DOPAS Work Package 4: Deliverable D4.9 Lessons Learnt for Other Programmes, from the DOPAS Project

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Executive Summary

The Full-scale Demonstration of Plugs and Seals (DOPAS) Project was a European Commission (EC) programme of work jointly funded by the Euratom Seventh Framework Programme and European nuclear waste management organisations (WMOs). A set of full-scale experiments, materials research projects and performance assessment studies of plugs and seals for geological repositories were carried out in the course of the project.

The DOPAS Project focused on tunnel, drift, vault and shaft plugs and seals for crystalline, clay and salt rocks. The project was coordinated by Posiva Oy, Finland.

The DOPAS Project was initiated by the Implementing Geological Disposal of Radioactive Waste Technology Platform's (IGD-TP's) Executive Group as part of the deployment of the IGD-TP's Strategic Research Agenda (SRA) including the common vision that, by 2025, the first geological disposal facilities for spent fuel, high-level waste, and other long-lived radioactive waste will be operating safely in Europe.

At the start of the Project, the participating WMOs included organisations that were close to licensing (i.e. had either submitted a licence application or expected to within a few years). Consistent with the IGD-TP Vision, for these organisations, the driver for participation in the Project was to support the development of reference or alternative plug/seal designs for which detailed design is required in the next few years.

The Project also included WMOs with plans to submit licence applications in several decades. For these organisations, the primary driver for involvement in the DOPAS Project was to support long-term research and development (R&D) on the feasibility of geological disposal. In addition, the results of the DOPAS Project are of benefit to other European WMOs. This report is Deliverable D4.9 of the DOPAS Project, and describes the lessons that can be learnt from the Project by WMOs that are not close to licensing.

At the request of the EC, Radioactive Waste Management (RWM) and Galson Sciences Limited (GSL), who are both partners in the DOPAS Project, have worked collaboratively to identify the lessons that can be learnt from the DOPAS Project by WMOs that are less close to licensing. The report identifies a series of topics addressed in the DOPAS Project that are potentially of interest to WMOs that are not close to licensing. For each topic, a high-level discussion of the work undertaken in the DOPAS Project related to that topic is provided and used as a basis for identifying the potential lessons for the relevant WMOs. The topics are: design basis process; types of plugs and seals, and their functions; conceptual designs of plugs and seals; plug and seal materials, and detailed design; technical aspects of siting, excavation and installation; monitoring of plugs and seals; performance of plugs and seals; and project management.

The DOPAS Project provides a significant number of lessons for programmes that are less close to licensing. At a high-level, these include the demonstration of the feasibility of plug and seal designs which can be used to underpin geological disposal feasibility demonstration projects; an illustration of the work required to develop detailed designs of plugs and seals, which can be used for planning design work; and potential solutions for plug and seal designs, which can act as a starting point for programme-specific designs. In particular, the work of the DOPAS Project provides a significant body of work on the challenges and potential solutions for repository plugs and seals both for generic studies and for programmes considering specific host rocks.

List of DOPAS Project Partners

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

Posiva	Posiva Oy	Finland
Andra	Agence nationale pour la gestion des déchets radioactifs	France
DBETEC	DBE TECHNOLOGY GmbH	Germany
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit	Germany
Nagra	Die Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle	Switzerland
RWM	Radioactive Waste Management Limited	UK
SÚRAO	Správa Úložišť Radioaktivních Odpadu (Radioactive Waste Repository Authority – RAWRA)	Czech Republic
SKB	Svensk Kärnbränslehantering AB	Sweden
CTU	Czech Technical University in Prague	Czech Republic
NRG	Nuclear Research and Consultancy Group	Netherlands
GSL	Galson Sciences Limited	UK
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

DOMPLU:	Dome Plug
DOPAS:	Full-scale Demonstration of Plugs and Seals
EBS:	Engineered barrier system
EC:	European Commission
EE:	Expert elicitation
ELSA:	Entwicklung von Schachtverschlusskonzepten (development of shaft closure concepts)
EPSP:	Experimental Pressure and Sealing Plug
FE:	Full-scale Emplacement experiment
FSS:	Full-scale Seal
GAST:	Gas-permeable Seal Test
HRL:	Hard Rock Laboratory
IGD-TP:	Implementing Geological Disposal – Technology Platform
ILW:	Intermediate-level waste
LASA:	**La**ngzeitsicherer **S**chachtverschluß im S**a**linar (long-term safe shaft closure in salt)
LAVA:	**La**ngzeitsicherer Schacht**v**erschluß im S**a**linar (long-term safe shaft closure in salt)
POPLU:	Posiva Plug
R&D:	Research and Development
RSC:	Rock Suitability Classification
SCC:	Self-compacting concrete
SRA:	Strategic Research Agenda
THMCB:	Thermal, hydraulic, mechanical and chemical
THM-Ton:	Untersuchung der THM-Prozesse im Nahfeld von Endlagern in Tonformationen (investigation of THM processes in the near field of a repository in clay)
URC:	Underground research centre
URCF:	Underground rock characterisation facility
URL:	Underground research laboratory
WMO:	Waste management organisation
WP:	Work package

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1 Introduction

1.1 Background

The Full-Scale Demonstration of Plugs and Seals (DOPAS) Project was 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 was undertaken in the period September 2012 – August 2016. Fourteen European WMOs and research and consultancy institutions from eight European countries participated in the DOPAS Project, which was coordinated by Posiva, Finland. The Project focused on tunnel, drift, vault and shaft plugs and seals for crystalline, clay and salt rocks. A set of full-scale experiments, materials research projects, and performance assessment studies of plugs and seals for geological repositories were carried out in the course of the Project.

The DOPAS Project was initiated by the Implementing Geological Disposal of Radioactive Waste Technology Platform's (IGD-TP's) Executive Group as part of the deployment of the IGD-TP's Strategic Research Agenda (SRA) including the common vision that, by 2025, the first geological disposal facilities for spent fuel, high-level waste, and other long-lived radioactive waste will be operating safely in Europe.

At the start of the Project, the participating WMOs included organisations that were close to licensing (i.e. had either submitted a licence application or expected to within a few years[1]). Consistent with the IGD-TP Vision, for these organisations, the driver for participation in the Project was to support the development of reference or alternative plug/seal designs for which detailed design is required in the next few years.

The Project also included WMOs with plans to submit licence applications in several decades. For these organisations, the primary driver for involvement in the DOPAS Project is to support long-term research and development (R&D) on the feasibility of geological disposal. In addition, the results of the DOPAS Project are of benefit to other European WMOs.

1.2 Report Objective

At the request of the EC, Radioactive Waste Management (RWM) and Galson Sciences Limited (GSL), who are both partners in the DOPAS Project, have worked collaboratively to identify the lessons that can be learnt from the DOPAS Project by WMOs that are less close to licensing. This report is Deliverable D4.9 of the DOPAS Project, and describes such learning.

1.3 Scope and Terminology

This report provides a succinct summary of the lessons from the DOPAS Project for programmes that have not submitted a licence application and do not expect to do so in the next few years. These programmes are referred to as *less close to licensing* in this report. It is not a detailed summary of the results of the Project. Such summaries are provided elsewhere, in particular, in a series of experiment summary reports (Noiret *et al.*, 2016a;

[1] Posiva received a construction licence for the Olkiluoto spent fuel repository in November 2015.

Svoboda *et al*., 2016a; Grahm *et al*., 2015; Holt and Koho, 2016; Jantschik and Moog, 2016; Czaikowski and Wieczorek, 2016; and Zhang, 2016), in a series of work package (WP) reports (DOPAS, 2016a; DOPAS, 2016b; DOPAS, 2016c; and DOPAS, 2016d), and in the Project Synthesis (DOPAS, 2016e). Instead, the focus is on highlighting lessons that can be learned by programmes that are not close to licensing and signposting the reports where further information is available.

In discussing lessons that can be learnt from programmes that are not close to licensing, it is of benefit to identify different types of programmes in relation to the progress in siting and licensing activities. In the early stages of implementation, disposal programmes may be entirely *generic* and not be focusing on any particular region or host rock. The aim of the *generic* phase is to examine a wide range of potentially suitable geological disposal concepts (e.g. in crystalline rocks, clay rocks and salt rocks) so that a well-informed assessment of options can be carried out at appropriate decision points in the future as the programme progresses. Other programmes may be *host-rock-type specific*, i.e. be focused on a particular type of rock such as granite, clay or salt. Programmes at the *host-rock-type-specific* stage aim to apply the learnings from the generic phase to the particular host rock of interest, and to focus the resources on the sites or regions that would be suitable for geological disposal in such a host rock. Once a preferred siting region is identified, programmes may focus on a particular geological unit in which disposal is planned. These are referred to as *formation-specific programmes* in this report. Examples include the Opalinus clay in Switzerland or the Callovo-Oxfordian clay in France.

The extent to which lessons can be learned from the DOPAS Project is affected by the stage to which any disposal programme has advanced, and specific examples are provided throughout this report. The scope of this report is not to comprehensively identify lessons specific to each of the three groups identified above. Rather, general lessons are drawn, and, only where obvious distinction between the three groups is possible, are the lessons specified accordingly.

1.4 The DOPAS Project Structure

The DOPAS Project aimed to improve the technical 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 their safety and other objectives. To achieve these objectives, development activities were divided between work on the design basis, technology, and material development, on full-scale implementation; and on performance assessment of the materials and components. Figure 1.1 shows the interaction and integration of work in the DOPAS Project, and how a new state-of-the-art resulted from the Project.

The work breakdown structure of the DOPAS Project (Figure 1.2) responded to the conceptualisation shown in Figure 1.1. The Project was undertaken in seven Work Packages (WPs). WP1 of the DOPAS Project included project management and coordination and was led by Posiva.

WP2 addressed the design basis for plugs and seals. WP2 was led by SKB (Sweden). The WP2 summary report is Deliverable D2.4 of the DOPAS Project (DOPAS, 2016a). The report describes the outcomes from WP2, including the requirements on plugs and seals considered in the DOPAS Project, conceptual and basic designs, and the strategy adopted in programmes for demonstrating compliance of the designs with the design basis. The design basis is presented for both the repository reference design, i.e., the design used to underpin the safety case or licence application, and the full-scale experiment design, i.e., the design of the plug or seal that is being tested in the DOPAS Project.

