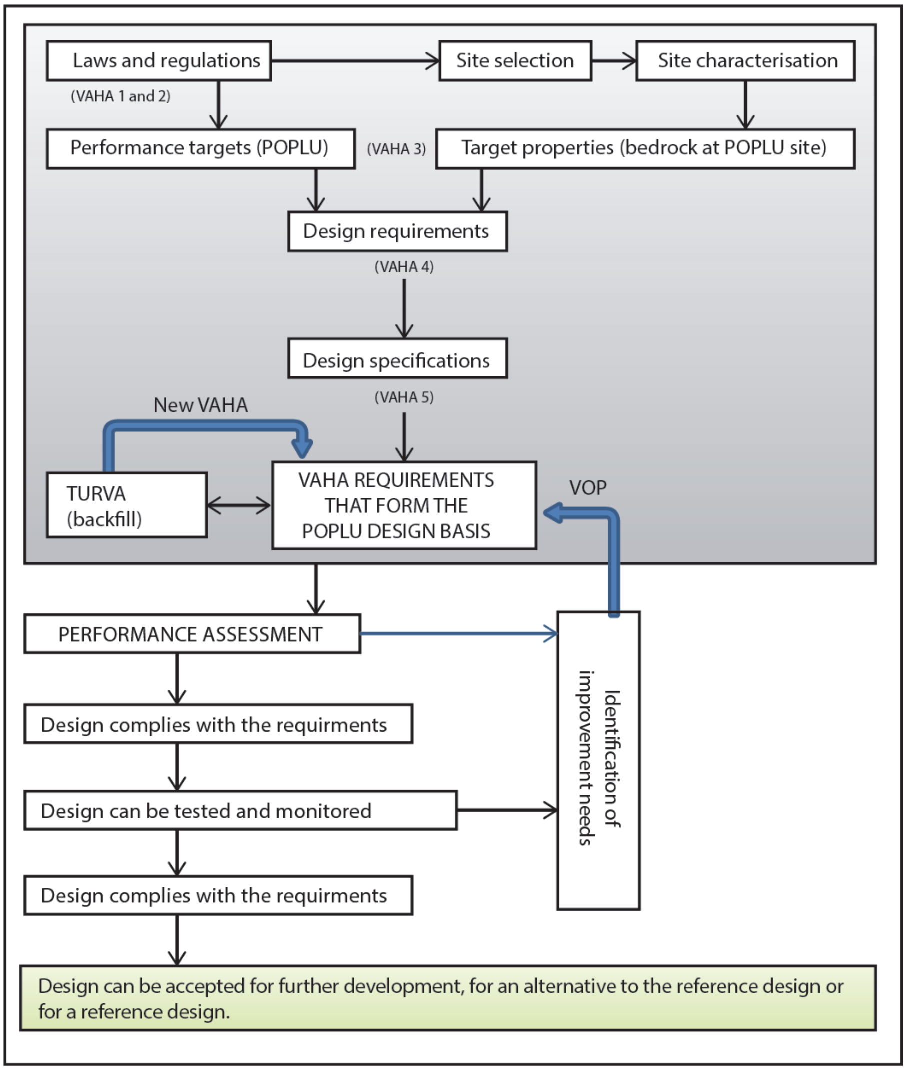

Figure 2.12: Illustration of the process used to develop the POPLU design basis and role of performance assessment. TURVA-2012 is Posiva's safety case supporting the construction licence application submitted in 2012 for the Olkiluoto spent fuel disposal facility. Other acronyms are defined in the text. Figure provided by Posiva.

The 2009 study of different plug concepts for deposition tunnels (Haaramo and Lehtonen, 2009) specified some general and detailed requirements for deposition tunnel plugs using wedge-based structures. These requirements have been used as a basis for developing the current design basis for POPLU (White *et al*. 2014).

Requirements and specifications for POPLU have been set to ensure the fulfilment of the safety functions of the plug. The objective is to meet high-level safety requirements by limiting water flow in the excavated openings, limit degradation of the EBS components (especially corrosion of the canister and the erosion of the buffer and/or backfill), and to minimise any other negative effects that the closure materials might have on other EBS components (e.g., chemical interaction between cement and bentonite).

2.5 German Shaft Seal Design Basis

2.5.1 Shaft Seal Safety Functions

The reference repository concept for disposal of spent fuel, HLW, ILW, graphite and depleted uranium in Germany is based on a repository design for the Gorleben salt dome[3]. A site-specific research project, the Preliminary Safety Analysis for Gorleben (VSG), was conducted between July 2010 and March 2013. The VSG analysis built on a previous safety assessment focused on demonstration of the integrity of engineered barriers (Krone *et al.*, 2008). The repository concept considered in the VSG assumed disposal at a depth of 870 m and a series of 12 emplacement fields.

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 sealing elements and multiple static abutments which absorb the horizontal and vertical rock stress in order to restrict deformation of the seals.

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.

In general, the long-term containment of radioactive waste in rock salt is provided by the host rock, the salt backfill, and the sealing system. The crushed salt backfill compresses over time and achieves a sufficiently low hydraulic conductivity to avoid flow of brine into the repository. Seals must provide their sealing function during the early post-closure phase, until the compaction of the backfill is adequate and the hydraulic conductivity of the backfill is sufficiently low. Research during the VSG Project concluded that the compaction process takes up to 1,000 years. However, to provide defence-in-depth, the functionality of shaft seals is designed to last until the next expected ice age, (estimated to be in 50,000 years in the VSG). After the ice age, hydrogeological and topographic conditions change dramatically and a reliable prediction is not possible. After the next ice age, the main sealing function is provided by the host rock and backfill (Müller-Hoeppe *et al.*, 2012a).

2.5.2 Process used in Germany to Develop the Shaft Seal Design Basis

The development of the design basis for shaft seals in the German programme is based on experience from the mining industry, previous shaft sealing experiments, the VSG, and research into shaft sealing elements.

Experience from the Mining Industry

In Germany, there is comprehensive knowledge on the long-term performance of shaft seals (referred to as shaft *safekeeping*), which is based on the experience gained from the sealing of

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[3] In Germany, other types of rock are also under consideration as potential repository host rocks.

salt and potash mine shafts in the past 90 years. The knowledge is used and developed further in the development of repository shaft seal designs.

The Shaft Sealing Experiment at Salzdetfurth

DBE TEC together with the Technical University of Freiberg participated in the four-year large-scale shaft sealing experiment at Salzdetfurth, Germany between 1998 and 2002. This experiment provided fundamental understanding of bentonite saturation and swelling processes.

The VSG Safety Analysis

A preliminary shaft sealing system has been developed within the scope of the VSG. This has been performed in four steps:

- Step 1: The site-specific boundary conditions for the sealing system were defined. All stratigraphic units were considered and evaluated with regard to placement of individual sealing components. One characteristic of the host rock is the presence of several faults. Sealing elements would be emplaced at all of these locations.
- Step 2: Regulatory and other requirements that have to be met were identified. In particular, new safety criteria for disposal of radioactive waste as well as the recently developed safety assessment concept (Mönig *et al.*, 2012) were considered. In addition to this, results of previous large-scale *in situ* experiments were compiled and evaluated. Based on this evaluation, reference materials were selected for the different sealing elements.
- Step 3: A preliminary design of the sealing system was developed taking into account chemical, mechanical, and hydraulic impacts on all individual components to check whether these impacts could be controlled.
- Step 4: Performance assessment calculations were carried out based on expected component properties in order to determine the effectiveness of the sealing system and to check whether the system as a whole will fulfil its safety functions.

In order to determine the necessary functional period of the shaft seal system, integrated process modelling was performed. As a result of this analysis, the functional period was defined to be 1,000 years (Müller-Hoeppe *et al.* 2012a, Müller-Hoeppe *et al.* 2012b). This period is necessary for the backfill in the repository drifts, access ways and emplacement fields to seal the repository in response to compaction driven by host rock creep.

Research into Shaft Sealing Elements

The Technical University of Freiberg, a partner in the ELSA Project, completed a research project in 2009 (Kudla *et al.*, 2009) to develop specific shaft sealing elements, select suitable materials, and develop a practical solution for implementation. These materials form a basis for current developments of shaft seal concepts.

In Germany, no formal RMS or systems approach has been adopted in the national repository programme. Instead, general regulations, such as the Eurocode standard for geotechnical design EC7 (DIN EN 1997-1), national regulations such as the BMU repository safety requirements and mining law, and an iterative cycle of design and performance assessment are used to define requirements on monitoring and quality management of the construction process, the material properties, and investigation of any potential repository site.

A concept for the demonstration of safety, called the *Safety Assessment Concept*, has been developed (Mönig *et al.*, 2012). The safety concept relies on siting to ensure confinement by the geological barrier, and demonstration of confinement of radionuclides by the waste and the engineered barriers, in particular the drift and shaft seals. The safety concept is captured within a hierarchical structure of protection goals, safety assessment components and safety functions (Figure 2.13). This hierarchy allows a link to be established between the safety functions of the repository components and the protection goals.

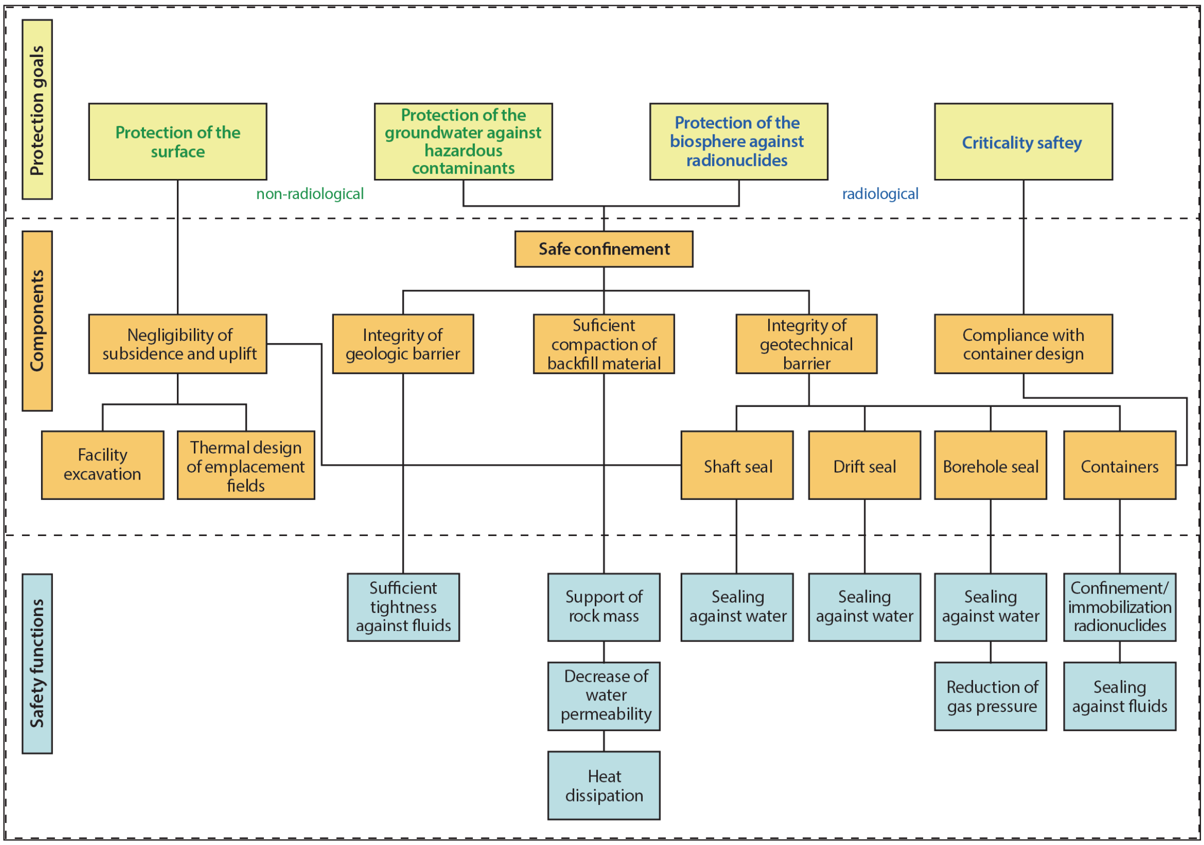

Figure 2.13: Hierarchy of protection goals, safety assessment components and safety functions for the German Safety Assessment Concept. Provided by DBE TEC.

2.5.3 Shaft Seal Reference Conceptual Design

The reference conceptual design for a shaft seal in the German repository programme, which is developed for the site-specific conditions at Gorleben (see Figure 2.14), includes three sealing elements designed to provide a sealing function during the early post-closure phase while the backfill is compacting (at least 1,000 years), and a longer-term sealing element designed to function alongside containment functions provided by host rock and backfill.

The three sealing elements designed to provide sealing during the early post-closure phase consist of different materials to ensure that the performance of the seal system meets requirements. The design of these sealing elements takes into account the different kinds of salt solutions present in the host rock and the need to avoid chemical corrosion:

- 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 at the depth level 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[4] is envisaged. 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.

The long-term sealing element is made of crushed salt. It is located between the two concrete sealing elements. This salt layer compacts and reaches a hydraulic conductivity that is similar to the hydraulic conductivity of the host rock (Müller-Hoeppe *et al.*, 2012a). The functionality of this long-term sealing element is designed until the next expected ice age.

General and specific requirements on shaft seals in the German concept are compiled in Jobmann (2013) and Kudla *et al.* (2013) and include:

- Requirements pursuant to safety assessment concepts.
- Requirements in accordance with the engineering verifications of functionality.
- Requirements derived from site-specific boundary conditions.
- Requirements derived from other specifications.

