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Preface

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. The Project was coordinated by Posiva (Finland). A set of five full-scale experiments, materials research projects, and performance assessment studies of plugs and seals for geological repositories were undertaken in the course of the Project.

This document is the DOPAS Project summary report and describes the overall learning from the Project. The report has been compiled by four editors, Slimane Doudou, Johanna Hansen, Marjatta Palmu and Matt White. Editing of the report has built on contributions from Project partners, including Work Package Leaders and Experiment Leaders:

- Johanna Hansen (Posiva): WP1 Leader
- Behnaz Aghili, Esther Jonsson since July 2016 (SKB): WP2 Leader.
- Jean-Michel Bosgiraud (Andra): WP3 Leader.
- Mark Johnson, Dean Gentles since April 2015 (RWM): WP4 Leader.
- André Rübel (GRS): WP5 Leader.
- Marjatta Palmu (Posiva): WP6 Leader
- Johanna Hansen (Posiva): WP7 Leader
- Régis Foin (Andra): FSS Experiment Leader.
- Jaroslav Pacovský, Jiří Svoboda since February 2014 (CTU): EPSP Experiment Leader.
- Markéta Dohnálková (SURAO) as WP4 Deputy Leader.
- Pär Grahm (SKB): DOMPLU Experiment Leader.
- Petri Koho (Posiva): POPLU Experiment Leader.
- Erika Holt (VTT): POPLU Experiment Project Manager.
- Michael Jobmann (DBE TEC): ELSA Project Leader.
- Oliver Czaikowski (GRS): LAVA, LASA and THM-Ton Project Leader and Contact Person

In addition, expert advice has been received from the elicitations of the Work package summary reports.

DOPAS Project wishes to thank the European Commission, the waste management organisations and the ministry involved in funding the project. Further thank you goes to all of the committed project participants and subcontractors who have contributed to the success of the DOPAS Project.

Executive Summary

DOPAS Project, Full-scale Demonstration of Plugs and Seals, is co-funded by the Euratom FP7 programme and by eight waste management agencies and the German Ministry BMWi. The project has 14 partners from 8 European countries. The Project was carried out during 2012 - 2016.

The DOPAS Project consisted of seven work packages and it was coordinated by Posiva Oy. The Posiva coordinator lead work packages WP1 (Project management and coordination) and WP7 included the coordination and project management and various dissemination activities of the project including a training workshop and an international seminar. WP2, WP3, WP4 and WP5 addressed, respectively, the design basis, construction, compliance testing, and performance assessment modelling of full-scale experiments and materials research projects.

WP2 lead by SKB included the development of the design basis for the experiments and lead to a generic work flow for developing the design basis for sealing from the requirements and the functions of the sealing structures.

In the DOPAS Project, Research, Development and Demonstration work was carried out on five full-scale sealing experiments belonging to the WP3 that was lead by Andra: WP4 that was lead by RWM assessed the compliance of the experiment designs and experiments to their developed design basis and collected the major lessons learnt from the experiments. Extensive monitoring and material development programmes were implemented as a part each experiment in cooperation with the other project partners.

The DOPAS Project focused on drift, vault, tunnel and shaft plugs and seals for clay, crystalline and salt rock environments. Following experiments were carried out: FSS seal by Andra and Nagra in France, EPSP plug by SURAO (former RAWRA) and CTU in the Czech Republic, DOMPLU and POPLU plugs in cooperation between SKB (Sweden) and Posiva (Finland) in their respective countries and ELSA project related experiment work in Germany by GRS and DBETEC.

- Clay host rocks: the Full-scale Seal (FSS) experiment, undertaken by Andra in a surface facility at St Dizier, was an experiment of the construction of a drift and intermediate-level waste (ILW) disposal vault seal.
- Crystalline host rocks: experiments related to plugs in disposal tunnels, including the Experimental Pressure and Sealing Plug (EPSP) experiment 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 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 host 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 materials research projects performed by GRS and co-funded by the German Federal Ministry for Economic Affairs and Energy (BMWi). The German ELSA Project will be undertaken in three phases. Work related to the Phase 2 (and some minor parts of Phase 1) was part of the DOPAS Project, and focused on the early stages of design

basis development and on demonstration of the suitability of designs through performance assessment studies. Phase 3 is a full-scale experiment to be carried out after the DOPAS Project. The sealing materials research that is planned to be utilised in the shaft seals was undertaken in three subprojects by GRS including work in the "Langzeitsicherer Schachtverschluß im Salinar" (subprojects LASA and LAVA) and "Untersuchung der THM-Prozesse im Nahfeld von Endlagern in Tonformationen" (THM-Ton) projects. This materials research by GRS and the compaction work method tests by DBETEC provided supporting information to the ELSA Project.

WP5 lead by GRS carried out and collected the experiences of the different types of modelling used to predict and access the processes that the experiments were influenced with and at the performance of the experiments including the work on developing suitable performance indicators for the longer term. WP6 lead by Posiva included the quality assurance of the WP2-WP5 final summary reports by using expert elicitation as a means of independent peer review, promoted knowledge transfer with a staff exchange programme and integrated and summarized the project results in this report.

The DOPAS Project succeeded in improving 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 main outcomes of the DOPAS Project are that the experiments and the work carried out related the conceptual and basic design of the sealing structures in the participating countries enables the waste management programmes to move forward to the next level of technical maturity. In addition, the lessons learned described in detail in the work package and experiment summary reports provide valuable input also for waste management programmes needing further information to develop their own plugging and sealing solutions.

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 gGmbH	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

Cigéo:	Centre Industriel de Stockage Géologique (Industrial Repository in France)
COX	Callovo-Oxfordian argillaceous formation
CSH	Calcium - Silicate - Hydrate
DAC:	Demande d'Autorisation de Construction
DEM:	Demonstration
DOMPLU:	Dome Plug
DOPAS:	Full-scale Demonstration of Plugs and Seals
EBS:	Engineered barrier system
EC:	European Commission
ECGA:	European Commission Grant Agreement
EDZ:	Excavation damaged zone
EE	Expert elicitation
ELSA:	Entwicklung von Schachtverschlusskonzepten (development of shaft closure concepts)
EPSP:	Experimental Pressure and Sealing Plug
ESP:	Enhanced Sealing Project
EU:	European Union
EURATOM:	Treaty establishing the European Atomic Energy Community
FSS:	Full-scale Seal
FMEA:	Failure modes and effects analysis
FSAR:	Final safety assessment report
FP7:	EU Seventh Framework Programme for Research and Technological Development
GAST:	Gas-Permeable Seal Test
H2020:	Horizon 2020 the EU Framework Programme for Research and Innovation
HLW:	High-level waste
HRL:	Hard Rock Laboratory
IGD-TP:	The Implementing Geological Disposal of Radioactive Waste Technology Platform
ILW:	Intermediate-level waste
LASA:	Langzeitsicherer Schachtverschluß im Salinar (a set of experiments on shaft sealing concepts in Germany focusing on mechanical-hydraulic behaviour of materials)
LAVA:	Langzeitsicherer Schachtverschluß im Salinar (a set of experiment on shaft sealing concepts in Germany focusing on chemical-hydraulic behaviour of materials)

LECA®:	Light-weight expanded clay/concrete aggregate
LLW:	Low-level waste
Low pH	Concrete material pH levels equaling or below pH 11 (in the geological disposal context)
PA:	Performance assessment
PHM:	Physical hydraulic model
PIM:	Physical interaction model
POPLU:	Posiva Plug
R&D:	Research and development
RD&D:	Research, development and demonstration
REM:	Résaturation Échelle Métrique (metric-scale experiment)
RTD:	Research and technological development
SA:	Safety assessment
SCC:	Self-compacting concrete
SET-Plan:	Strategic Energy Technology Plan of the European Commission
SFRC:	Steel-fibre-reinforced concrete
SRA:	Strategic Research Agenda
STUK:	Radiation and Nuclear Safety Authority
THM-Ton:	Untersuchung der THM-Prozesse im Nahfeld von Endlagern in Tonformationen (a set of experiments on clay sealing materials focusing on thermal- mechanical-hydraulic issues)
TRL:	Technology Readiness Level
TSO:	Technical Support Organisation
URC:	Underground research centre
URCF:	Underground Rock Characterisation Facility
URL:	Underground research laboratory
VAHA:	Vaatimusten hallintajärjestelmä (Posiva's requirement management system)
VSG:	Vorläufige Sicherheitsanalyse Gorleben (Preliminary Safety Analysis for Gorleben)
WMO:	Waste management organisation
WP:	Work package

Table of Contents

Part 1. The Framework for Development of Plugs and Seals within the DOPAS Project

1.1 Introduction

1.1.1 Background and Relationship of the DOPAS Project to Research, Development and Demonstration of the Waste Management Programmes

The Implementing Geological Disposal of Radioactive Waste Technology Platform (IGD-TP) was launched on 12 November 2009 (IGD-TP, 2011). The vision ("Vision 2025") of the IGD-TP is that *"by 2025, the first geological disposal facilities for spent fuel, high-level waste (HLW) and other long-lived radioactive waste will be operating safely in Europe (IGD-TP, 2009). The IGD-TP's activities are driven by this vision that, and its commitment to:*

- *Build confidence in the safety of geological disposal solutions among European citizens and decision-makers.*
- *Encourage the establishment of waste management programmes that integrate geological disposal as the accepted option for the safe long-term management of long-lived and/or HLW.*
- *Facilitate access to expertise and technology and maintain competences in the field of geological disposal for the benefit of Member States."*

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 2011). (IGD-TP, 2011). In parallel with the work on the IGD-TP, the European Commission (EC), launched the Strategic Energy Technology Plan (SET-Plan), to support the delivery of sustainable, secure and competitive energy (EC, 2007), and published the European Union (EU) Directive 2011/70 on the Responsible and Safe Management of Spent Fuel and Radioactive Waste in Member States (the EU Directive), which requires member states to have national programmes for the implementation of their management policies for spent fuel and (relevant) radioactive waste (EC, 2011).

Plugging and sealing belong under the IGD-TP's SRA's Key Topic 3 "Technical feasibility and long-term performance of repository components". The full scale demonstrations of plugs and seals in the DOPAS Project make until today the largest full-scale demonstration European co-operation project deployed under the IGD-TP engaging not only a large number of organisations responsible for a waste management programme but also research organisations, academia and engineering companies.

The Euratom 2012 Work Programme for Nuclear Research and Training Activities (the Euratom Seventh Framework Programme) (EC, 2012) recognised that the Key Topics of the IGD-TP's SRA were in alignment with the European Commission's and with the Directive 2011/70 priorities and the call included support for work to be undertaken in alignment with the SRA (IGD-TP, 2011), the SET-Plan and the EU Directive. In particular, the Work Programme called for work on the technical feasibility and long-term performance of repository components, including full-scale demonstration of plugs and seals.

This call reflected Key Topic 3 of the Strategic Research Agenda of the IGD-TP, entitled Technical Feasibility and Long-term Performance of Repository Components (IGD-TP, 2011). Key Topic 3 called for RD&D activities for demonstrating and optimising technology and construction of a repository and its components, with two specific objectives (IGD-TP, 2011):

a) *"To demonstrate, to the level required by national licensing rules, that the technical design requirements based on safety of construction and operations, safety during the post-operational transient phase, and long-term safety after closure can be met in practice by available construction technologies and related working procedures. This includes confirmation of repository components against pre-defined design specifications to determine their state before closure. Further on, this extends to optimising operations and costs over the lifetime of a repository.*
b) *The second objective consists of showing that the system demonstrated, according to objective (a), will provide all the safety functions needed for the system as a whole to fulfil the long-term safety criteria. This requires that the evolution of the engineered components and materials is sufficiently understood in the actual repository conditions over the specified timeframe. Because of the relationship between technical design requirements and long-term performance requirements these usually must be defined iteratively. In this context, robust design may be necessary to account for uncertainties."*

The planning of the Full-Scale Demonstration of Plugs and Seals (DOPAS) Project had been initiated already prior the call as the IGD-TP's Joint Activity. The Joint Activity was in alignment with the Euratom Framework Programme's Work Programme and thus a proposal to the call was submitted in 2011 and consequently approved. 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.

The Project was coordinated by Posiva (Finland). A set of full-scale experiments, materials research projects, and performance assessment studies of plugs and seals for geological repositories were undertaken in the course of the Project. The partners of the DOPAS Project included six WMOs and two organisations from Germany representing the German Federal Government who is responsible for the final disposal of radioactive waste in Germany. The full list of partners is provided in Preface. The waste management programmes at the partner countries are at different stages in development, and, therefore, the individual drivers for collaboration differ. Appendix A provides an overview of the overall R&D schedule of WMOs and countries participating in the DOPAS Project, the scope of the R&D programmes including the status of the disposal concept development, and the role of plugs and seals within the programmes. This information summarises the reasons for the WMOs participation in the DOPAS Project and, at a higher level, how they expect to utilise the results. At the start of the Project, the participating WMOs included organisations that were quite close to licensing (i.e. had either submitted a licence application or expected to within a few years[1]). For these organisations, the driver was to support the development of reference design or alternative plug/seal designs for which detailed design needs to be available within the next few years. The Project also included WMOs with plans to submit licence applications after 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. The research and development questions addressed in the Project are discussed in Section 1.2.

The DOPAS Project contributes to the IGD-TP vision by conducting full-scale technical feasibility demonstrations and related experiments of plugs and seals, monitoring of the

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

experiments and the laboratory experiments set up, undertaking materials research and evaluating the performance of plugs and seals after their emplacement.

The DOPAS Project also contributes to the implementation of geological disposal across Europe. The eight WMOs in the consortium benefitted from the continuous exchange of experience and expertise. The Project advanced the state-of-the-art by including a broad scope of work, and by integrating activities between different programmes and between different disciplines. This state-of-the-art has been captured in guidelines for future exploitation of the Project findings. The Project results are mainly focused on waste management programmes that are close to licensing, but they also demonstrate the technical feasibility of repository designs and thus also supports less advanced programmes.

1.1.2 Objectives and Scope of this Report

The objectives of this report are to provide an integrated state-of-the-art summary of the outcomes of the DOPAS Project. This includes the progress in design, site selection and characterisation, construction, monitoring and performance evaluation in relation to plugs and seals considered in WMO programmes. Further description of the achievements in the DOPAS Project is included in work package summary reports, experiment summary reports and additional underpinning references (see Section 1.3).

This report is presented in two parts. Part 1 provides a description of the high-level background, methods, results and conclusions from the DOPAS Project. Part 2 provides a more detailed discussion of the work undertaken and the results from specific work packages.

Following this introduction, Part 1 provides the following information:

- Section 1.2 presents the research, development and demonstration questions addressed in the DOPAS Project.
- Section 1.3 provides the concept and work breakdown structure of the DOPAS Project, including the Project structure and an overview of the Project reports that provide more detailed information than can be included in this summary report.
- Section 1.4 describes the full-scale experiments, reduced-scale tests and materials research projects undertaken in the DOPAS Project.
- Section 1.5 summarises the main conclusions from the DOPAS Project, focusing on the technical aspects of how the DOPAS Project contributes to the industrial feasibility of plugs and seals for programmes that are close to implementation, and how the DOPAS Project contributes to generic studies for programmes that will implement geological disposal in several decades from now.
- Section 1.5 summarises the cross-cutting items related to the discussion of the representativeness of experiments for repository operations, dissemination and next steps in developing designs of plugs and seals suitable for implementation in operating repositories.

Part 2 of the report provides more details on each of the steps in the Project:

- Section 2.1 describes the starting points for the DOPAS Project.
- Section 2.2 describes the management of the DOPAS Project.
- Section 2.3 describes the design bases and requirements for the plugs and seals considered in the DOPAS Project, and lessons from the development of the design bases related to general repository design processes.

- Section 2.4 describes the design, siting and construction of the DOPAS experiments, and captures the key learning related to these activities.
- Section 2.5 describes the performance evaluation of the full-scale experiments and the feedback to the design basis.
- Section 2.6 describes the work undertaken in the DOPAS Project related to long-term performance assessment of plugs and seals.
- Section 2.7 describes integration activities in the DOPAS Project, including external quality assurance using the Expert Elicitation (EE) process and sharing of information amongst partners via a staff exchange programme.
- Section 2.8 provides an analysis of the dissemination activities undertaken in the DOPAS Project.
- Section 2.9 provides a summary of the state-of-the-art, lessons learned and way forward for plugging and sealing based on the DOPAS Project
- Section 2.10 provides the conclusions for this report.

1.2 RD&D Questions, Scope and Objectives of the DOPAS Project

For all types of host rocks, geological disposal concepts include engineered barrier systems (EBS) made from specific technical structures, e.g. plugs and seals, consisting of engineered and natural materials that are designed to provide a range of isolation and containment functions in combination with other elements of the engineered barrier system.

Plugs and seals may be needed and implemented in various repository locations, including tunnels/drifts, vaults, access ramps, shafts and boreholes. The plugs and seals envisaged in the context of an underground repository may include, for example (Figure 1-1):

- 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 other 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 (connecting tunnels/drifts, access tunnels 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 and function 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 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, access 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.

Although plug and seal designs may consist of a single component (e.g., a concrete wall), most of them are usually complex composite structures. Plugs and seals are typically designed to perform a range of functions in challenging underground environments, for example under the influence of high hydrostatic and backfill swelling pressures. Composite structures are typically best suited to carry out this task.

The repository volumes and their dimensioning are dependent on the quantities of the different types of radioactive waste to be disposed of, having a clear influence on the number of plugs and seals required. Different disposal concepts require different types of plugs and seals, and the exact number of plugs and seals and their specifications can only be finalised following the repository construction, when the conditions prevailing on the host rock and the surrounding site are known and understood in detail. An estimate of the number of plugs and seals expected in different concepts is presented in Table 1-1 by the countries participating in the DOPAS Project. These estimates are used in the planning for the implementation of the repository systems.

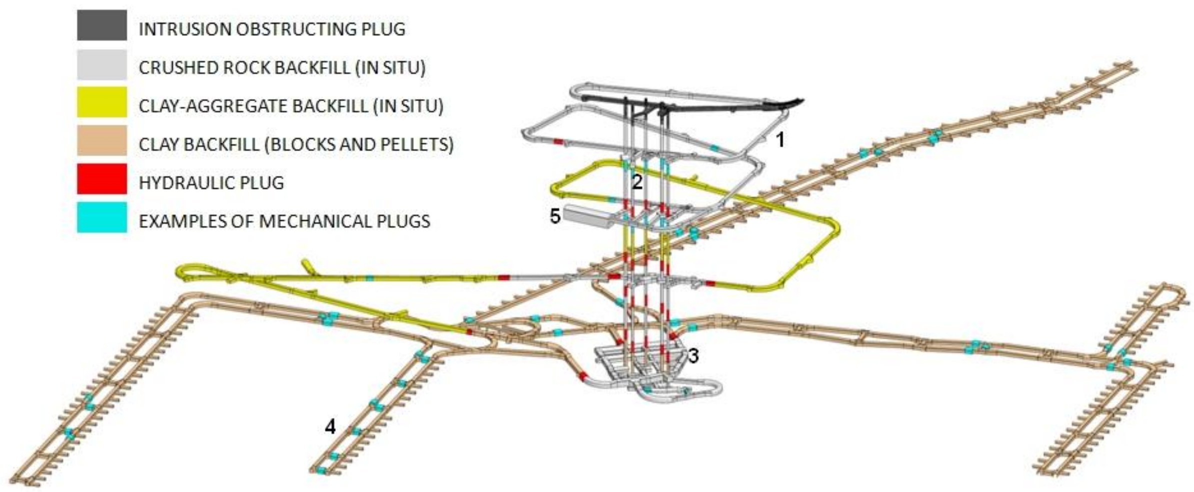

Figure 1-1: Generic Closure Design for © Posiva Oy by Saanio and Riekkola (not in scale) 1- access tunnels, 2-shafts, 3-technical facility, 4 central and deposition tunnels, 5 possible LILW area.

Table 1-1: Estimates of the number of plugs and seals envisaged in the conceptual design of different disposal programmes represented in the DOPAS Project. This table does not distinguish between the types of the plugs and seals. The numbers are based on estimates provided by the WMOs of the respective countries.

Country/programme	Czech Republic	Germany	Finland *	France ***	Sweden	Switzerland	United Kingdom****
HLW and Spent Fuel							
Deposition tunnel or drift plugs /seals	tbd	4	~100	~100	~200	>20	~ 336
Other plugs/seals in disposal depth	tbd	24	4	4-10 for	6	~4	~336
Access tunnels plugs/seals	tbd		2	2	2	~2	Unknown
Shafts plugs/seals	tbd	2	12	5 or 6	8	~4	Unknown
Investigation boreholes seals**	tbd		57		50		Unknown

* In addition, the disposal facility will include L-ILW facility (for encapsulation facility waste) which requires one seal.