WP3 addressed the detailed design and construction of the full-scale tests in DOPAS. WP3 was led by Andra (France). The WP3 summary report is Deliverable D3.30 of the DOPAS Project (DOPAS, 2016b). The report describes the outcomes from WP3, and summarises the work undertaken and the lessons learned from the detailed design, site selection and characterisation, and construction of the experiments. These include the full-scale demonstrators, materials research and its upscaling, and the learning provided by the practical experience in constructing the experiments.

WP4 addressed the performance appraisal of the full-scale experiments in DOPAS. WP4 was led by RWM (United Kingdom). The WP4 summary report is Deliverable D4.4 of the DOPAS Project (DOPAS, 2016c). The report describes the outcomes from WP4, and summarises what was learnt in the DOPAS Project with respect to the repository reference designs for plugs and seals, drawing heavily on the summary reports for the five experiments and materials research projects (Noiret *et al*., 2016a; Svoboda *et al*., 2016a; Grahm *et al*., 2015; Holt and Koho, 2016; Jantschik and Moog, 2016; Czaikowski and Wieczorek, 2016; and Zhang, 2016). The WP4 summary report also considers alternatives to the reference designs. 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. D4.4 also considers the feedback from the work to the design basis which may include modifications to the design basis.

WP5 addressed the performance assessment of plugs and seals. WP5 was led by GRS (Germany). The WP5 summary report is Deliverable D5.10 of the DOPAS Project (DOPAS, 2016d). In the DOPAS Project, performance assessment was taken to cover the performance of plugs and seals following the installation of the plug/seal materials in the experiment/repository. This included, therefore, the saturation of the materials following installation, their long-term thermal, hydraulic, mechanical and chemical (THMC) behaviour, and their representation in safety assessments. Much of the work in WP5 was used to support the design of the experiments in WP3.

WP6 was led by Posiva. In WP6 an Expert Elicitation (EE) process was used to integrate critical analyses of the achievements and results from the implementation and monitoring of the DOPAS Project plugs and seals, including external experts' review of drafts of the main WP2 - WP5 summary reports. In addition, three staff exchanges were organised under WP6 for competence exchange between the experiments and the participating organisations' staff. The production and compilation of the DOPAS Project final public technical summary report (Deliverable D6.4, DOPAS, 2016e) is a part of this work package, too.

WP7 addressed dissemination activities of the Project results to other interested organisations in Europe and beyond. WP7 included dissemination around the full-scale experiments and two major events, an international seminar, DOPAS 2016, and a training workshop, the DOPAS Training Workshop 2015, both of which were used to facilitate dissemination of the Project results. WP7 was also led by Posiva.

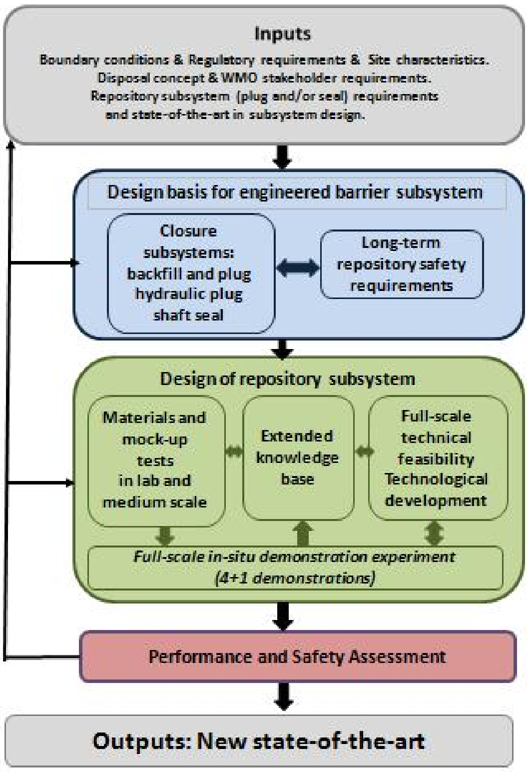

Figure 1.1: Schematic illustration of the development and demonstration of plug and seal designs for feasibility and safety performance, as conceptualised in the DOPAS Project.

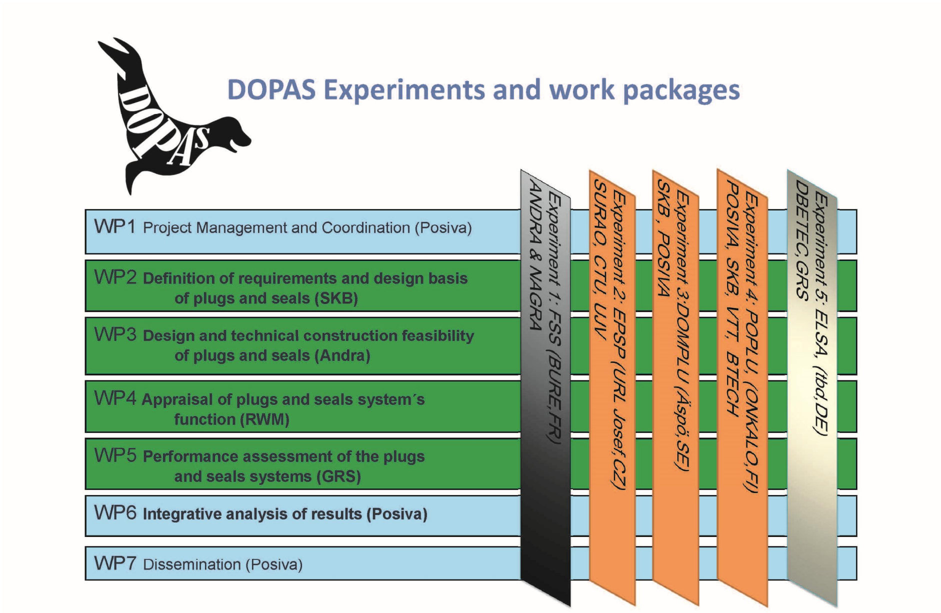

Figure 1.2: The work breakdown structure of the DOPAS Project.

1.5 The DOPAS Project Experiments

The DOPAS Project focused on tunnel/drift, vault and shaft plugs and seals for clay, crystalline and salt rocks (Figure 1.2):

- Clay rocks: the Full-scale Seal (FSS) experiment (Figure 1.3), undertaken by Andra in a surface facility at St Dizier, France, is an experiment of the construction of a drift and intermediate-level waste (ILW) disposal vault seal. The results of the FSS experiment are reported in the FSS experiment summary report, Deliverable D4.8 (Noiret *et al*., 2016a).
- Crystalline rocks: experiments related to plugs in disposal tunnels, including the Experimental Pressure and Sealing Plug (EPSP) experiment undertaken by SÚRAO and CTU at the Josef underground research centre (URC) and underground laboratory in the Czech Republic (Figure 1.4), the Dome Plug (DOMPLU) experiment undertaken by SKB and Posiva at the Äspö Hard Rock Laboratory (Äspö HRL) in Sweden (Figure 1.5 and Figure 1.6), and the Posiva Plug (POPLU) experiment undertaken by Posiva, SKB, VTT and BTECH at the ONKALO Underground Rock Characterisation Facility (URCF) in Finland (Figure 1.7). The results of the experiments are reported in the EPSP, DOMPLU and POPLU experiment summary reports, which are Deliverables D4.7 (Svoboda *et al*., 2016a), D4.3 (Grahm *et al*., 2015) and D4.5 (Holt and Koho, 2016) respectively.
- Salt rocks: tests related to seals in vertical shafts under the banner of the Entwicklung von Schachtverschlusskonzepten (development of shaft closure concepts – ELSA) experiment (Figure 1.8), being undertaken by DBE TEC together with the Technical University of Freiburg and associated partners, complemented by materials research projects performed by GRS and co-funded by the German Federal Ministry for Economic Affairs and Energy (BMWi). The ELSA experiment is being undertaken in three phases. The work carried out as part of the ELSA Project's Phase 1 and Phase 2, and performed under the DOPAS Project, consisted of work method and material tests as a part of the conceptual design for shaft sealing in salt rock. The work included materials research and performance assessment studies, and will feed into a full-scale experiment of prototype shaft seal components in Phase 3 of the ELSA Project to be carried out after the DOPAS Project. The materials research undertaken by GRS includes work in the Langzeitsicherer Schachtverschluß im Salinar (LASA and LAVA) and Untersuchung der THM-Prozesse im Nahfeld von Endlagern in Tonformationen (THM-Ton) Projects, and addressed sealing materials planned to be utilised in the shaft seals. The materials research undertaken by GRS provided supporting information to the ELSA Project. The results of the LAVA, LASA, and THM-Ton Projects are reported in the DOPAS Deliverables D3.29 (Jantschik and Moog, 2016), D3.31 (Czaikowski and Wieczorek, 2016), and D3.32 (Zhang, 2016) respectively. The results of the ELSA Phase 2 experiments are described in the ELSA Phase 2 report (Kudla *et al*. 2016).

The DOPAS experiments are related to plugs and seals at different stages of development in their respective programmes. Three of the experiments, FSS, DOMPLU and POPLU, are full-scale experiments of plugs and seals in the basic design stage. The FSS and DOMPLU experimental designs are based on the reference designs for Andra's, SKB's and Posiva's repositories. The POPLU experiment represents an alternative basic design to the DOMPLU experiment and may become a reference design. The Czech EPSP experiment design and the German ELSA related material tests and work method developments are part of a work programme to develop the conceptual designs of plugs and seals for the Czech and German programmes, and they will contribute to the preliminary design requirements of a future reference design.

The timing of the work on the DOPAS experiments and their implementation also differed. The DOMPLU experiment was started prior to the start of the DOPAS Project and was pressurised during the early months of the DOPAS Project. The POPLU, EPSP and FSS experiments were designed and constructed during the Project. Initial pressurisation of the POPLU and EPSP experiments occurred within the last year of the DOPAS Project.

The French FSS experiment was a full-scale surface-based technical feasibility demonstration of seal material emplacement and, therefore, the experiment did not include the pressurisation of the seal. However, dismantling of the FSS experiment was undertaken during the Project. The work in the FSS experiment is supported by a laboratory-scale experiment, entitled REM, which is investigating saturation of the same bentonite admixture as used in the FSS experiment (Conil *et al*., 2015).