Design specifications are derived from applying a compliance assessment methodology. Checking a preliminary seal design concept and modifying it until compliance with standards and regulations can be achieved yields a detailed design which meets the requirements.

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[4] Sorel concrete consists of a mixture of magnesium oxide (MgO) with magnesium chloride ($MgCl_2$).

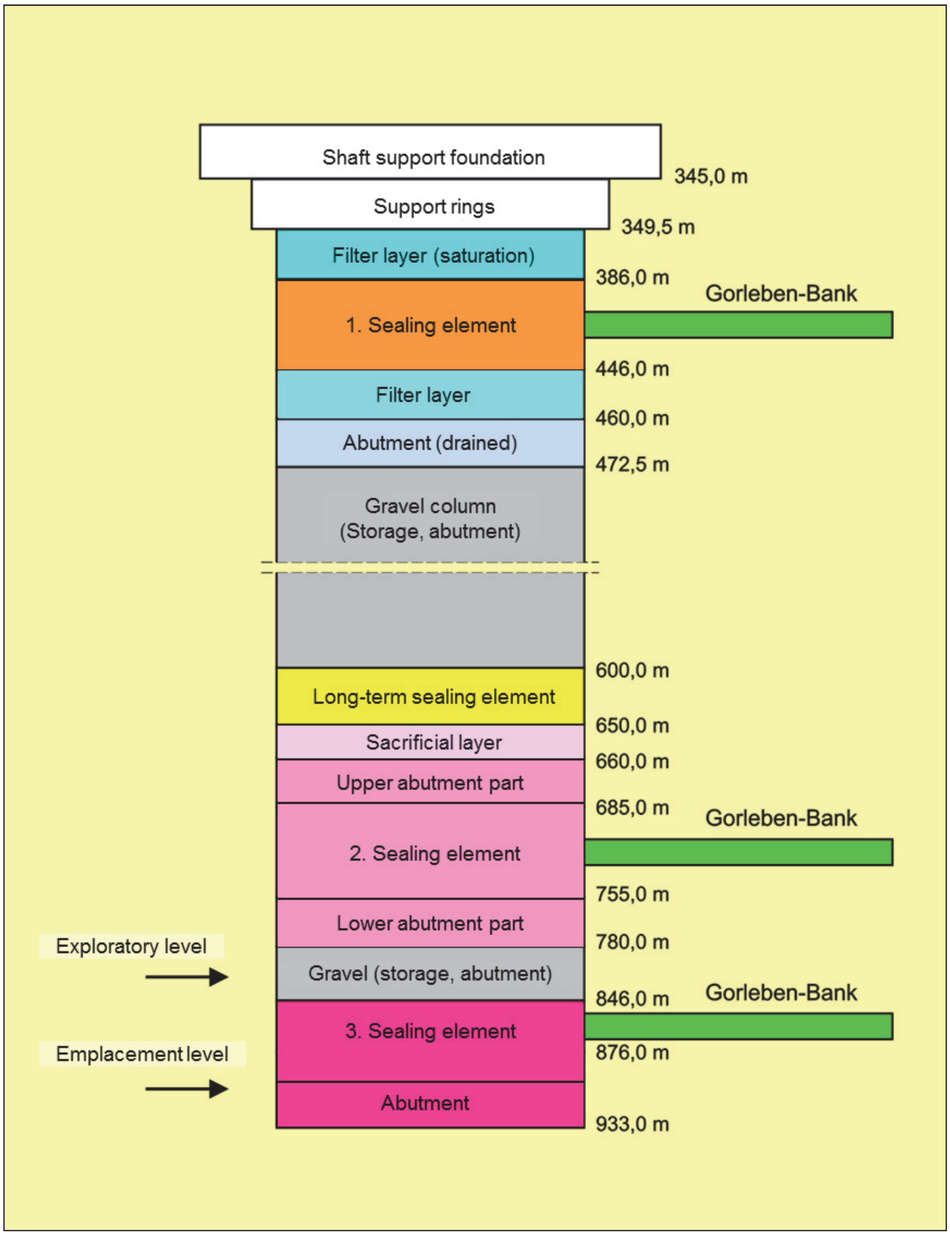

Figure 2.14: Reference conceptual design for the German shaft seal. The Gorleben-Bank is a folded anhydrite layer in the rock salt (Müller-Hoeppe *et al*. 2012a). The Gorleben-Bank is a folded anhydrite layer in the rock salt.

2.5.4 ELSA Experiment

The work in ELSA during the DOPAS Project is largely focused on studies that will support the development of a shaft seal 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 in the shaft seal design project.

The detailed objectives of ELSA were to:

- Give a summary of the state-of-the-art in long-term stable shaft sealing systems.
- Provide documentation on how to achieve compliance of a shaft sealing system design with national and international standards and regulations (Design basis analysis).
- Compile boundary conditions for shaft sealing systems in Germany.
- Define requirements for shaft sealing systems in Germany.
- Develop new and modular-based shaft sealing concepts for HLW repositories in Germany sited in both a salt and a clay environment.
- Perform *in situ* tests of specific functional elements (modules) of a reference shaft sealing design or modifications to them (Figure 2.14).
- Develop mathematical models to characterise the material behaviour of specific sealing elements of a reference shaft sealing design or modifications to them.

These objectives have been tackled during the Phases 1 and 2 of the ELSA project (within the DOPAS Project). The objective for Phase 3 (not part of the DOPAS Project) is to perform one or two large-scale demonstration experiments of particular sealing components and adjustment of the sealing concept. The main requirements of the experiment are to demonstrate technical feasibility and long-term effectiveness. It has not yet been determined which components will be tested within Phase 3 of the ELSA project.

In addition to the above investigations, the laboratory programme of GRS (which is undertaken within the auspices of the LAVA and LASA Projects) address sealing materials planned to be utilised in the shaft seals as well. This laboratory programme provides supporting information to the ELSA project. For example, the programme aims at providing experimental data needed for the theoretical analysis of the long-term behaviour of MgO concrete (Figure 2.14, third sealing element) and cement-based salt concrete (Figure 2.14, second sealing element) in interaction with the host rock and fluids. The data gained will be needed to show the long-term preservation of the required hydraulic conductivity of the seals. The experiments comprise the following mechanical and geochemical investigations:

- Uniaxial multistep creep tests on samples of salt concrete and sorel concrete for the determination of creep parameters.
- Triaxial compression tests on samples of salt concrete and sorel concrete with axial flow of salt solutions (NaCl and IP21) for determination of time-dependent compaction and sealing effectiveness against brines.
- Long-term recompaction tests on pre-damaged samples of salt concrete and sorel concrete under isostatic load with injection of salt solutions (evolution of brine conductivity as the self-sealing indicator).

- Experimental long-term simulations of the systems rock salt/salt concrete and rock salt/sorel concrete using large hollow salt cylinders filled with concrete under varying triaxial load and brine pressure.
- Batch experiments with crushed concrete suited to determine the geochemical path of the alteration until a final equilibrium between material and brine is reached.
- In-diffusion experiments with the concrete and the brine in order to determine the velocity of the alteration in the porous matrix.
- Experiments with the concrete and brine at the contact with the EDZ in order to determine the velocity of the alteration of the sealing material due to advective flow at the boundary with the rock formation.

2.5.5 ELSA Design Basis

During the ELSA Project, it is not intended to implement a full-scale demonstration of the current reference conceptual design of the shaft seal, but to test prototypes of the different sealing elements or modifications to them on a large scale. Therefore, no detailed design requirements or specifications have yet been developed. The experiment design will have to be adapted to the geological and geometrical conditions to be found at the actual testing site, which has not yet been decided.

2.6 Plugs and Seals in Other Countries involved in the DOPAS Project

In addition to the five DOPAS Project experiments, information on the approach to development of the design basis for plugs and seals has been collected from the other programmes represented in the Project, namely the Netherlands (Section 2.6.1), Switzerland (Section 2.6.2), and the United Kingdom (Section 2.6.3).

2.6.1 The Netherlands

The Dutch waste management programme is in the generic phase. There are currently two disposal concepts under consideration: disposal of HLW and ILW in a clay host rock in horizontal tunnels, and disposal in vertical boreholes and large excavated rooms in a salt host rock.

In the Dutch concept, plugs and seals are not explicitly defined. However, the o*utline disposal concept in clay* (OPERA, 2011) states:

> *"A plug is used to hydraulically seal off a disposal drift after emplacement of waste packages. Seals are used to seal the shafts and ramp when the facility is closed."*

In clay host rocks, shaft seals and drift plugs must suppress flow of water through the repository after it has been resaturated with water from the host rock. In salt rocks, shaft and drift seals must ensure that the waste and waste packages remain dry until they are completely isolated by the impermeable rock salt.

2.6.2 Switzerland

It is envisaged that repositories for HLW and ILW will be built in a clay-rich host rock, with two sites currently selected for further investigations (Zürich Nordost and Jura Ost). It has not yet been decided whether one repository will be constructed for both HLW and ILW or one for each type of waste. For HLW, carbon steel disposal canisters will be emplaced horizontally in drifts of ~2.5-m diameter and several hundreds of meter length and several tens of metres apart. Hydraulic seals are foreseen in between each tenth canister and at the end of each emplacement tunnel. For ILW, caverns of 6-12 m diameter are envisaged. The final design option of the caverns strongly depends on the site-specific geological conditions.

In the Swiss repository concept, seals are defined as elements that hydraulically isolate parts of the repository and/or the repository from the geosphere and biosphere. Seals are composed of a sealing element (e.g., bentonite) and mechanical supporting elements (e.g., concrete and gravel). Plugs are defined as temporary mechanical seals, and have no post-closure function.

The following primary functions of the different seal components need to be achieved:

- **Sealing element** (e.g., bentonite, sand-bentonite mixture): suitable materials are chosen ensuring low hydraulic conductivity, high conductivity for gas, high radionuclide retention, and a swelling behaviour to reduce EDZ conductivity after resaturation of the system.
- **Supporting elements** (e.g., concrete, rock blocks, gravel): these provide a mechanical support load to facilitate adequate emplacement of the sealing element, and to protect it from high differential water pressures or gas pressures.
- **Transition layer** (filter layer consisting of gravel and/or sand): this can act as a "buffering of chemistry" layer to avoid or limit chemical interactions between the seal, support material, and backfill material.

In the Swiss concept, requirements on plugs and seals are derived from, and depend on, details of repository design and layout.

2.6.3 United Kingdom

At the current stage of the United Kingdom programme, Radioactive Waste Management Limited (RWM) are examining a wide range of potentially suitable disposal concepts so that a well-informed assessment of options can be carried out at appropriate decision points in the implementation programme. The programme is in the generic phase and considers three possible host rocks: higher-strength rocks, lower-strength sedimentary rocks, and evaporites. RWM has set out illustrative concepts for each of the three host rocks. For example, the illustrative disposal concept examples for higher-strength rocks are based on:

- The concept previously developed in the United Kingdom for ILW/low-level waste (LLW) disposal (Nirex, 2005).
- The KBS-3V method developed in Sweden and Finland for the disposal of spent fuel.

In the United Kingdom, *sealing systems* are defined as engineered seals that will be used to prevent the flow of fluids in excavated tunnels (NDA RWMD, 2010a). Seals may be placed where parts of the rock are more permeable. In addition, the backfill and seals are defined as materials that fill the access ways and emplacement regions of a geological disposal facility and isolate key aspects of it (NDA RWMD, 2010b). Plugs, although not explicitly defined, may be considered as a component of the sealing system, providing mechanical support and resisting the water and seal swelling pressures that will develop.

Although the United Kingdom programme is in the generic phase, some work has been undertaken to identify generic safety functions of sealing plug. These structures shall be designed to (NDA RWMD, 2010c):

- Provide mechanical support to the backfill material in a disposal module and be strong enough to withstand the combined pressure from the groundwater and the swelling of the backfill or buffer materials.
- Limit water flow from a disposal module to the access ways.
- Consider requirements on gas migration from a disposal module to the access ways.

The design of the sealing systems will be developed as the programme progresses and site-specific information becomes available.

The United Kingdom has captured requirements on a geological disposal facility in a disposal system specification (DSS) document.

3 Discussion of the Content of Design Bases for Plugs and Seals

This section provides a discussion of the content of design bases for plugs and seals. This includes the influence of host rock type on the design basis for plugs and seals (Section 3.1), the content of the design basis for plugs and seals in the form of THMCGR-related requirements (Section 3.2), and an analysis and discussion of the differences between the design bases for plugs and seals in different repository concepts, focusing on the different safety functions performed by each plug and seal, and how this impacts on the requirements placed on the structure (Section 3.3).

3.1 Impact of Host Rock on Design Basis

3.1.1 Clay Host Rocks

One seal design considered in the DOPAS Project concerns sealing of the drifts and ILW vaults of a clay host rock in France (FSS). Clay rocks generally have low hydraulic conductivity, and can be plastic and soft. The plasticity and creep properties of most clay rocks contribute to the self-sealing of any fractures that may develop during the construction and operation of the repository. However, these fractures may become reactivated in the presence of high gas pressures (Zhang, 2014). 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 hydraulic conductivities are reached. This is achieved in FSS through the 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 of 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. No time limit is applied to this requirement.

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. In this region, the competence of the rock is such that full removal of the tunnel lining can be undertaken, rather than partial removal as 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 feature has both positive and negative effects. Self-sealing of the near-field host rock (i.e., EDZ) improves the hydraulic performance of the seal over time by reducing the hydraulic conductivity. In addition, development of shear stresses between the near field host rock, concrete containment walls, and the clay core of the seal owing 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. However, the concrete support removal operations may result in rock fall, due to creep, and compromise the safety of workers.