** The value is the total number of boreholes which need to be plugged. Individual boreholes might need several plugs.

*** Andra is considering in this table the number of seals planned for Cigéo. The deposition tunnel or drift plugs /seals might use engineered backfill material consisting of crushed argillite mixed with bentonite powder.

**** This is based on RWM's 2016 generic illustrative designs, and is subject to change.

The DOPAS Project was the first European collaborative project focused specifically on full-scale demonstration of plugs and seals. Prior to the DOPAS Project, work related to plugs and seals had either been undertaken by smaller groups working on specific RD&D projects or as part of wider projects focusing a range of technological issues. Some of the most relevant international collaborations on plugs and seals prior to the DOPAS Project, are summarised in Appendix B.

The first consideration of plugs and seals by the international radioactive waste management community was at a "Sealing of Radioactive Waste Repositories" workshop over 25 years ago (NEA, 1989). This workshop considered both the design and performance of specific plugs and seals, and the overall closure of repositories using clay and cementitious materials (i.e. sealing using backfill as well as the construction of plugs and seals).

Since then, extensive research has been carried out on the use of clays for buffer and backfill systems, and cementitious materials for backfilling of repositories. The main focus has been on the basic understanding of the potential materials, their interactions with other materials, and processes influencing the material behaviour. A large amount of data from laboratory and modelling studies exists and has been reported in various topical conferences and international collaborative projects too numerous to mention here. Nonetheless, this prior information has an important role in the DOPAS Project, in particular in providing an information base on which long-term performance of the materials tested within DOPAS Project can be assessed.

Furthermore, recent technology demonstration focused projects such as the Engineering Studies and Demonstration of Repository Designs (ESDRED) Project (ESDRED, 2009) and the Large Underground Concept Experiments (LUCOEX) Project (Gugala et al., 2015), have provided valuable background information on supporting structures and their requirements, emplacement methods, location and design.

Over the last decade, and based on the outcomes of the previous research activities, it was recognised that the role of plugs and seals is significant in a repository systems, especially when considering their safety functions and their requirements to support the functions of other natural and engineered barriers (e.g., host rock, buffer, backfill). In addition to this, it was recognised that emplacement of plugs and seals is a challenging task, which would influence the timing of repository operation and early evolution of the repository system. Therefore, the need for a specific collaborative project on plugs and seals was identified.

Based on this prior knowledge, and guidance from the IGD-TP's SRA, a series of technical themes and cross-cutting themes, can be recognised against which key outcomes of the DOPAS Project can be discussed. Technical themes are:

- Design basis processes: How are requirements on plugs and seals structured, and how can compliance with requirements be demonstrated? Can the learning from development of design bases for plugs and seals be applied to other repository elements?
- Conceptual designs of plugs and seals: What conceptual designs exist for plugs and seals and what are their roles within the overall safety concept?
- Plug and seal materials, and detailed design: The DOPAS Project addressed further development of plugs and seals materials, and the detailed design of the full-scale demonstration experiments.
- Siting and excavation of plug/seal locations: How are the locations of plugs and seals selected? Further development of methods for the excavation of plug and seal locations. What operational safety issues are posed by the excavation of plug and seal locations and how can one overcome these?
- Installation of plugs and seals: Further developments in the technology for emplacing plug and seal materials. What are the operational safety and logistical issues posed by the installation of plugs and seals?
- Monitoring of plugs and seals: Does suitable technology for monitoring the performance of plugs and seals exist. What are the issues and time span with monitoring of plugs and seals?
- Performance of plugs and seals: How do plugs and seals perform with respect to detailed requirements on their performance?
- Compliance of plug and seal designs with their functions: To what extent can the current designs of plugs and seals be considered to meet their overall and safety functions?

Cross-cutting themes are:

- Project management during plug and seal construction and full-scale testing: What learning has the DOPAS Project provided with respect to the management of plug and seal implementation, conducting of full-scale tests and repository operations?
- Dissemination about and integration of learning on plugs and seals: Have the dissemination activities in the DOPAS Project been successful, and can the approaches adopted in the DOPAS Project be applied elsewhere?
- Technical readiness level of plugs and seals and remaining issues: What further development including testing of plugs and seals is required before designs are ready for implementation in operating repositories?

First, in Section 1.3 the DOPAS Project concept and strategy is presented, including the work breakdown structure that addressed the key themes and Work package-specific objectives addressed by the work in the DOPAS Project. Then, in Section 1.4 the Project's demonstrations and experimental work are introduced. The outcomes with respect to the technical themes are discussed in Section 1.5 and with respect to the cross-cutting themes in Section 1.6.

1.3 Description of the DOPAS Project's Concept and Strategy

The DOPAS Project aimed at to improve the technical feasibility of full-scale plugs and seals, as noted in Section 1.2, for the future industrial scale repository operations, the monitoring of the plug or seal component and subsystem characteristics, the control of their behaviour in repository conditions, and their performance with respect to their safety and other objectives. To achieve these objectives, the DOPAS Project addressed the development of the design basis, reference design's and strategies to demonstrate the compliance of the reference designs to the design basis for plugs and seals in repositories. In the DOPAS Project, the 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 1-2 shows how the conceptualisation of the interaction and integration in the DOPAS Project and how a new state-of-the-art results from the Project.

The work breakdown structure of the DOPAS Project (Figure 1-3) responded to the conceptualisation shown in Figure 1-2. The Project was undertaken in seven Work packages (WPs). WP1 of the DOPAS Project included project management and coordination and was led by Posiva. WP7 addressed dissemination activities of the Project results to other interested organisations in Europe and beyond. WP7 included 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. The other main technical WPs and the key reports produced by these WPs are described below. Work package-specific objectives and results are presented in Part 2 of this document.

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). This 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 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 for 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 up-scaling, and the learning provided by the practical experience in constructing the experiments.

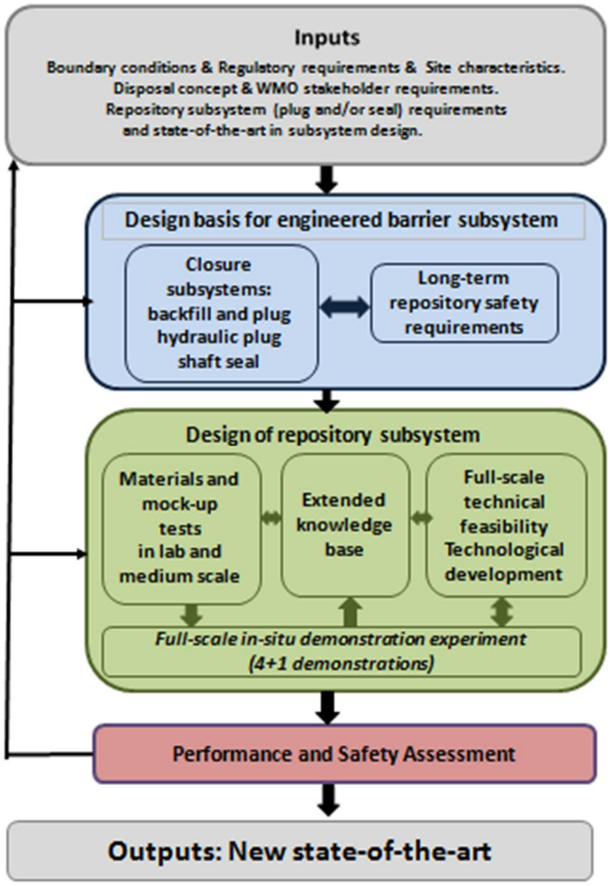

Figure 1-2: Schematic illustration of the development and demonstration of plug and seal designs for feasibility and safety performance, as conceptualised in the DOPAS Project.

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*., 2016; Svoboda *et al*., 2016; Grahm *et al*., 2015; Holt and Koho, 2016; Jantschik and Moog, 2016; Czaikowski and Wieczorek, 2016; and Zhang, 2016). The 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. WP4 summary report (DOPAS, 2016c) also considers the feedback from the work to the design basis which may include modifications to the design basis.

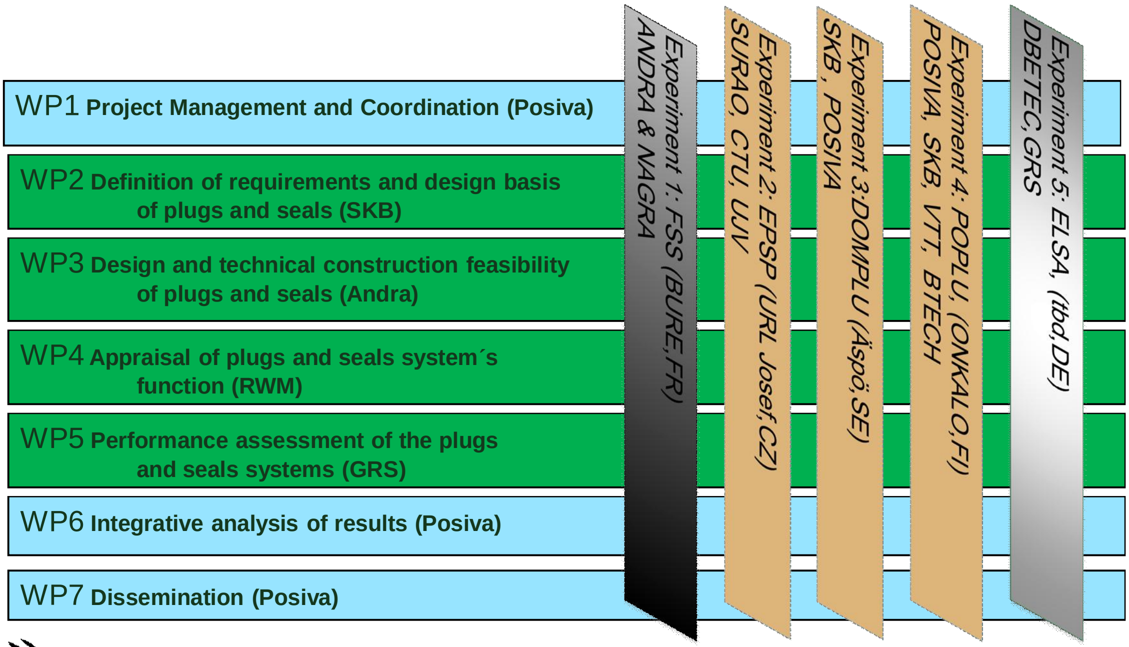

Figure 1-3: Illustration of the DOPAS Project work breakdown structure, as implemented in the seven work packages and the cross-cutting experiments and materials research projects.

WP5 addressed the performance assessment (PA) 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 done in WP5 was used to support the design of the experiments in WP3.

WP6 was led by Posiva and included the use of an Expert Elicitation (EE) process to integrate critical analyses of the achievements and results from the implementation and monitoring of the DOPAS Project plugs and seals. The work also included external experts' review of drafts of the main WP2 - WP5 summary reports (D2.4, D3.30, D4.4 and D5.10). The Work package 6 content is described later in this report. WP6 incorporated a revision of Posiva's safety case elicitation process for this type of technical work by carrying out a pilot elicitation prior the summary deliverable drafts' elicitation. 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, which is this report) is a part of this work package, too.

1.4 Summary of the DOPAS Project's Experiments

The DOPAS Project focused on tunnel/drift, vault and shaft plugs and seals for clay, crystalline and salt rocks (Figure 1-3):

- Clay rocks: the Full-scale Seal (FSS) experiment, undertaken by Andra in a surface facility at St Dizier, 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*., 2016).
- Crystalline rocks: experiments related to plugs in disposal tunnels, including the Experimental Pressure and Sealing Plug (EPSP) experiment 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 undertaken by SKB and Posiva at the Äspö Hard Rock Laboratory (Äspö HRL) in Sweden, and the Posiva Plug (POPLU) experiment undertaken by Posiva, SKB, VTT and BTECH at the ONKALO Underground Rock Characterisation Facility (URCF) in Finland. The results of the experiments are reported in the EPSP, DOMPLU and POPLU experiment summary reports, which are Deliverables D4.7 (Svoboda *et al*., 2016), D4.3 (Grahm *et al*., 2015) and D4.5 (Holt and Koho, 2016) respectively.
- Salt rocks: tests were performed 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 materials research projects performed by GRS and co-funded by the German Federal Ministry for Economic Affairs and Energy (BMWi). The German ELSA Project will be undertaken in three phases. Work related to the Phase 2 (and some minor parts of Phase 1) was part of the DOPAS Project, and focused on the early stages of design basis development and on demonstration of the suitability of designs through performance assessment studies. Phase 3 is a planned to be a large-scale experiment phase to be carried out after the DOPAS Project. The sealing materials research that is planned to be utilised in the shaft seals was undertaken in three subprojects by GRS including work in the "Langzeitsicherer Schachtverschluß im Salinar" (subprojects LASA and LAVA) and "Untersuchung der THM-Prozesse im Nahfeld von Endlagern in Tonformationen" (THM-Ton). This materials research by GRS and the compaction work method tests by DBETEC provided supporting information to the ELSA Project. The results under ELSA project from LASA, LAVA, and THM-Ton subprojects are reported in the DOPAS Deliverables e.g. D3.29 (Jantschik and Moog, 2016), D3.31 (Czaikowski and Wieczorek, 2016), and D3.32 (Zhang, 2016).

The DOPAS Project's 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- 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 design 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 technical feasibility demonstration and the experiment did not include the pressurisation of the seal as it was an industrial scale above ground experiment. However, a dismantling of the FSS experiment was undertaken during the Project.

The work carried out as part of the German ELSA Project's Phase 1 and Phase 2, and performed under the DOPAS Project under the name "ELSA" experiment, 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 outcomes of the German experimental and performance assessment studies are described in more details in the WP3 and WP5 summary reports.

The progress in the full-scale demonstrations and of the experimental work is provided in the Part 2 of this report summarizing the outcomes of the DOPAS Project work. Further descriptions of the achievements of the experiments in the DOPAS Project are be included in the final versions of the individual experiment summary reports for the four full-scale experiments (Noiret *et al.*, 2016; Svoboda *et al.*, 2016; Grahm *et al.*, 2015; and Holt and Koho, 2016).

This section provides a summary of the DOPAS experimental work (Sections 1.4.1 to 1.4.5). For each of the experiments identified in Section 1.3, we describe the following:

- The safety or other functions of the plug/seal investigated.
- The design of the plug/seal derived from the design basis at the start of the DOPAS Project.
- The objectives of the full-scale experiment or of the experimental programme (for the German case).
- The experimental design as a part of the relevant design basis development process.
- Definition of the scope of the experimental works with respect to the DOPAS Project, i.e., which parts of the activities were part of the DOPAS Project and which parts of the work were undertaken outside of the DOPAS Project.
- Statement of the progress of the experiment during the DOPAS Project.

At the end of this section, a summary table provides an outline of the different experimental aspects of the plugs and seals considered in the Project (Section 1.4.6).

1.4.1 Andra's Drift and ILW Vault Seal

Functions of the Drift and ILW Vault Seal in Cigéo

The French HLW and ILW will be disposed of in a repository included in the "Centre Industriel de Stockage Géologique" (also known as Cigéo) that will be implemented and operated by Andra. The repository is located in a clay host rock (argillite) in the Meuse and Haute Marne Departments of Eastern France. The primary function of the repository 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 to safety in Andra's concept is the containment of radionuclides.

In Andra's concept, seals are defined as hydraulic components for closure of large-diameter (up to 10 m) underground installations and infrastructure components. The safety functions of the drift and ILW vault seals are specified as follows:

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

Design of the Drift and ILW Vault Seal envisaged in Cigéo

There are three types of seals envisaged in Andra's disposal concept: shaft seals, ramp seals, and drift and ILW disposal vault seals. Each seal is planned to consist of a swelling clay core and two concrete containment walls (Figure 1-4). 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 (especially following saturation when the bentonite will swell and exert pressure on the walls and host rock).

The primary difference between the different types of seal (shaft, ramp, and drift and ILW vault) is the extent to which the concrete lining of the tunnels is removed before installation of the swelling clay core. Shaft and ramp seals will be located in the upper part of the Callovo-Oxfordian Argillite (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 and pose less risk to workers from falling rocks. 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, which are located in the lower parts of the host rock where it has a higher clay content, only partial removal of the lining is envisaged.

Objectives of the FSS Experiment

The main objective of the FSS experiment is to develop confidence in, and to demonstrate, the technical feasibility of constructing a full-scale drift and ILW disposal vault seal. The experiment is housed in a concrete "test box" in a surface facility. The test box is a model of a repository drift in which the conditions are controlled such that they represent the underground environment.

Technical feasibility includes demonstrating the ability of the approach used to emplace the clay core to be suitable for filling recesses in the clay host rock, i.e., any potential breakouts generated during the removal of the concrete support lining. Therefore, the concrete test box includes recesses that mimic breakouts.

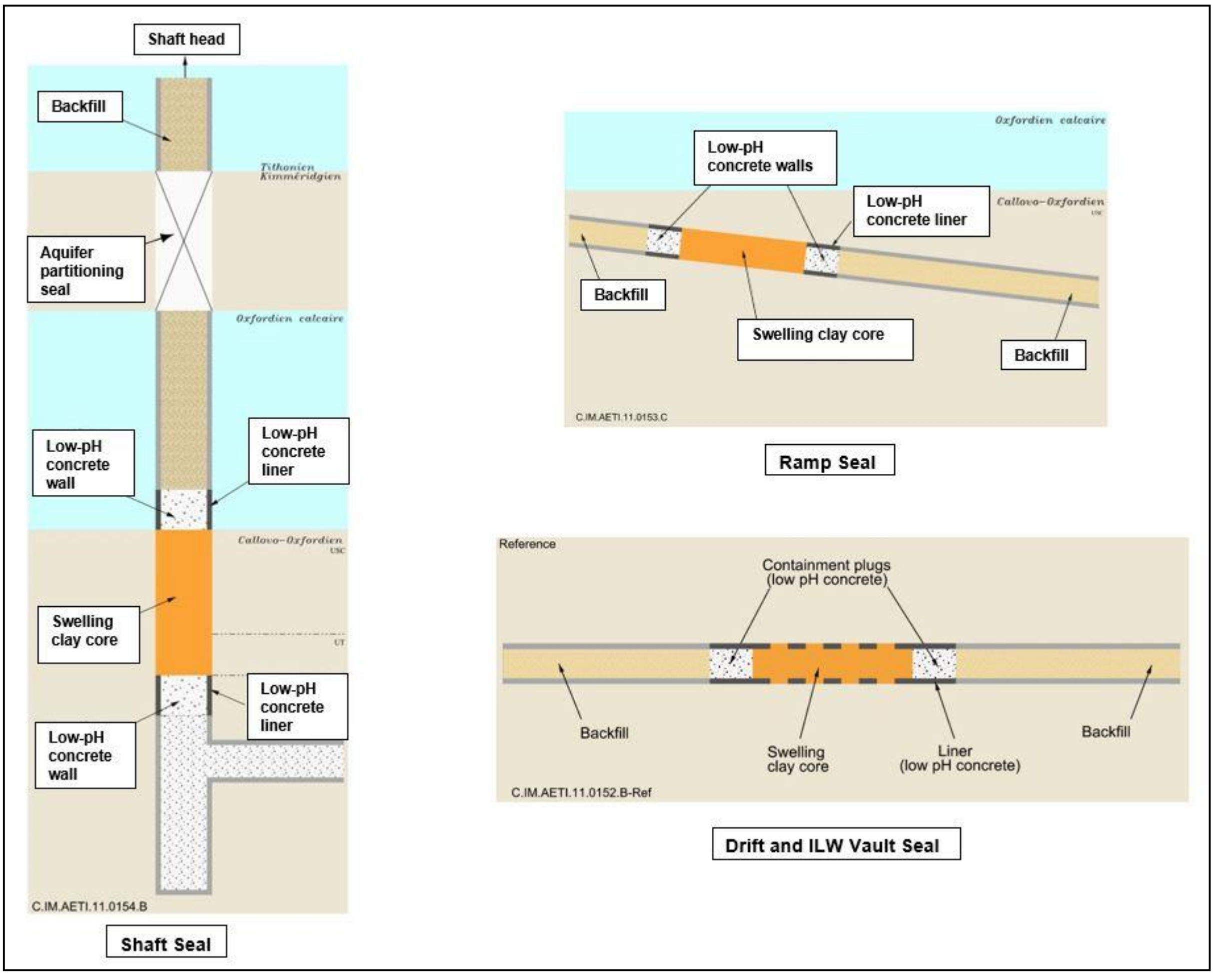

Figure 1-4: Schematic illustration of the conceptual designs for shaft, access ramp, and drift and ILW disposal vault seals for the Cigéo's reference disposal concept. From Wendling *et al*. (2015).