Description of the progress in the full-scale demonstrations and of the experimental work is provided in the experiment summary reports (Noiret *et al*., 2016a; Svoboda *et al*., 2016a; Grahm *et al*., 2015; Holt and Koho, 2016; Jantschik and Moog, 2016; Czaikowski and Wieczorek, 2016; and Zhang, 2016), in a series of WP reports (DOPAS, 2016a; DOPAS, 2016b; DOPAS, 2016c; and DOPAS, 2016d), and in the Project Synthesis (DOPAS, 2016e).

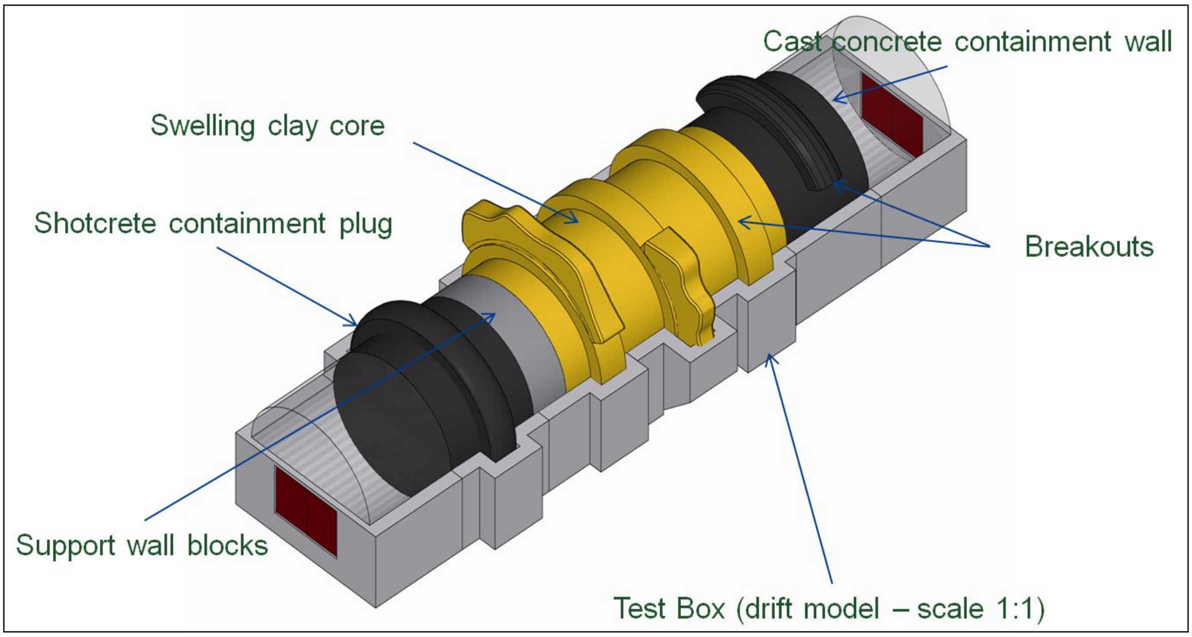

Figure 1.3: Schematic illustration of the FSS experiment design. From Bosgiraud and Foin (2013).

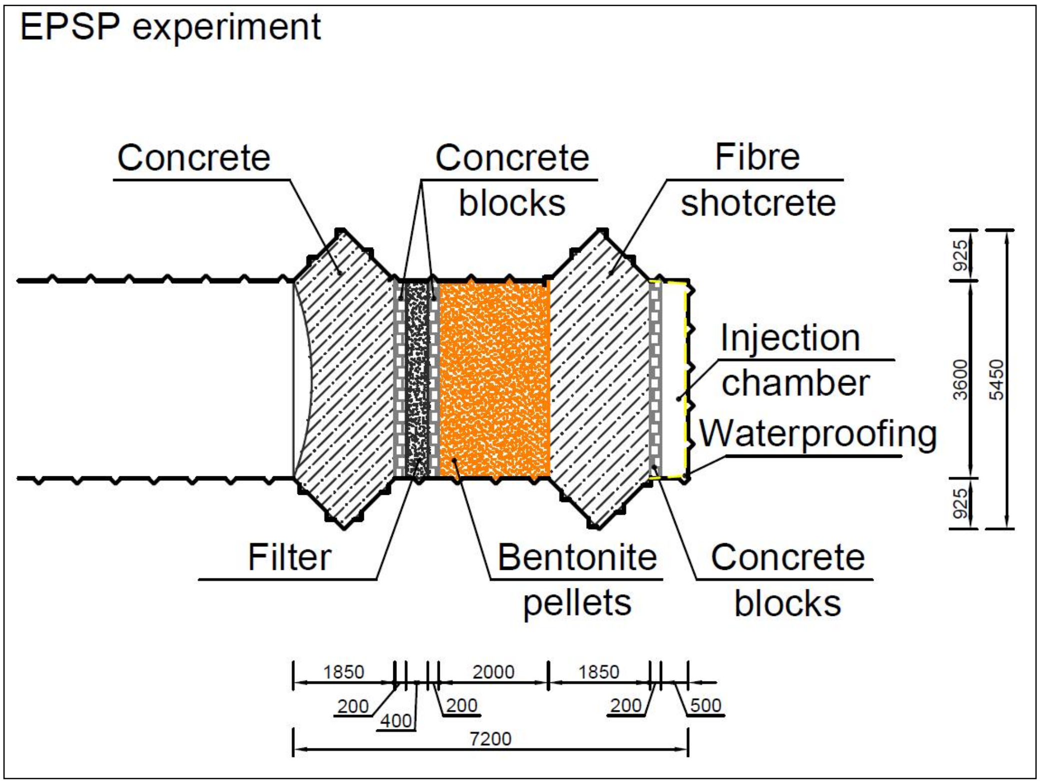

Figure 1.4: Schematic illustration of the EPSP experiment design. Dimensions are in mm. From Svoboda *et al.* (2016a).

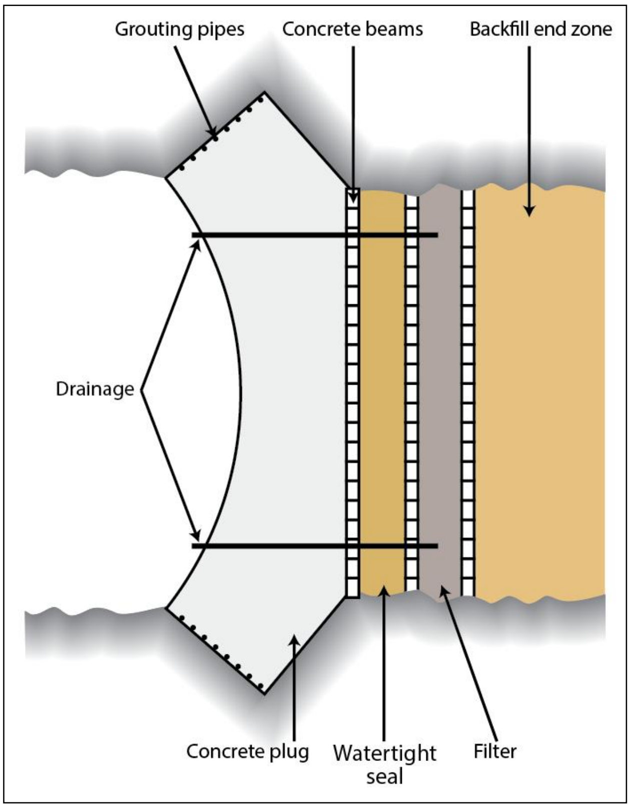

Figure 1.5: Schematic illustration of the deposition tunnel plug components in SKB's reference conceptual design (SKB, 2010b). There are three concrete beams in the conceptual design; these are sometimes referred to as the inner, middle and outer concrete beams or delimiters, with the inner concrete beam being adjacent to the backfill end zone.

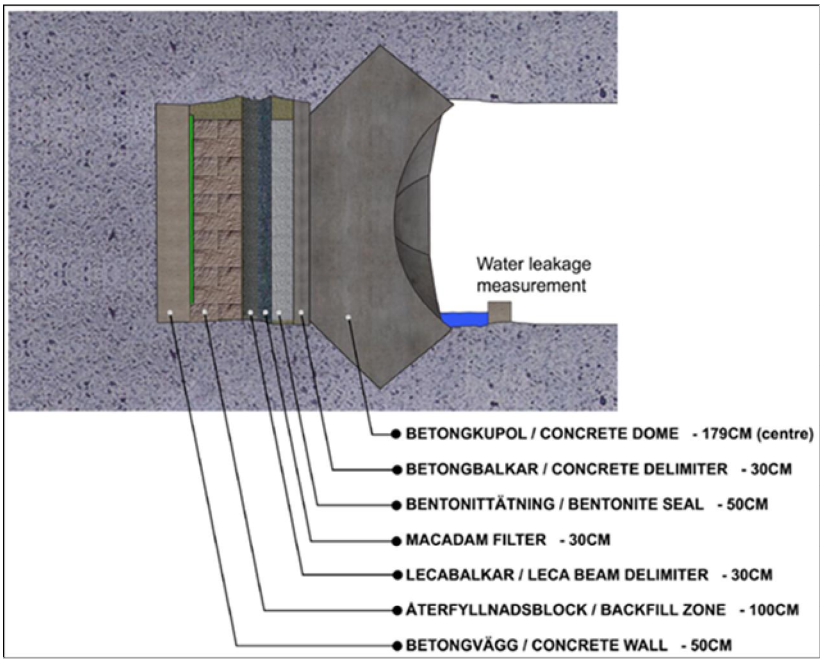

Figure 1.6: Schematic illustration of the DOMPLU experiment design (Grahm *et al.*, 2015).