3.1.2 Crystalline Host Rocks

Three plug designs considered in the DOPAS Project concern sealing of the EBS in crystalline host rocks in Sweden (DOMPLU), Finland (POPLU) and the Czech Republic (EPSP). The KBS-3 multi-barrier concept is the reference disposal concept in Finland and Sweden (KBS-3V is the reference adopted by Posiva in Finland and SKB in Sweden, and a concept based on KBS-3H is the reference adopted by SÚRAO in the Czech Republic). DOMPLU and POPLU are testing different designs of deposition tunnel plugs, whereas EPSP is a test of tunnel plug materials and implementation technology.

The KBS-3 multi-barrier concept 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. In the KBS-3V reference design, adopted by Posiva and SKB in their respective construction licence applications, the principal role of the deposition tunnel plug is to hold the backfill in place during operations and to prevent high flows from the backfilled tunnel into the rest of the pumped repository in order to ensure that the bentonite material will not be eroded away from the buffer and the backfill; this is achieved through the use of a strong concrete plug. The other role is to ensure any cracks in the concrete are sealed and the contact with the host rock is tight; this is achieved through the use of a bentonite sealing layer. The concrete composition is chosen to be of low pH in order to limit any potential for deleterious effects caused by interactions between alkaline leachates from the concrete plug and bentonite materials used in the plug, backfill, and buffer.

Owing to the potential for water flow to erode the bentonite backfill in the deposition tunnel and buffer in the deposition hole, the water flux across the plug must be low. The method for providing a low hydraulic conductivity across the deposition tunnel plug is under development. In the DOMPLU experiment undertaken in the Äspö HRL, the design includes 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 hydraulic performance.

Crystalline rocks have a high modulus of elasticity (e.g., Young's modulus) and are relatively brittle compared with clay and salt rocks, where creep is an important mechanical property of the rock. Water-conducting fractures may be present and may facilitate groundwater flow. Plugs should provide a low hydraulic conductivity by ensuring a good contact between the plug and the rock. In competent crystalline rocks, grouting of the interface between the concrete and the rock, following curing and shrinking of the concrete, is frequently used to achieve this. In addition to contact grouting, bentonite strips, acting as sealing bands, can help in meeting the hydraulic conductivity requirements (e.g., Posiva's design of the massive wedge-shaped plug tested in POPLU) or a bentonite watertight seal can be introduced (e.g., in SKB's design of the dome-shaped plug tested in DOMPLU). Successful shrinkage and contact-grouting can also be supported by cooling of the concrete (e.g., as done in DOMPLU).

In the case of crystalline rock, both the host rock and the EDZ[5] have potential to provide groundwater flow paths that could short-circuit the plug. Therefore, the plugs must be keyed into the host rock, and the selection and acceptance of each plug location must be based on criteria established in advance. Typically, the criteria aim at avoiding or rejecting volumes of rock, where natural fracturing might enable formation of hydraulic connections or

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[5] An EDZ can also form in clay and salt host rocks; the significance of which will be dependent on site-specific factors.

groundwater flow paths spanning the entire length of the plug. Further evaluation and development of these criteria are currently being undertaken by Posiva and SKB.

Depending on the rate of groundwater flow, 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 to withstand the pressures.

As the function of deposition tunnel plugs in the crystalline rock concepts is related to operational activities, the design life of the structures is at least 100 years in Sweden and Finland and 150 years in the Czech reference concept. Deposition tunnel plugs do not have any post-closure barrier functions, but they are required to not impair the post-closure safety functions of other barrier system components.

3.1.3 Salt Host Rocks

One seal design considered in the DOPAS Project concerns sealing of the shafts in a salt host rock in Germany (ELSA). 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 owing 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 containers. 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. However, the design life of the shaft seal considered in ELSA is 50,000 years, so that the seal lasts until the next expected ice age.

Materials used in seals in salt host rocks require chemical compatibility with the host rock for the timescales over which they must function. Materials such as salt concrete and sorel concrete are envisaged. Other materials that may be affected by chemical interactions with the salt can be used, for example bentonite, as long as the period over which alteration of the bentonite occurs 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 system, especially within vertical shaft seals, as envisaged in the German concept.

3.2 THMCGR-Related Requirements

The design bases for plugs and seals described in this report have illustrated different approaches to specification of the requirements for similar features and processes that are taken into account. These are discussed below in relation to THMCGR properties and processes.

3.2.1 Thermal Requirements on Plugs and Seals

All plugs and seals may have to withstand specific temperatures owing to their location in a repository. Examples drawn from the DOPAS design bases presented in White *et al.* (2014), include requirements on Andra's drift seals, which have to be located at least 100 m from the nearest HLW disposal cell so that the temperature of the seal does not exceed 50ºC, and requirements on SKB's deposition tunnel plug, which must withstand the thermal loads caused by the rock and concrete expansion during the sealing phase.

Another aspect of thermal requirements on plugs and seals relate to the plug or seal material properties. In the DOPAS design bases, requirements on the maximum curing temperature of concrete components of plugs and seals are specified to limit the development of cracks owing to thermal stress development during hydration of the concrete. For example, the maximum temperature of the concrete and shotcrete containment walls in FSS shall not exceed 50ºC. The DOMPLU design basis requires that *cooling pipes shall be installed and cooling of concrete shall be performed from start of concreting*. A requirement for DOMPLU that the temperature of the concrete during concrete hydration shall not exceed 20ºC was also set. Other approaches do not specify the temperature of the concrete explicitly; instead, qualitative requirements are set to control the temperature during cement curing in order to limit shrinkage and crack formation.

3.2.2 Hydraulic Requirements on Plugs and Seals

The hydraulic function of plugs and seals responds to different safety functions in different disposal concepts. Hydraulic requirements have been specified for all plugs and seals in the DOPAS Project. For the Cigéo repository concept, the hydraulic conductivity of the seal must be equal to or less than 1×10^{-9} m/s, to meet the performance requirement that groundwater flow is predominantly through the host rock. However, the requirement for the swelling clay core currently set in the Andra programme is 10^{-11} m/s. This is regarded as a realistically achievable value, and the current testing programme is evaluating whether this target value can indeed be met.

For the crystalline rock cases, especially the deposition tunnel plug designs developed by SKB and Posiva, the requirement is that the water flow does not lead to piping and erosion of the deposition tunnel backfill and buffer, leading to a hydraulic conductivity of 1×10^{-11} m/s being specified for the plug concrete. This is significantly lower than required to manage groundwater flow across the plug. In addition, requirements on the hydraulic performance of plugs and seals also need to consider the overall flux of water across a plug, including through the (concrete) plug, through the contact zone with the host rock, through the EDZ and through the intact host rock. DOMPLU is investigating the water leakage value that can be achieved for a plug. The target value for the acceptable leakage through the plug is presently adopted to be "*as low as possible*". Recent calculations predicted an allowed maximum leakage of 0.1 l/min to prevent loss of bentonite from the buffer and backfill (Börgesson *et al*., 2015). A water leakage rate has not yet been set for deposition tunnel plugs by Posiva but a rate is likely to be set in the future.

Definition of the hydraulic function is undertaken following an analysis of the main pathways through the plug or seal. For DOMPLU, the experiment design assumed that the main pathways for groundwater flow are likely to be the contact between the concrete dome and the rock and through the EDZ. In terms of the contact zone, the design basis requires that the concrete dome releases from the host rock so that successful contact grouting can occur. This requirement is expressed in the design basis as "cooling should not stop before it is assured that the adhesion between rock and concrete is released along the roof and walls". Meeting this requirement relies on a smooth rock surface (which is produced by wire sawing) and homogeneous cooling of the concrete (which leads to the introduction of cooling pipes in the design). The shrinkage gap that is formed during cooling is grouted, and, owing to the small volume of grout required, it was decided to use high-pH grout. Based on the DOMPLU experience, the exact amounts of the different materials needed for a plug can be derived from the experiment and used to assess and consider if they have any significant effect on the safety analysis. In terms of the EDZ, meeting the hydraulic requirements requires appropriate construction techniques to be employed and the plug to be sited in an appropriate location. Existing requirements on the EDZ call for the region to be free from through-going discontinuities, but this requirement may not be verifiable by existing methods (e.g., imaging using ground penetrating radar). Therefore, further work is required to understand how a verifiable requirement on the hydraulic conductivity of the EDZ can be set – such a requirement would need to be site-specific.

For Andra and SÚRAO, the bentonite in the plug/seal provides a significant hydraulic function. However, the design basis for both experiments recognises that definition of the hydraulic conductivity of the bentonite depends on the density that can be achieved during emplacement. For EPSP the decision has been made to define the density of the bentonite; this is regarded as a practical approach to definition of the design basis. For FSS, the design basis has been defined in terms of the required swelling pressure and hydraulic conductivity, as this has been defined in response to performance assessment studies, although the bentonite dry density will be measured to establish whether the required hydraulic conductivity is achieved. Construction procedures that respond to the requirements in the design basis will define these measurements.

For salt rock, the GRS and DBE TEC shaft seal is required to be "*sufficiently tight*" and the volumetric flow to be "*low*" until creep of the crushed salt backfill has sealed the repository.

3.2.3 Mechanical Requirements on Plugs and Seals

In terms of mechanical performance, a key issue to be considered in the development of a design basis is whether or not a transition zone is required to reduce pressures acting on the principal component of the plug. A transition zone is included in DOMPLU to reduce the swelling pressure loads of the backfill from 6-10 MPa to ~ 2 MPa.

The strength of plugs and seals is specified to withstand the loads on them. The loads can vary owing to the depth of the plug or seal location (e.g., 7 MPa for SKB, SÚRAO and Andra; 7.5 MPa for Posiva). These loads generally include contributions from the hydrostatic pressures at depth as well as swelling pressures from the backfill.

3.2.4 Chemical Requirements on Plugs and Seals

In terms of chemical performance, the issues include the potential for interaction of any cementitious materials with clay materials, in particular the potential for high-pH waters emanating from concrete reducing the performance of bentonite seals and/or clay host rocks, and the possible impact of any harmful substances included as additives in concrete recipes. This has been addressed in all designs by requiring low-pH concrete to be used for all cementitious materials, with the exception of the contact zone grout to be used in DOMPLU.

However, the approach to specifying the chemical performance of cementitious materials for each of the full-scale experiments in the DOPAS Project is different:

- For SKB, there is a requirement that the pH value of concrete in the post-closure phase is ≤11, and the design basis specifies B200 as the concrete recipe that is used in DOMPLU.
- For Posiva, achieving a low-pH is specified in terms of a calcium to silica mass ratio (the value of this ratio is currently under review).
- For SÚRAO, which concentrates on fundamental understanding of materials, a less stringent requirement is set which requires that concrete with a relatively low pH shall be used for all the concrete and shotcrete components. A specific value was not specified for EPSP.

- For Andra, an original specification that required the concrete plugs to have a pH of 10.5 to 11 by 28 days after mixing was found to be quite optimistic during initial testing. This requirement has been modified so that this pH value has to be achieved by 90 days after mixing.

Requirements on the introduction of harmful substances are recognised by Posiva in the POPLU design basis, which states that plug materials shall be selected so as to limit the contents of harmful substances (organics, oxidising compounds, sulphur, and nitrogen compounds) and microbial activity. This is recognised in the other reference designs, but is not a requirement in other experiment design bases, as these experiments are not at potential repository sites.

3.2.5 Gas Requirements on Plugs and Seals

There are no gas permeability requirements for reference designs of plugs and seals represented in the DOPAS Project. Of the DOPAS Project experiments, the only requirements related to gas, are for the gas permeability of the FSS concrete to be measured. However, SKB and Posiva are considering implementation of requirements concerning gas migration through deposition tunnel plugs. Should gas/oxygen migrate through the plug and backfill into the tunnel deposition holes, canister corrosion could be affected. For SKB, a requirement (a new design premise) on gas tightness will be set for the Dome Plug in the future. It is believed that a saturated bentonite seal will efficiently provide a barrier against gas migration. For dry deposition tunnels, the bentonite seal could be saturated by injecting water into the filter via its drainage pipes. This procedure could fulfil any gas-tightness requirement.

3.2.6 Radionuclide Transport Requirements on Plugs and Seals

Most of the reference designs of plugs and seals represented in the DOPAS Project do not have radionuclide containment or retardation functions. DOMPLU, POPLU and EPSP are designed to hold the backfill in place, although a low leakage rate through these structures is required. FSS represents a hydraulic structure with a low hydraulic conductivity to ensure that any radionuclide migration is through the host rock and not through the seal.

For the shaft seal in the German concept, the safety function includes a statement for the seal to "*avoid ... the movement of radionuclides out of [the repository]*". This is also reflected in the requirement to use material with high sorption capacity in the shaft seal components.

For Nagra, the sealing element materials are chosen such that they have, among other features, a high radionuclide retention capacity.

3.3 Comparison of Design Basis Requirements for the DOPAS Project Plugs and Seals

3.3.1 General Comparison

The repository host rock and disposal concept have a significant impact on the design basis for plugs and seals. Deposition tunnel plugs being developed for KBS-3V are focused on keeping the backfill in place. Seals developed for clay and salt rocks can make use of the creep properties of these rocks.