Design of the FSS Experiment

A schematic lay-out of the FSS experiment design is illustrated in

Figure 1-5. The concrete box is 35.5 m long and has a concrete lining thickness of 0.7 m. Its internal diameter is 7.6 m. The box is constructed using ordinary concrete and contains:

- An upstream entrance hall.
- A section for installing the upstream low-pH cast concrete containment wall.
- A section for installing the swelling clay core.
- A section for installing the downstream low-pH concrete support wall blocks.
- A section for installing the downstream low-pH shotcrete containment wall.
- A downstream entrance hall.

The dimensions and materials of the FSS components are given in Table 1-2.

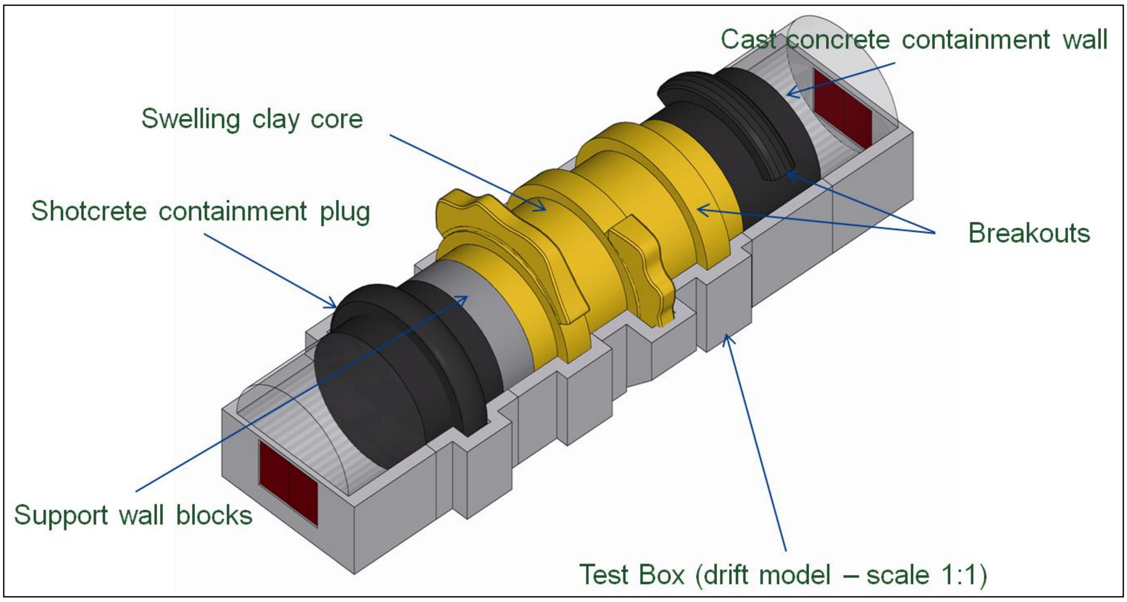

Figure 1-5: Schematic illustration of the FSS experiment design. From Bosgiraud and Foin, (2013).

Table 1-2: Dimensions and materials of the FSS components.

FSS Component	Dimensions	Materials
Test box	Internal diameter: 7.6 m. Internal length: 35.5 m Concrete lining thickness: 0.7 m.	Ordinary Portland Concrete
Upstream entrance hall	Length of 5 m to allow for installation of equipment (e.g. core drilling machines).	N/A
Upstream low-pH SCC wall	Length of 5 m, with a recess on its upper part that is 1.5-m long and 0.3-m deep beyond the concrete lining. Volume of ~250 m^3	Low-pH SCC
Swelling clay core	Length of 13.5 m and has three recesses, each recess is 1.5 m long. The recesses are 3 m apart.	WH2 bentonite from Wyoming
Downstream support wall	Length of 2 m.	Half-cubic-meter low-pH concrete blocks made with the same SCC as that used for the first containment wall
Downstream low-pH shotcrete wall	Length of 5 m, with a recess on its upper part that is 1.5 m long and 0.3 m deep beyond the concrete lining.	Low-pH shotcrete
Downstream entrance hall	Length of 5 m to allow for installation of equipment (e.g. core drilling machines).	N/A

The main difference between the reference design and FSS design for the Andra drift and ILW vault seal is in the length of the seal. The real seal underground will be longer than the seal considered in FSS. The FSS experiment investigates two types of low-pH containment wall, one using self-compacting concrete (SCC) and the other using shotcrete, to allow the preferred method to be selected and incorporated into the reference concept. Further information on the FSS conceptual design and design basis is presented in DOPAS (2016a).

As the experiment is focused on the construction and installation of the seal, the materials are not saturated or otherwise pressurised. Complementary experiments are being undertaken in parallel with FSS. These include the REM experiment (Conil *et al*., 2015), which 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.

FSS Experiment Progress within the DOPAS Project

Work on the FSS experiment within the DOPAS Project included the design, construction and monitoring of the experiment. The dismantling (see below) of the FSS Experiment was funded separately.

For FSS, design work was undertaken in the period August 2012-April 2014, the upstream containment wall was cast in July 2013, the clay core was emplaced in August 2014 and the downstream shotcrete plug was emplaced in September 2014. Investigations of FSS were undertaken in the period October 2014 to July 2015, and the dismantling and rehabilitation of the experimental surface facility was completed in December 2015.

Unlike the other DOPAS full-scale experiments, the FSS experiment was not hydraulically pressurised. Instead the FSS experiment was dismantled during the duration of the DOPAS Project. The dismantling of the FSS experiment included the collection of observations about the success of the construction and materials and additional information related to the properties of the installed components. By collecting further information during dismantling, Andra benefits from a thorough assessment of the works carried-out, at a marginal additional cost.

1.4.2 SÚRAO’s Tunnel Plug

Functions of SÚRAO’s Tunnel Plug

The first national assessment for the disposal of spent fuel and HLW in the Czech Republic considered a generic reference concept based on KBS-3 in a crystalline host rock (SKB, 2010c). However, subsequent studies have focused on a crystalline host rock concept based on horizontal emplacement of waste in disposal drifts within steel supercontainers. 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 Reference Project update (SÚRAO, 2012). Although the horizontal emplacement concept is now regarded as the reference concept in the Czech Republic, both horizontal and vertical emplacement variants are being further developed in parallel.

In the current Czech reference concept, a plug is defined as a structure for closure of tunnels in the repository. Functions of the plug recognised to date 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.

Design of SÚRAO's Tunnel Plug

Consistent with the conceptual approach taken in the 2012 update (SÚRAO, 2012), in which the horizontal emplacement concept was adopted, the reference design for the tunnel plug in the repository concept development is not highly advanced and the specific requirements on the reference plug have not yet to been specified. In the 2012 update, it was assumed that disposal drifts would be closed by a steel-concrete end plug, in which the concrete would have a low pH (Figure 1-6).

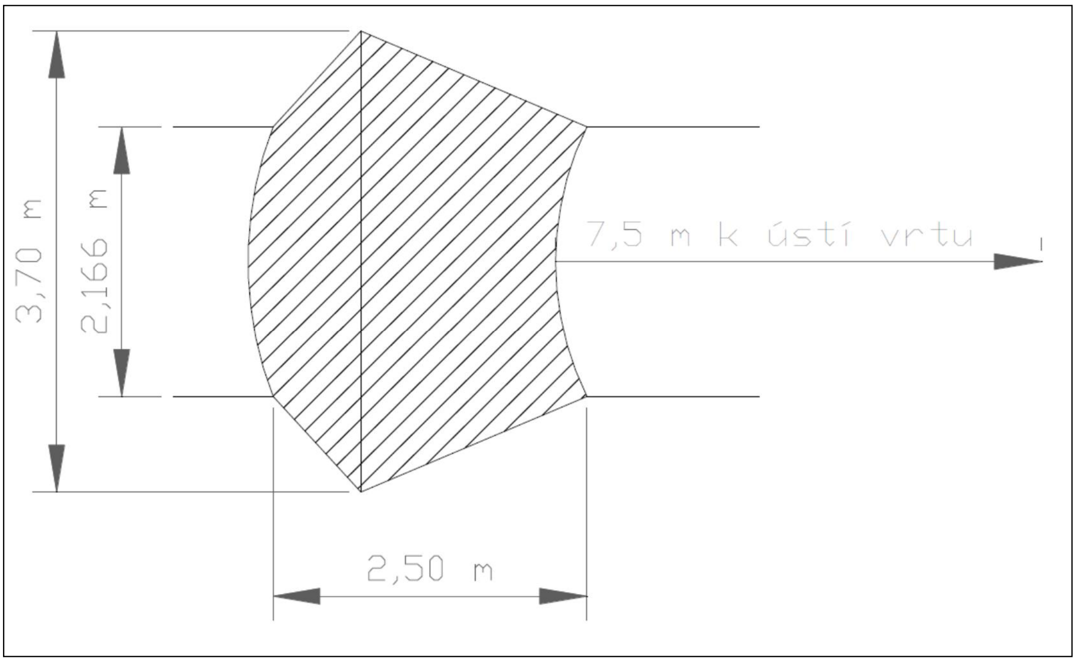

Figure 1-6: Schematic illustration of the Czech deposition tunnel plug (SÚRAO, 2012).

Objectives of the EPSP Experiment

The EPSP experiment is the first time that SÚRAO has carried out any detailed work on plugs and seals. The key objectives of the experiment are to test materials and technology, extending laboratory experience to the underground environment and to full-scale, and to build the practical expertise of the SÚRAO personnel and other partners. Implementation of the reference design itself is not being tested. At this early stage in the Czech geological disposal programme (SÚRAO, 2012), about 50 years prior to the scheduled commencement of operation, it is considered more important to build knowledge and experience rather than to refine implementation designs for an, as yet, unidentified site with unknown mechanical, hydrogeological and chemical characteristics. However, EPSP also provided an important test-bed in developing a final plug design and procedure for implementation, will contribute towards the development of a reference design for tunnel plugs by giving indications on crystalline host rock requirements and may give support to the site selection programme.

Design of the EPSP Experiment

The design for EPSP includes the following components (see Figure 1-7):

- 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 was built to be as small as possible to allow the pressure to be readily controlled. The pressure chamber was sealed with a membrane.

- Concrete Walls: concrete separation walls (or blocks) were used to facilitate construction of EPSP. Three concrete walls were 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 was constructed using glass-fibre-reinforced low-pH shotcrete. The mix and its pH values were determined during the laboratory testing stage.
- Bentonite Pellets: the bentonite pellet zone is comprised of B75 bentonite (a Czech origin extracted material), 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.
- Filter: the filter collects any water leaking through the bentonite layer. 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 Plug: the outer concrete plug is similar to the inner plug (i.e., made using glass-fibre-reinforced low-pH shotcrete) and was designed to hold the other components of EPSP in place. However, should the direction of pressurisation of EPSP be reversed, the outer concrete plug would 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.

The dimensions and materials of the EPSP components are given in Table 1-3.

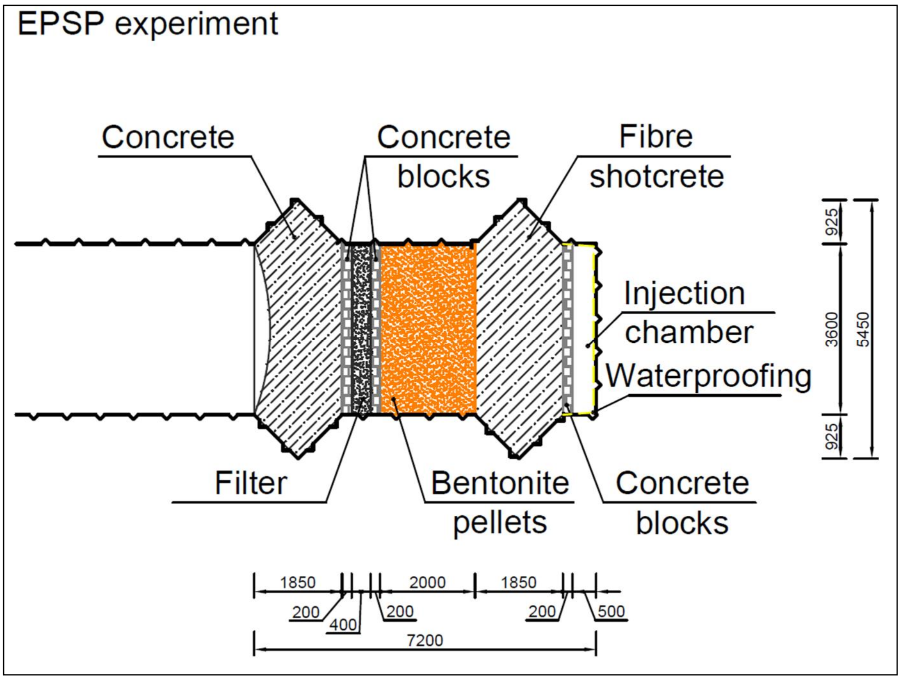

Figure 1-7: Schematic illustration of the EPSP experiment design. Dimensions are given in millimetres (mm). Source: CTU.

Table 1-3: Dimensions and materials of the EPSP components.

EPSP Component	Dimensions	Materials
Tunnel	Cross-section of ~ 15 m^2 (experiment length ~ 7.2 m)	In crystalline rock (granitoid with quartz veins)
Pressure chamber	Length of 0.1 m and diameter of 3.6 m.	The walls and floor were prepared using shotcrete and resin. The surface of the remodelled chamber was treated with a 3 mm thin resin waterproofing finish.
Concrete separation walls	Length of 0.2 m and diameter of 3.6 m.	Concrete blocks
Inner shotcrete plug	Length of 1.85 m and diameter of 3.6 m (slots are 0.925 m into the rock).	Glass-fibre-reinforced low-pH shotcrete
Bentonite pellets	Length of 2 m and diameter of 3.6 m.	B75 Czech Bentonite (>95% vibration-compacted bentonite pellets, remainder is sprayed bentonite)
Filter	Length of 0.4 m and diameter of 3.6 m.	Inert gravel
Outer shotcrete plug	Length of 1.85 m and diameter of 3.6 m (slots are 0.925 m into the rock).	Glass-fibre-reinforced low-pH shotcrete

EPSP Experiment's Progress within the DOPAS Project

Work on the EPSP experiment within the DOPAS Project included the design, construction and initial monitoring of the experiment.

The location of the EPSP plug was selected in the period September 2012 - December 2012, and ground works were undertaken in the period January 2013 - August 2014. The EPSP's inner plug was sprayed in November 2014, the bentonite core was emplaced in June 2015 and the outer plug was sprayed in June 2015.

Experimental testing and pressurisation of EPSP started during the construction process. The inner plug was pressurised to check the water tightness of the concrete and to determine if grouting was needed through injection of water and air into the injection chamber up to 0.5 MPa. A series of short water injection tests followed by long-term tests at various pressure levels (starting at 0.1 MPa going gradually to up to 1 MPa) were undertaken once the outer plug had cured. The testing sequence was then interrupted and the bentonite sealing section was saturated by injection of water into both the filter and the pressurisation chamber to allow swelling pressure to develop. A short pressure test was then undertaken involving injection of bentonite slurry into the pressurisation chamber at pressures up to 3 MPa (2.5 MPa being the original target value). The pressurisation chamber was then cleaned up, and water pressurisation of the experiment through the pressurisation chamber was resumed. Further pressurisation and monitoring of the EPSP experiment, and evaluation of the results, will be undertaken after the completion of the DOPAS Project.

1.4.3 SKB's Deposition Tunnel Plug

Functions of SKB's Deposition Tunnel Plug

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 long-term 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 closure) 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 1-8).

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[2]:

- 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[3].

[2] The requirements on the plug are still being developed. The list of safety functions represents the status at the start of the DOMPLU experiment. Since the start of the DOPAS experiment, SKB has recognised that a "gas-tightness" requirement should be added to the list of safety functions.

[3] It may take a long time before the outer part of the deposition tunnel saturates after closure. During the period when the deposition tunnel backfill is saturating, which may take from several decades to a few centuries depending on the local rock conditions, the plug should provide a barrier against water flow.

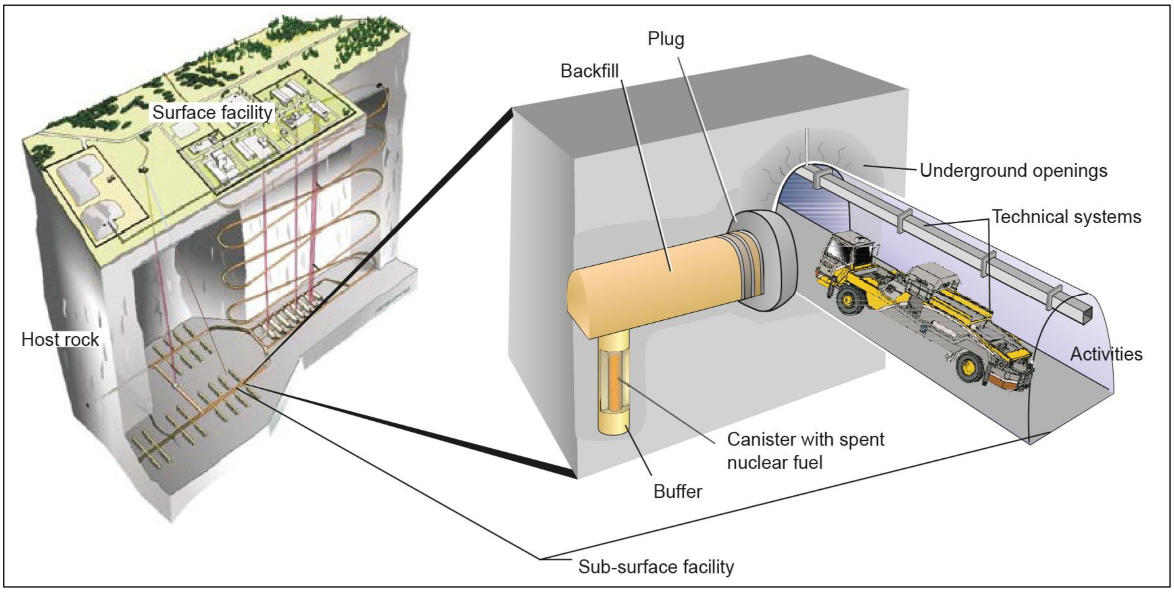

Figure 1-8: The KBS-3V repository and the location of the deposition tunnel plug (SKB, 2010a).

Current Reference Design of SKB's Deposition Tunnel Plug

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 1-9):

- Concrete Plug: the reference concrete plug is a dome-shaped structure made of low-pH reinforced concrete. It contains pipes for auxiliary equipment such as air ventilation pipes, cooling pipes, and grouting tubes. The cooling pipes are used to avoid internal cracking due to cement hydration and to pre-stress the concrete dome before contact grouting. The function of the concrete plug is to resist deformation and to keep the watertight seal, filter, and backfill in place.
- Watertight Seal: the watertight seal is made of bentonite blocks and pellets in a similar configuration to the backfill. 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, to 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., to act as an inner formwork for the concrete dome. The inner beams (towards the deposition tunnel) keep the backfill in place during installation. The middle beams keep the filter in place during installation and they 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 plug's foreseen 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 of grout. They are used for grouting when the dome concrete has reached a certain level of strength and shrinkage. The grout tightens the contact area between the concrete plug and rock, and contributes to keeping the concrete plug under compressive pressure.

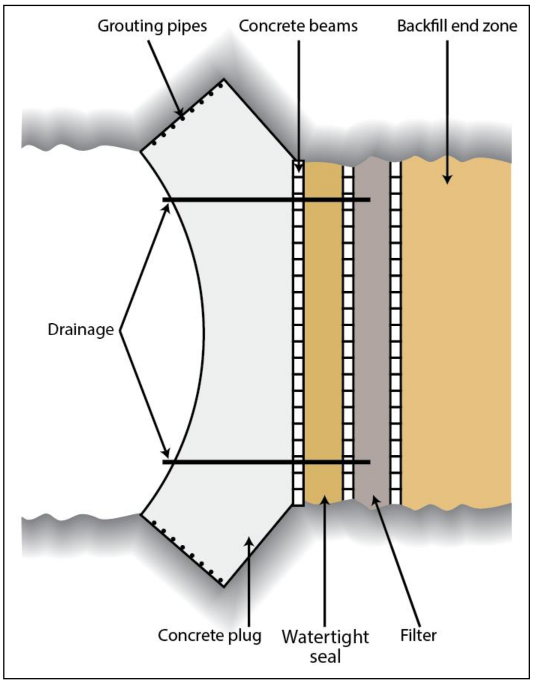

Figure 1-9: Schematic illustration of the deposition tunnel plug components in SKB's reference conceptual design (SKB, 2010b). There are three concrete beams in the conceptual design; these are sometimes referred to as the inner, middle and outer concrete beams or delimiters, with the inner concrete beam being adjacent to the backfill end zone.