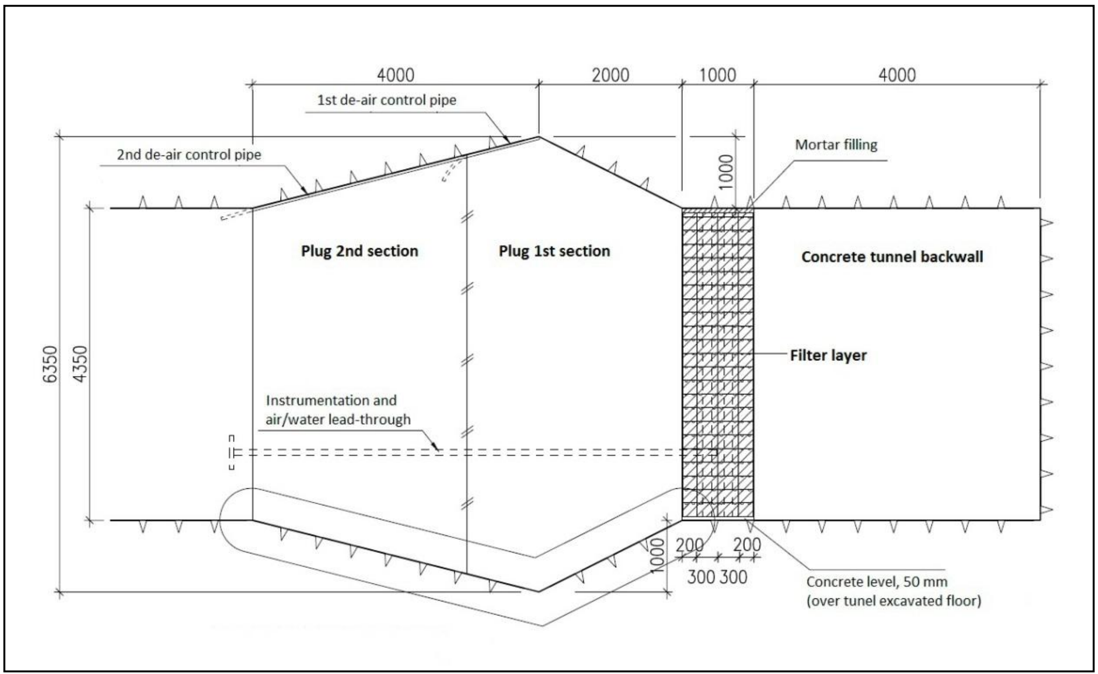

Figure 1.7: Schematic illustration of the Posiva's wedge-shaped plug being tested in POPLU (Holt, 2014).

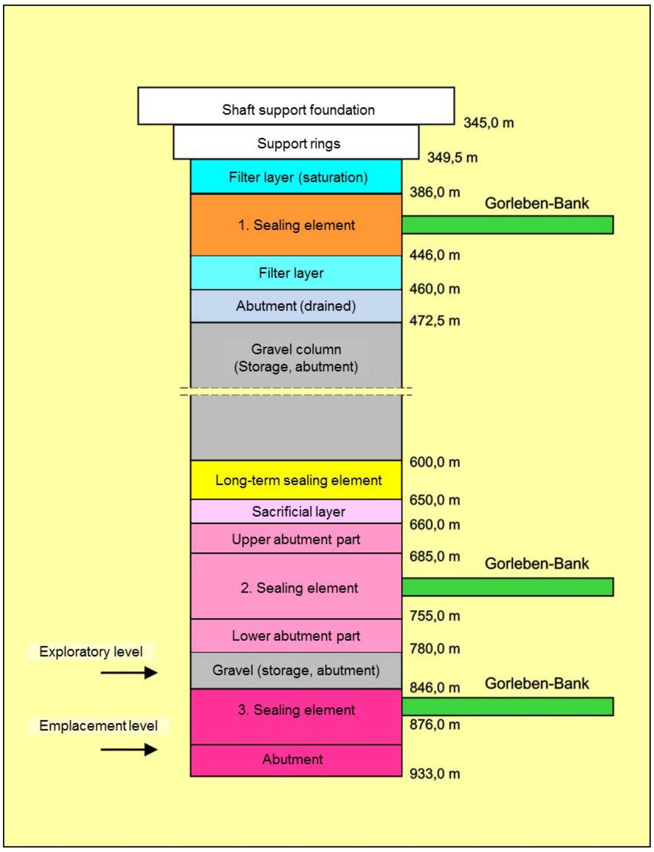

Figure 1.8: Schematic illustration of the German shaft seal reference conceptual design in a salt dome (Müller-Hoeppe *et al*., 2012a). The Gorleben-Bank is a folded anhydrite layer in the rock salt.

1.6 Approach and Report Structure

The identification and discussion of lessons to be learned by programmes less close to licensing has been approached on a topic-by-topic basis. The topics discussed are those that have been presented in the main technical WP summary reports from the Project (DOPAS, 2016a; DOPAS, 2016b; DOPAS, 2016c; DOPAS, 2016d; and DOPAS, 2016e). Each topic is discussed in a separate section of this report, with the section separated into a summary of the work undertaken and main outcomes from the DOPAS Project, and a discussion of the main lessons for programmes less close to licensing. Referencing to underpinning reports and documents, where more detailed information can be found, is extensively used in the sections summarising the work undertaken in DOPAS and the main outcomes. The topics discussed in this report and section numbers are as follows:

- Design basis process (Section 2).
- Types of plugs and seals and their functions (Section 3).
- Conceptual designs of plugs and seals (Section 4).
- Plug and seal materials, and detailed design (Section 5).
- Technical aspects of siting, excavation and installation (Section 6).
- Monitoring of plugs and seals (Section 7).
- Post-closure safety (Section 8).
- Project management in plug and seal design and construction (Section 9).

Conclusions focused on the high-level lessons to be learned by programmes less close to licensing are presented in Section 10.

2 Design Basis Process

2.1 Design Basis Process Work in the DOPAS Project

The design basis is the set of requirements and conditions taken into account in design (White *et al*., 2014; NASA, 1995).

In WP2 of the DOPAS Project, detailed design bases were collated for the four full-scale experiments (FSS, EPSP, DOMPLU and POPLU) and for the design of the German shaft seal (ELSA). The design bases are presented in White *et al*. (2014). The collation of the design basis for each experiment did not follow a predefined method or structure the requirements according to a standard, to allow for programme-specific approaches or issues to be included within the resulting design basis.

However, cross-comparison of the design bases following their collation allowed a common consideration of current practice with regard to the process used to develop and describe the design basis. 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 was therefore used to describe a generic process for development of the design basis for plugs and seals called the "DOPAS Design Basis Workflow" (Figure 2.1). The terms used in the Workflow are defined in the glossary of DOPAS (2016a). The Workflow is structured to be consistent with 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 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 generally described qualitatively, although quantitative information may also be used to a lesser extent.

- 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 detailed design specifications need to be defined in a manner that would allow them to be checked and verified during construction.

The work in the DOPAS Project has demonstrated how a systems engineering approach that uses a structured hierarchy of requirements management can be applied in repository design. The Design Basis Workflow and the general lessons derived from the DOPAS Project work on design basis development are discussed in the WP2 Summary Report (D2.4; DOPAS, 2016a).

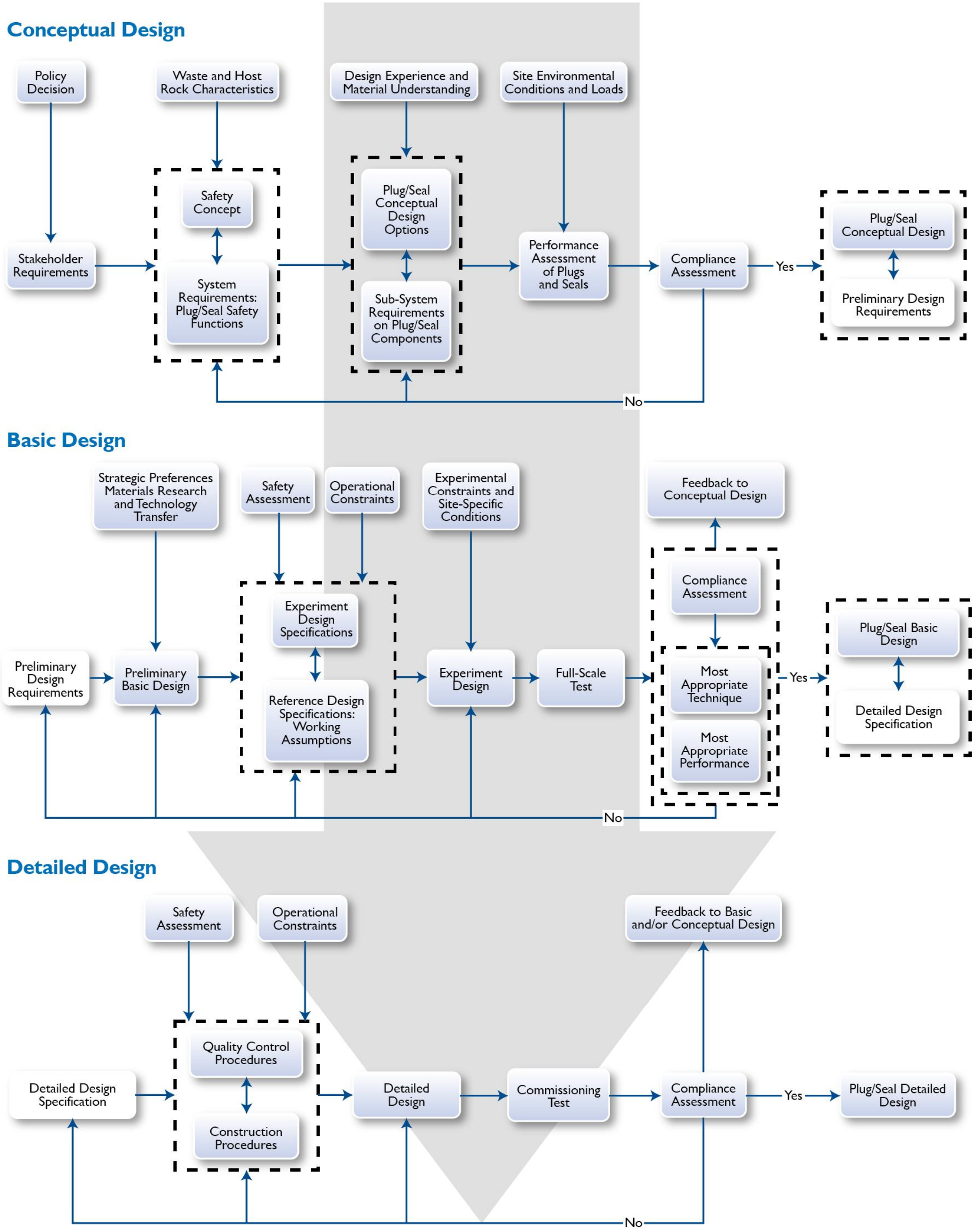

Figure 2.1: The DOPAS Design Basis Workflow, which illustrates the iterative development of the design basis, undertaken in parallel with the development of conceptual, basic and detailed designs. Dashed boxes are used to show activities undertaken in parallel. Terminology used in the Workflow is defined in DOPAS (2016a), which includes a glossary of the terms in the Workflow.