Collation of the design basis of the reference conceptual designs and of the DOPAS Project experiments has highlighted key differences and issues for further consideration with respect to the definition of the design basis:

- Cementitious materials should have low pH; this is defined by a pH target in some programmes and by a calcium to silica ratio in others.
- A great deal of work has been conducted on the density to which bentonite can be emplaced for some of the plugs and seals being considered in the DOPAS Project. Programmes express the bentonite properties at different levels of detail. For some programmes, plug/seal bentonite properties are expressed in terms of the swelling pressure and hydraulic conductivity to be achieved; in others it is expressed as the density of the bentonite.
- For Andra, the seal is required to build up enough pressure, through the swelling of the bentonite core, to meet its performance requirements. For SKB and Posiva, the plug is needed to withstand the existing hydrostatic pressures at depth and the backfill swelling pressure.
- Plugs and seals may be needed to remain intact and perform their primary function for the operational period only (at least 100 years, e.g., SKB, Posiva and SÚRAO) or for post-closure (e.g., 50,000 years for the German shaft seal and throughout the post-closure period for the Andra drift and ILW vault seal).
- Requirements on gas migration may have to be considered for some types of plugs and seals. Other reference plugs not considered in the DOPAS Project do have gas permeability requirements, e.g., the gas permeable seals designed by Nagra in Switzerland (Rueedi and Marschall, 2011).
- Operational issues are important in establishing the design basis. The DOMPLU and FSS experiments recognise requirements related to operational issues. For example, the methods for construction and inspection of DOMPLU shall, as far as possible, be based on experience and established practice from similar applications. As implementation of geological disposal moves closer, operational considerations may become a more significant aspect of the design basis, especially for KBS-3V, where construction of deposition tunnel plugs may need to take account of other underground activities.

3.3.2 Comparison between DOMPLU and POPLU Deposition Tunnel Plug Design Basis

SKB and Posiva have both submitted a construction licence application in the last few years based on the KBS-3V method, and have the same reference design for deposition tunnel plugs (i.e., the dome plug). However, the DOMPLU and POPLU experiments are testing different designs of the deposition tunnel plug. This is primarily driven by a desire to assess a different type of plug to the reference design, especially one that might be constructed using simpler methods.

Although the high-level requirements on DOMPLU and POPLU are the same (i.e., the plugs shall keep the backfill in place during the operational phase, they shall isolate the deposition tunnels hydraulically, and the chemical composition of the plugs shall not jeopardise the performance of the backfill, buffer and canister), the more detailed design basis is different.

The differences between DOMPLU and POPLU are mainly driven by Posiva's desire to test an alternative to the reference deposition tunnel plug design. The purpose of this alternative design is to:

- Evaluate whether the previous Posiva reference wedge design is still valid.
- Evaluate if an alternative design could be added to the reference design to provide flexibility during implementation.
- Evaluate if a simpler design could be introduced.

Other significant differences between the DOMPLU and POPLU design bases are as follows:

- For POPLU, it has been proposed to use stainless steel reinforcement, which means that there is no need for cooling pipes to manage the shrinkage of the concrete structure during curing. The DOMPLU design adopted cooling pipes and no reinforcement based on site-specific conditions and consideration of the overall conceptual design. For the specific case of DOMPLU, the arguments in favour of using cooling pipes and no reinforcement were that this approach would:
    - Minimise the risk of thermal cracks developing in the concrete.
    - Improve the effectiveness of contact grouting.
    - Be cost efficient.
    - Would be efficient in terms of construction time.
- POPLU is implemented in ONKALO, which has strict requirements on the use of materials, owing to its future development as part of the repository. In particular, this means that superplasticisers that incorporate polycarboxylates cannot be used in current concrete recipes (Andersson *et al*., 2008). An example is Glenium 51, a superplasticiser that is not allowed in ONKALO, but is used at the Äspö HRL as part of the B200 concrete recipe.
- SKB plans to implement a water leakage requirement into the design basis of the reference deposition tunnel plug design with the learning gained from DOMPLU. Posiva currently has no value specified for a water leakage rate through the plug in the VAHA requirements but a rate is likely to be set in the future.

Nonetheless, in order for the results of the experiments to be compared, the design basis for performance monitoring of POPLU is as close as possible to the performance monitoring plans of DOMPLU and the pressurisation steps will also be similar.

With respect to the Posiva and SKB reference deposition tunnel plugs, the principal difference is the manner of presentation of the design basis. SKB has divided the design basis into three phases related to the production phase (which includes construction and curing of the concrete dome), the sealing phase and the post-closure phase. Posiva does not divide their requirements in the same manner in their RMS. The difference in presentation of these phases makes a comparison of the design basis details difficult. In addition, the safety function requirements on Posiva's deposition tunnel plug are integrated with the safety function requirements on the deposition tunnel backfill (Posiva, 2012b), whereas the safety function requirements on SKB's deposition tunnel plug are expressed separately to the safety function requirements on the deposition tunnel backfill.

However, these are only presentational issues, and the requirements on the reference designs are essentially the same. These include the identification of the main components of deposition tunnel plugs (concrete dome, bentonite seal and filter layer), the operational lifetime (at least 100 years), and the requirements for low hydraulic conductivity, low pH and low organic content in the plug materials. There are differences in the presentation of these last three requirements.

4 Strategies for Demonstrating Compliance of Reference Designs with Design Basis

This section describes the approaches to demonstration of compliance of the reference designs of plugs and seals to the design bases. Information on these approaches was compiled through responses to a questionnaire that was completed by WMO partners. Much of the work in the DOPAS Project is focusing on the specific plugs and seals under consideration in the experimental programmes (deposition tunnel plugs for DOMPLU and POPLU, general tunnel plugs for EPSP, drift and ILW disposal vault seals for FSS, and shaft seals for ELSA), and the majority of information and discussion on compliance strategies is based on the strategies WMOs are adopting for these plugs and seals. This is because WMO compliance strategies are most highly developed for these plugs and seals. However, the discussion and conclusions are also relevant to other types of plugs and seals.

More detail on the compliance strategies discussed in this section is provided in the WP2 Task 2.3 report (White and Doudou, 2015).

4.1 Strategies for Demonstrating Compliance of Designs with Safety Functions

All WMOs in the DOPAS Project use similar generic approaches to demonstrate compliance of plug and seal designs to the safety functions contained within a design basis. Some organisations focus on a particular approach more than others, but, generally, demonstrating compliance uses a set of similar methods. These methods are discussed below.

Full-scale testing is the main strategy adopted by WMOs to compliance demonstration of plugs and seals. Major full-scale compliance demonstration experiments are planned by Posiva (the Full-scale *In Situ* System Test (FISST)) and Andra (Industrial Pilot) as part of the licensing process. DOMPLU currently represents the main compliance demonstration test for deposition tunnel plugs in the SKB programme (although there may be a need for additional compliance tests in the future). DOMPLU is the latest in a sequence of full-scale plug tests undertaken by SKB working in collaboration with Posiva (see Section 2.3.2).

ELSA includes a full-scale experiment to be conducted after the completion of the DOPAS Project, but further site-specific full-scale experiments will be conducted in Germany following siting. Full-scale experiments will also be undertaken in the Czech Republic. Full-scale experiments include demonstration of technical feasibility, tests of performance, and combined technical feasibility and performance tests.

The German programme has developed a quantitative approach to compliance demonstration, where specific requirements are demonstrated to have been met by means of “assessment cases” (or load cases) in which the loads on a structure are compared to the ability of a structure to perform under the induced loads, with uncertainty accounted for by the application of a safety coefficient (referred to sometimes as a *partial factor*). This approach is a semi-probabilistic, reliability-oriented concept, and is based on the internationally recognised Eurocodes (EC-JRC, 2008). The Eurocodes contained in ten European standards, with each of these codes consisting of several parts. This quantitative approach is described further in White and Doudou (2015) and Herold and Müller-Hoeppe (2013).

WMOs have different views on the use of construction procedures for compliance demonstration. Posiva regards documentation of construction procedures as one of two principal elements of the compliance strategy (the other being monitoring, see below). Full-scale testing, as discussed above, is used to support development of the construction procedures. SKB considers construction procedures to be part of quality control rather than compliance demonstration. Andra's approach is that construction procedures are defined to be consistent with the design, and, therefore, are *a priori* compliant with the design basis.

Monitoring can be used to provide additional information on the performance of plugs and seals during repository operation, and thereby provide confidence in the evolution of the plug/seal post-emplacement. WMOs have adopted different approaches to the use of monitoring as part of compliance demonstration strategies for plugs and seals. SKB has not made any final decisions on how to monitor deposition tunnel plugs, but any monitoring undertaken will be done in a manner that does not significantly impair the performance of the repository. Such monitoring may include water leakage measurement and water pressure control inside the filter. Posiva expects to monitor deposition tunnel plugs, although no specific details are available at present. In contrast, detailed illustrations of shaft seal monitoring have been developed in Germany (White, 2013), involving the use of monitoring levels positioned at the interfaces between the elements of the shaft seal. Monitoring of the shaft seal may include parameters such as total pressure and pore pressure. Monitoring of shaft seals in the German programme will extend into the post-closure period and may continue for a couple of years after closure (as required by regulations). Monitoring in the French programme is mainly focused on demonstration of retrievability of waste from disposal cells; no firm plans for monitoring drift seals have been developed.

Other approaches to building confidence in the performance of plugs and seals are generally considered to be part of the design development process rather than compliance demonstration. These include research into long-term material performance, small-scale testing, numerical modelling, and potential use of complementary arguments based on natural analogue information.

4.2 Strategies for Assessing Compliance of Designs with Specific Design Requirements and Design Specifications

In addition to high-level strategies for demonstrating compliance of designs with the safety functions contained in the design basis, work in the DOPAS Project has addressed strategies for demonstrating compliance of designs with detailed aspects of the design basis, especially design specifications. This work has been undertaken in WP4, and is reported separately in DOPAS (2016b). However, this work is related to the iterative development of the design basis, which is discussed in the next section of this report, and is therefore summarised here.

To assess the compliance of the DOMPLU and FSS experiments with the requirements in their corresponding design bases, an approach that involves a review of each requirement (or condition) in the design basis and the strategy used to demonstrate compliance against that requirement (or condition) was implemented. The development of the compliance strategy statements in this way allowed for a reconsideration of the design statements, and in certain cases suggestions for rewording or other types of feedback related to the design basis statements. This is part of the iterative development of the design basis. The requirement-by-requirement review of the design basis allows generic methods for demonstrating compliance to be identified. This approach also allows feedback to the specification of the design basis to be captured and the methodologies and technologies used during each experiment to be evaluated and assessed.

The compliance assessment approach was conducted, in collaboration with the organisations implementing the experiments, by evaluation of tables listing all of the design requirements and specifications. For each requirement, the following information was discussed:

- *Requirement justification*: The purpose of setting a particular requirement.
- *Compliance approach*: The method used to assess the experiment performance against the requirement.
- *Compliance assessment*: Statement on whether the requirement has been met. This is usually linked to documented evidence, e.g., a report. The statement on compliance should include a clear conclusion, i.e., a statement that the requirement has been met, has been partially met or has not been met, and this statement should be supported by a summary of the evidence for making this conclusion.
- *Feedback to design basis*: Statement on whether the requirement should be revised based on the assessment and/or based on the outcome of the experiment. A revised requirement could be provided if a revision is proposed, with a new justification.
- *Learning points on plugs and seals*: Provides a method for capturing the learning from the experiment to feed into the DOPAS Project outcomes.

The main outcomes from this compliance assessment exercise that are relevant to the design basis work under WP2 of the DOPAS Project include:

- Compliance of designs with the design basis requires the development of a hierarchy, with compliance focusing on the more detailed quantitative design specifications. Generally, in a design basis hierarchy, top-level requirements dictate the more detailed requirements. Therefore, compliance of the detailed requirements implies also compliance of the top-level requirements. There may also be a need to check that the higher level requirements, for example the safety functions for plugs and seals, and their quantitative expression as determined through safety assessment, is met by the overall performance of the design as implemented.
- Undertaking a compliance assessment is a good process for developing construction procedures and quality assurance requirements. Construction procedures and quality control requirements should be linked to design specifications listed in the design basis, and thereby tracked back to safety functions provided by the structure.
- Evaluating the compliance of designs with a design specification is an intensive activity. Design bases can include many tens of requirements and discussion of each requirement is undertaken. Therefore, it is recommended that compliance assessments are undertaken by small groups of well-informed staff; ideally 3-5 staff should be included in the intensive review process. This is considered to be an efficient and cost-effective approach.

In general, compliance checking consists of a chain of validation, verification and qualification activities[6]:

1. First the understanding of the safety functions is validated by demonstrating that the assumed technical design requirements produce the safety performance needed, i.e., a "sufficient" level of the safety functions is reached. To achieve this, a criterion for what is "sufficient" must be defined and normally this can only be formulated through safety (performance) assessment. An example from the DOPAS design bases would be the requirement that the hydraulic conductivity of seals must be equal to or less than 1×10^{-9} m/s.
2. Second a method is required to verify that the system produced and installed complies with the technical design requirements. Since the verification method may not be trivial in practice, it has to be formulated in parallel with formulation of the requirement. Formulation of the verification method ensures that the requirement is practicable to implement (i.e., it can be verified) and is useful.
3. Third there has to be a strategy to show that the system to be built and used in the repository fulfils the requirements. In part, the strategy will be to argue that the design has been shown to meet requirements in tests/demonstrations. However, in the demonstration experiments compliance with requirements may be shown by various monitoring/instrumentation systems that may not be available for use in the real repository. Therefore, there has to be a further strategy on how to show that the real system corresponds to the system demonstrated.

In DOPAS, the main component of the strategy is to develop construction and quality control procedures for application in the repository based on the procedures used for the experiments, i.e., to argue that, if the structures built in the repository are constructed in the same manner as the experiments, and the experiments meet the requirements, that the repository structures will also meet the requirements. Given the differences that there will necessarily be between experiments and repository structures, additional arguments are required that the differences are negligible and do not affect the overall performance. Indeed, with respect to monitoring and instrumentation systems, it is likely that removal of these features will improve the performance of the structure.