Objectives of the DOMPLU Experiment

The DOMPLU experiment is a full-scale test of the reference deposition tunnel plug in SKB's repository design. The DOMPLU experiment is part of an on-going SKB testing and demonstration programme. The overall objective of the test is to reduce uncertainties in the performance of deposition tunnel plugs and in the description of the initial state of the deposition tunnel plugs. The DOMPLU experiment design represents a detailed iteration of the reference design rather than a fundamental change. Specific objectives of the DOMPLU experiment were:

- To finalise the details of the reference design.
- To demonstrate the feasibility of plug installation.
- To validate the requirements on construction methods.
- To demonstrate that the plug works as intended under realistic conditions, up to the reference design total pressure of 7 MPa. The load case is a combination of the hydrostatic pressure from the groundwater (up to 5 MPa) and the swelling pressure from the backfill transition zone (approximately 2 MPa), acting together on the plug system in the repository.
- To develop a method for leakage measurement and use it to determine a leakage rate across the deposition tunnel plug. Evaluate whether a low enough hydraulic conductivity can be achieved to reduce the leakage to less than 0.1 l/min as discussed by Grahm *et al.* (2015).
- To improve testing and quality control during repository construction.

Design of the DOMPLU Experiment

The DOMPLU design consists of an unreinforced low-pH concrete dome with a bentonite seal, a filter layer, and a backfill transition zone located upstream of the concrete component (Figure 1-10). The dimensions of each layer are shown in the figure.

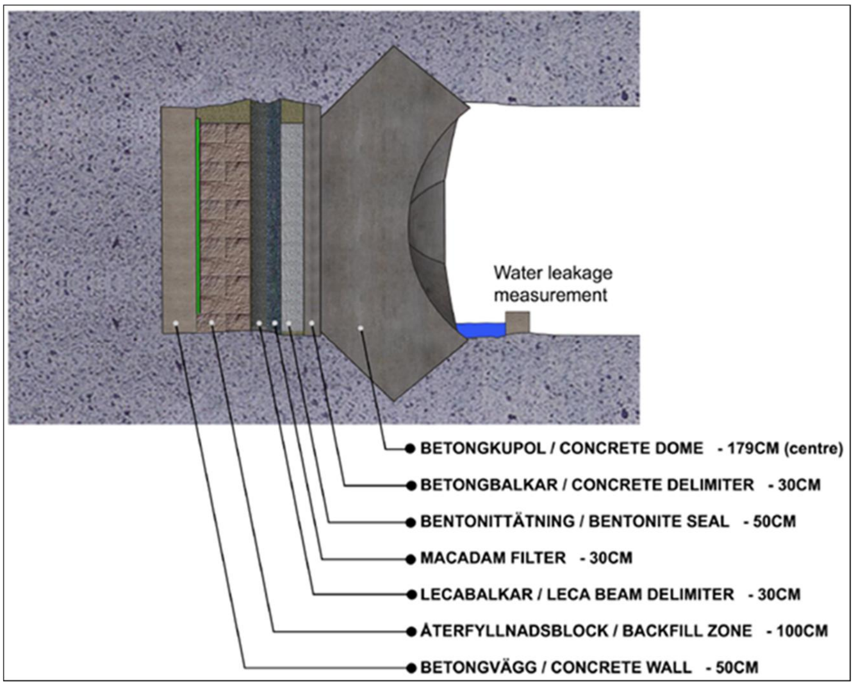

Figure 1-10: Schematic illustration of the DOMPLU experiment design (Grahm *et al.*, 2015).

In order to meet the experiment objectives, the DOMPLU design included specific design modifications compared to the reference design. These modifications were introduced to test to evaluate if they could be adopted in the reference design in the future:

- 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). Malm (2012) concluded that the dome plug is strong enough without reinforcement, that reinforcement has some undesirable properties (e.g., potential for concrete 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 and pressure on the concrete plug.
- In DOMPLU, the innermost (towards the backfill) delimiter is considered to be part of the filter. Instead of concrete beams, light-weight expanded clay/concrete aggregate (LECA®) beams and gravel with a high hydraulic conductivity were used. The filter thickness was 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 bentonite seal is composed of a geotextile instead of concrete beams. The purpose of introducing a geotextile instead of concrete beams in DOMPLU is to simplify installation and improve wetting of the bentonite seal.
- The outer delimiter is composed of low-pH concrete beams like in the reference design. In addition, a double geotextile layer was introduced between this delimiter and the concrete dome to prevent adhesion of the delimiter to the concrete dome, and therefore to avoid potential cracking of the concrete dome during shrinkage.
- Cooling pipes were made of copper. This is a material easy to work with, is likely to be approved for future use, and is common for similar applications.
- Grouting tubes were made of cross-cut 50 mm plastic drainage tubes surrounded by strips of geotextile. This is a new promising design of injection tubes, but has never before been tested by SKB.
- The thickness of the bentonite seal is 500 mm in DOMPLU compared to 710 mm in the reference design. A thinner seal is used in the DOMPLU experiment to reduce the period required for the bentonite to fully saturate.
- The installed dry density of the gravel (“macadam”) filter is 1,400 kg/m^3 in DOMPLU while 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.

The dimensions and materials of the DOMPLU components are summarised in DOMPLU Experiment (Table 1-4).

DOMPLU Experiment Progress within the DOPAS Project

Work on the DOMPLU experiment within the DOPAS Project included the management, final installation and monitoring of the DOMPLU experiment up to 30 September 2014, and evaluation and technical reporting. The main part of the design and construction of the DOMPLU experiment was not part of the DOPAS Project.

Excavation work for the DOMPLU experiment was undertaken between February and October 2012. The DOMPLU experiment's concrete dome was cast in March 2013 and the contact grouting was undertaken in June 2013. Monitoring was undertaken from March 2013.

Pressurisation of the system was started in December 2013 by injection of water into the filter and backfill, followed by saturation and development of swelling pressure in the watertight seal and backfill transition zone. The water pressure was artificially increased in steps inside the plug until it reached 4 MPa in February 2014. The water pressure was kept at this level for the remainder of the testing reported here. Further monitoring of the DOMPLU experiment, and evaluation of the results, will be undertaken after the completion of the DOPAS Project.

Table 1-4 Dimensions and materials of the DOMPLU components.

DOMPLU Component	Dimensions	Materials
Tunnel	Length of 13.5 m (experiment length of 6.5 m). Cross section of ~ 18 m^2	In crystalline rock (granite)
Concrete back wall	Length of 0.5 m	Unreinforced low-pH SCC B200 mix
Backfill end zone	Length of 1 m made of blocks of dimensions: 300x150x75 mm	Bentonite blocks (also included 15 cm pellets between the backfill blocks and the LECA® beam)
LECA® delimeter	Length of 0.3 m	LECA® beams
Filter	Length of 0.3 m	Gravel with grain sizes of 2-4 mm
Geotextile delimeter		Geotextile delimiter was also installed to separate the gravel from the bentonite seal.
Watertight seal	Length of 0.5 m	MX-80 bentonite blocks, compacted by uniaxial compression to a size of 500 mm x 571 mm x 300 mm.
Concrete delimiter	Length of 0.3 m	Low-pH concrete beams
Concrete dome	Length of 1.79 m at the centre (length of slot excavation is 3.2 m).	Unreinforced low-pH SCC B200 mix

1.4.4 Posiva's Deposition Tunnel Plug

Functions of Posiva's Deposition Tunnel Plug

The spent fuel disposal concept in Posiva's construction licence application is based on KBS-3V, the same as the SKB method described in Section 1.4.3. In this method the long-term 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 backfill system 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 on the repository lifetime the plug design should be such that it does not reduce the performance of the backfill and the plug is needed to keep the backfill in place. Posiva's functions for the deposition tunnel plug are as described in Section 1.4.3.

In the beginning of the DOPAS Project, the requirements systems of Posiva and SKB were not harmonised and the WP2 work is based on the state-of-the-art at the beginning of the DOPAS Project. Therefore, in the DOPAS Project, the requirements on the plugs have been expressed using slightly different terminology. During the project, SKB and Posiva have carried out the requirements harmonisation work (KUPP-VAHA), and, in the future, the requirements will be expressed using the same terminology.

Conceptual Design of Posiva's Deposition Tunnel Plug

The current reference design for the Posiva deposition tunnel plug is the same as that described for the reference SKB deposition tunnel plug (i.e., the dome-shaped design, Section 1.4.3 and Figure 1-9) (Posiva, 2012a). 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 heights being used.

Objectives of the POPLU Experiment

An alternative plug design to the dome-shaped reference deposition tunnel plug, the so-called wedge plug, is being tested in POPLU. The differences to the reference design arise from a desire to test if a concrete structure with fewer components will perform as required, in which case 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.

The POPLU demonstration is implemented to fulfil the YJH-2012 (Posiva, 2012b) plans to:

- Construct a full-scale deposition tunnel plug.
- Develop the detailed structural design for the deposition tunnel plug, including development of the concrete mix.
- Develop the method for excavation of the deposition tunnel plug location.
- Develop Quality Management Practices for the Deposition Tunnel Plug.
- Develop instrumentation and techniques for monitoring the performance of deposition tunnel plugs (e.g., mechanical load transfer, concrete shrinkage and watertightness), including modelling of the performance.
- Observe and solve practical challenges associated with installation of deposition tunnel plugs prior to repository operation, including, for example, challenges related to occupational safety, documentation, quality assurance and practical work procedures.

Design of the POPLU Experiment

The principal component of the POPLU experiment is a wedge-shaped low-pH reinforced concrete structure (the "concrete wedge") that is cast in place into a slot that has been notched into the Excavation damaged zone (EDZ) (Haaramo and Lehtonen, 2009). In the POPLU design (Figure 1-11), the wedge-shaped concrete structure is cast, in two sections, directly adjacent to a filter layer in front of a concrete tunnel back wall. Stainless steel reinforcement is used in the concrete structure. The concrete back wall was considered to simplify installation.

In the real repository, bentonite tunnel backfill will be present behind the plug. The POPLU experiment was constructed without a bentonite sealing layer behind the plug. Inclusion of a bentonite sealing layer was considered during the structural design work. However, numerical modelling of the plug hydraulic performance concluded that the massive concrete structure, together with injection grouting of the concrete-rock interface and the introduction of bentonite tapes would render the plug sufficiently watertight during pressurisation. The planning work recognised that the addition of bentonite behind the plug would increase the water tightness of the POPLU plug design, but building the experiment without a bentonite sealing layer would allow evaluation of the reliability of the concrete structure specifically. Absence of the bentonite seal would also allow much more rapid pressurisation of the concrete plug (further information on the design work is available in Holt and Koho (2016) Holt and Dunder (2014), DOPAS (2016d) and Rautioaho (2016)).

The plug contains grouting tubes, used to emplace 750 litres of low-pH grout, and bentonite circular strips (or tapes) at the rock-concrete interface to ensure watertightness. The conceptual design of the wedge plug that is being tested in POPLU is illustrated in Figure 1-11.

The purpose of the tunnel backwall was to shorten the demonstration tunnel as the full length of the tunnel was not needed for the POPLU experiment. In addition, low-pH SCC was used for the approximately 2.5 metre long non-reinforced backwall as a method test prior to POPLU casting. The filter layer has the length of 1,200 mm, width of 3,500 mm, and height of 4,350 mm. It is constructed using lightweight low-pH concrete blocks with high water permeability. The filter layer contains the pressurisation pipes and is used in the pressurisation POPLU test. The concrete wedge has the dimensions of 6,000 mm in length, max 5,500 mm in width, and max 6,350 m in height.

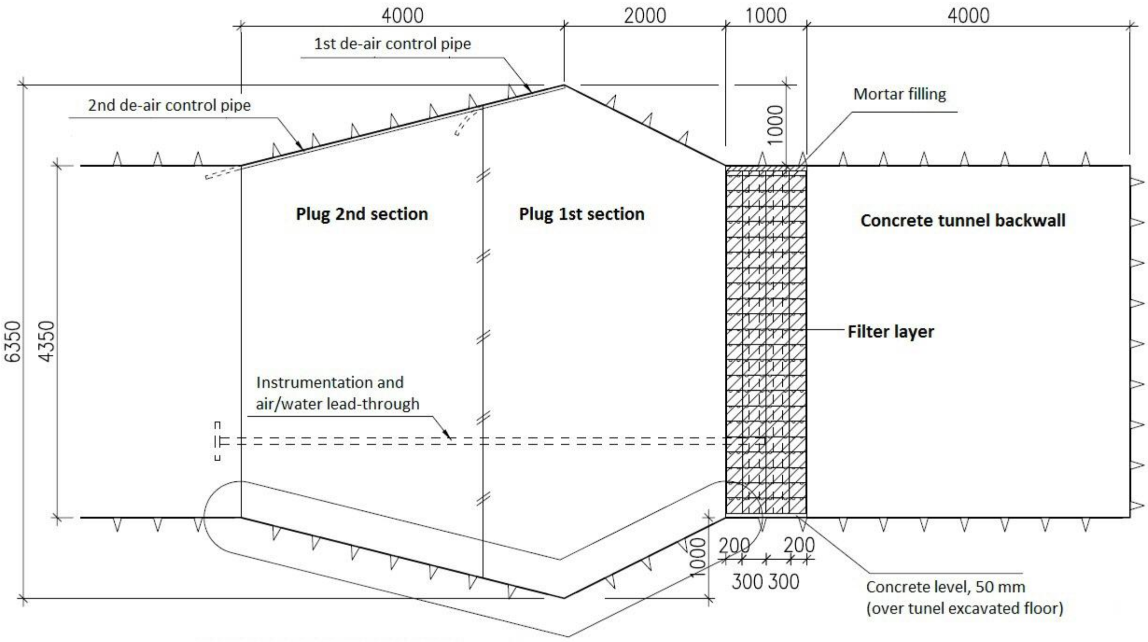

Figure 1-11 Schematic illustration of the Posiva's wedge-shaped plug being tested in POPLU (Holt, 2014).

The dimensions and materials of the POPLU components are summarised in Table 1-5.

Table 1-5: Dimensions and materials of the POPLU components.

POPLU Component	Dimensions	Materials
Tunnel	Length of 25 m (experiment length of 11 m). Cross section of ~ 14.5 m^2	In crystalline rock (mainly veined mica gneiss)
Concrete back wall	Length of 2.6 m	Unreinforced low-pH SCC
Filter	Length of 1.2 m	Lightweight concrete blocks, manufactured using LECA® with a maximum grain size of 10 mm
Wedge sections	Length of 6 m in total consisting of two sections (4 m and 2 m of length)	Reinforced low-pH SCC
Bentonite tapes	3 x Circumference (60 kg of tape)	Granular bentonite

POPLU Experiment's Progress within the DOPAS Project

Work on the POPLU experiment within the DOPAS Project included the concrete recipe design and performance evaluation, bentonite tape and filter system planning, slot excavation planning and implementations, monitoring and pressurisation systems' design and implementation, modelling of water tightness and mechanical integrity, pressurisation of the experiment plug and its performance assessment. Outside the scope of the DOPAS Project (self-funded by Posiva) were some aspects of the plug design, the tunnel excavation and construction activities themselves.

The design of the POPLU experiment was undertaken between November 2012 and September 2013. Excavation of the demonstration tunnels (one for the plug experiment and one for its monitoring data collection) and then the slot were undertaken in the period September 2013-February 2015. The first section of the POPLU concrete wedge was cast in July 2015 and the second section was cast in September 2015. Grouting of the plug-rock interface was undertaken in December 2015. Pressurisation of the plug commenced in mid-January 2016.

Once the filter section was filled with water, pressurisation of the plug could commence. In the early stage of pressurisation, the water pressure in the filter was increased to 1.4 MPa over a one month period, and a shorter duration higher pressure test. Based on the results achieved to date, it was decided to re-grout the plug interface with an improved grout mix and methodology. It is expected that the pressurisation and performance evaluation will be undertaken again with pressures up to 4.2 MPa after the re-grouting is completed. Further monitoring of the POPLU experiment and the evaluation of the results will be undertaken after the completion of the DOPAS Project.

1.4.5 German Shaft Seal

Functions of the German Shaft Seal

The considered 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[4]. 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 Gorleben repository concept envisages two sealed shafts, one in each of the mine shafts, 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 in a salt formation has been specified as being to provide a sufficiently low hydraulic conductivity to avoid brine paths into the repository and the movement of radionuclides out of it. The period (assessment period or lifetime) required for the functioning of the shaft sealing system in the preliminary safety assessment for the Gorleben site was 50,000 years (Müller-Hoeppe *et al.*, 2012a and Müller-Hoeppe *et al.*, 2012b). However, integrated process modelling has been performed. It showed that the functional time needed can be shorter. Accordingly, the minimum functional period needed is until the backfill in the repository drifts, access ways, and emplacement

[4] In Germany, other types of rock are also under consideration as potential repository host rocks. However, the national regulation requires technical demonstrations of the planned solutions and the German ELSA project is one of these demonstrations projects

fields seal off the repository in response to compaction driven by the creep of the host rock. This is estimated to be achieved, depending on the boundary conditions, after some thousands years up to 20,000 years.

Design of the German Shaft Seal

The conceptual design for a shaft seal in a salt formation in the German repository programme, which is developed for the site-specific conditions at Gorleben, includes four sealing elements consisting of different materials to ensure diversity in the seal system and to consider the different kinds of salt solutions present in the host rock to avoid chemical corrosion of the sealing elements (Figure 1-12):

- The first sealing element (sealing element 1, Figure 1-12) 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 properties of the bentonite allow the closure of the EDZ at shallow depths with only low rock pressure. This makes it suitable for use in the upper sealing element to prevent water intrusion into the repository.
- The second sealing element (sealing element 2, Figure 1-12) is made of salt concrete. Salt concrete is stable against the expected brines at the depth level in question and provides an alternative barrier to the bentonite, thus delivering robustness to the shaft seal design.
- A third sealing element made of sorel concrete (sealing element 3, Figure 1-12) is located directly above the emplacement fields at the disposal level. The sorel concrete consists of magnesium oxide (MgO) 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 magnesium-rich brines. Both types of concrete create sufficiently low permeabilities, and the convergence of the salt closes the EDZ.
- A long-term sealing element (Figure 1-12) made of crushed salt that provides a sealing function even after the designed functional period. It is located between the upper -bentonite and the middle salt concrete sealing element. This seal consisting of a compacted salt layer and reaches a hydraulic conductivity that is similar to the hydraulic conductivity of the host rock in the salt dome (Müller-Hoeppe et al., 2012a).

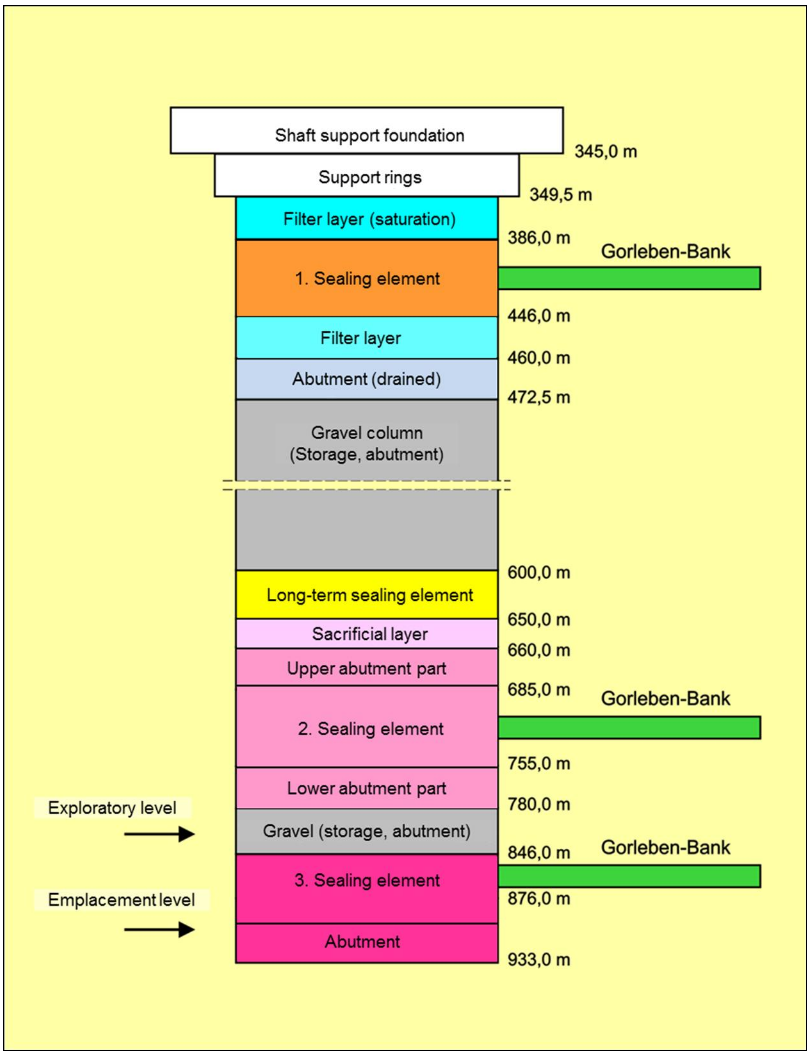

Figure 1-12: Schematic illustration of the German shaft seal's conceptual design for the the Gorleben salt dome (Müller-Hoeppe *et al.*, 2012a). Terms are defined in the text.