2.2 Lessons on the Design Basis Process for Programmes Less Close to Licensing

The DOPAS Design Basis Workflow is a systematic approach to the development of a design basis in parallel with stepwise development of designs. The most significant benefit of this process to programmes less close to licensing is that it provides a high-level view of the work that is required to progress from a policy decision to managing radioactive waste through to the completion of detailed design in preparation for implementation. Understanding these steps can be a basis for lifecycle programme plans and to identify what information is required in the programme and when. The Workflow can also be used to communicate how work currently being undertaken relates to the overall development of repository designs.

In addition, the DOPAS Design Basis Workflow is generic, i.e. it can be utilised for design of all repository elements and the components that they comprise (or, expressed another way, the Workflow is not specific to plugs and seals). This means that a common approach to requirements development can be established for each element of the repository.

Recognition that the design basis is developed in parallel with development of designs, and that different design bases are required for reference and experimental designs are important lessons for programmes less close to licensing, which will support the development of engineering design processes within specific organisations.

The Workflow incorporates activities at each stage to demonstrate compliance of designs with the design basis. This means that there is a framework under which WMOs can plan for compliance at an early stage, and specific projects can be undertaken to directly feed into the demonstration of compliance with safety functions and design specifications.

Several lessons were learned in the DOPAS Project regarding the iterative nature of design basis development. In particular, an analysis of the results of the experiments against key design specification (see DOPAS, 2016c) demonstrated that revision of some specifications was required. Examples include requirements that were set initially to be unnecessarily onerous and others for which ranges rather than single values were required. This illustrates that writing of good requirements remains challenging and time consuming. As such, WMOs need to begin the process of design basis development early on in the implementation of geological disposal, to allow for several cycles of revision. Early development of the design basis during generic studies and feasibility demonstration should focus on higher-level requirements (e.g. the safety functions of plugs and seals), for a range of conceptual designs that could be implemented once information on site-specific conditions is available.

The DOPAS Project illustrated a structured approach to description and evaluation of the requirements in the design basis (see DOPAS, 2016c). This included an initial listing of the requirements alongside a justification (the justification included references to underpinning science) and a description of the method by which compliance would be demonstrated. The evaluation of the requirement was then undertaken by listing the results of the full-scale test, a statement of compliance or non-compliance and an evaluation of the need to provide feedback to the design basis (i.e. a statement on whether the requirement should be modified going forward).

Finally, the design bases of the plugs and seals in the DOPAS Project have illustrated the different types of requirements and constraints that need to be included in the design basis. These should include requirements on post-closure performance, operational safety and non-functional requirements such as the use of appropriate engineering practices. These requirements and constraints can be used as either a starting point or a cross-check for development of design bases in programmes that are less close to licensing.

3 Types of Plugs and Seals and their Functions

3.1 Plugs and Seals in the DOPAS Project and their Functions

In the DOPAS Project, four different types of plugs and seals have been investigated:

- Drift and ILW vault seals for clay host rocks (FSS experiment).
- Generic tunnel plugs for crystalline host rocks (EPSP experiment).
- Deposition tunnel plugs for crystalline host rocks (DOMPLU and POPLU experiments). Both dome-based and wedge-based plug design were tested.
- Shaft seals for evaporite and clay host rocks (experiments under the umbrella of the ELSA experiment).

These plugs and seals have a range of different functions listed in Table 3.1 (see also DOPAS, 2016a and White *et al*., 2014).

Table 3.1: The safety functions of the plugs and seals considered in the DOPAS Project.

DOPAS Experiment	Type of Plug or Seal	Safety Function
FSS	Drift and ILW vault seal	Limit water flow between the underground installation and overlying formations through the access shafts/ramps, and limit the groundwater velocity within the repository
EPSP	Deposition tunnel plug	Separate the disposal container and the buffer from the rest of the repository; provide a safe environment for workers; and provide better stability of open tunnels
DOMPLU	Deposition tunnel plug	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. On-going work is currently being undertaken to add a "gas-tightness" requirement to the list of safety functions
POPLU	Deposition tunnel plug	
ELSA	Shaft seal	Provide a sufficiently low hydraulic conductivity to avoid brine paths into the repository and the movement of radionuclides out of it

In addition to the functions described for the plugs and seals, partners in the DOPAS Project have recognised and highlighted that a range of other plugs and seals will need to be constructed during the closure of the repository. Plugs and seals may be constructed in various repository locations, including tunnels/drifts, vaults, ramps, shafts and boreholes. The plugs and seals envisaged in the context of geological disposal may include, for example (Figure 3.1):

- Plugs and seals to close the (backfilled) deposition/disposal tunnels and vaults to enable them to reach the initial state defined in their design basis.
- Plugs and seals used in the underground openings and tunnels in the vicinity of the disposal area (near-field) with the aim to isolate this area from the rest of the repository.
- Plugs and seals in the access connections (tunnels/drifts, ramps and shafts) with the aim of isolating the repository from the geosphere and the biosphere.
- Plugs and seals in deep investigation boreholes leading from the surface to the vicinity of the repository area.

In different disposal concepts, the roles of plugs and seals vary from short-term supporting components to long-term barriers used to isolate the repository and prevent the release of harmful substances. The plugs and seals are generally considered to be an integral part of the engineered barrier system (EBS) and are expected to function alongside other barriers or support the functions of those barriers and those of the host rock. In particular, plugs and seals in tunnels/drifts, ramps and shafts will operate in concert with the backfill placed in these areas to deliver the necessary functions for the overall repository closure or sealing system.

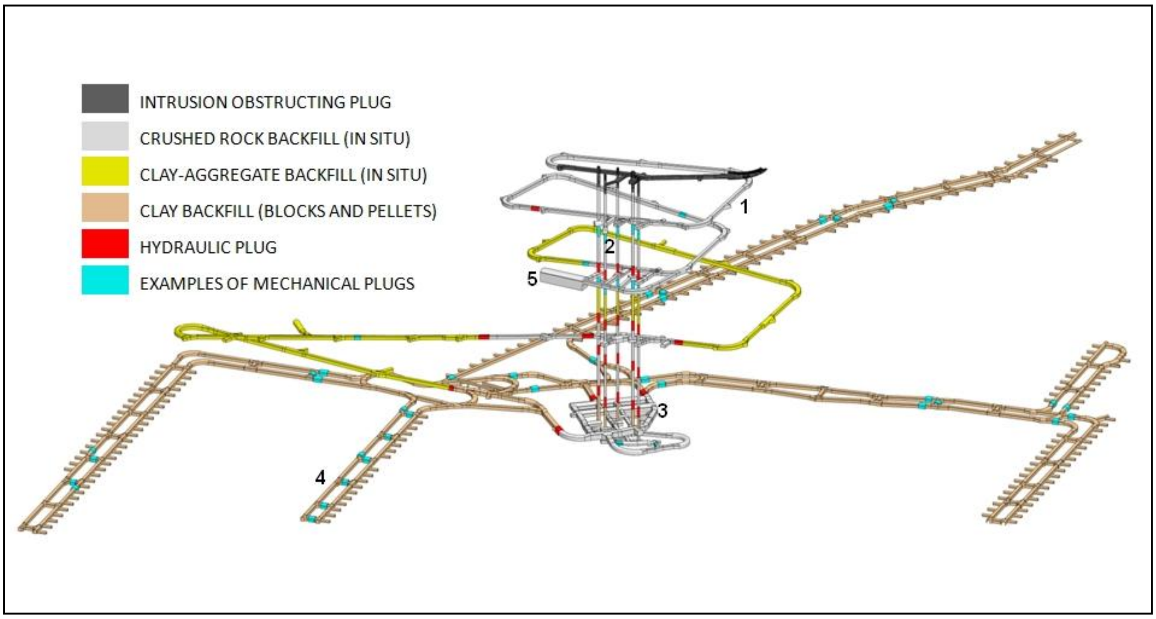

Figure 3.1: Generic Closure Design (c) Posiva Oy by Saanio and Riekkola (not to scale). 1 is the access tunnel, 2 represents the shafts, 3 is the technical rea, 4 shows the deposition tunnels, and 5 is the low and intermediate-level waste area.

3.2 Lessons on Plug and Seal Types and their Functions for Programmes Less Close to Licensing

The work in the DOPAS Project has helped to illustrate the range of different types of plugs and seals that will be constructed in repositories during its operation and closure. The clear communication of this need through the DOPAS Project will support programmes less close to licensing in defining the range of plugs and seals required in repository designs from an early stage. For example, rather than developing a single set of safety functions for plugs and seals, WMOs should, from an early stage, identify all of the different types of plugs and seals that will be required and develop separate safety functions for each type. This will help to communicate how the whole repository system will function post-closure, and will also help to identify and prioritise research needs as the programmes progress.

The Project has also recognised, and helped to communicate, that most plugs and seals have both hydraulic and mechanical functions. The recognition of this complexity in plug and seal functions will support programmes less close to licensing, as it will facilitate the process of developing functional specifications for plugs and seals, providing greater opportunity for the specification to be "right-first-time", or, at the least, to require less iteration than if starting without the experience and information that has been garnered in the DOPAS Project.

This greater understanding of the functions of plugs and seals will help programmes that are less close to licensing to plan for the design of plugs and seals in their repository programmes. The information will also help in describing generic repository designs and how plugs and seals interact with other parts of the repository design. The information will allow practical solutions for plugs and seals to be adopted from the early stages of design development, and, perhaps, reduce the complexity of conceptual design option studies.

The information will also help WMOs to make pragmatic decisions regarding plugs and seals from the early stages of design development. Plugs and seals can be both expensive and time-consuming to implement, and considering optimised solutions early in the programme and during early planning, can avoid pitfalls in the design process. A good example here is to avoid specifying a large number of plugs and seals in the closure system if this is unnecessary. Rather than specifying an "over-engineered" repository by introducing large numbers of plugs and seals at regular intervals as part of the closure system, the early stage of repository design should identify what would be sufficient to meet the specified functions.

4 Conceptual Designs of Plugs and Seals

4.1 Conceptual Designs of Plugs and Seals Addressed in the DOPAS Project

The DOPAS Project has demonstrated the technical feasibility of a range of conceptual designs for plugs and seals (White and Doudou, 2014). These include:

- Swelling clay, supported by concrete/shotcrete walls (e.g. FSS, Figure 1.3).
- Shotcrete walls, supported by a zone of bentonite pellets and a filter for pressure control (e.g. EPSP, Figure 1.4).
- An unreinforced self-compacting concrete (SCC) dome, with a watertight bentonite seal and filter zone (e.g. DOMPLU, Figure 1.5 and Figure 1.6).
- A reinforced SCC wedge, with a filter zone (e.g. POPLU, Figure 1.7).