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[6] The term "validation" is used here to mean a series of theoretical modelling and experimentation tasks through which reasonable evidence is acquired to show that our understanding and description of features and processes has been demonstrated from a scientific point-of-view.

5 A Generic Process for the Development of the Design Basis

In this section, the learning developed during the conduct of WP2 is used to describe a generic process, the *DOPAS Design Basis Workflow*, for development of the design basis for plugs and seals. The purpose is to illustrate the steps used to develop a design basis, and thereby facilitate planning of the design process, and recording and presenting the outcomes as part of licensing processes. The Workflow represents a synthesis of the approaches used by the different WMOs in developing design bases for plugs and seals.

It is envisaged that the WMOs could compare their own specific design processes for plugs and seals to the Workflow, to demonstrate consistency with approaches in other programmes and as a cross-check that all necessary steps have been completed. The Workflow may also be a useful tool in planning design basis development, by providing an insight into the timing of when different levels of requirements should be specified.

Issues that have been identified during WP2 and which need to be factored into the process of design basis development are described in Section 5.1; the design basis development process itself is described in Sections 5.2, 5.3, and 5.4 for the conceptual design, basic design, and detailed design stages, respectively.

5.1 The DOPAS Design Basis Workflow

Design bases are hierarchical and consist of high-level requirements and low-level requirements. WMOs organise this hierarchy in different ways. The high-level design basis, including the safety functions of plugs and seals, can be specified and stabilised once the geological disposal concept has been selected and the national regulations developed. This remains fixed unless there is a change in the disposal concept or in the national policy decisions or regulations. The high-level design basis describes the principal safety functions of a plug or seal, typically in a qualitative fashion. The lower-level, more specific design basis (and in parallel the basic design and the detailed design) is developed through an iterative process (see Figure 5.1). The design basis for all of the experiments being conducted in the DOPAS Project specifies the components of the plugs and seals, their dimensions and their expected performance.

The work in the DOPAS Project has illustrated that the process used to develop the design basis is intimately linked with the development of the design. Although the design basis describes what the design has to achieve, and might be considered as something that needs to be specified before the design, the hierarchy of requirements means that lower-level requirements will be dependent on design decisions made in relation to the higher-level requirements. Therefore, although lower-level requirements may typically be considered as part of the *solution*, they also present requirements on what the basic and detailed designs must achieve, and are therefore referred to as requirements in the Workflow.

The requirements and design development processes are integrated and iterative. The development of the design basis can be considered to consist of three stages operating in parallel with conceptual, basic and detailed design (see Section 1.5.2). It is recognised that specific WMO programmes may develop their own more detailed design process, with more stages, but the three-stage process is used here as a generic process that covers different stages applied in different programmes.

The design basis is developed in an iterative fashion with inputs from regulations, technology transfer, tests and full-scale demonstrations, and performance and safety assessments. The DOPAS Design Basis Workflow (Figure 5.1) is described further in the subsequent sections of this chapter. In the description, terms used in the Workflow are highlighted in bold italic font upon first use. These terms are also defined in the glossary and are consistent with the IAEA glossary (IAEA, 2007).

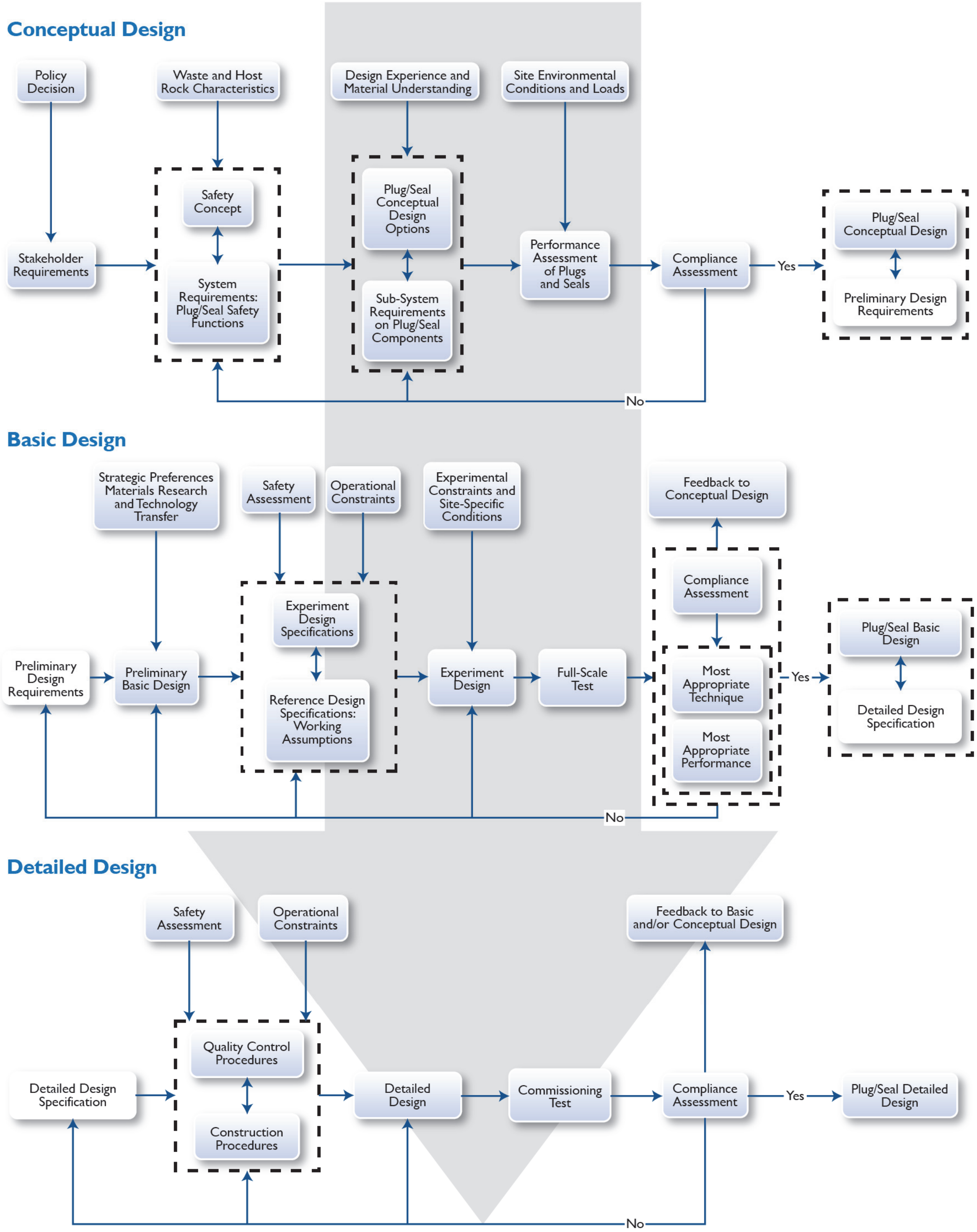

Figure 5.1: The DOPAS Design Basis Workflow, which illustrates the iterative development of the design basis, undertaken in parallel with the development of conceptual, basic and detailed designs. Dashed boxes are used to show activities undertaken in parallel. See Sections 5.2, 5.3, and 5.4 for discussion and description of this Workflow.

5.2 Design Basis Development during Conceptual Design

Summary

The design basis for a plug/seal ***conceptual design*** includes the ***stakeholder requirements*** that define the overall objectives of geological disposal, ***plug/seal safety functions*** for each of the components of the disposal system, and the ***sub-system requirements*** on each of the components of a plug/seal. A plug/seal conceptual design is a qualitative description of the plug/seal components and how they are arranged with respect to each other. The conceptual design includes identification of the type of material used for each component (e.g., concrete or bentonite). In the V-model scheme used by SKB and Posiva, the sub-system requirements include requirements on structures such as plugs and seals themselves, whereas in the Workflow, sub-system requirements are for components of plugs and seals (e.g., concrete dome, bentonite seal, etc.). In the Workflow, the requirements on plugs and seals are considered to be part of the ***system requirements.***

Description

The starting point for development of a design basis for a plug/seal conceptual design is a ***policy decision*** to manage radioactive waste through geological disposal. An example of such a policy decision is the United Kingdom Government acceptance of a recommendation made by the Committee on Radioactive Waste Management (CoRWM) that geological disposal is the way forward for the long-term management of the United Kingdom's higher-activity waste (Defra *et al*., 2006).

Following a national policy decision, stakeholder requirements that define what must be achieved by geological disposal are established. Stakeholder requirements include principles, regulations and criteria defined in regulatory guides and policy statements. Examples include the risk criteria presented in the Swedish radiation safety authority's spent fuel and nuclear waste final management regulations and general advice (SMFS 2008:37; SSM, 2009) and the annual dose constraint specified in the Finnish radiation and nuclear safety authority's guidance on the disposal of nuclear waste (YVL Guide D.5; STUK, 2013). In addition, stakeholder requirements could include specific approaches that must be considered in the repository design, for example the Reversibility Principle included in the French national policy for the management of radioactive materials and wastes (Assemblée Nationale, 2006).

Consideration of the stakeholder requirements, and the ***waste and host rock characteristics***, leads to the development of a ***safety concept*** upon which the disposal system requirements can be defined. Waste characteristics to be described include identification of the key radionuclides contained in the waste, and their chemical and physical form, and properties. The host rocks would be described in terms of their fundamental characteristics, e.g., a fractured crystalline rock, low-permeability clay or a dry salt. This would include, for example, a conceptual description of the geological structure, hydrogeological regime and groundwater chemistry. The main functions of a disposal system are isolation and containment of the waste. These functions are provided by a combination of the geological barrier and the EBS.

The safety concept is a description of the disposal system (the geological barrier and the EBS including plugs and seals), and a description of how each barrier of this disposal system contributes to safety. Elaboration of this safety concept allows parallel development of the system requirements, including definition of plug/seal safety functions. For plugs/seals, this includes, for example - in the Swedish KBS-3V concept, confinement of the backfill in the deposition tunnel (see Section 2.3.1); in the French Cigéo concept, to limit the water flow between the underground installation and overlying formations through the access shafts/ramps, and to limit groundwater velocity within the repository (see Section 2.1.1); and, in the German VSG concept, to provide a sufficiently low hydraulic conductivity to avoid brine paths into the repository and the movement of radionuclides out of it (see Section 2.5.1).

Once the safety functions of the plug/seal have been defined, the conceptual design of the structure can be developed. This is typically progressed through consideration of a range of ***plug/seal conceptual design options***. Conceptual design options would be identified through consideration of existing knowledge including ***design experience*** (e.g., designs of plugs/seals tested in URLs or applied in other industries) and general ***material understanding*** (e.g., the use of concrete as the material for a load bearing structure and swelling clay to provide low hydraulic conductivity). Examples of design option studies include:

- SKB Report R-09-50: Plugs for Deposition Tunnel in a Deep Geologic Repository in Granitic Rock. Concepts and Experience (Dixon *et al*., 2009): In this report, sealing demonstrations in URLs and generic plug designs were reviewed and a recommendation was made that the reference deposition tunnel plug in the Swedish KBS-3V system should comprise a composite construction, consisting of both low-pH concrete and compacted swelling clay components.
- Posiva Working Report 2009-38: Principle Plug Design for Deposition Tunnels (Haaramo and Lehtonen, 2009): In this report, five different plug types were evaluated (Section 2.4.2 and Figure 2.9) (see further discussion below).

Development of the conceptual design options allows parallel development of ***sub-system requirements on plug/seal components***, i.e., elaboration of the role of each of the components (e.g., concrete dome, watertight seal, filter and delimiter) in the design options. The list of requirements included in the description of the deposition tunnel plug, presented in Section 2.3.3, provides an example of sub-system requirements on plug/seal components. General technical requirements may also be included in the design basis at this level. For example, the need for the design to be robust, durable and cost-effective.

Consideration of the ***site environmental conditions*** in which the structure might have to perform (e.g., relative humidity, temperature and rock characteristics), and conversion of these conditions into the ***loads*** that the structure might have to withstand (e.g., expected stress conditions and the groundwater head across the structure and their evolution over time) will provide a basis for ***performance assessment of plugs and seals*** focused on the proposed conceptual design options. This performance assessment will take place through a programme of laboratory testing and computer modelling. An example of an integrated laboratory testing and performance assessment programme is the ELSA activities undertaken within the scope of the DOPAS Project, which are summarised in Section 2.5.4.

Evaluation of the outcome of the plug/seal performance assessment studies through conduct of a ***compliance assessment***, allows the conceptual design options to be evaluated and a ***plug/seal conceptual design*** to be selected. At this early stage in design basis development, it is expected that the compliance assessment will consider a few key criteria in choosing between the design options. For example, Haaramo and Lehtonen (2009) concluded that wedge-shaped and dome-shaped plugs were preferred, based on consideration of the relative use of construction materials, impact on operational activities and ease of construction (one of the plug options reviewed in the study required significantly greater amounts of reinforcement) for the five plug types considered. However, this initial conclusion was reconsidered by Posiva during the development of the construction licence application for the

Olkiluoto spent fuel disposal facility, and, because the SKB reference plug design was more advanced than the wedge-shaped and dome-shaped plugs considered by Haaramo and Lehtonen (2009), the Swedish design was used as a reference in the construction licence application. This decision by Posiva illustrates how changes in safety functions and sub-system requirements on plugs/seals components might occur in response to the compliance assessment (see feedback arrows in Figure 5.1), although, in this specific case, there were no changes in the safety functions as a result of adopting the SKB reference plug design.