ELSA and Related Materials Research Projects

No full-scale test as part of the German ELSA project has been carried out within the DOPAS Project. The aims of the experiments were to develop generic design concepts for shaft seals's sealing elements in both salt and clay host rocks that comply with the requirements for a repository for high-level waste (Jobmann, 2013; Kudla *et al.*, 2013; Herold & Müller-Hoeppe, 2013) and to carry out the necessary preparatory work in the shaft seal design project. Large-scale demonstration tests of individual shaft sealing elements will be undertaken after the DOPAS Project. The German experiments within the DOPAS Project consist of ELSA Project phase two work method development and of the related material studies (LASA, LAVA and THM-Ton). The relation between ELSA Project and LAVA, LASA and THM-Ton are presented in Figure 1-13.

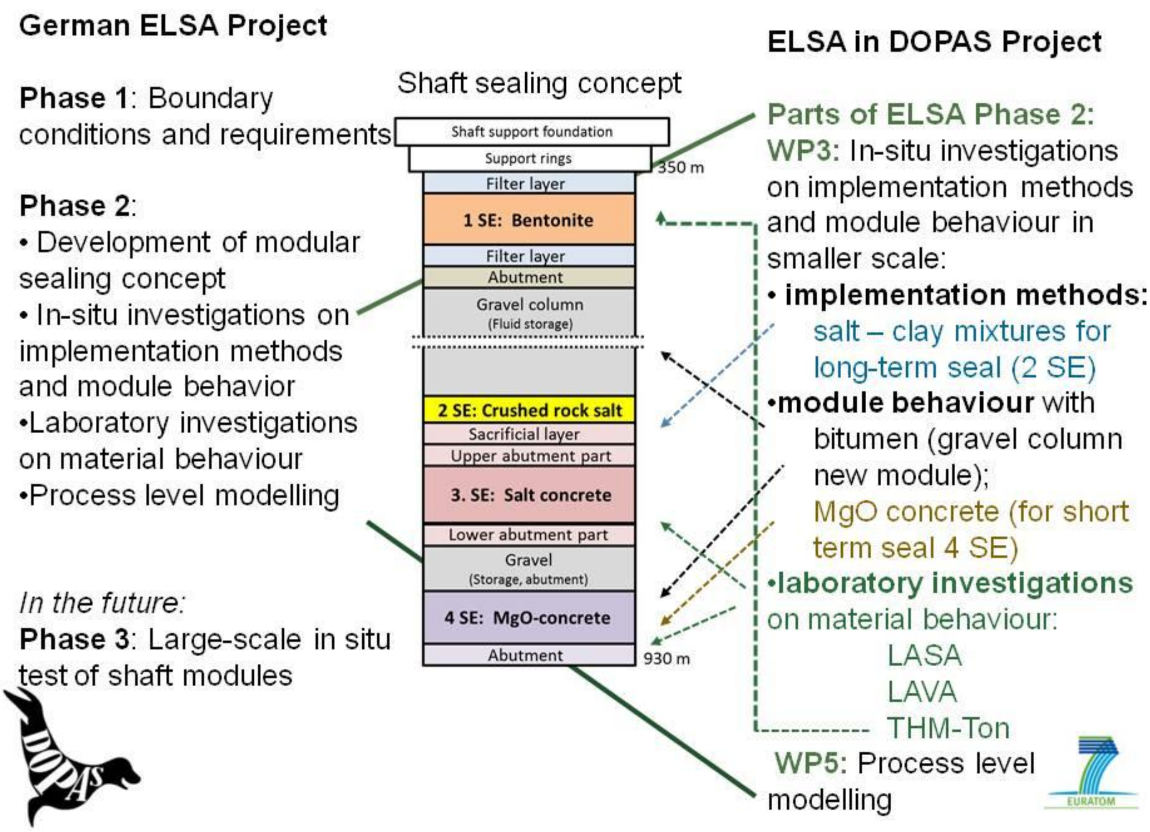

Figure 1-13 The relation between ELSA Project and LAVA, LASA and THM-Ton

ELSA Project

The German national ELSA Project is divided into three phases. Phase 1 deals with boundary conditions and requirements for shaft seals in German salt and clay formations. Phase 2, focuses on development of: modular shaft seal concepts; smaller scale in-situ investigations on implementation methods and module behaviour; laboratory testing of different materials for the sealing modules; and process level modelling. Phase 1 was almost complete at the start of the DOPAS Project and is not included in DOPAS Project. Phase 2 work has been undertaken within the DOPAS Project in different subprojects under Work Package 3 and the project level modelling under Work Package 5. The work done in DOPAS Project has contributed to the state-of-the art of the shaft sealing concept modules and as a result it is now possible to move to the ELSA Phase 3 that is not part of the DOPAS Project. The Phase 3 will carry out large-scale tests of the individual functional shaft sealing elements. This work will be planned and implemented after the DOPAS Project. The DOPAS Project results have contributed to the decision making related to the next ELSA phase.

The detailed objectives of ELSA are to:

- Give a summary of the state-of-the-art of long-term stable shaft sealing systems and its modules.
- Provide documentation on how to achieve compliance of a modular shaft sealing system design with national and international standards and regulations (design basis analysis).

- Compile boundary conditions for a modular shaft sealing systems in Germany.
- Define requirements for a modular shaft sealing systems in Germany.
- Develop new and modular-based shaft sealing concepts for HLW repositories in Germany sited in both salt and clay environments.
- Perform smaller scale *in situ* tests of specific functional elements (modules) of the modular shaft sealing design or alternative modules that may be incorporated in the future reference design at a later date (Figure 1-12).
- Develop process level modelling to characterise the material behaviour of specific sealing elements for a reference shaft sealing design or alternative elements that may be incorporated into the future reference design at a later date.

These objectives have been tackled during the Phases 1 and 2 of the ELSA Project. During DOPAS Project in Phase 2 of the ELSA Project, materials research and characterization studies, and small scale in-situ investigations on the following sealing elements were undertaken:

- Bentonite saturation (e.g. for sealing element 1, SE1) Figure 1-12.
- Small scale in-situ investigations on MgO-concrete (Sorel concrete) (sealing element 4 (SE4), Figure 1-12).
- Compaction behaviour and the effects of adding clay to the crushed salt (long-term sealing element, sealing element 2 (SE2) Figure 1-12).
- Options for an additional new sealing module using bitumen ("hard core -soft shell").

The work has been carried out in laboratory investigations divided into three subprojects. The outcomes of the laboratory results have been compared with numerical modelling and simulations carried out for the same laboratory experiments (part of work in WP5). The work included:

LASA studies by GRS on mechanical behaviour of the sealing materials for the short term seals planned to be utilised in the shaft seals. These studies address the hydro-mechanical (HM) behaviour of cement based salt concrete (planned for the sealing element 3 (SE3) and 2 (SE2 potentially), Figure 1-12) with the purpose to provide the experimental data needed for the theoretical analysis of the long-term behaviour regarding mechanical stability and deformation properties in this seal material. Both laboratory testing and numerical modelling were used in the studies. The material changes resulted from the influence different predefined stress levels (10 MPa vs. 20 MPa), the outset of dilatancy could be pinpointed, and the development need of the constitutive model was identified (Czaikowski, 2014, p.76). The data gained on the hydro-mechanical behaviour of the materials is required to support the demonstration of the long-term preservation of the mechanical stability and deformation behaviour and the sealing capability of the seals.

LAVA studies by GRS on the chemical behaviour of the sealing materials planned to be utilised in the shaft sealing elements SE3 and SE4 address the chemical diffusion and advective corrosion of the sealing material. The material research aimed at studying the chemical behaviour of salt concrete (planned for use in sealing element 3, Figure 1-12) and of the Sorel concrete (planned for use in sealing element 4, Figure 1-12). The preliminary conclusions from the laboratory tests were that the Sorel concrete in contact to NaCl solutions behaves chemically unstable; the reaction with the corrosive brine causes dissolution of the strength-forming phase. On the contrary, the strength-forming cement phases (CSH) of the salt concrete are dissolved in Mg-rich test solutions (Meyer and Herbert, 2014, p. 34). The data gained on the characteristics of the chemical reaction paths and their consequent numerical modelling supports the selection of the sealing materials for demonstrating the the long-term behaviour of the sealing elements.

The **THM-Ton** studies address properties of the Callovo-Oxfordian Argillite (clay, COX) as a sealing materials for planned use in drift and shaft seals (that are made of e.g., crushed claystone and bentonite). The studies serve sealing needs in both salt and argillaceous host rock formations. The laboratory experiments covered the sealing behaviour of damaged clay rock originating from Bure URL in France and the comprehensive characterization of the geotechnical properties of clay-based seal materials. Comparison between the compacted claystone-bentonite mixture tested by GRS and the compacted bentonite-sand mixture tested by ANDRA was carried out (Zhang, 2014, p. 4-5). Numerical modelling under WP5 was carried out in parallel with the characterization and laboratory testing.

ELSA Related Progress within the DOPAS Project

With regard to the long-term sealing element (SE2) consisting of crushed rock salt and potentially a clay admixture, laboratory and mock-up compaction tests had been completed by December 2015. In parallel, a small-scale mock-up test applying MgO-concrete was performed (Kudla *et al*., 2015).

Small-scale mock-up tests on the use of bitumen as sealing material in a new sealing module have also been undertaken during 2015 at a different location in Germany (Glaubach *et al*., 2016).

1.4.6 Summary of the DOPAS Project Full-scale Tests

To enable comparison and identification of differences between the four full-scale experiments undertaken within the DOPAS Project, an integrated summary is provided in Table 1-6. For each plug or seal being tested, Table 1-6 provides information on the following aspects:

- Type of plug or seal.
- Type of rock.
- Safety functions.
- Concrete materials.
- Bentonite materials.
- Grout and/or contact zone materials.
- Filter materials.
- Pressurisation plan.

The information presented in Table 1-6 provides information on pressurisation of the three experiments that is relevant to the period of the DOPAS Project. The pressurisation and monitoring of the EPSP, DOMPLU and POPLU experiments will continue following the DOPAS Project, with the final pressurisation schemes responding to the results and learning derived from the on-going analysis and evaluation of the monitoring results.

Table 1-6 illustrates the breadth of full-scale demonstration experiments undertaken in the DOPAS Project. The experiments and material development encompass work on:

- Reinforced (POPLU) and unreinforced SCC (FSS and DOMPLU)
- Glass-fibre-reinforced (EPSP) and binary mixture (FSS) low-pH shotcrete.
- Pellet (FSS, EPSP and DOMPLU) and block (DOMPLU) bentonite systems
- Standard (DOMPLU), low-pH (FSS and POPLU), bentonite-based (POPLU) and resin-based (EPSP) grout and contact zone materials.

Table 1-6 Summary of the DOPAS full-scale experiments, including the pressurisation of the experiment during the DOPAS Project.

	FSS	EPSP	DOMPLU	POPLU
Plug/seal Type	Drift and ILW vault seal	Deposition tunnel plug	Deposition tunnel plug	Deposition tunnel plug
Rock Type	Clay (although experiment was undertaken in a surface facility)	Crystalline (Josef underground laboratory)	Crystalline, granite (Äspö HRL)	Crystalline, mica gneiss (ONKALO)
Safety Functions/ Functions	To limit water flow between the underground installation and overlying formations through the access shafts/ramps. To limit the groundwater velocity within the repository.	To separate the disposal container and the buffer from the rest of the repository. To provide a safe environment for workers. To improve the stability of open tunnels.	To confine the backfill in the deposition tunnel. To support saturation of the backfill. To provide a barrier against water flow that may cause harmful erosion of the bentonite in the buffer and backfill.	To provide a barrier against water flow that may cause harmful erosion of the bentonite in the buffer and backfill. To support the saturation of the backfill at the required density. To support the confinement of the backfill in the deposition tunnel.
Concrete Materials	Two low-pH concrete containment walls (one SCC and one shotcrete) confining a swelling clay core.	Two low-pH shotcrete plugs on either side of the bentonite and filter zone.	Unreinforced low-pH SCC dome.	Reinforced low-pH SCC wedge.
Bentonite Materials	A mixture of bentonite pellets and crushed pellets (WH2 bentonite from Wyoming).	Czech bentonite pellets (Bentonit 75).	Compressed MX-80 bentonite blocks and pellets.	No bentonite layer. Bentonite tapes (see below).
Grout and/or Contact Zone Materials	Low-pH grout (for contact of SCC containment wall with box walls).	Resin used for rock and plug-rock interface grouting.	Grout product *Injektering30* for plug-rock interface grouting	Low-pH cementitious grout using a blend of ultrafine cement and silica fume slurry, and bentonite tapes (Super Stop)
Filter Materials	None	Inert gravel	Gravel with a grain size range of 2-4 mm	Lightweight concrete blocks, using LECA® with a maximum grain size of 10 mm
Pressurisation during DOPAS Project	Not pressurised (not applicable)	Water pressurisation up to 1.25 MPa, and bentonite slurry pressurisation up to 3 MPa.	Water pressurisation up to 4 MPa	Water pressurisation up to 1.4 MPa.

1.5 Summary of Main DOPAS Project Outcomes: Technical Aspects

The major themes of the DOPAS Project were identified in Section 1.2. In this section, the main technical outcomes of the DOPAS Project with respect to these themes are presented. The following section addresses the cross-cutting outcomes. More specific results aligned to Work package specific objectives are presented in Work package summary reports and summarised in Part 2 of this report. For each theme, we summarise the main learning that has been achieved in the DOPAS Project and identify remaining issues that will need to be addressed in future work. The main outcomes have been presented and work done reasoned in Work Package summary reports and experiment summary reports as well.

1.5.1 Design Basis Processes

The DOPAS Project has demonstrated how the design basis, consisting of the set of requirements taken into account in design and of the conditions under which those requirements must be met, is developed in parallel with the design (concurrent design). The work in the Project has illustrated the iterative development of the design basis, its hierarchical structure, and the need to develop specific design bases for both reference designs and for full-scale experiments.

Compliance of designs with the design basis is typically addressed through full-scale testing, quantitative assessment of performance, quality control and/or monitoring. In particular, the work has illustrated how safety and other functions for plugs and seals can be linked to design specifications, for which compliance can be demonstrated through the quality control programme. Final demonstration of compliance is likely to include a commissioning test based on the final detailed design, but this is dependent on judgements made on a programme-specific basis. Monitoring of plugs and seals to demonstrate compliance with the design basis as a part of any future full-scale tests is an open question (see discussion of the monitoring of plugs and seals below).

The experience of the DOPAS Project has allowed the development of a structured process, the DOPAS Design Basis Workflow that captures this iterative development of the design basis in parallel with the iterative development of the design (Figure 1-14). The Workflow demonstrates the activities and the evolving status of the design basis and design during three stages of development: conceptual, basic, and detailed design. The Workflow on a generic level is applicable to any elements of the repository design. See Section 2.3 for a summary of the Workflow.

Systematic application of systems engineering approaches to design processes is not yet routine within all repository development programmes. Repository design presents particular challenges, for example the possibility of conflicts between short-term (operational) safety and long-term (post-closure) safety requirements and the long timeframe over which safety functions must be demonstrated. This requires recourse to a range of approaches to demonstrating safety in the safety case, including full-scale testing, accelerated experiments, numerical modelling, robust design, and complementary evidence from natural systems (e.g. natural analogues).

In addition, practical experience needs to be developed in the application of systems engineering approaches in repository projects and repository design. Further work on the design bases of plugs and seals could include structuring of the requirements and conditions into hierarchies that include full and explicit links and dependencies between all of the requirements on plug and seal design (e.g., the link between safety functions and design specifications). Development of the design basis for plugs and seals will need continued structured work. Effective and efficient methods are required to manage potentially large databases of requirements and to be able to identify the interactions between them.

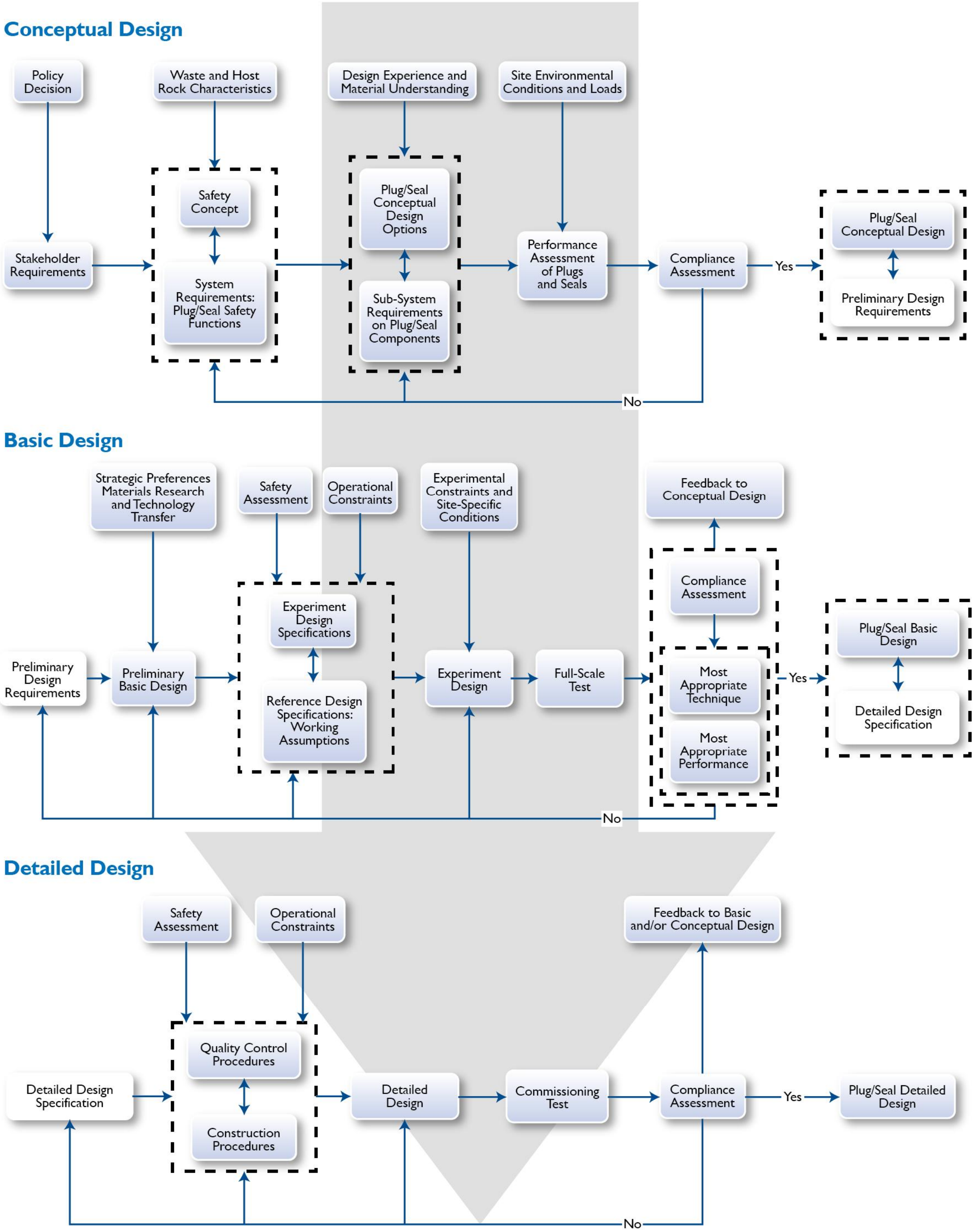

Figure 1-14: The DOPAS Design Basis Development Workflow, which illustrates the iterative development of the design basis, undertaken in parallel with the development of conceptual, basic and detailed designs. Dashed boxes are used to show activities undertaken in parallel.

1.5.2 Functions and Conceptual Designs of Plugs and Seals

The DOPAS Project has addressed plugs and seals with a broad range of functions, which are simplified here as (the full text for the functions is provided in Section 1.3):

- To limit groundwater flow in support of post-closure hydrogeological and radionuclide transport performance during the entire assessment period (e.g. FSS).
- To limit groundwater flow in support of post-closure hydrogeological and radionuclide transport performance until host rock creep has re-established *in situ* conditions (e.g. ELSA).
- To contribute to confinement of the backfill and support its saturation (e.g. DOMPLU and POPLU).
- To support mechanical stability (e.g. EPSP and POPLU).
- To provide a safe environment for workers (e.g. all Experiments).