In the German programme, work has progressed on various sealing elements that will form part of the conceptual design for shaft seals (Figure 1.8). These include further development of materials understanding and development of new sealing concepts such as a multi-layer ‘hard shell – soft core’ concept using bitumen (see Kudla *et al*. 2016 and DOPAS, 2016b).

In addition to the aspects of conceptual designs presented above, contact grouting is also an important element of all plug and seal designs, and the importance of the contact grouting in the conceptual design and provision of the safety functions required of plugs and seals has been demonstrated in all of the full-scale experiments (see DOPAS, 2016c).

The conceptual designs for plugs and seals include various components in order to meet the safety functions on plugs and seals. These include components primarily focused on providing the main safety function (e.g. a zone of bentonite to provide a low hydraulic conductivity), and components that provide supporting functions (e.g. a filter to control the rate of pressure development relative to concrete curing and to provide homogeneous saturation of a bentonite zone).

Therefore, the work in the DOPAS Project has also illustrated the complex nature of plugs and seals, with composite designs generally being favoured. This means that the design basis is also more complex and includes significant numbers of short-term and long-term requirements. This can be a benefit to the design process, as it provides design specifications that can be included in quality control programmes and against which the construction of plugs and seals can be judged for compliance demonstration.

4.2 Lessons on Plug and Seal Conceptual Designs for Programmes Less Close to Licensing

The conceptual designs of plugs and seals are dependent on the disposal concept and the host rock environment. The DOPAS Project has evaluated a range of conceptual designs for plugs and seals. The experimental conceptual plug and seal designs used in the DOPAS Project provide a sound basis for the first stage of generic design development in programmes at an early stage, for example with no identified host rock or site. The conceptual designs considered could be adopted for use in other repository concepts until host rock information becomes available to allow choices between conceptual design and to drive basic and detailed design development. Information derived from the DOPAS Project could be used as a basis, for example, for planning and cost estimation at a generic stage.

At a generic phase, when a range of disposal concepts are being investigated, going any further than a first principle conceptual design is not necessary. Technology and materials will advance/change over the coming decades so there is no driver to make decisions at an early stage that could become redundant as technology changes. A first principle conceptual design should be integrated within the repository concept to allow development of generic understanding of, for example safety functions required for the closure system, without full feasibility or performance having to be demonstrated at a generic level.

For programmes at a formation-specific stage with an identified type of host rock, conceptual designs of plugs and seals will be required to be at a more advanced stage than a generic programme (i.e. at a basic design stage). Basic designs from the DOPAS Project, as implemented in the experiments, can be used as a basis for plug and seal designs at this stage, including use of information concerning technology and materials research from the DOPAS Project as inputs to further developments and to demonstrate the expected performance of plugs and seals.

Plug and seal designs for a range of repository locations, functions and host rocks are also available from sources other than the DOPAS Project, with varying levels of associated supporting understanding. This information also provides a valuable resource, especially at a generic stage before basic design and large-scale experiments are performed by a WMO, and should also be taken into account. Examples of different plug /seal designs from sources other than the DOPAS Project include:

- Gas-permeable seals for ILW vaults. The Gas Permeable Seal Test (GAST) is a large-scale experimental test of a sand/bentonite seal concept installed at the Grimsel Test Site (Spillmann *et al*., 2016). The aim of the gas-permeable seal is to increase the capacity of the backfilled underground structures to transport gas generated by corrosion of metals and degradation of organic materials, so that no undue gas over-pressurisation occurs; such over-pressurisation can cause the hydraulic or the radionuclide retention capacity functions to be compromised.
- Sealing of high-level waste and spent fuel disposal tunnels in clay. The emplacement concept for bentonite materials developed by Nagra for the Opalinus Clay in the Full-scale Emplacement (FE) experiment at the Mont Terri underground rock laboratory (Müller *et al*., 2015) is different from that of Andra in the FSS experiment. Although the FE experiment is focused on emplacement of a buffer, both the FE and FSS experiment addressed installation of bentonite pellets/granulates. The FE experiment approach provides an alternative to industrial emplacement of bentonite using augers in clay host rocks.
- The Tunnel Sealing Experiment at the Whiteshell underground research laboratory. The experiment was used to demonstrate the technologies for constructing bentonite and concrete bulkheads, to quantify the performance of each bulkhead, and to identify the factors affecting their performance (Martino *et al*., 2007).
- The Enhanced Sealing Project at the Whiteshell underground research laboratory (URL). Two shaft plugs, spanning a water-bearing fracture, were installed at a depth of approximately 275 m as part of closure of the URL. These composite plugs consist of a 3-m-long compacted bentonite-sand component sandwiched between two 3-m-long concrete segments (Priyanto *et al*., 2016)

In addition, the experience on development of conceptual designs for plugs and seals has illustrated the range of materials that could be included in these structures. The knowledge that these materials may be included in the repository may help to guide general research undertaken within a waste management programme. For example, generic research on bentonite and concrete may consider the application of these materials in plugs and seals, as well as their application in other parts of the EBS.

5 Plug and Seal Materials, and Detailed Design

5.1 Learning on Plug and Seal Materials, and Detailed Design in the DOPAS Project

The work in the DOPAS Project has extended the knowledge of plug and seal materials and how these materials can be incorporated into detailed designs.

Bentonite sealing materials have been incorporated in the FSS, EPSP and DOMPLU full-scale tests. The work in FSS optimised the distribution of pellet and powder in the admixture used in the sealing zone (DOPAS, 2016b and Noiret *et al*., 2016a). In the EPSP experiment, Czech bentonite has been utilised for the first time in a full-scale experiment (Svoboda *et al*., 2016a and Vašíček *et al*., 2016). The DOMPLU experiment tested a bentonite block sealing layer combined with a filter layer behind the concrete dome aiming to hydrate the seal to ensure the plug tightness (Grahm *et al*., 2015 and Börgesson *et al*., 2015). Further work will include continued monitoring and evaluation of the experiments during on-going pressurisation, evaluation of the requirements on bentonite homogeneity and greater understanding of homogenisation processes for bentonite seals used as part of plug/seal design.

The project has developed and applied low-pH concrete containment walls, utilising either SCC or shotcrete. Although the exact concrete mixes developed in the DOPAS Project cannot be used directly for other applications, they can be adapted and tailored to take account of local needs, locally-sourced materials, and any other boundary conditions specific to the application of interest. For SCC, a range of approaches have been developed and tested, including the use of non-reinforced concrete domes (Grahm *et al*., 2015) and walls (Noiret *et al*., 2016a and Svoboda *et al*., 2016a), and use of reinforced concrete wedges (Holt, 2014 and Holt and Koho, 2016). These provide alternatives that can be considered for application in specific programmes depending on their needs. For shotcrete, the experiences of the FSS and EPSP experiments were quite different, partly as a result of the type of cements used, the inclusion of the glass-fibre reinforcement in the shotcrete used for EPSP, and the dimensions of the plug/seal components, having an influence on the emplacement technologies used. Improved shotcrete mixes and delivery methods (e.g. reducing rebound to ensure a more homogeneous product) are required before application in repositories.

There has been further development of materials used for contact grouting and approaches to their emplacement, including application of bentonite tapes and/or cementitious grouts in crystalline rock (Holt and Koho, 2016 and Grahm *et al*., 2015), and use of highly-mobile bitumen to seal the plug/seal-rock interface in anhydrites (DOPAS, 2016c). The success of the grouting has been variable and further evaluation of grouting mixes is required, especially following dismantling of the experiments when a greater understanding of the penetration of the grouts can be gained.

As a result of the German experimental programme, existing seal types consisting of MgO or salt concrete could be improved and new seal types based on the use of bitumen as well as on a mixture of crushed salt and fine clay were developed (Glaubach *et al*., 2016).

The work on plug and seal materials, and detailed design allowed the development of detailed design specifications that could be demonstrated through laboratory work linked to upscaling trials, through numerical modelling and structural design work, through siting and excavation and through quality control during plug/seal installation. Although developed for the experiments, and, therefore, requiring modification before use for reference designs, these design specifications will form the basis for the final detailed design of repository plugs and seals.

Design work in the DOPAS Project has utilised the Eurocode standards. For example, the German programme has adopted a quantitative approach to compliance demonstration based on the Eurocodes (EC-JRC, 2008 and White and Doudou, 2015), and the design of the POPLU concrete wedge utilised Eurocode standards to demonstrate early age performance and hardened properties (Holt and Koho, 2016).

All of the full-scale experiments were supported by a series of mock-ups undertaken at a range of scales to support the upscaling of the design from the laboratory to the full scale. For example, Posiva used mock-up castings of the concrete wedge and the tunnel back wall to fine tune the maximum aggregate size and admixture dosages of the preferred SCC mix (this underpinned a change of the aggregate maximum grain size in the upper and lower parts of the concrete wedge, where most of the reinforcement was located, from 32 mm to 16 mm) (Holt, 2014 and DOPAS, 2016c), and Andra rearranged the transfer system used to emplace the bentonite pellet and powder mix based on metric-scale testing of the backfilling machine (DOPAS, 2016b and Noiret *et al*., 2016a). Mock-up tests may be required by the regulator prior to implementation of a process within an operating repository; the experience from the DOPAS Project has illustrated the general benefit from undertaking such activities.

5.2 Lessons on Plug and Seal Materials, and Detailed Design for Programmes Less Close to Licensing

It is difficult to adopt design specifications (e.g. concerning concrete mixes) directly from other programmes, or the experiments carried out in the DOPAS Project, because of the need to take local conditions into account even if the safety function and higher-level requirements are similar. This applies to the design specifications for structure, components and dimensions of a plug or seal, as well as for the specific materials. However, programmes less close to licensing can learn some lessons from the experience in the DOPAS Project.

The materials or material combinations that are suitable for the construction of plugs and seals at a site are host rock dependent. For example, for evaporite environments, such as those considered within the ELSA Project, salt-based materials such as crushed salt or salt concrete have been investigated. Crushed salt is expected to be used for backfilling of the repository tunnels as well as the access drifts. For shaft seals in the German concept, in addition to salt-based materials, gravel and bitumen were tested. In the uppermost layers of the shaft, in the formations overlying the evaporite host rock, bentonite-based materials are also expected to be used.