Once a ***plug/seal conceptual design*** has been selected and confirmed as appropriate using compliance assessment, the design can be documented. In parallel with the documentation of the conceptual design, ***preliminary design requirements*** can be elaborated. These will be identified through analysis of the performance assessment results during the compliance assessment, and by adding further detail to the requirements on plug/seal components. The preliminary design requirements are the starting point for development of basic designs.

5.3 Design Basis Development during Basic Design

Summary

The design basis for a plug/seal ***basic design*** includes the ***design requirements***, which are qualitative statements describing the qualities or performance objectives for plug/seal components. A plug/seal basic design includes quantitative information on the geometrical and material parameters of the plug/seal, and details on the composition of the materials used to construct it. Dimensions are approximate, for example metre-scale dimensions such as tunnel cross-sections or component lengths might be expressed to the nearest centimetre or decimetre, with a similar level of precision used for other components.

Description

The starting point for development of a design basis for a plug/seal basic design is the set of ***preliminary design requirements*** developed in parallel with the elaboration of the plug/seal conceptual design. Preliminary design requirements are an initial set of qualitative statements describing the qualities or performance objectives for plug/seal components that will be tested in experiments. Requirements in the design basis deal mostly with scientific and technical considerations, but other requirements, such as the constructability (the ability and ease to construct in a constrained environment), robustness, durability, cost-effectiveness of the structures, the construction methods deployed underground, and the overall repository conditions, are also included.

Examples of design requirements, drawn from the detailed design bases presented in the DOPAS Project D2.1 deliverable (White *et al.*, 2014), and tested in the DOPAS Project demonstrator experiments, are:

- The plugs shall be designed to withstand the sum of the swelling pressure of the backfill and the hydrostatic pressure of the groundwater at the repository depth.
- The temperature of the concrete shall be controlled in order to avoid crack formation.
- All concrete components shall be of low pH.
- Swelling pressures in the sealing elements are not to exceed the rock strength.

It is typical for these qualitative statements to be developed in parallel with the development of the more detailed and quantitatively expressed design specifications that engineers will use to design plugs and seals. Haaramo and Lehtonen (2009) recognised several preliminary design specifications in their options study, for example a value for the minimum quantity of aggregate in plug/seal concrete expressed as a percentage of the concrete by volume (70%).

The key aspect of the basic design phase for plugs/seals, as undertaken within the DOPAS Project, is the use of full-scale testing as a means of further developing the design basis and the associated design. ***Strategic preferences*** (e.g., the choice to use local sources of bentonite in EPSP), the results from ***materials research*** (e.g., testing of candidate concrete recipes), and ***technology transfer*** (e.g., for EPSP, use of national experience in steel-fibre reinforced shotcrete) are considered during the development of a ***preliminary basic design*** based on the preliminary design requirements.

In order to conduct a full-scale experiment of the preliminary basic design, the requirements on the experiment need to be defined, and these requirements form a set of ***experiment design specifications*** that are developed in parallel with a set of ***working assumptions for the reference design specifications***. The working assumptions will form the basis for preliminary design specifications produced as an output of this basic design development process taking advantage of the full-scale testing process. These design specifications will include quantitative requirements (criteria) on the design, such as the pH of concrete water, the densities or swelling pressures of bentonite materials, the allowable curing temperatures of concrete, and fluxes of groundwater across the plug/seal structure. One of the purposes of full-scale testing is to investigate whether the experiment meets the preliminary design specifications and the experiment specifications, and to propose alternative values if the preliminary criteria cannot be met.

The elaboration of the experiment design specifications is supported by the ***safety assessment*** calculations undertaken as part of the safety case. For example, safety assessment of the Cigéo repository has demonstrated that, as long as the hydraulic conductivity of the drift seals is equal to, or less than, $1x10^{-9}$ m/s, radionuclide migration occurs through the host rock rather than the access tunnels. A hydraulic conductivity of $1x10^{-9}$ m/s can be achieved with different types of swelling clays (pure or mixed) and corresponds to a wide range of emplaced dry density and emplacement methods. Therefore, Andra has selected $1x10^{-11}$ m/s as a preliminary design specification for the swelling clay core, as this is considered to be a reasonable objective that is achievable within the repository (Section 3.2.2).

The elaboration of the experiment design specifications and the set of working assumptions for the reference design specifications is also supported by consideration of any ***operational constraints*** that affect how the plug/seal must be installed in the repository. These would include any processes that respond to requirements from operational safety or other operational constraints including the feasible underground working methods in the limited dimensions of the underground space (e.g., improvements and cost-effectiveness of the design, siting in the repository system, monitoring of performance and contingency planning during their operational lifetime).

Following the elaboration of experiment design specifications, an ***experiment design*** can be developed. This will take account of ***experimental constraints*** (e.g., time available to perform the experiment and consideration of operational safety, which may be different to the constraints on plugs/seals in an operating repository) and ***site-specific conditions*** encountered at the actual location of the experiment. Experimental constraints may result in changes to the experiment design compared to the reference design, for example the shorter time available may lead to accelerated pressurisation sequences, or reduced thickness for certain components (e.g., the watertight seal in the reference deposition tunnel plug in SKB's design is 710-mm thick, whereas the seal in DOMPLU was 500-mm thick to allow for more rapid saturation, Section 2.3.4). Experimental constraints may also impact the manner in which the experiment is undertaken. For example, methods used in the experiment may have to be modified so as not to interfere with other experiments being conducted locally at the same time. Site-specific environmental conditions may also require changes to the experiment design compared to the reference design, for example a need for additional rock strengthening for EPSP. The reference design may also be modified in the experiment to allow testing of specific aspects of the structure, for example the replacement of low-pH reinforced concrete beams with LECA® beams and the replacement of steel or titanium cooling pipes with copper pipes in the DOMPLU design (Section 2.3.4).

After establishing an experiment design, ***a full-scale test*** may be undertaken. Full-scale experiments can evaluate the performance of the plug/seal (e.g., the leakage rates across a deposition tunnel plug in DOMPLU), and/or can be used to evaluate if it is technically feasible for the structure to be constructed to meet the requirements in the preliminary design specification. For example, can the bentonite density proposed for the Cigéo seals be achieved using the envisaged methods? Full-scale tests would be undertaken in an environment that provided an adequate representation of the expected conditions in the repository; this would represent relevant environmental testing, an important aspect of technology development in certain design processes.

In practice, it is not feasible for requirements on performance in design specifications to be verified during repository operation, and, therefore, another purpose of full-scale testing, or other testing and modelling, is to convert performance requirements into requirements on the materials and the methods used to emplace them. Examples of these types of requirements include:

- Material requirements: the concrete in plugs and seals is required to be of low pH to avoid deleterious impacts on bentonite. The pH of concrete waters is typically measured after 28 and 90 days, and should be less than 11 for the concrete to be classed as low pH (Bäckblom, 2007). However, it would be challenging to verify the concrete water pH in an operating repository, and, therefore, it is preferable to specify the components of the concrete recipe that will result in a low pH. For the Posiva deposition tunnel plug concrete, this is done by specifying a calcium:silica ratio (Section 2.2.3). Such a specification is readily verifiable by taking samples at the concrete mixing factory.
- Methodological requirements: requirements on SKB's deposition tunnel plug include the use of a cooling system to pre-stress the concrete dome prior to contact grouting. The results from DOMPLU can be used to define requirements on the cooling sequence that would contribute to an effective pre-stress of the concrete dome. A further example of a methodological requirement that has been elaborated based on the results of DOPAS Project full-scale tests is the mixing time used for shotcrete in FSS; this was increased to 2 minutes from 30 seconds as a result of the tests.

The outcomes of full-scale tests should be evaluated using a structured ***compliance assessment*** methodology, for example the methodology summarised in Section 4.2. This would involve consideration of the full-scale test results on a requirement-by-requirement basis, and assessment of how closely the test met the specification. This process would typically include re-evaluation, and, potentially, re-writing of the design requirements or the design specification statements, as part of an iterative development of the design basis. Any changes to design requirements identified in this way would need to be made in a structured way and integrated with the safety case. In particular, once a licence is obtained, the regulator would need to approve the change.

An example of the revision of requirements as a result of the DOPAS Project experiments includes the required density of the swelling clay core in Andra's drift and ILW vault seals: The design basis for FSS states that the "*seals shall include a swelling clay core comprised of a clay-based material with a … swelling pressure close to but not exceeding the effective mechanical stress of 7 MPa*" (White *et al*., 2014). Research into bentonite materials during the DOPAS Project initially proposed that a swelling pressure of 7 MPa could be achieved with an overall density of the pellet-powder mixture of 1,600 kg/m^3. However, results obtained in a preliminary oedometric tests undertaken as part of the REM experiment have shown that with a dry emplaced density of 1,510 kg/m^3, the swelling pressure obtained is approximately 4.5-5 MPa when either argillite formation water or low-pH concrete leachate water is used to saturate the bentonite. This value is considered to be sufficient to meet hydraulic conductivity requirements and will not negatively impact the host rock by exceeding the effective mechanical stress. This value is also considered to be enough to allow self-sealing of the EDZ.

The compliance assessment will ensure that the revised requirements are consistent with the safety functions of the plug/seal.

Full-scale testing also provides an opportunity for selection of the most appropriate design of plug/seal design. Two aspects are considered:

- ***Most appropriate technique***: Are installation/construction techniques applied in the test the most appropriate for use in the repository, and, therefore, are these the techniques that should be included in the implementation of the reference design and taken forward to the detailed design stage? For example, do these techniques represent the safest, cheapest, quickest and/or most reliable approach, and is the technique compatible with on-going nuclear operations in the repository?
- ***Most appropriate performance***: Does the design provide the most appropriate performance or can performance be improved without affecting the technical feasibility of construction?

Should the compliance assessment show that the design does not fully meet the design specifications or the optimisation evaluation conclude that the experiment design does not represent the most appropriate technique or the most appropriate performance, a new preliminary basic design can be developed and the iterative design development cycle revisited. Depending on the conclusions and feedback from the compliance assessment and optimisation evaluation, a decision might be made to change the plug/seal conceptual design, the preliminary design requirements, the preliminary basic design, the experiment design specifications and/or the working assumptions for the reference design specifications, or the experiment design for further full-scale testing.

POPLU is an example of a full-scale test supporting selection of the most appropriate deposition tunnel plug design. POPLU represents an alternative design to the reference that may be favoured under certain conditions. Therefore, the results from POPLU may result in two options for the deposition tunnel plug being available.

Once the outcome from the compliance assessment and optimisation evaluations support further development of the preliminary basic design, this option is taken forward as the ***plug/seal basic design*** and the preliminary design requirements are adopted as the final design requirements. In parallel with documentation of the plug/seal basic design, the working assumptions for the reference design specifications are used to elaborate a set of ***detailed design specifications*** upon which detailed design work is based.

5.4 Design Basis Development during Detailed Design

Summary

A ***detailed design*** of a plug/seal is a representation of the structure in sufficient detail that it can be constructed in a repository, i.e., it provides precise information/technical drawings on all aspects of the structure's components.

Description

The starting point for the detailed design development is the information from full-scale testing of the basic design and the set of ***detailed design specifications*** that describe the expected quantitative requirements on the design. The quantitative requirements include values for all parameters that influence performance of the structures. As discussed above, these must be expressed in a manner that would allow them to be checked and verified during construction of the plug/seal. This includes expressing values as measurable quantities and expressing ranges for tolerances rather than single values (e.g., a value for concrete slump flow of 700±30 mm, rather than a value of 700 mm).

In order to convert the basic design into a detailed design that can be implemented in the repository, ***quality control procedures*** and ***construction procedures*** need to be written, and the design tested to ensure that following these procedures will result in a plug/seal that meets the design specifications. Quality control procedures will define the manner in which the implementer will ensure that the plug/seal meets the design specifications within the given tolerances. This includes listing of the standards that will be followed during construction. For example, for the construction of DOMPLU, the following tests were conducted on fresh concrete delivered to the experiment site (see discussion in Grahm *et al*., 2015):

- Slump flow according to the standard for self-compacting concrete (SS-EN 206-9).
- t_{500} according to the standard for self-compacting concrete (SS-EN 206-9).
- Air content according to the standard for testing fresh concrete for air content using pressure methods (SS-EN 12350-7).
- Density according to the standard for testing fresh concrete for air content using pressure methods (SS-EN 12350-7).

Such tests will need to be conducted routinely during the implementation of plugs/seals, and development of the detailed design will need to confirm that the quality control procedures can be met by the design.

Construction procedures will define the manner in which the plug/seal will be implemented. For example, these procedures will define the approach to excavation of the plug/seal location, mixing of concrete (e.g., length of time to ensure homogeneous mixtures), the installation of the components of the plug/seal, and, for plugs/seals where active intervention is part of the design, the manner in which this active intervention is undertaken. The design of DOMPLU includes the use of active intervention to control the development of bentonite swelling pressures acting on the plug through drainage of the filter layer, and also through the use of a cooling system to control curing of concrete (limiting crack formation) and to achieve a detachment of the concrete dome from the rock prior to contact grouting.

Quality control and construction procedures elaboration are supported by the ***safety assessment*** calculations undertaken as part of the safety case. Quality control and construction procedures will take account of any ***operational constraints*** that affect how the plug/seal must be installed. These would be taken into account during the detailed design stage, and include any processes that respond to requirements from operational safety or other operational constraints including the feasible underground working methods in the limited dimensions of the underground space (e.g., improvements and cost-effectiveness of the design, siting in the repository system, monitoring of performance and contingency planning during their operational lifetime). These procedures will also be informed and aligned with the safety assessment.