In addition, the DOPAS Project has demonstrated the technical feasibility of a range of conceptual designs for plugs and seals. These include:

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

In the German ELSA project, work has progressed on various sealing module developments that contribute to the future full-scale test and to the preliminary design requirements for shaft seals. These include further better understanding of the sealing material's behaviour (see below) and the development of new sealing module concepts such as the multi-layer ‘hard shell – soft core’ concept using bitumen.

Contact grouting is an important element of all plug and seal designs, and the importance of the contact grouting in the conceptual design and provision of the functions required of plugs and seals has been demonstrated in all of the full-scale experiments.

The conceptual designs for plugs and seals include various components in order to meet the 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 consisting generally of composite designs. 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, since 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.

The results from the DOPAS Project will be used to revise reference designs for plugs and seals, and to consider the compliance of the revised designs with the design basis. In particular, WMOs will evaluate how to simplify designs to make them more readily implemented in repositories (see discussion of industrialisation below).

1.5.3 Plug and Seal Materials, and Detailed Design

The work in the DOPAS Project has extended the knowledge of plug and seal materials and how these materials can be incorporated into the 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. In the EPSP experiment, Czech bentonite has been utilised for the first time in a full-scale experiment. The DOMPLU experiment tested a bentonite block sealing layer combined with filter layer behind the plug aiming to hydrate the seal to ensure the plug tightness. 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 and walls, and use of reinforced concrete wedges. 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 experiment 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. 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 contact grouting materials and approaches, including application of bentonite strips in crystalline rock, and use of highly-mobile bitumen to seal the plug/seal-rock interface in anhydrites. 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. Further development of the LOPOS code to account for the EDZ around plugs and seals, and to account for concrete-groundwater interaction was undertaken. The models used for abstraction of these two processes were developed to describe experiment and process-level results achieved before the DOPAS Project started and during the early phase of the Project. The new model was successfully tested on a simplified test case with deterministic and probabilistic simulations and applied to the ELSA shaft sealing concept.

1.5.4 Siting and Excavation of Plug/Seal Locations

The DOPAS Project provided a platform for the testing of 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. 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 construct the full-scale experiments considered 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.

1.5.5 Installation of Plugs and Seals

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.

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.

The installation of the materials and work sequences were according to the planned, 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.

Industrialisation of the construction of plugs and seals will be required prior to repository operation. This will include optimisation of material delivery routines, and, more significantly, WMOs will need to consider the number and complexity of the plugs and seals included in the repository closure and sealing strategy.

1.5.6 Monitoring of Plugs and Seals

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.

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 have 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.

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. The outcome and lessons learned are shared with other monitoring initiatives (like Modern2020 and GeoRepNet projects).

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/seals during repository operation. Nonetheless, the experiments have also demonstrated that monitoring of experimental plugs and seals 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 or to respond to specific stakeholder requirements.

1.5.7 Plugs and Seals Performance: Compliance with the Design Basis

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

- *Short-term performance* has 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 includes the response of the full-scale experiments to pressurisation during the period of the DOPAS Project.
- *Medium-term performance,* which considers the saturation of the materials used in the experiments (for example in parallel experiments such as REM dealing with hydration issues for the FSS bentonite materials) and reference designs, and related modelling.
- *Long-term (lifetime) performance*, which, in the DOPAS Project has focused on understanding of specific material behaviour and related modelling over the design life of the plug/seal.

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 accelerated lab tests during the mix development stages of WP3 and during quality control testing associated with construction of WP4.

The response to pressurisation of the experiments by the end of the project, has mostly been 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 have been experiment-related leakage issues experienced for the EPSP, DOMPLU and POPLU experiments, but these are 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.

Bentonite saturation was addressed by work in the REM experiment associated with FSS and process modelling in the PHM 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 are contributing to the understanding of early-stage bentonite saturation. The total resaturation of the REM experiment is expected to be 30 years. The PHM 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 safety of the bentonite materials in the plug and seals environments was linked to the specifications as defined in 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 development in other programs such as the H2020 CEBAMA project.

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.

In all cases, the evaluation of the experimental results with respect to the safety functions and design specifications has demonstrated that, based on the results achieved by the end of the project, the designs are consistent with the design basis. There is a need, however, for further higher pressurisation and monitoring of the full-scale experiments and consideration of the plug and seal design suitability based on the full range of information that will become available as RD&D programmes progress. Demonstration that plug and seal designs are fully compliant with the design basis may benefit from a requirement-by-requirement evaluation of the full range of design specifications and development of key arguments with respect to safety functions.

1.6 Summary of Main DOPAS Project Outcomes: Cross-cutting Aspects

1.6.1 Representativeness of experiments for repository operations

All of the plug/seal design programmes have had to respond to challenges during the conduct of the experimental work, and this illustrates the need for flexibility during the planning for full-scale tests and demonstration work. As noted above, logistical issues will need to be optimised for implementation of plugs and seals in repositories. Optimisation of both implementation and design can benefit from involvement of both WMO experts and contractors with experience of working in similar environments. Industrialisation of plug and seal implementation will also require the development and documentation of construction processes and quality control programmes.

Conducting full-scale experiments always has constraints related to the actual work and several issues were considered within the DOPAS Project at the time of planning and conducting the experiments. It would be useful for all organisations implementing full-scale experiments, including those related to engineered barriers other than plugs and seals, to consider the following issues:

- How to simulate the expected loads appropriately? Using water pressurisation only is a quick and reliable way of building up the pressure load, however this may cause phenomena, which do not occur in repository, such as free water behind the concrete wall.
- In comparison to the actual disposal facility conditions the loads on the plug and seal materials resulting from, for example, bentonite swelling do not occur during the experiment period. This requires additional approaches to include representative conditions in the experimental design.
- The monitoring of experiments may cause disturbances to the setup, which needs to be taken into account when interpreting the results. (See Chapter 1.5.6)

1.6.2 Risk Management

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 process during the Project.

A final assessment of the technical risks was made for the individual experiments by the experiment leaders and its outcomes are reported in the WP4 experiment summary reports and the experiences have been incorporated into the lessons learned of the project.

The final assessment of other project and work package risks was made in connection with preparation of the D6.4 final technical summary report and it is included into the project's progress report. The general and work package risks that had been identified in the DOPAS Project risk plan were mainly avoided.

The main project risks in addition to the technical risks realised were connected with the technical risks of the experiments resulting in timetable risks; with the financial risks related to subcontracting procurement, and with some regulatory risks.

The technical risks resulted a timetable risk by the shifting the reporting time in general as the desired information was not available at the original data freeze dates. This also influenced the implementation of the expert elicitation (EE) on the final deliverables of WP3, WP4 and WP5.

In general for a demonstration project where a full-scale experimental work is combined with a desire to use the output data and related analysis results as a part of the performance assessment a longer project duration is recommended e.g. at least six years.

The financial risks related to the procurement resulted partly from the limitations in the use of subcontractors due to the financial EC rules and from some unexpected subcontractor related difficulties or changes in the volume of the originally foreseen work. This had the consequence on the consortium’s use of funding. The partners needed more own funding and work related to the procurement administration than originally anticipated for the DOPAS Project subcontracting work. Also the preparatory works, which were not part of the DOPAS Project work were more expensive than originally anticipated.

A further regulatory risk was realised when some regulatory guidelines were changed during the time of the project from the requirements that existed during the time of preparing the DOPAS Project proposal. The new regulatory requirements concerning the design and implementation of the engineered barriers needed to be complied with and this required the use of additional resources in both the experiment implementation and also for the implementation of the preparatory work done underground (see more POPLU experimental summary report, Holt & Koho, 2016).

1.6.3 Dissemination and Integration of Learning on Plugs and Seals

The DOPAS Project has held two main dissemination activities: the DOPAS 2016 Seminar and the DOPAS Training Workshop. Both of these events included innovative approaches to provide added value.

The DOPAS 2016 Seminar was structured to present summary conclusions from the Project at the start of the Seminar. In this way, the audience was introduced to key conclusions at the start, which allowed the context of more detailed information to be understood ahead of time. The Seminar also benefitted from Panel Sessions in which experiment leaders were able to provide the benefit of their experience direct to the Seminar participants, in particular to address questions that were submitted to a bulletin board via the internet during the meeting. The Seminar Programme Committee also invited specific presentations to bring in experience in the design of plugs and seals from outside of the DOPAS Project and from outside the geological disposal community (e.g. oil and gas, mining and carbon sequestration).

The DOPAS Training Workshop 2015 applied experimental learning principles and took advantage of the opportunity to use the practical training facilities, including the Josef URC and underground laboratory, and the Czech UJV Řež laboratories. This allowed the integration of the practical experience in underground and in the laboratory facilities with the more theoretical contents of the training workshop. The training workshop covered all aspects of repository implementation, using the experience of plugs and seals as gained through the DOPAS Project and from the RD&D programmes, and covered the design basis, repository design, construction and operational safety, and long-term performance and safety assessment as a part of the different RD&D programmes. This allowed participants to gain an overall understanding of the work needed prior moving to the repository implementation. The materials from the training workshop are available for further use by interested stakeholders.

1.6.4 Status of Plugs and Seals and Remaining Issues

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

The outcomes, as discussed above, have provided a significant advancement in the state-of-the-art in implementing plugs and seals in operating repositories. This includes further development of methods for specifying requirements, plugs and seals materials, numerical modelling of plug and seal performance, plug and seal monitoring, construction methodologies, and quality control.

Following the DOPAS Project, individual WMOs may still need to select preferred concepts for plugs and seals, further develop design bases to take on board the learning from the Project outcomes, and develop detailed designs. The extent to which these detailed designs will require further full-scale testing will vary from programme to programme. However, for most programmes, it would be expected that a further full-scale commissioning test of the final detailed design will be undertaken.

For programmes with licensing in the future, the outcomes of the DOPAS Project are useful to support technical feasibility demonstrations, which are a necessary input for site selection.

2 Part 2. Technical DOPAS Project Summary Report

2.1 Starting Points of the DOPAS Project and the Background Information and Methods Used

Within the DOPAS Project, various technical design and installation solutions for plugs and seals have been studied in three different generic host rock environments including one repository site. The demonstration experiments relate to different stages in the implementation of geological disposal (see Table 2-1), and aim to support effective implementation of different disposal solutions. The consortium members representing WMOs planning various disposal concepts for implementation in their respective countries. The consortium was united in a unique way for initiating a large-scale common effort to provide the best available support to a project addressing a RD&D Key Topic identified in the IGD-TP's SRA and Euratom Work Programme for Nuclear research and training programme 2012 under Fission 1-1 (EC, 2012). The plugging and sealing topic was given the urgency for deployment as a Joint Activity derived by the IGD-TP Executive Group. As such, the DOPAS Project directly addressed a topic or technical issues, which need to be demonstrated in repository conditions.

Table 2-1: The DOPAS Project experiments and the programme stages (according to the IGD-TP SRA 2012) to which they belong.

Stages	Facility and component design
Generic studies and concept development	Concept variant studies (EPSP, ELSA)
Selection of host rock and site	Repository design concepts adapted to specific rock type
Technology development and repository design	Component design and layout design (POPLU) Operational safety studies
Technology development and repository construction	Full-scale prototypes constructed (DOMPLU) Industrial scheme developed (FSS)
Industrial-scale manufacturing and repository operation	Full-scale production and operation

The work was initiated by creating design bases and reference designs using existing knowledge of the DOPAS Project partners. Thereafter, the detailed designs for the experiments were produced. Based on this, the demonstration of the "initial state" conditions for plugs and seals took place in the form of demonstrators or DOPAS Experiments FSS, EPSP, DOMPLU, and POPLU and compaction tests and supporting materials research projects for ELSA.

A reference design is generally the most mature design in the disposal concept in question and it presents a design producing the conditions that must prevail during the whole lifetime of plugs' and seals' performance. Initial state of an EBS presents the conditions that must prevail directly after installation in order to comply with the reference design in the long run. The initial state conditions thus address the accuracy by which manufacturing and installation of plugs and seals meet the defined specifications. The initial state defines the starting conditions and possible variations for the long-term safety assessment. By verifying that initial state can be achieved, long-term safety can be demonstrated to prevail in accordance to the results of the long-term safety assessment.

Quality control during emplacement confirmed that the “initial state” of the plugs and seals was consistent with design specifications, although, for some processes (like bentonite saturation), further monitoring will be required to demonstrate that performance is consistent with the planned performance. The design process is always stepwise and iterative, and heading for full-scale implementation requires iteration and sometimes the design basis needs to be reconsidered; which has been the case for the FSS and DOMPLU experiments

As explained in the DOPAS Description of Work (DoW) (DOPAS, 2012) the work was carried out in seven Work Packages of which two (WP6, WP7) address cross-cutting activities common to the whole Project i.e. the integrating analysis of results and dissemination of public results for European value added. The work related to the experiment, are divided into research and technological development (RTD) activities (WP2 and WP5) and demonstration (DEM) activities (WP3 and WP4). WP1 includes project management and coordination, and ensures the coordination and interaction between the work packages. The more detailed distribution and content of the work are described in following Chapters.

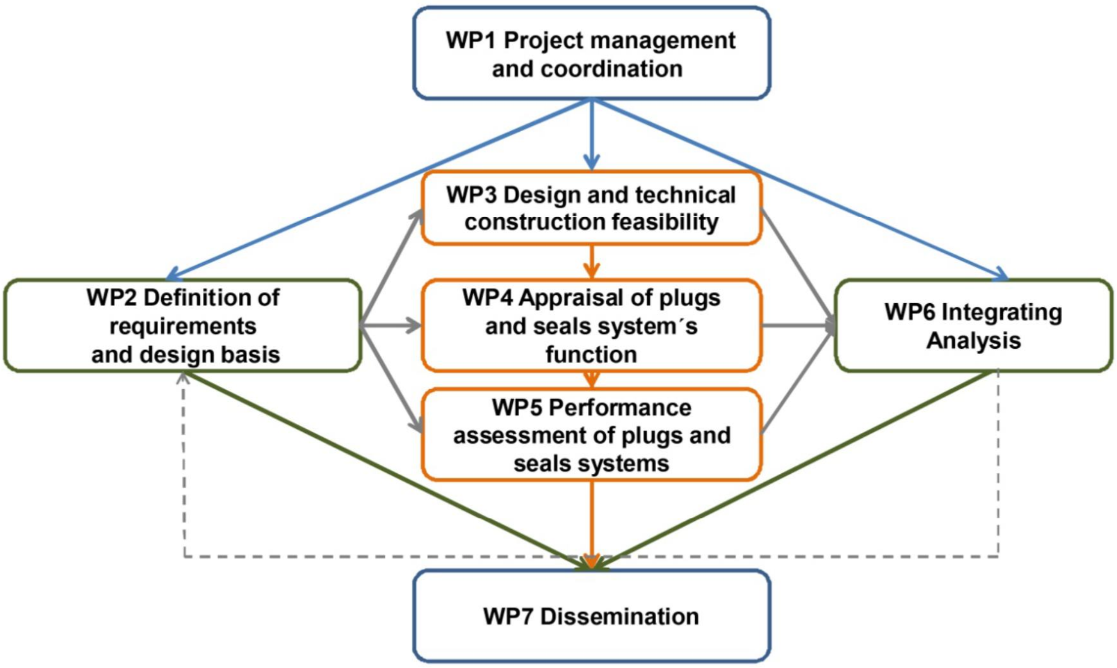

Figure 2-1 DOPAS Project’s Work package interactions (DOPAS, 2012)

Before the implementation phase, optimisation is needed, and with support of full-scale experiments, the list of practical issues is solved. The DOPAS Project feeds input to the organisations further work. For further safety assessment evaluations, details on components which can be implemented are needed. The DOPAS Project also provides good examples on processes and methods for evaluation of long term safety of plugs and seals. As an example, a failure modes and effects analysis (FMEA), which is a step-by-step approach for identifying all possible failures in a design, a manufacturing or assembly process, or a product or service, was undertaken for the POPLU Experiment after construction activities were finished to be used as a starting point for final safety case considerations when evaluating possible deviations in the initial state. Without conducting the full-scale experiment the detailed data and information on what can be achieved would not have been possible to produce.

2.2 WP1: Project Management and Coordination

The objectives for WP1 were:

- To manage and coordinate the DOPAS Project and provide project management coordination support to activities and to the DOPAS work in the different work packages;
- To steer and support the work package leaders and in the work package planning.
- To organise in cooperation with the IGD-TP Secretariat the DOPAS Project website and extranet and publish the public Project results with open access on the public website.
- To act as an information and communication centre about the public activities of the DOPAS Project including a website for open access and a restricted extranet.
- To collect and compile project management information of the DOPAS Project to ensure compliance with the requirements set in the ECGA and the Consortium Agreement (CA) and organise for the distribution of EC financial contribution and for collecting audit certificates.
- To provide means of quality assurance and control of DOPAS Project results.

The work was divided in three different work packages and below is summarised the main tasks and achievements.

2.2.1 Organisation of DOPAS Project and the management procedures

DOPAS Consortium consisted of 14 partners. They included six waste management organisations from Finland (Posiva), France (Andra), Czech Republic (SÚRAO), Sweden (SKB), Switzerland (Nagra) and United Kingdom (RWM). In addition, the consortium members were complemented with German organisations responsible for RD&D activities under the Bundesministerium für Wirtschaft und Technologie (BMWi), namely GRS and DBE TEC. Further, the consortium included Technical Support Organisations (TSOs) from the Netherlands, NRG, United Kingdom (GSL), Finland (VTT and BTECH) and Czech Republic (UJV) and a technical university CTU from the Czech Republic, operator of the Josef URC and underground laboratory. The technical support organisations participating for DOPAS Project are independent research organisations providing services internationally for different work areas which may vary from design and laboratory services into the modelling work and Safety case knowledge. DOPAS members create together General Assembly which is responsible for steering the DOPAS Project and making its financial and scientific statements. General Assembly have been invited to the meeting yearly and altogether 4 General Assembly meetings were held during the course of DOPAS Project.

The scientific coordination of the DOPAS Project work was undertaken by a nominated DOPAS Project management team, consisting of Work Package leaders and experiment leaders from four WMOs and three universities/TSO's. The discussions both in Work Package meetings and Management Team meetings have been important for guiding the scientific RTD and DEM work and their reporting. The DOPAS Project Management Team met five times during the course of the Project, WP2 partners met twice, combined WP3 and WP4 meetings were held around once a year, and WP5 partners met three times. Additionally, several smaller internal work meetings and task-related meetings were arranged. The main objectives of the meetings were information exchange between experiments and related work in the plug and seal area, and integration of the results. DOPAS Project has not been only a series of independent demonstrations and experiments in different waste management programmes even though the individual experiments mainly does feed input to the programmes conducting the experiments. One of the DOPAS Project's objectives was to analyse the results in integrated manner and summarise the pros and cons of different experiences from demonstrations and supporting work. This would provide a basis to provide a more comprehensive set of specifications to be used in plug and seal design, and improve the understanding of plug and seal behaviour in different conditions for DOPAS members and for organisations working with similar questions. Still, the fact is that material specifications or procedures developed and tested cannot be directly copied to be used in other programmes, but the learning can be utilised for others working with similar issues. To be able to provide a sufficient understanding of the DOPAS Project outcome, the experimental details for each experiment are provided in the experiment summary reports, while the WP summary reports integrates the information from the individual experiments and analyses it based on the set objectives for the DOPAS Project.

2.2.2 Management and coordination of the DOPAS Project

The management and coordination of the work was divided in different parts, which were related to the compiling and follow up the DOPAS Project management related to the budget, schedule, risk, quality and consortium administration.

The total budget of the work included in the DOPAS Project work was 15.8 M€, of which the EC grant was 8.7 M€. The full-scale demonstrators consumed more budget than was reserved within the DOPAS Project, but that was known in beforehand and certain parts of implementing experiments were excluded in original budget. Still experiments did require extensive amount of scientific work and sometimes the iteration on the way to the full scale did require reconsideration of design basis or additional mock up tests or laboratory tests. Experiments were all constructed and instrumented during the DOPAS Project as planned within the budget and the most part of the additional work was funded directly by implementing organisations. The DOPAS Project progressed according to the plans, but the scope of the actual work undertaken was larger than planned due the fact that the experiments have required more work. Examples of the additional work include: development of justifications for changing requirements (DOMPLU, FSS), dismantling methods with sampling (FSS), additional method tests (POPLU) and additional material studies (all Experiments). Work phases which were excluded in DOPAS project were DOMPLU design, material studies, modelling activities, construction activities, POPLU construction activities including part of design aspects, testing the wireless monitoring system (not included in DOPAS).