Most detailed design specifications cannot typically be transferred between experimental plug designs and reference designs. For example, the plugs and seals developed and tested within the DOPAS Project were specifically designed for the repository concepts of SKB, Posiva and Andra, taking into account detailed knowledge of characteristics of the host rock in the repository. Based on this knowledge, specific requirements and safety functions were formulated for the plugs in the repository. However, in order to demonstrate implementation at full scale and, particularly, carry out performance tests on the constructed plugs, it was necessary to develop experiment site-specific designs that respond to the actual conditions of the experiment location. In the case of DOMPLU, for example, this was not in the same location or host rock as the Forsmark repository. In the DOMPLU case, the experiment was sited 450 m below ground level in the Äspö HRL in order to replicate as far as possible the groundwater pressure conditions expected in the repository location, but it is likely that other conditions, such as *in situ* stress, fracture density or spacing, are less similar to eventual locations in a repository and this needs to be reflected in the design specifications.

Various concrete recipes were developed in the DOPAS Project and tested in the demonstration experiments. The materials used, including cement, additives, aggregates and reinforcing materials, were chosen based on the specific detailed design requirements. These detailed requirements included the definition of the component / subsystem lifetime, as well as the detailed geological and geochemical boundary conditions imposed in the demonstration experiments. Thus, a simple transfer of concrete recipes is not possible and would not be of value for a WMO programme. Further, the availability of materials used in the DOPAS project is not guaranteed in the future. For example, chemical additives for concrete formulations; even within the DOPAS project, some materials selected were no longer available and acceptable substitutes had to be found.

Andra, Nagra and SÚRAO have developed different techniques for the production of bentonite pellets and for auger emplacement technologies. Different raw materials, grain size distributions, water content and compaction pressures were applied to obtain an optimum workability, grain size distribution and emplacement density in order to meet the design specifications for the as-emplaced material. Similarly, the detailed specification for block-type bentonite materials need to address the humidity and temperature conditions in the disposal tunnel, in order to comply with the performance targets set (e.g. stability and emplaced density). However, these experimental design details are not necessarily directly transferable to other repository concepts and sites as the emplacement technologies were specifically tailored to the concept, volumes (diameter and length of the disposal tunnel), the geometry of the tunnel/vault, including possible breakouts to be filled and the emplacement equipment used.

For programmes far from licensing, it is important that design specifications are developed with emphasis on the properties and performance that are required of a component, rather than in terms of a specific composition or material that may be redundant, as a result of technological advances, or unavailable by the time that the repository is being constructed. Where the operational period of a repository is long, this is especially important for plugs and seals that will only be implemented at the end of operations, potentially 100 years or more in the future.

Furthermore, development of concrete recipes or bentonite blocks / pellets, without knowing the details of the site and the repository concept is not a sensible use of resources for programmes at a generic stage. Until site-specific information, and possibly programmatic requirements (e.g. to use local materials if at all possible), are known (e.g. for programmes at a formation-specific stage), generic specifications based on materials tested in DOPAS work can be used in conceptual design development.

An additional constraint, as demonstrated by the POPLU project, is that all materials used for construction may need approval from the regulator. This applies to materials that are already known to have post-closure safety implications, such as superplasticisers and additives in concrete and grout, but also secondary materials like nitrate-rich residues introduced through drill and blast excavation. If it is likely that specific materials, such as cement additives, will change over the period before repository implementation, seeking authorisation at an early stage for their use is also not an efficient use of resources.

Although the same material specifications used in the DOPAS Project cannot not be readily adopted by programmes less close to licensing owing to the constraints discussed above, there is still value in using the specifications in illustrative work. For example, to demonstrate feasibility of certain designs using concrete, it is necessary to show that the concrete leachate is of low pH and that the concrete can also be satisfactorily emplaced. To do this requires specific work, e.g. recognition that specific additives (e.g. superplasticisers and retardants) must be incorporated into the concrete mix. Technical feasibility must, therefore, consider whether use of such materials would have a significant detrimental impact on the performance and feasibility of the repository or not. Such work could be done by using some of the bentonite and concrete material formulations tested in the DOPAS Project as illustrative examples.

A further benefit of the materials work undertaken in the DOPAS Project for programmes that are less close to licensing is development of state-of-the-art understanding of the advantages and disadvantages of material options. Examples include understanding the characteristics that might influence the choice, at a later stage in the programme, between low-pH self-compacting concrete and low-pH shotcrete for concrete bulkheads, and between pelleted and pre-compacted bentonite materials for installation of massive clay structures. If these decisions can be made relatively early in a programme (e.g. once a programme becomes host-rock-type generic), it can help to focus R&D resources; the requirement for programmes in entirely generic phases is to ensure understanding of the factors that need to be taken into account in such decisions.

6 Technical Aspects of Siting, Excavation and Installation

6.1 Learning on Siting, Excavation and Installation of Plugs and Seals in the DOPAS Project

The DOPAS Project provided a platform for the testing of plug siting processes in crystalline rocks, in particular the SKB and Posiva methodologies. This included the first successful application of Posiva's Rock Suitability Classification (RSC) methodology to the siting of deposition tunnel plugs (Kosunen, 2014). Further development of plug and seal location rock requirements will be undertaken once further pressurisation, monitoring and evaluation of the experiments has been undertaken.

Techniques used to excavate the locations of the full-scale experiments undertaken in the DOPAS Project include hydraulic wedge splitting and pressure disintegration techniques (the EPSP experiment), wire sawing (the DOMPLU experiment) and wedging and grinding (the POPLU experiment), which were all shown to be promising technologies for application in repositories. Wire sawing will require optimisation with respect to the *in situ* repository conditions, and the application of wedging and grinding can be improved by on-going interaction with the design process (finalising the detailed design following the excavation of the wedge).

Health and safety during rock excavation is of significant concern in repository projects; high precision excavation is required, including in the roof of underground openings, which introduces a potential for rock fall accidents. Solutions were tested in the DOPAS Project, e.g. use of safety scaffolds, but the acceptability of such approaches must be assessed on a project-specific basis. Wedging and grinding using an extendable boom provides an alternative solution.

Four full-scale plugs and seals have been successfully installed in the DOPAS Project, which has provided significant experience in the issues to be addressed during the construction of plugs and seals in repositories. In addition to the experience gained with bentonite and concrete materials, this has allowed methods for the installation of filters, delimiters and formwork to aid the installation of plugs and seals (DOPAS, 2016b).

In addition, methods for compaction of crushed salt and clay mixtures have been tested and improved as part of *in situ* tests undertaken as part of the ELSA programme (DOPAS, 2016b).

The installation of the materials and work sequences were according to the planned schedule, the experiments were installed taking into account the occupational safety issues and were largely consistent with quality control criteria that were linked to design specifications included in the design basis. The implementation related procedures for POPLU experiment were implemented according to the Finnish Radiation and Nuclear Safety Authority guidance, providing invaluable experience of construction under a licence.

Challenges were encountered in placing materials at the edges of the experiments, especially close to the roof. Specific methods will be required to meet these challenges, for example use of composite materials or emplacement methods, or use of an auger delivery system in the lower parts of a bentonite seal and shotclay method at the top (DOPAS, 2016b).

6.2 Lessons on Siting, Excavation and Installation for Programmes Less Close to Licensing

The most significant lesson for programmes less close to licensing from the siting, excavation and installation work in the DOPAS Project is the understanding of the complexity of implementation of repository designs in "real-world" situations, which will allow for greater realism to be incorporated in conceptual designs at an early stage in design development. There is no requirement for conceptual designs to incorporate complex solutions to installation challenges (e.g. use of composite materials to mitigate problems with installation of materials towards the roof of tunnels), but illustrations of repository designs can account for complexity to avoid the impression that a WMO only has a simplistic understanding of underground engineering. Understanding the challenges that have been faced by construction of the DOPAS full-scale experiments can be used to support generic testing that WMOs will undertake to support demonstration of technical feasibility and design development in their programmes. Further details on the challenges faced during the siting, excavation and installation of the DOPAS experiments can be found in (DOPAS, 2016b)

The experience from the DOPAS Project provides good experience in integrating industrial health and safety (safety during construction) with the, sometimes, conflicting requirements of post-closure safety. The experience of the DOPAS Project can act as a test bed for integrating these two considerations during design.

The experience will also help WMOs responsible for programmes less close to licensing to develop engineering methods. For example, there is a need to take account of unexpected site conditions in some host rocks, and, for some excavation methods the scheduling of detailed design in relation to excavation can be optimised.

7 Monitoring of Plugs and Seals

7.1 Learning on Monitoring of Plugs and Seals in the DOPAS Project

The monitoring of the full-scale experiments in the DOPAS Project was underpinned by detailed test plans that were based on predictive modelling of plug and seal performance undertaken in WP3 and WP5. This work identified the monitoring that was necessary for experimental purposes. Example monitoring data reports for the DOPAS experiments are (Noiret *et al*., 2016b) for FSS and (Svoboda *et al*., 2016b) for EPSP. The summary reports of the experiments also provide more details on the monitoring systems and their performance.

The experiments utilised a range of sensors to monitor a series of common parameters, for example:

- Temperature.
- Total pressure and pore pressure.
- Strain and displacement.
- Relative humidity and water content.

In addition, the POPLU experiment tested wireless transmission of data from additional temperature sensors to increase confidence in the monitoring system. System development could be beneficial with respect to application in future full-scale experiments and commissioning tests.

In general, the sensors operated as expected and allowed monitoring of the performance of the plugs and seals with respect to the design specifications that have been set, and also the overall performance of the plugs/seals with respect to the safety functions (see Section 8).

The work in the DOPAS Project experiments has demonstrated some of the complexity in installing monitoring systems, with complex routing of wires required, issues arising with unexpected electromagnetic fields underground (generated in other experiments and other equipment used in ONKALO) and the need to check compatibility between sensors and data loggers. In addition, the sensor cables provided routes for leakage; this has the potential to jeopardise the functions of plugs/seals.