Elaboration of the quality control and construction procedures would provide the additional basis for developing a ***detailed design***. This design would be the basis for a ***commissioning test*** ahead of implementation (if required based on the technical outcome of previous full-scale tests). An example of this type of test is the Industrial Pilot that Andra plans to implement at the commencement of Cigéo operations (see Section 4.1). The Industrial Pilot will be used to check and adapt the initial parameters used in long-term estimates specifically linked to the repository, and to provide demonstration that the design is fit-for-purpose.

The results of the detailed design commissioning test will be checked by a final ***compliance assessment***. Although it would be expected that the commissioning test would be mainly confirmatory, the compliance assessment will check that all of the design specifications in the requirements hierarchy are met, and may therefore lead to revisions in design specifications, quality control and construction procedures, or detailed design. Where these are minor, it would be expected that these can be implemented in the design basis without the need for a further iteration of the design cycle. In such a case, the detailed design specifications would be adopted (with necessary revisions) as the final design specification and the detailed design adopted as the final ***plug/seal detailed design*** (again with revisions identified through the full-scale test). Alternatively, major compliance issues may lead to a need for revision to the design specifications, quality control and construction procedures, and/or the preliminary detailed design, and further full-scale testing. Major compliance issues could also lead to reconsideration and ***feedback to basic and/or conceptual design***, if the full-scale tests identified any fundamental issues with the design. Given the iterative nature of the development of the design basis as described above, in particular the inclusion of an optimisation step as part of the process for developing the basic design, it is unlikely that there would be a need to reconsider the basic and conceptual designs at the detailed design stage.

5.5 Design Basis Workflow and Scope of DOPAS

The DOPAS Design Basis Workflow presented above can be related to the work being undertaken in the technical work packages of the DOPAS Project (WP2, WP3, WP4 and WP5). WP2 addresses the design basis for plugs and seals and their reference designs. WP3 addresses the full-scale experiment designs and their construction. WP4 addresses the appraisal of the full-scale experiments in DOPAS including monitoring and dismantling activities. WP5 addresses performance assessment modelling of plugs and seals and the implications of their performance on the overall safety of a repository. Figure 5.2 shows how aspects of the Workflow are encompassed by each work package in the DOPAS Project. This figure only illustrates the approximate scope of work undertaken in each work package and not all of the highlighted Workflow steps have been addressed explicitly in the DOPAS Project.

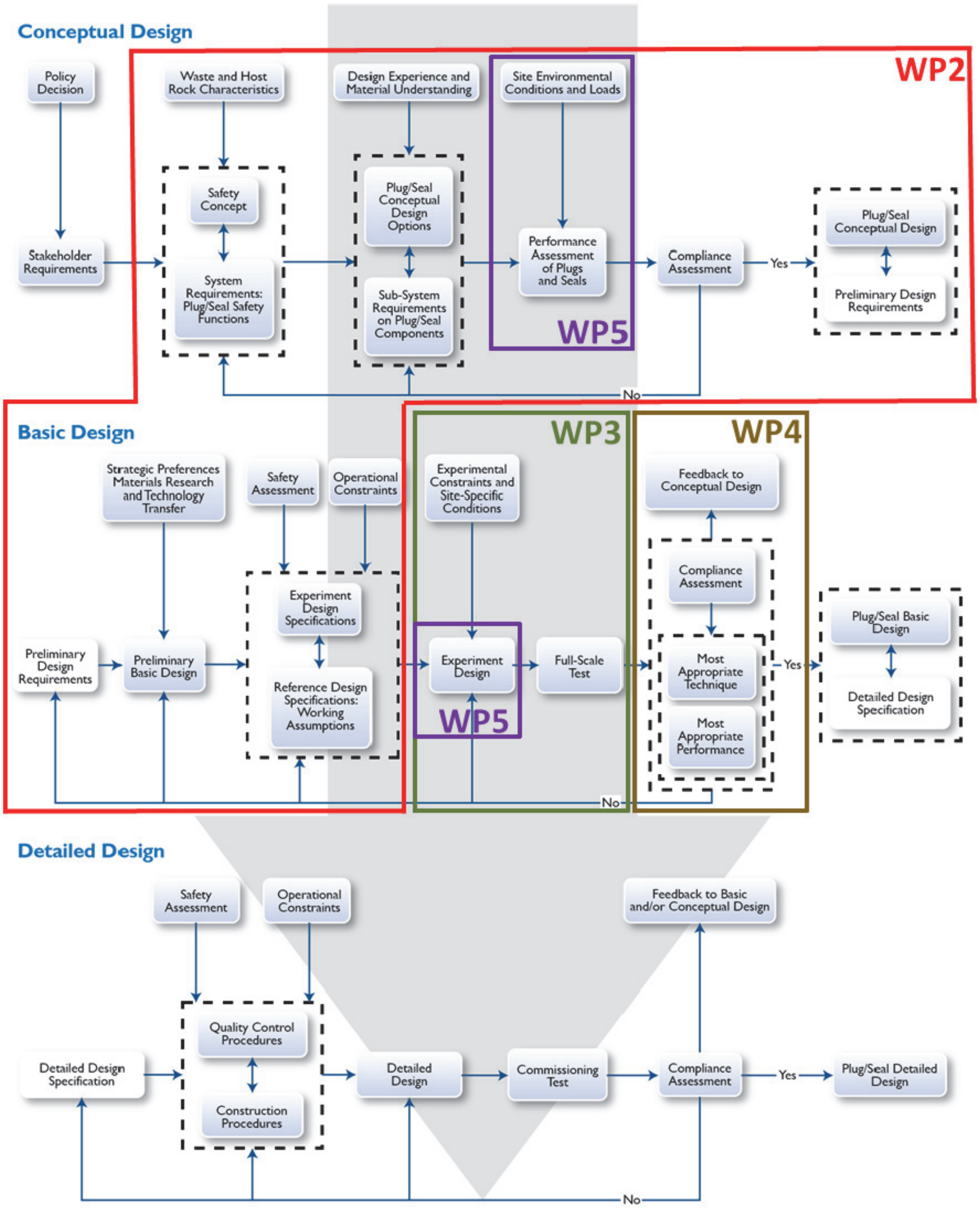

Figure 5.2: The DOPAS Design Basis Workflow and the scope of DOPAS work under the technical WPs (WP2, WP3, WP4 and WP5) shown in red, green, brown and purple boxes, respectively. Note that this is an approximate mapping and that not every step in the Workflow within a WP scope has been explicitly covered in DOPAS.

6 Conclusions from WP2 of the DOPAS Project

6.1 Design Basis of Plugs and Seals

The design bases of plugs and seals considered in the DOPAS Project have been described in this report. This includes the design bases for:

- Andra's reference conceptual design for drift and ILW disposal vault seals in clay host rock and for the FSS experiment.
- SÚRAO's reference conceptual design for disposal drift plugs design in crystalline host rock and for the EPSP experiment.
- SKB's reference conceptual design for deposition tunnel plugs in crystalline host rock and for the DOMPLU experiment.
- Posiva's reference conceptual design for deposition tunnel plugs in crystalline host rock and for the POPLU experiment.
- The German reference design for shaft seals in salt host rock.

In addition, information has been presented on the design bases for plugs and seals in the other waste management programmes represented in the DOPAS Project (Switzerland, the Netherlands and the United Kingdom).

Plugs and seals are generally required to achieve either combined or stand-alone safety functions; these include confinement of the tunnel backfill in place, the need to prevent water flow through waste repository areas, and the need to prevent access to the disposal facility after it is closed. The safety functions of plugs and seals differ between waste management programmes depending on the geological environment, disposal concept, and approach to the safety case.

6.2 Impact of Host Rock Type on the Design Basis of Plugs and Seals

The type of host rock plays an important role in defining the design requirements for plugs and seals.

In clay host rocks, the creep properties of the host rock are taken into account in plug and seal design. Plugs and seals need to ensure that hydraulic conductivities are achieved to match those of the clay rock. The function of drift and shaft seals is to provide a sufficiently low hydraulic conductivity to limit water fluxes and radionuclide migration through the backfilled excavations (and, in the case of salt host rocks, brine inflow into the repository). Swelling bentonite is suitable for use in providing this low hydraulic conductivity.

In crystalline rocks, the disposal concept places a high reliance on the EBS and the function of the deposition tunnel plug is to hold the backfill in place during operations. This is potentially achieved by providing a strong concrete plug. Owing to the potential for erosion of the bentonite buffer and backfill, the groundwater flux across the plug has to be low, and this can potentially be achieved through the use of a watertight seal or by using a massive concrete plug. The aim is to achieve a low hydraulic conductivity by ensuring a good contact is established between the plug/seal material and the rock. 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 salt host rocks, the creep properties of the host rock are also taken into account in plug and seal design. A range of materials may be used, including salt concrete, sorel concrete and bentonite. Any sealing in salt rocks must be done in such a way that brine migration to the waste canisters is avoided.

6.3 Compliance of Designs with the Design Basis

This report has also documented the strategies and approaches used by WMOs to demonstrate compliance of the reference designs of plugs and seals to the design basis include:

- Full-scale Testing: Full-scale testing is the main strategy adopted by WMOs to compliance demonstration of plugs and seals. Full-scale experiments include demonstration of technical feasibility, tests of performance, and combined technical feasibility and performance tests. The experiment design will take account of experimental constraints (e.g., the time and space available to perform the experiment and consideration of operational safety, which may be different to the constraints on plugs/seals in an operating repository) and site-specific environmental conditions encountered at the actual location of the experiment.
- Quantitative Approaches to Compliance Demonstration: The German programme has developed a quantitative approach to compliance demonstration in which the loads on a structure are compared to the ability of a structure to perform under the induced loads, with uncertainty accounted for by the application of quantitative performance criteria modified to account for uncertainty and to provide an additional safety margin.
- Construction Procedures: WMOs have different approaches to describing the application of construction procedures for compliance demonstration. Some describe construction procedures as an important element of compliance demonstration, and others consider it to be part of quality control during repository implementation. In any case, the focus of quality control relies to a large extent on the practical experiences gained during "compliance demonstration".
- Monitoring: WMOs have different approaches to the use of monitoring as part of compliance demonstration strategies for plugs and seals. Some WMOs have not made firm decisions on how to monitor repository plugs and seals (e.g., SKB), while others are considering monitoring of repository plugs and seals (e.g., through instrumentation) to provide for compliance demonstration (e.g., Posiva).

6.4 Key Messages from WP2

Work on the design basis in the DOPAS Project has allowed assessment of current practice with regard to both the process used to develop and describe the design basis and the content of the design basis. As such, there are general conclusions to be drawn that are relevant to the design basis for other aspects of repository design as well as lessons specific to plugs and seals. The learning provided by WP2 has been used to develop and describe a generic process for development of the design basis for plugs and seals. The design basis is developed in an iterative fashion with inputs from regulations, technology transfer, tests and full-scale demonstrations, and performance and safety assessments. All of these tools have been used to develop an overall "DOPAS Design Basis Development Workflow" consistent with the three design stages (conceptual design, basic design, and detailed design).

The DOPAS Design Basis Workflow is based on the design basis work undertaken for plugs and seals within the DOPAS Project. However, the Workflow is generic in nature, and could probably be applied to other repository design activities. The general applicability of the

DOPAS Design Basis Workflow is considered as part of the wider DOPAS Project dissemination activities (WP7).

The key messages from WP2 of the DOPAS Project are summarised under the different headings below.

6.4.1 Design Basis Development

The development of the design basis is generally undertaken in parallel with development of the design and development of the safety case rather than as a sequential process. For example, development of a disposal concept requires description of the components that make up the conceptual design at the same time as developing the statements regarding the functions that these components must provide (safety functions or system requirements using the terminology adopted in the DOPAS Design Basis Workflow). At a more detailed level of design development, designing a specific plug/seal component (e.g., defining the recipe for a concrete mixture) requires information on what the concrete recipe must achieve (e.g., strength, curing temperatures and hydraulic conductivity), but also leads to detailed design specifications (e.g., the acceptable range of constituents that can be used when mixing the concrete). These design specifications can be transferred into quality control statements and construction procedures for implementation during repository operation.

The processes used by WMOs to develop requirements and design specifications that form part of the design basis are expressed in different ways using different terminology. However, these processes are largely comparable to each other and are consistent with the DOPAS Design Basis Workflow. Some commonalities that have been identified include:

- Using the experience gained from previous tests and experiments on plugs and seals and/or from underground mining activities.
- Using an iterative process involving the design basis, performance assessment and safety evaluation to fine tune the design basis for the final plug/seal system, paying due consideration to the constructability and durability of these complex structures. This shows that requirements may be subject to change as the design process evolves.
- Performing critical reviews periodically to assess the results, verify their compliance with the design basis, and identify possible modifications to the design basis.

All of the work undertaken to develop the design basis needs to be reflected in the safety case, and integrated with work undertaken on development and management of the safety case.

The design basis for a reference design and an experiment are usually different because the design basis for an experiment needs to respond to experimental constraints and site-specific environmental conditions (e.g., the location of the experiment and limited duration of the experiment). The design basis for experiments might represent a preliminary design basis for a detailed design.

6.4.2 Design Basis Content

The design basis incorporates both requirements and the conditions under which the requirements must be met. Significant work has been done on requirements; future development of the design basis for plugs and seals should also concentrate on the way conditions are expressed in the design basis. Conditions that are important to include in the design basis include the outcomes of safety assessments, the loads on a structure, and the nature of the underground environment, which, using the terminology adopted in the DOPAS

Design Basis Workflow, includes the host rock characteristics (e.g., creep rate, heterogeneity, thermal conductivity, and fracture distribution).