Detailed content of the DOPAS work, with interactions between Work Packages and individual experiments were planned and a combined schedule containing general schedule of the experiments were published in the beginning of the DOPAS Project (DOPAS 2013). As part of the work a production plan for reporting was done to be able to see the interactions and boundaries between experiment schedules toward to the DOPAS summary reports. The final DOPAS schedule showing the original plan included the actual implemented schedule is presented in DOPAS public website (http://www.posiva.fi/en/dopas). The major changes in schedule are related to the Experiments and their longer time needed for full scale implementation. The main delays were related to the one or several items listed below:

- Experiment related factors not part of DOPAS (like underground facility excavation or other work underground simultaneously).
- The scaling of the results from laboratory into the field conditions did require few cycles, and the concrete and bentonite analyses takes several months and if iteration is needed that easily may cause months delay.
- The selection of subcontractor and related tender process was much more time consuming than expected.
- The innovative and specific work phases underground takes longer than planned (both preparation and implementation and reporting).

The delays did not have a major influence to the DOPAS budget.

The main risks in DOPAS were identified before commencing the Project and the reported risks were distributed to the Project risks (management risks) and to the experiment related risks (scientific risks) with proposed methods for mitigation and preventing them. Few scientific risks were realized even there were plans for the prevention and mitigation. Still it is useful for future to observe the different risks when implementing full scale experiment and to report as part of lessons learned in a way that the organisations may get preparedness for actual repository operation. The risk handling plan was updated yearly and the risk passing was followed. The experiment related risks have been presented in experiment summary reports

The DOPAS Project quality assurance is part of the WP1 but the actions are divided along the whole Project. All Deliverables and other material produced within DOPAS Project undergo a review process which depends on the nature and publicity of Deliverable in question. The organisation responsible takes care of review and approval process according to their quality assurance handbooks. For example a design memorandum will undergo a design procedure according to the quality handbook. The design may contain the review of source data, the review of results and the review and approval of final products. In addition, the DOPAS Project will do simultaneously own review if data from other Beneficiaries or DOPAS foreground are used for preparation of the products. Finally DOPAS Project coordinator approves all DOPAS Deliverables which will be submitted to the European commission or published as part of the DOPAS foreground. The same procedure is valid for Dissemination activities and the process is described in the DOPAS Dissemination plan D7.1. Major part of the DOPAS work is presented and published within international seminar and conferences and the work is in that way subjected to the review when published in proceedings but also discussed with other scientists in that area.

Consortium administration took place throughout the DOPAS Project and the duties were varying and mostly they occurred in steps. The DOPAS Project was launched in September 2012 and the DOPAS Project did end in August 2016.

2.2.3 Coordination of documentation of DOPAS Project

The work in this task was divided into the two main parts:

- to compile the DOPAS periodic report and financial statements and update the Project documentation
- to create and maintain the DOPAS public website, intranet, Project templates and to approve and submit all Deliverables to the European Commission.

The DOPAS Project was reported toward European Commission in three periods. The reports did explain how the scope and objectives were reached for the period in question and also explained the use of resources. The DOPAS Project will publish a public Final report (DOPAS 2016f) where the main reported items are highlighted.

The DOPAS Project has its own public website http://www.posiva.fi/en/dopas and two mail addresses, which has been used for external communication DOPAS@posiva.fi and DOPAS2016@posiva.fi, which is used for DOPAS 2016 seminar communication purposes. The DOPAS Project produced 92 Deliverables, and 78 of those are published on the DOPAS web site and will be available for 5 years after the end of the DOPAS Project.

2.3 WP2: Definition of Requirements and Design Basis of the Plugs and Seals to be Demonstrated

This section presents the outcomes of WP2 of the DOPAS Project. The focus is on the design basis of the plugs and seals tested in DOPAS (Section 2.3.1) and the factors affecting the design basis, including impact of the host rock (Section 2.3.2). The strategies used by WMOs to demonstrate the compliance of the reference designs to the design basis are also summarised (Section 2.3.3). One of the main outcomes of the WP2 is development of a Workflow outlining how the design basis and designs of plugs and seals are developed throughout a programme at an increasing level of detail. This Workflow is also presented here (Section 2.3.4). Key messages from WP2 of the DOPAS Project are provided in Section 2.3.5. More information on the design basis of plugs and seals can be found in the WP2 deliverables D2.4 (DOPAS, 2016a) and D2.1 (White *et al*., 2014).

2.3.1 The Design Basis of DOPAS Project 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).

In the next sections, the design basis is briefly summarised for each experiment, including the manner in which the requirements were grouped, and some of the design specifications included in the design basis.

Andra's Drift and ILW Vault Seal

As mentioned in Section 1.4.1, 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 are not 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.

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 (Andra, 2012). The main design specifications relate to the following topics:

- Context of the experiment: the experiment is 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 are used for the REM experiment box.

SÚRAO's Tunnel Plug

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 (see Section 1.4.2 for a more detailed description of EPSP). The design basis of EPSP 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. The design basis of the 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 the 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.

Other significant requirements on the test plug 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 mix 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-placed reinforcing.

SKB's Deposition Tunnel Plug

DOMPLU is a full-scale experiment of the reference deposition tunnel plug in SKB's repository design (see Section 1.4.3 for a more detailed description of DOMPLU). Development of the DOMPLU design basis has been driven by the need for setting water tightness and plug production requirements. In addition to this, material specifications have been modified with respect to long-term safety driven requirements, e.g., the change from conventional concrete to low-pH concrete and exclusion of steel reinforcement. The design basis for DOMPLU is established around the design basis for the reference deposition tunnel plugs, but is presented in a more detailed fashion. The DOMPLU design requirements and specifications are grouped as follows (DOPAS, 2016a; White *et al.*, 2014):

- 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 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 only 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 mix (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[5].
- 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.

Posiva's Deposition Tunnel Plug

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 (see Section 1.4.4 for a more detailed description of POPLU).

The functions of the POPLU plug are the same as those defined for the reference design, because the design is made to comply with the requirements in Posiva's requirement

[5] 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 recognised 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.

management system (Vaatimusten hallintajärjestelmä – VAHA). Although the design basis of POPLU is in principle the same as for the reference deposition tunnel plug, there are some significant differences because POPLU is an experiment rather than an implementation of the reference design:

- A larger range and quantity of stray materials will be allowed for POPLU than in the actual plug in the repository. These materials can be recovered during the dismantling of POPLU.
- The use of sensors and wires for monitoring will be allowed, however no monitoring sensors are foreseen in the final plug design.
- In the planned repository, there will be two variations for deposition tunnel heights depending on the origin of the spent fuel being disposed. Therefore, two different plug dimensions will be used in the actual repository.

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

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 also been used as a basis for developing the current design basis for POPLU.

German Shaft Seal Design Basis

The aim of the ELSA Project (see Section 1.4.5) is to support the development of conceptual designs 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. The design basis for the ELSA experiment is based on the shaft seal design basis described in Section 1.4.5. 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. Currently, it is not intended to test a complete shaft seal but to only test prototypes of the different sealing elements on a large scale.

2.3.2 Factors Affecting the Design Basis

The 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 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. 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 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.

2.3.3 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:

- Large-scale Testing: Large-scale and full-scale testing, including the supporting analytical and numerical modelling used to support design, predict performance and compare experiment performance data with modelling results (and which, following calibration, may be used to demonstrate compliance for certain requirements), 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. Some of the numerical modelling is described in DOPAS (2016d).
- 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 to provide for compliance demonstration (e.g., Posiva).

2.3.4 DOPAS Design Basis Development 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 1-14). 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 systems and sub-systems

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 would be met by different conceptual design options, and to set the safety envelope on plug and seal components (design requirements) that can be applied in the next step of the design process. 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).

2.3.5 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 – Figure 1-14). At a more detailed level of design development, designing a specific plug/seal component (e.g., defining the concrete mix) requires information on what the concrete mix 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 design 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 include requirements during the operational period and post-closure. Requirements during the operational period 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

The design basis for plugs and seals is derived using a systems engineering approach that includes the structuring of the requirements and conditions into hierarchies providing full and explicit links and dependencies between all of the requirements on plug and seal design (e.g., the link between safety functions and design specifications). 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 requirements 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.

2.4 WP3 Design and Technical Construction Feasibility of the Plugs and Seals

This section gives a general introduction to the work done in the Work package 3 and presents the outcomes of WP3 for each individual experiment of the DOPAS Project.

WP3 addresses the experiences from the developing the design, producing it, siting and implementing the experiment designs and their monitoring systems. It draws the lessons from the implementation of these full-scale experiments.

The WP3 work is complemented with the Work package 4 of the DOPAS Project (see Section 2.5) that focuses on performance of both monitoring systems and of the components shortly after the construction of the plugs and seals either under pressurisation or resulting from the dismantling of the seal (in the case of FSS). Both work packages also cover the learning feeding to improve the reference designs and to the implementation of the experimental designs.

The monitoring and performance discussed in Section 2.5 includes the monitoring of the materials in response to installation (e.g., the monitoring of the curing temperature and shrinkage of concrete following emplacement) and the monitoring of the plug performance subsequent to pressurisation of the relevant experiment.

2.4.1 Overview to the WP3 work

WP3 included the largest portion of the project work in DOPAS. The work included several work stages needed to move from the basic design basis into an experimental design of a plug or seal. In addition, this work package included a range of different types of tests and mock-ups for testing the functions and performance of the experimental plugs and seals.

Within WP3 of the DOPAS Project, four full-scale experiments of plugs and seals have been designed and constructed. These include the FSS experiment in France, the EPSP experiment in the Czech Republic, the DOMPLU experiment in Sweden, and the POPLU experiment in Finland. In addition, a series of mock-up tests and complementary materials research projects have been completed in Germany.

Structure of work for coming up with experimental plug or seals

A simplified work process structure for the development, design and implementation of the experimental plugs or seals is presented in Figure 2-2. This structural process resulted from the preparatory work done for the expert elicitation for the WP3 summary deliverable D3.30 and from the experiences and lessons learned from the experiments 1-4 in the DOPAS Project. This description that was originally produced by Marjatta Palmu was commented by Posiva staff members and the elicitation experts of the WP3. The process steps have been integrated mainly from the work carried out for the three full-scale experiments FSS, DOMPLU and POPLU. These three experiments represent the maturity of the basic design phase as identified in D2.4 of WP2. The simplified structural process is thus best suited as a preliminary guidance for basic design development phase experiments.

Figure 2-2 describes the three main sub-processes of the work needed for the implementation of the experiment's design basis that has been derived from the requirements and constraints. The first sub-process is the development work, the second sub-process is the design, and the third sub-process is the implementation of the experiment design.

The development process includes the development and preliminary testing of the materials needed for the full-scale experiment's components (e.g. low-pH concretes, shotcretes, grouts and bentonite components). It requires the development and use of the procedures to select a location for the plug/seal in the underground environment to meet the suitability criteria assign for the plug/seal location. For excavation of the plug location, development of a suitable working method for the specific location is needed. Method tests for the materials and their emplacements need to be developed. The water collection systems, and monitoring and test plans e.g. for pressurisation need to be developed and designed in the next stage. Further, the criteria for approval are needed. This is especially critical, if the experiment is implemented in repository conditions and is thus subject to pre-approvals by the nuclear regulatory authority.

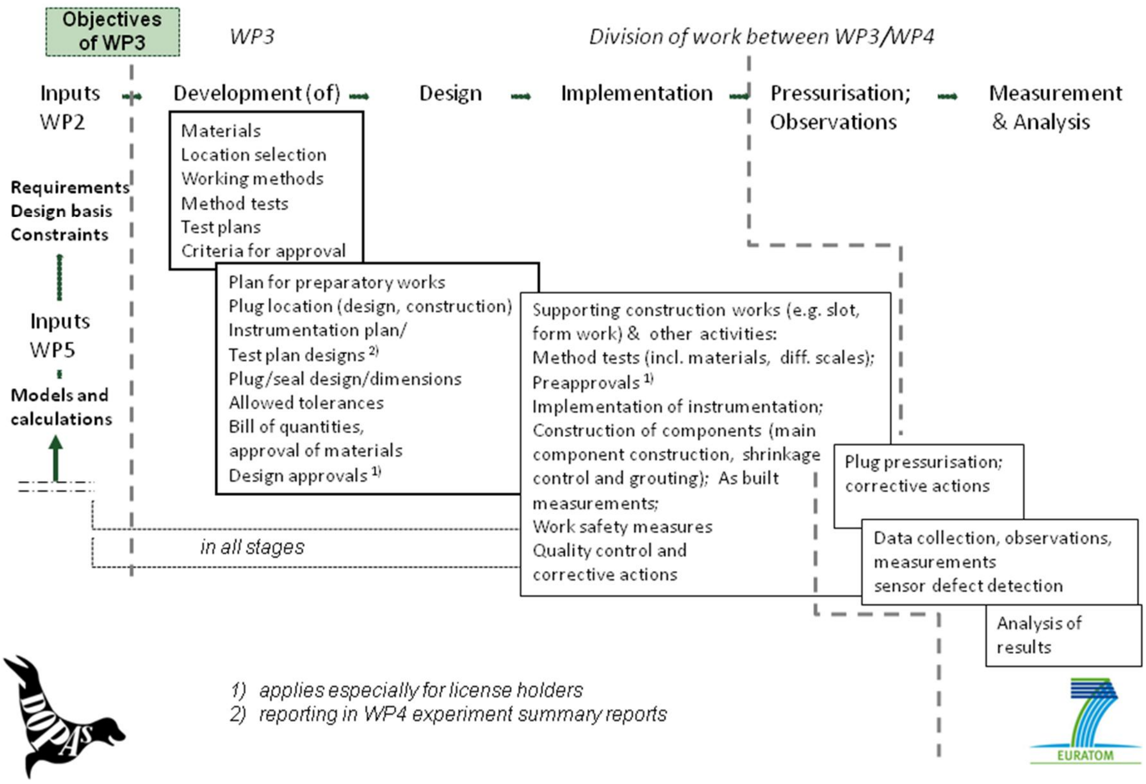

Figure 2-2 Simplified structure of the lessons learned from WP3 work resulting from the Expert Elicitation process (Palmu, 2016a).

The experiment design is to be finalised for the construction as a part of the design process. The design results are in the form of structural drawings for the plugs/seals (for all components) including the material specifications and their quantities. This design phase also includes a large amount of preparatory work that needs to be planned and carried out prior proceeding to implementation. The preparatory works include the selection of the slot location using the suitability criteria developed and decided, the method design including activities for ensuring work safety during the slot excavation, and the production of the structural design of the slot indent with the allowable tolerances. It also includes e.g. additional support structure design and/or designs of the filter structures and/or backfill elements upstream the plug or seal. In addition, this sub-process includes the selection, procurement and testing of the sensors and finalising the detailed design of the instrumentation plan for emplacement in the plug and plug area. Before one can proceed to implementation, the sequences of the different implementation phases need to be planned and the approvals need to be acquired for the amount and type of foreign materials (safety classified consumables) and for the designs produced. The must for approvals applies for licensed environments and for potential future repository locations.

The implementation process includes first the detailed scheduling of the work sequences and the realisation of all the supporting works needed for the construction and for any other activities e.g. access to electricity, water, lighting, and for the work safety measures needed prior the implementation begins. All work plans need to include contingency plans and change management procedures that take into account the modifications needed due to the actual work conditions. The plug and instrumentation tunnels need to be excavated and supported and their as-built dimensions are recorded, and their geology, structures and water leakages measured and documented. The lead-through for instrumentation cables need to be bored between the adjacent tunnels and the data collection systems need to be installed and connected to the data storing and processing systems. The plug slot indent needs to be excavated and measured and the design is then modified to meet the as-built measures of the site. The upstream structures need to be constructed, plug formwork procured and/or constructed and produced. In the case of above-ground experiments, the corresponding implementation of the test facility (e.g. a test box) needs to be carried out.

The underground logistics need to be planned so that the construction materials can be transported in a timely fashion to the plug construction site without deterioration of the material quality or workability during the transport. The material workability needs to be tested with method tests in different scales above ground and underground, and the quality control procedures need to be refined. Pre-approvals need to be acquired prior to the start of construction and the instrumentation plan needs to be implemented in the plug or seal areas prior to the plug being cast or otherwise constructed. The emplaced instrumentation system also needs to be tested and the potential sensor failures need to be identified and sensors replaced. This functionality testing is repeated after the plug/seal casting or construction to set a baseline for the date collection. Supporting activities may include installation of solutions for controlling the cast shrinkage like cooling systems or reinforcement of the plug. Grouting materials need to be tested and grouting needs to be carried out at several stages according to the leakage water control requirements (e.g. pre-grouting, post-grouting, other corrective activities). The casting or filling of the plug/seal structure is carried out in one or several parts, the concrete humidity is controlled with necessary measures and the formwork and other structures not belonging to the plug/seal are removed. In all stages especially work safety measures, quality control and logistics and related limitations need to be considered and corrective actions taken when needed. Especially in crystalline rock the shrinkage of the concrete is observed and the curing temperatures, loading and displacements are measured, observed and documented during the implementation process prior the plug/seal is subjected to the design loads by using pressurisation (see WP4 for more details about this process).

Testing and mock-ups carried out in WP3 and WP4

The work related to the testing and mock-ups in the DOPAS project is divided between the WP3, WP4, and WP5. The emphasis of the testing in WP3 and WP4 is on either ensuring the construction feasibility of the plugs and seals (WP3 emphasis) or providing information about their performance. WP5 in contrast has an emphasis on predicting longer term performance and the emphasis in it is to provide input for process understanding, abstractions and for predictive and integrative modelling of the plugs' and seals' performance (especially for ELSA shaft sealing).

A summary of the WP3-WP4 testing and mock-ups is given in Figure 2-3 and in Chapter 2.4 and Chapter2.5**.** The testing in both work packages focused mainly on:

- Construction and other work methods needed for selecting the plug location and for underground excavation for plugs and seals.
- Methods for achieving planned densities, required component and module behaviours including compaction and functions of sealing materials like bentonite pellet and crushed salt materials or salt-clay material mixes; and techniques for shotclaying, shotcreting and casting; and methods for grouting.
- Low-pH material developments for plug and seal components, e.g., SCC, concrete elements, shotcrete and grouts.
- Development of clay materials and testing their properties, e.g., bentonite mixes, bentonite tapes and backfill.
- Development of filters and other upstream structures and sealing modules as part of the sealing experiments.

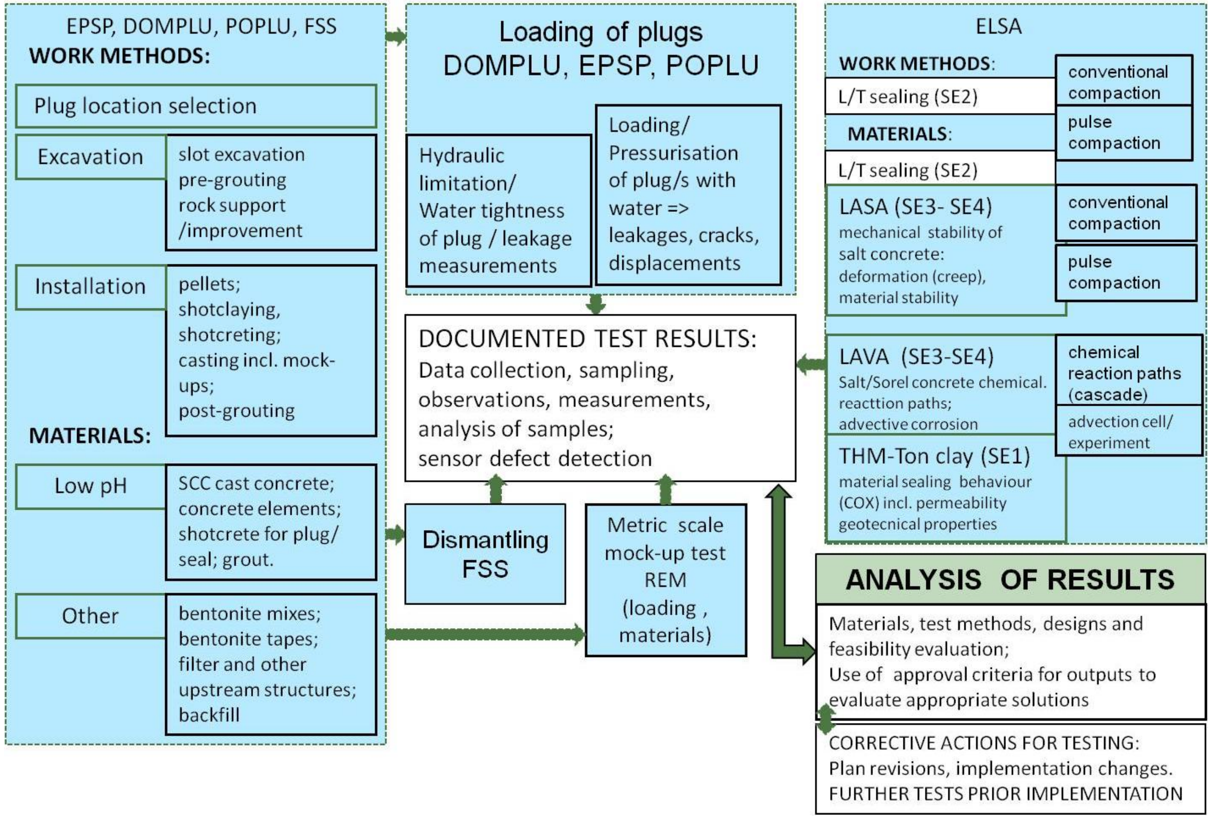

Figure 2-3 Testing work done in WP3 and WP4 prior to analysing the results modified from Expert Elicitation (Palmu, 2016a). The German sealing elements in the figure correspond to German shaft sealing concept in Figures 1-12 and 1-13. SE1, SE3 and SE4 indicate short-term sealing elements and SE2 indicates the long-term sealing elements.