In addition, the monitoring of the plugs/seals has illustrated close consistency with predictions made from numerical modelling. This demonstrates the possibility that the experimental results can be used to calibrate numerical models, and thereby avoid the need for extensive monitoring of plugs and seals during repository operation. Nonetheless, the experiments have also demonstrated that monitoring of plugs and seals in the repository is feasible and might produce relevant data. For example, monitoring of the pressure inside filters can be used to understand the development of stress acting on retaining walls, and the leakage monitoring systems developed for DOMPLU and POPLU can be used to evaluate the performance of plugs against water tightness-related safety functions.

Any monitoring of plugs and seals in repositories will have to be significantly reduced in scale to allow disposal to be achieved efficiently and effectively. Introduction of monitoring systems into a repository requires strategies to ensure that post-closure performance of the system is not undermined and the schedule for implementation is not significantly affected. Therefore, there is a need to identify what relevant monitoring data must be acquired and the methods to acquire it, to provide further confidence in repository performance and/or to respond to specific stakeholder requirements.

The systems engineering-based approach used to evaluate performance of the experiments in the DOPAS Project provides a method for identifying the monitoring systems that could be applied in a repository, as it provides an explicit discussion of the evidence on which compliance with requirements is based in order to underpin statements that the design meets requirements.

7.2 Lessons on Monitoring of Plugs and Seals for Programmes Less Close to Licensing

For programmes that are less close to licensing, there may be a requirement to demonstrate that monitoring of the repository is feasible, in terms of monitoring sensors performing as expected, in terms of monitoring sensors not affecting the passive safety of the system, and in terms of monitoring providing useful information on a timescale of relevance to decision making (e.g. years to decades). Demonstration of monitoring feasibility might play an important role in gaining stakeholder acceptance during siting programmes, in particular gaining acceptance of public stakeholders.

There have been issues with the monitoring of the plugs and seals in the DOPAS Project, for example some sensors failed owing to lack of water protection and there were some leakages through plugs associated with monitoring wires. However, the monitoring of the plugs and seals was successful. In particular, monitoring was used during the early-stage evolution of the plugs and seals to demonstrate compliance with design specifications (e.g. curing temperature of concrete) and to build confidence in the longer-term evolution of the plug and seal systems (e.g. by demonstrating that bentonite saturation was proceeding in line with expectations using water pressure monitoring). Furthermore, the results from monitoring of the experiments were consistent with numerical predictions of behaviour, building confidence in the predictive capability of coupled models. Therefore, the results from the DOPAS experiments may benefit programmes less close to licensing by demonstrating the practical feasibility of safely installing the EBS as designed.

The experience from monitoring of the DOPAS also provides a basis for undertaking monitoring of experiments in the research programmes of programmes less close to licensing. This might include application of the wireless technologies developed as part of the wider POPLU Project. However, application of the lessons from the monitoring is mainly applicable to formation-specific programmes that might be undertaking focused experiments in a URL.

8 Performance of Plugs and Seals

8.1 Work on Performance of Plugs and Seals in the DOPAS Project

The performance of plugs and seals in the DOPAS Project was considered over a range of periods – these periods were defined specifically for the DOPAS Project:

- *Short-term performance* included consideration of the response of materials to their installation in plugs and seals (e.g. the temperature of the concrete during curing).
- *Full-scale experiment-period performance*, which included the response of the full-scale experiments to pressurisation during the period of the DOPAS Project.
- *Medium-term performance,* which considered the saturation of the materials used in the experiments (for example in parallel experiments such as REM) and reference designs, and related modelling.
- *Long-term (lifetime) performance*, which, in the DOPAS Project focused on understanding of specific material behaviour and related modelling over the design life of the plug/seal.

In the DOPAS Project, all four of the full-scale tests have been designed, constructed and initial evaluation of performance has been undertaken. For FSS, this performance evaluation has been in response to monitoring during installation of the seal components. For EPSP, DOMPLU and POPLU, evaluation has been in response to installation and initial pressurisation of the experiment.

The concretes developed in the DOPAS Project met a wide range of performance criteria, including low-pH leachate, workability, low temperature during hydration, acceptable pressures on formwork, appropriate shrinkage and long-term durability achieved by strength and permeability of the concrete. The performance demonstrated the suitability of the mixes for application in repositories. Fulfilment of the intended design, or structural, service life of the plug based on concrete material selection was validated by application of appropriate standards, by accelerated laboratory tests during the mix development stages, and during quality control testing associated with construction.

The response to pressurisation of the experiments by the end of the Project, was mostly consistent with expectations, with pressures being transmitted through the bentonite, swelling of bentonite commencing and leakages of water across plugs reducing as a result. There were experiment-related leakage issues experienced for the EPSP, DOMPLU and POPLU experiments, but these were the result of a combination of local rock and pressurisation regime conditions (the DOMPLU experiment) or have been addressed by additional contact grouting (the EPSP and POPLU experiments) to mitigate realised risks. In addition, some leakages were also related to monitoring equipment cabling (DOMPLU and EPSP experiments).

Bentonite saturation was addressed by work in the REM experiment associated with FSS and process modelling in a reduced-scale experiment for EPSP. Monitoring of the REM experiment, which uses the same bentonite material used in FSS, is planned to last for decades; but early results contributed to the understanding of early-stage bentonite saturation. The total resaturation of the REM experiment is expected to take 30 years. The EPSP-related experiment allowed the development of water retention models for the new bentonite material applied in the EPSP experiment and prediction of the saturation of the bentonite zone in the experiment. Long-term performance of the bentonite materials in the plug and seal environments was linked to the specifications as defined in the design basis (such as emplaced bulk density), as well as compatibility with adjacent materials (such as low-pH leachate interaction from concrete).

Regarding long-term processes affecting plug and seal material performance, new information on clay and concrete-based sealing materials have been gathered in the LASA, LAVA and THM-Ton projects. This learning will be applied in constitutive models used to predict long-term behaviour of sealing materials following the DOPAS Project. The interaction of materials, like cement-bentonite interactions, from DOPAS is also feeding into future developments in other programmes such as the H2020 CEBAMA project (CEBAMA, 2016).

8.2 Lessons on Plugs and Seals Performance for Programmes Less Close to Licensing

The DOPAS Project has provided further understanding of the performance of plugs and seals with different designs and under different load conditions. Analysis of the DOPAS plug and seal performance and compliance is still ongoing, and experiment dismantling is expected to provide further information on the compliance of plugs and seals to the design basis. Detailed performance assessment of plugs and seals is not likely to be a high priority for programmes that are less close to licensing. However, the results from the DOPAS Project could be used to underpin scenarios that considered a certain amount of leakage across plugs and seals. This leakage performance can also be used as a basis for overall conceptual designs of closure systems, and to define the requirements on these systems. In addition, satisfactory performance of plugs and seals in the DOPAS Project provides confidence in the conceptual designs that are based on the DOPAS experiments and that may be adopted by programmes less close to licensing.

An important observation from the full-scale testing undertaken in the DOPAS Project is the challenges faced when attempting to fully grout the contact zone between plug and seal components and the host rock. Grouting remains a key issue for which further work is required. Programmes that are less close to licensing might look to mitigate issues associated with grouting by undertaking long-term research into development of grouting materials or by developing siting approaches coupled with plug and seal designs that minimise the risks of inadequate grouting.

9 Project Management in Plug and Seal Design and Construction

9.1 Learning on Project Management in the DOPAS Project

The DOPAS Project has illustrated some of the complexity that will need to be addressed during the industrialisation of plug/seal construction and installation activities during repository operations. The installation of plugs and seals requires many activities, and, therefore, there is a need to develop simple and repetitive commissioning methods. Much of the work in the DOPAS Project has been of a “one-off” nature, for example some material emplacement methods used in the experiments may not be the exact solutions to be used in a repository, but this experience has been useful to identify where routine application of methods can be undertaken.

The experience from the DOPAS experiments has demonstrated the impact of logistical issues on the installation of plugs and seals. In particular, the need for back-up machinery to be utilised during routine maintenance or to counteract delays owing to unexpected failure is good practice, and contingencies should be included in project programmes. During the planning of experiment schedules, it is considered good practice to involve contractors early in discussions, as they can have valuable experiences that should be taken into account when scheduling work. Contractors should be provided with clear definitions and justifications for requirements and design issues, so they understand the impact of logistics and construction works. This is also important during the procurement phase for supply contracts and later work acceptance/approval to progress.

Project management activities within the DOPAS Project included production of a comprehensive risk plan at the start of the project. Subsequently, the risk plan was monitored and the status of the risks assessed on a regular basis during the Project.

9.2 Lessons on Project Management for Programmes Less Close to Licensing

Detailed project management is mainly an issue to be addressed during the final preparations for repository construction and operation. However, as a disposal programme approaches licensing there is a need to demonstrate that project management procedures are in place. Undertaking of large-scale experiments in underground research laboratories will benefit from the lessons in project management gained through the DOPAS Project. In addition, good project management should be embedded in an implementing organisation from an early stage, and experience in applying project management practices from the early stages of a project would support their smooth operation at later stages in the project.

The project management lessons learnt in the DOPAS project can provide a valuable insight into the project management requirements that are likely to pertain during repository implementation - the precise requirements in this regard will depend on national regulatory regimes.

10 Conclusions

Within the DOPAS Project, four full-scale experiments of plugs and seals were designed and constructed. One of the full-scale experiments (FSS) was dismantled, and three of the experiments (EPSP, DOMPLU and POPLU) were pressurised and initial results were evaluated. Mock-up tests and materials research projects have provided further underpinning of the conceptual designs of shaft seals.

The outcomes have provided a significant advancement in the state-of-the-art in implementing plugs and seals in operating repositories. This includes: design basis process; types of plugs and seals, and their functions; conceptual designs of plugs and seals; plug and seal materials, and detailed design; technical aspects of siting, excavation and installation; monitoring of plugs and seals; performance of plugs and seals; and project management.

The driver for the project and the main project results are primarily focused on the needs of WMOs that had have received a repository construction licence, that have submitted a licence application, or that expect to submit a licence application within a few years.

The DOPAS Project provides a significant number of lessons for programmes that are less close to licensing. At a high-level, these include the demonstration of the feasibility of plug and seal designs which can be used to underpin geological disposal feasibility demonstration projects; an illustration of the work required to develop detailed designs of plugs and seals, which can be used for planning design work; and potential solutions for plug and seal designs, which can act as a starting point for programme-specific designs. In particular, the work of the DOPAS Project provides a significant body of work on the challenges and potential solutions for repository plugs and seals both for generic studies, for programmes considering specific host rock types and for programmes focusing on a specific formation.

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