The design basis should include requirements on the performance of the plug/seal (e.g., water leakage rate) and requirements on the methods that are suitable for its installation. Performance requirements should reflect both the long-term (post-closure) requirements and short-term requirements. Short-term requirements include factors that are required for successful implementation of a plug/seal (e.g., management of the stresses acting on a concrete dome during curing, robustness, durability, and cost-effectiveness), and factors related to human activities (e.g., health and safety and choice of construction methods, and the operational constraints such as the time and space available for undertaking specific activities). All of these different types of requirements should be recognised within the design basis. The design basis requirements at the specifications level should be worded so that they can be readily implemented during construction and their compliance assessed, i.e., they should include appropriate ranges for material properties and be measurable during the practical operation of the repository.

6.4.3 Design Basis Structure

Some WMOs use hierarchies to describe and present the design basis. For example, Posiva and SKB use a five-level requirements hierarchy based on the V-Model to structure requirements. This hierarchy, an adaptation of which has been used in the DOPAS Design Basis Workflow, is considered appropriate for describing the design basis of plugs and seals. The principal safety functions of a plug or seal can be specified and stabilised once the repository concept has been specified and the national regulations developed. Further updates may be needed as the design work proceeds since the design work may imply that some overall design requirements may be hard to meet/verify and then a valid question is whether the design requirement based on the simplifications made in the safety assessment are justified – or could be altered without jeopardising overall safety.

More detailed requirements are developed through an iterative process in parallel with specific design activities, including materials research and full-scale testing. There is a need to identify and describe change management processes to respond to design basis revisions to operate alongside these processes.

A hierarchical and structured design basis can be used as part of a structured approach for demonstrating to the regulator the manner in which safety functions are met, and how this will be ensured during implementation. Compliance assessment during development of a design basis can be part of structured methods for developing comprehensive construction and quality control procedures.

7 References

AFNOR (1999). RG AERO 000 40, dans NF X50 410. Recommandation générale pour la spécification du management de programme, Editions AFNOR.

Alonso, J., Garcia-Siñeriz, J.L., Bárcena, I., Alonso, M.C., Luco, L.F., Garciá, J.L., Fries, T., Petterson, S., Bodén, A., Salo, J-P. (2008). ESDRED Module 4 (Temporary Sealing Technology) Final Technical Report.

Andersson, M., Ervanne, H., Glaus, M. A., Holgersson, S., Karttunen, P., Laine, H., Lothenbach, B., Puigdomenech, I., Schwyn, B., Snellman, M., Ueda, H., Vuorio, M., Wieland, E. and Yamamoto, T. (2008). Development of Methodology for Evaluation of Long-term Safety Aspects of Organic Cement Paste Components. Posiva Working Report 2008-28.

Andra (2005). Dossier 2005 Argile: Safety evaluation of a geological repository.

Andra (2013). The Cigéo Project. Meuse/Haute-Marne Reversible Geological Disposal Facility for Radioactive Waste. Project Owner File Public Debate of 15 May to 15 October 2013.

ASN (2008). Guide de sûreté relatif au stockage définitif des déchets radioactifs en formation géologique profonde. Version of 12/02/2008.

Assemblée Nationale (2006). The 2006 Programme Act on the Sustainable Management of Radioactive Materials and Wastes.

Bäckblom, G. (2007). Supporting Documents of Second Training Workshop (Proceedings of the Third Low pH Workshop Paris June 13-14, 2007). ESDRED Report Mod5-WP2-D4.

Börgesson L, Sandén T, Dueck A, Andersson L, Jensen V, Nilsson U, Olsson S, Åkesson M, Kristensson O, Svensson U. (2015). Consequences of water inflow and early water uptake in deposition holes. EVA-project. SKB TR-14-22, Svensk Kärnbränslehantering AB.

Bosgiraud, J-M. and Foin, R. (2013). DOPAS Work Package 3, Deliverable D3.2: FSS tunnel model design report, Version A, December 2013.

Defra, Department of the Environment, Scottish Executive and Welsh Assembly Government (2006). Response to the Report and Recommendations from the Committee on Radioactive Waste Management (CoRWM).

Dixon, D.A., Börgesson, L., Gunnarsson, D. and Hansen. J. (2009). Plugs for Deposition Tunnels in a Deep Geologic Repository in Granitic Rock. SKB Report R-09-50.

DOPAS (2016a). WP3 Final Summary Report: Summary of, and Lessons Learned from, Design and Construction of the DOPAS Experiments. DOPAS Work Package 3, Deliverable D3.30.

DOPAS (2016b). WP4 Integrated Report: Summary of Progress on Design, Construction and Monitoring of Plugs and Seals. DOPAS Work Package 4, Deliverable D4.4.

DOPAS (2016c). DOPAS Work Package 5, Deliverable D5.10. WP5 Final Integrated Report. DOPAS Project Deliverable D5.10.

EC-JRC (2008). The Eurocodes: Implementation and use. Booklet B1, Joint Research Centre (JRC) and Enterprise and Industry Directorate General (DG ENTR), European Commission.

European Standard DIN EN 1997-1 (2014). Eurocode 7: Geotechnical design - Part 1: General rules; German version EN 1997-1:2004 + AC:2009 + A1:2013.

Grahm, P.; Malm, R. and Eriksson, D. (2015). DOPAS Work Package 4, Deliverable D4.3: DOMPLU Summary Report, Version 1, December 2015 (content identical to SKB publication SKB TR-14-23).

Gray, M. (1993). OECD-NEA International Stripa Project, 1980-1992, Overview. Volume III, Engineered Barriers.

Haaramo, M. (1999). Sijoitustunneleiden Sulkurakenteiden Rakennesuunnittelu. Working Report 99-71. Posiva Oy. (In Finnish).

Haaramo, M. and Lehtonen, A. (2009). Principle Plug Design for Deposition Tunnels. Working Report 2009-38.

Herold, P. and Müller-Hoeppe, N. (2013). Safety Demonstration and Verification Concept – Principle and Application Examples. Technical Report (Extraction from Kudla *et al.*, 2013), DBE TECHNOLOGY, Peine.

Hilar, M. and Pruška, J. (2011). Fiber Concrete – Construction Material of Underground Structures. *fib* Symposium Prague, 2011.

Holt *et al.* (2016). POPLU Experiment Summary Report. DOPAS Work Package 4 Deliverable D4.5.

IAEA (2001). Technical Considerations in the Design of Near Surface Disposal Facilities for Radioactive Waste. IAEA-TECDOC-1256.

IAEA (2007). IAEA Safety Glossary. Terminology used in Nuclear Safety and Radiation Protection. 2007 Edition.

Jobmann, M. (2013). Requirements for Shaft Seals for HLW Repositories in Germany – Technical Report, DBE TECHNOLOGY GmbH, Peine, Germany.

Krone, J., Buhmann, D., Mönig, J., Wolf, J., Heusermann, S., Keller, S., Weber, J.R., Bollingerfehr, W., Filbert, W., Kreienmeyer, M., Tholen, M. (2008). DBE TECHNOLOGY, Peine. (2008). Review and Appraisal of the Tools available for a Safety Assessment of Final Repositories for HLW – ISIBEL – Status of the total performance assessment for a repository for HLW in rock salt, DBE TECHNOLOGY, Peine.

Kudla, W., Dahlhaus, F., Glaubach, U., Gruner, M., Haucke, J., Hofmann, M., Wasowiecz, B. (2009). Diversitäre und redundante Dichtelemente für langzeitstabile Verschlussbauwerke, TU BAF Institut für Bergbau und Spezialtiefbau, Freiberg (in German).

Kudla, W., Schreiter, F., Gruner, M., Jobmann, M., Bollingerfehr, W., Müller-Hoeppe, N., Herold, P., Freyer, D., Wilsnack, T., Grafe, F. (2013). Schachtverschlüsse für Endlager für hochradioaktive Abfälle – ELSA Teil 1–, TU Bergakademie Freiberg und DBE TECHNOLOGY, Freiberg, Peine (in German).

Malm, R. (2012). Low-pH concrete plug for sealing the KBS-3V deposition tunnels. SKB Report R-11-04.

Malm, R., Eriksson, D. And Grahm, P. (2014). System design and full-scale testing of the Dome Plug for KBS-3V deposition tunnels. Main Report. TR-14-23.

Martino, J.B., Dixon, D.A., Kozak, E.T., Gascoyne, M., Vignal, B., Sugita, Y., Fujita, T., and Masumoto, K. (2007). The Tunnel Sealing Experiment: an International Study of Full-Scale Seals. Physics and Chemistry of the Earth 32, 93-107, 2007.

Mönig, J.; Buhmann, D.; Rübel, A.; Wolf, J.; Baltes, B.; Fischer-Appelt, K. (2012). Sicherheits- und Nachweiskonzept. Bericht zum Arbeitspaket 4. Vorläufige Sicherheitsanalyse für den Standort Gorleben. GRS-277, Gesellschaft für Anlagen- und Reaktorsicherheit, Köln.

Müller-Hoeppe, N.; Engelhardt, H.-J.; Lerch, C.; Linkamp, M.; Buhmann, D.; Czaikowski, O.; Herbert, H.-J.; Wieczorek, K.; Xie, M. (2012a). Integrität geotechnischer Barrieren Teil 1: Vorbemessung. Bericht zum Arbeitspaket 9, Vorläufige Sicherheitsanalyse für den Standort Gorleben, GRS-287, Gesellschaft für Anlagen- und Reaktorsicherheit, Köln.

Müller-Hoeppe, N.; Breustedt, M.; Wolf, J.; Czaikowski, O.; Wieczorek, K. (2012b). Integrität geotechnischer Barrieren - Teil 2 Vertiefte Nachweisführung. Bericht zum Arbeitspaket 9, Vorläufige Sicherheitsanalyse für den Standort Gorleben, GRS-288, Gesellschaft für Anlagen- und Reaktorsicherheit, Köln.

NDA RWMD (2010a). Geological Disposal: Steps towards Implementation. NDA-RWMD Report NDA/RWMD/013.

NDA RWMD (2010b). Geological Disposal: Proposed Approach to Optioneering. NDA Technical Note No. 12860687.

NDA RWMD (2010c). Geological Disposal: Generic Disposal System Technical Specification. NDA-RWMD Report NDA/RWMD/044.

Nirex (2005). The Viability of a Phased Geological Repository Concept for the Long-term Management of the UK's Radioactive Waste. Nirex Report No. N/122.

OPERA (2011). Outline of a Disposal Concept in Clay. OPERA-PG-COV008.

Palmer, S. (2011). Design Criteria for the Plug Structure in KBS-3V Deposition Tunnels. SKB Document ID: 1273861, Version 1.

Posiva (2011). Foreign Materials in the Repository – Update of Estimated Quantities. Posiva 2011-32.

Posiva (2012a). Design Basis 2012. Safety Case for the Disposal of Spent Nuclear Fuel at Olkiluoto. Posiva Report POSIVA 2012-03.

Posiva (2012b). Backfill Production Line 2012. Design, Production and Initial State of the Deposition Tunnel Backfill and Plug. Posiva Report POSIVA 2012-18.

Rueedi, J. and Marschall, P. (2011). Demonstration of Gas-Permeable Seals for Radioactive Waste Repositories – Laboratory and *In-situ* Experiments. Proceedings of the ASME 2011 14th International Conference on Environmental Remediation and Radioactive Waste Management ICEM2011, September 25-29, 2011, Reims, France/

SKB (2005). Äspö Hard Rock Laboratory: Annual Report 2004. SKB Technical Report TR-05-10.

SKB (2010a). Design and Production of the KBS-3 Repository. SKB Technical Report TR-10-12.

SKB (2010b). Design, Production and Initial State of the Backfill and Plug in Deposition Tunnels. SKB Technical Report TR-10-16.

SKB (2012). KBS-3H Complementary studies, 2008–2010. SKB Technical Report, TR-12-01.

SSM (2009). Swedish Radiation Safety Authority Regulatory Code. SSMFS 2008:37. Published on 30 January 2009.

STUK (2013). Disposal of Nuclear Waste. Guide YVL D.5, Draft L5. Published on 29 May 2013.

SÚRAO (2012). Update of the Reference Project of a Deep Geological Repository in a Hypothetical Locality. Accompanying Report. Report EGP 5014-F-120055.

Vogt, C.; Lagerblad, B.; Wallin, K.; Baldy, F. and Jonasson, J-E. (2009). Low-pH Self Compacting Concrete for Deposition Tunnel Plugs. SKB Report R-09-07.

Wendling, J., Calsyn, L., Bosgiraud, J-M. (2015). DOPAS Work Package 5, Deliverable D5.2: Report on Andra's PA Methodology for sealing systems, Version B, May 2015.

White, M.J. (2013). Monitoring During the Staged Implementation of Geological Disposal: The MoDeRn Project Synthesis. MoDeRn Project Deliverable D-6.1.

White, M.J., Doudou, S., and Neall, F.B. (2014). DOPAS Work Package 2, Deliverable D2.1: Design Bases and Criteria, Version 1.1, February 2014.

White, M.J. and Doudou, S. (2014). DOPAS Work Package 2, Deliverable D2.2: DOPAS Reference Designs Report, Version 1, October 2014.

White, M.J. and Doudou. S. (2015). DOPAS Work Package 2, Deliverable D2.3: Strategies for Demonstrating Compliance of the Reference Designs with the Design Basis, Version 1, June 2015.

Zhang, C.L. (2014). Investigation of gas migration in damaged and resealed claystone. 19 pp. *In*: Shaw, R. P. (ed.) Gas Generation and Migration in Deep Geological Radioactive Waste Repositories. Geological Society, London, Special Publications, 415.