The main functions of the plugs in crystalline rock (DOMPLU, POPLU and EPSP) were to limit hydraulic flow and to withstand the loads resulting from the backfill behind the plug. The functions were tested by leakage and displacement measurements. Observation and measurement of cracks were also used. In the FSS experiment, the dismantling of the clay seal after its construction produced additional data on the behaviour of the clay materials resulting from the experiment.

These shorter term tests were complemented with longer-term experiments that are included in WP5 and their monitoring will continue beyond the DOPAS Project. The materials applied in the FSS experiments were put into a metric-scale mock-up test REM, where the capability of the materials to with stand loading and the material saturation in during couple of decades is planned to be studied as part of Andra's RD&D programme after the DOPAS project. Within the "ELSA" (THM-Ton sub-project), the material sealing properties and permeability of the clay material was tested. For the crushed salt material and for the salt concrete (Sorel) both mechanical and chemical material properties were tested. The mechanical properties' testing (LASA sub-project) included the deformation/creep properties and material stability in addition to gas/liquid permeability evolution testing. The chemical properties' testing includes the study of diffusion and chemical reaction paths and the study of interactions between concrete and groundwater under advective flow. These experiments are also running a longer time than the duration of the DOPAS Project.

The results from these tests, to the degree they are available at the end of DOPAS Project, have been collected and analysed as a part of the activities in WP4 and WP5.

The construction of the full-scale experiments and lessons learned from the perspective of an individual experiment implementation are described in Sections 2.4.2 and 2.4.6. Further details can be found in the WP3 summary report D3.30 (DOPAS, 2016b). Learnings with regards to the WP3 outcomes, including on plug and seal materials used in the DOPAS experiments are provided in Section 2.4.7.

2.4.2 FSS Experiment

Locating the FSS experiment at the surface provided the benefit of flexible access to the test box for both monitoring of the construction and for the ultimate dismantling activities. The additional space in the building meant that it was feasible to store materials and ensure their availability for the filling operations. Although the experiment was not undertaken underground, it was feasible to control the ambient temperature and relative humidity so that the conditions were suitably representative. Construction of the FSS experiment test box commenced in November 2012. The test box has an internal diameter of 7.6 m and is 35.5-m long. Materials research was undertaken in the period August 2012-April 2014, and the main components of the experiment were installed between July 2013 and September 2014.

A range of low-pH concrete mixes were tested in the laboratory, and in mock-up tests at the metre and several-metre scales. Design and selection of the SCC mix was undertaken in a three-step process in which the range of options was progressively narrowed. Final selection of the materials considered a global analysis using both technical parameters (compressive strength, shrinkage, organic matter concentration, pH, porosity and permeability, workability) and non-technical parameters (distance of the manufacturer to the test facility and cost). The preferred solution was a binary mix with 50% cement and 50% silica fume. Design and selection of the shotcrete mix followed a similar multi-step process, and similar parameters were used in the global analysis (the analysis also included the odour of the mixture as a result of sulphur presence in the slag materials). The preferred solution was again a binary mix, with the selection particularly affected by the pH and compressive strength of the mix.

Andra has adopted a pellet-based system for installation of the swelling clay core, as the use of pellets is considered by Andra to be an efficient industrial method for implementation of significant quantities of materials. Testing of candidate materials in the laboratory identified a preferred admixture of 32-mm diameter pellets combined with powder made of crushed pellets. The bentonite used was WH2 bentonite from Wyoming (a material very similar to MX-80, a brand more commonly known). Emplacement of the admixture used a dual auger system, preliminary metric-scale testing of which identified the need to arrange the augers one-above-the-other to achieve the best density. Although the original target for the admixture density was 1,620 kg/m^3, evaluation of the dry density and swelling pressure for WH2 undertaken in parallel with material testing showed that the required swelling pressure could be achieved with a dry density of 1,500 kg/m^3.

The installation of the FSS components was undertaken to plan. Several lessons were learned regarding the method of installation, for example the need to match the SCC retardant dose to the ambient temperature and the need to manage dust and control pellet breakages during the emplacement of the bentonite admixture. Although the casting of the low-pH SCC was successful as the concrete rose progressively inside the box, with smooth and regular emplacement, some problems were encountered with the shotcrete, notably the management of rebound and formation of gaps.

An important lesson for the material specifications is the selection of realistic and achievable targets. This was the case with the bentonite material dry density specification. Initially a high value of the dry density was specified even though a more realistic and lower target was found to be sufficient and more easily achievable. Where feasible, a range of values for material specifications should be provided rather than absolute values as this will facilitate quality control during installation. It, furthermore, provides “robustness” to the concept.

2.4.3 EPSP Experiment

Selection of the location of the EPSP experiment within the Josef URC and underground laboratory was undertaken in late 2012. The location was characterised and ground conditions improved in the period January 2013-September 2014. The EPSP tunnel diameter is approximately 3.6 m (5.4 m where slots were constructed for the concrete plugs) and the experiment length is approximately 7.2 m. Installation of the EPSP components was undertaken between November 2014 and July 2015.

The shotcreting technology and know-how used in EPSP was developed from previous Czech experience in the installation of concrete plugs using fibre-reinforced concrete. For EPSP, low-pH concretes were required. Low-pH concretes previously developed in the Czech national programme had low compressive strength and were unsuitable for EPSP. Therefore, new mixes were developed. The selected shotcrete was a mix of cement, sand and gravel, microsilica and glass fibres. The ratio of microsilica to cement was approximately 1:1.

One of the main aims of EPSP is to demonstrate the suitability of Czech materials and available technologies for construction of tunnel plugs, including the use of Czech bentonite. Following careful consideration of plug construction requirements, factory-produced B75 bentonite (milled, non-activated Ca-Mg bentonite from the Czech Republic) was selected as the principal material for the bentonite part of the plug. Development of the EPSP structural design was underpinned by the results obtained from two laboratory physical models, which were used to investigate physical processes and to provide parameter values for numerical modelling.

The Josef URC and underground laboratory is a former gold mine, located in a hillside with an overlying rock thickness of 90-180 m. Prior to the commencement of the construction of the EPSP experiment, it was necessary to reshape the experimental gallery niche and improve the ground conditions. Rock quality was improved through the injection of polyurethane resin. Niche excavation was initially undertaken using a hydraulic wedge splitting technique, but this approach was problematic and an alternative pressure disintegration technique using non-detonating gas cartridges was successfully applied during later stages of niche reshaping.

Installation of EPSP was undertaken largely to schedule. Although the inner concrete plug was initially emplaced without concrete grouting, preliminary testing of the plug demonstrated that grouting was necessary. Owing to the small size of the Josef URC and underground laboratory tunnels, the concrete for the shotcreting had to be supplied using small trucks, and there was the need to transfer the mix from a big truck that delivered the concrete from the production plant into the small trucks at the entrance of the facility. However, this did not have a significant impact on installation. Installation of the bentonite pellets was undertaken manually using a range of hand-held compaction machines.

Conducting experiments in pre-existing near-surface facilities will always have its limitations. Two limitations in EPSP were the ground conditions and the impact of the size of the underground tunnels on the delivery of the shotcrete to the experiment site. EPSP has demonstrated that in a pre-existing, near-surface facility, the selection of the experiment site is particularly important, as the impact of the ground conditions, tunnel dimensions and electricity supply can all be limiting factors on the manner in which the experiment can be conducted.

2.4.4 DOMPLU Experiment

The DOMPLU experiment was constructed inside a horseshoe-shaped tunnel, with a width of 4.2 m and a height of 4.8 m. The diameter of the plug is 9 m at the centre of the slot excavated for the concrete dome, and the experiment length is approximately 6.5 m, with the concrete dome approximately 3.2-m long.

DOMPLU was sited at the deepest part of the Äspö HRL in order to most appropriately represent the pressure conditions expected in the repository. Siting was supported by rock characterisation activities, including hydraulic testing in a pilot borehole to identify the location of the concrete dome slot. Similar procedures will be applied in the repository and the work in the DOMPLU experiment was a good test of the procedures.

Development of the DOMPLU structural design was supported by the testing of the overall design in a scaled laboratory model and by analytical and numerical modelling to predict the hydromechanical and thermal behaviour of the plug.

Excavation of the DOMPLU niche was undertaken in early 2012 and the concrete dome slot was excavated in two phases in April-May 2012 and August-October 2012. The experiment components were installed between January and June 2013.

A concrete mix for a low-pH SCC, denoted B200, had previously been developed specifically for use in the deposition tunnel plugs of SKB’s repository. Testing of this concrete was required to ensure that it provided the necessary strength, shrinkage, creep and binding properties to the host rock, given the ambition to demonstrate that the concrete could be emplaced without reinforcement. It was also necessary to demonstrate that properties measured in the concrete factory were representative of the properties the concrete would achieve when poured at the experiment site underground at Äspö. It was judged possible to use the concrete mix B200 without any further development, based on the results of the concrete testing. However, experiences from the B200 concrete test series also showed that further clarification is needed regarding quality control requirements and acceptance criteria of the young concrete properties.

Experimental tests were also carried out to investigate the properties of the bentonite sealing materials, including compaction properties of the bentonite, strength of the bentonite blocks, compressibility, swelling pressure, hydraulic conductivity, and self-sealing of fractures in the rock and slots between the bentonite blocks. The tests confirmed that compressed MX-80 bentonite blocks with a dry density of approximately 1,700 kg/m^3 and a water content of 17%, surrounded by a 10-20 cm thick layer of MX-80 pellets, would be a functional configuration for the seal.

A filter layer is included in DOMPLU to ensure that high pressures are not exerted on the concrete dome until it has cured and developed sufficient strength. Candidate filter materials included different combinations of sand and gravel, and geotextiles. The materials were subjected to compaction, compressibility, hydraulic conductivity and clogging tests. Gravel, with a grain size range between 2-4 mm, was selected as the preferred material for the filter. It was decided to test geotextile material at full scale in the DOMPLU experiment and use it as a delimiter between the gravel filter and the bentonite seal. The purpose was to facilitate distribution of water to the seal from the filter. In addition, light-weight expanded clay/concrete aggregate (LECA®) beams were used both as a delimiter and as part of the filter. LECA® was selected because it has a high hydraulic conductivity and also because it maintains it hydraulic performance when exposed to a water flow with high bentonite content (it does not clog).

The concrete dome slot was excavated using a new wire sawing technique. This technique might provide a more rapid excavation technique and might reduce the development of an EDZ compared to traditional drill and blast methods, and it may also provide a smooth surface that would allow release of the concrete dome prior to contact grouting. The excavation of the slot by wire sawing was more problematic than expected, mainly as a result of stresses in the rock. However, the method was shown to be feasible and resulted in smooth surfaces.

One of the main outcomes from the DOMPLU experiment was the demonstration that it is possible to build the dome plug system. This includes practical aspects of logistics and arranging of parallel construction activities in a tunnel system. The dome plug was successfully constructed without reinforcement. However, it was found that installation of the concrete beams, filter and seal-pellets near the tunnel ceiling was quite difficult. A cooling system applied to the concrete dome to limit cracking and to pre-stress the concrete prior to contact grouting was successfully demonstrated.

2.4.5 POPLU Experiment

POPLU was constrained as it was located in a repository site. This aspect was exploited by Posiva, who used the demonstrator experiment to test the Rock Suitability Classification (RSC) methodology for locating deposition tunnels and deposition tunnel plugs, and also used the POPLU experiment to test working practices related to working in an operating repository in which regulatory approval and strict compliance, such as with foreign materials acceptance, were required at key stages in the process.

The POPLU experiment was constructed in a horseshoe-shaped tunnel. The tunnel diameter is approximately 4.35 m (6.35 m where slots were constructed for the concrete plugs) and the experiment length is approximately 11 m, with the concrete wedge approximately 6-m long.

Concrete wedge slot production used a wedging and grinding method. This method was selected, instead of the originally-planned wire sawing method, owing to operational safety concerns with the best technology that could be demonstrated compared to the costs. It was also deemed beneficial to apply different slot production methods in the POPLU experiment compared to two of the other DOPAS Project experiments.

Characterisation and excavation of the POPLU demonstration tunnels and slot area, including the drilling of pilot boreholes, was undertaken between November 2012 and February 2015. The experiment components were installed between March and December 2015.

The design work undertaken for the POPLU experiment included use of analytical and numerical calculations to underpin the design and identify the required reinforcement on the wedge plug, to plan four mock-up tests, and to select and position monitoring sensors. The work included static and dynamic stress modelling and hydraulic modelling. The work recognised that the addition of bentonite behind the concrete wedge would increase the water tightness of the POPLU experiment plug design. However, building the experiment without a bentonite sealing layer would allow evaluation of the reliability of the concrete structure specifically and would allow much more rapid pressurisation of the concrete plug. Therefore, no bentonite seal layer behind the plug was included in the POPLU experiment.

Posiva's reference low-pH concrete is similar to B200 used in the DOMPLU experiment, but further development of the concrete mix was required to ensure workability in relation to the significant quantities of steel bar reinforcement used in the POPLU experiment concrete wedge. The preferred concrete was a ternary mix with 38% cement, 32% silica and 30% fly ash, which was judged to be the most durable and best at meeting performance requirements. Three mock-up tests (referred to as method tests by Posiva) were undertaken to finalise the mix and a fourth test was undertaken to finalise the contact grouting mix. Modifications were introduced in response to these tests, including reduction in the aggregate grain size in the upper and lower parts of the concrete wedge, where reinforcement is more closely arranged.

Six different bentonite strip (or tape) products were tested in the laboratory. The bentonite tape used was chosen as it had a high level of swelling in the first day and had the greatest mass of bentonite within the tape compared to the other products (and thus the lowest amount of foreign materials).

During installation of the POPLU experiment and related components, it was demonstrated that the construction sequence was well-planned and the schedule could be maintained. The formwork was well-designed and could be implemented and served its purpose. The reinforcement steel bars could be assembled efficiently on-site. The low-pH concrete materials developed in the laboratory within the DOPAS Project proved to be excellent when applied at full scale in the POPLU experiment. The SCC was fluid for placement without vibration, had a good open workability time and could be pumped into place. The low-pH grout material did not fully penetrate into the contact area between the concrete plug and the rock.

2.4.6 German ELSA Project within DOPAS Project

Work carried out in DOPAS Project's WP3 included the work of the German national ELSA Project's Phase 2. The Phase 1 was almost complete at the start of the DOPAS Project and is not included in DOPAS Project. The four major activities in Phase 2 included: development of: modular shaft seal concepts; smaller scale in-situ investigations on implementation methods and module behaviour; and laboratory testing of different materials for the sealing modules; and process level modelling. Phase 2 work has been undertaken within the DOPAS

Project in different subprojects under Work Package 3 and the project level modelling under Work Package 5.

The implementation method studies included small scale in-situ compaction tests for the crushed salt material using conventional compaction and pulse compaction (mainly for the long-term sealing element SE2). Improved compaction was obtained by adding clay to the crushed salt. The development of the modular shaft seal concepts included the development of a new module “hard shell – soft core” concept using bitumen in this module. Development of MgO concrete for the fourth sealing element was tested as a plug in a large-diameter borehole. The small-scale in-situ tests have been tested in a borehole in the Sondershausen mine in Germany.

In addition to the above implementation method and module developments, the several materials research projects were undertaken by GRS. Three subprojects in ELSA Phase 2 the LASA, LAVA and THM-Ton projects addressed sealing materials planned to be utilised in the shaft seals. The LASA related research addressed the mechanical properties and the hydro-mechanical behaviour (creep) of cement based salt concrete. LAVA related research investigated the chemical behavior of salt and Sorel (MgO) concretes in interaction with the host rock and fluids. THM-Ton addressed the geotechnical characteristics of clay rock and the sealing behaviour of damaged clay rock with the purpose to define their suitability as sealing material in either salt or clay host rock formations. All subprojects were complemented with comparative numerical modelling or simulations with the aim of improving the models used.

The work done in DOPAS Project has contributed to the state-of-the art of the shaft sealing concept modules and as a result it is now possible to move to the ELSA Phase 3 that is not part of the DOPAS Project. The Phase 3 will carry out large-scale tests of the individual functional shaft sealing elements. This work will be planned and implemented after the DOPAS Project.

Results from the small scale in-situ and the laboratory experiments performed so far under DOPAS Project, include the development of new modules for the sealing elements and materials have been identified that can significantly improve the sealing capabilities of the long-term and short term sealing elements (as defined in the German context). This contributes to one part of the current modular shaft sealing concept for repositories in salt dome structures and also partly for clay repository environments, too.

When using pure crushed salt for constructing the modular long-term sealing element, as in the current conceptual design, a long time is required to achieve the full sealing abilities through porosity and permeability reduction in response to compaction driven by rock convergence. Using an admixture that includes fine clay, the initial porosity directly after installation can be significantly reduced. Generally, it can be stated that the time which is necessary to develop the full sealing abilities is reduced significantly.

2.4.7 Key Outcomes of WP3 and Learnings on Plug and Seal Materials

Design and construction of the experiments have contributed to the technical readiness level of plug and seal installation in repositories in the near future. The completion of the experiment design and construction represents a successful collaboration between WMOs, research institutes and consultants.

The design and construction of the DOPAS experiments has demonstrated that plugs and seals are more challenging and complex sub-systems of the repository than previously recognised. The challenges and complexities of plug/seal design and construction can be met through available technology, methods and procedures currently available.

Common approaches to design and construction of plugs and seals have been developed and implemented by the WMOs responsible for different waste management programmes. These include, in crystalline rocks, the excavation of a slot through which the plug/seal can be keyed into the rock. In clay and salt host rocks, benefit is drawn from the creep properties of the rock to provide an effective seal when operating in conjunction with engineered features.

The host rock can significantly impact the installation of plugs and seals. Fractured rock, the presence of water-bearing fractures and formation of break-outs can be challenging, but approaches have been developed and demonstrated in WP3 of the DOPAS Project to overcome these challenges.

Logistics is a significant issue for plugs and seals. There may be multiple components requiring installation and appropriate time must be allowed for these materials to be installed and evolve prior to installation of the next component. There may be issues associated with manpower and machinery availability (and performance). Therefore, contingency planning, such as the provision of back-ups and spares may be necessary. Contingencies also need to be built into Project plans and schedules. Finally, workers' safety (e.g., during rock excavation) and workers' health (e.g., bentonite generated dust) must also be considered in the construction process.

Common approaches also include the use of low-pH concrete and/or bentonite systems as the primary components of plugs and seals. Significant work on low-pH concrete and bentonite pellet, tape and block systems has been undertaken within WP3 of the DOPAS Project. Contact grouting is a common feature to all four of the full-scale tests.

A range of different bentonite systems have been introduced in the full-scale demonstrators, including a mixed pellet and crushed pellet bentonite system used to provide the swelling clay core in FSS, a composite bentonite seal composed of a lower section of bentonite pellets compacted *in situ* and an upper sprayed layer in EPSP, and a bentonite block and pellet system for a backfill transition zone and for the bentonite seal in DOMPLU.

All of the bentonite systems have approaches to manage the heterogeneity in the system, particular the vertical heterogeneity, which results in a lower density being achieved towards the top of the bentonite layers according to the DOPAS, 2016b (Chapter 7.4). In principal, this is achieved by exceeding the design specification in the lower parts of the layer to compensate for lower densities in the upper parts of the layer. In these cases the overall density of the system meets the design specification like in the case/s of FSS, EPSP and DOMPLU reported in (Noiret *et al*., 2016; Svoboda *et al*., 2016; Grahm *et al*., 2015). The DOPAS Project experiments have demonstrated that reinforced and non-reinforced SCC, as well as shotcrete, can be emplaced successfully. The design and construction work undertaken in WP3 of the DOPAS Project has identified that a range of low-pH concrete recipes can be considered during the design of repository plugs and seals. This is further illustrated in Table 2-2, which provides a summary of the concrete recipes used in the four full-scale experiments. Laboratory testing of these mixtures has demonstrated that they have the required curing temperature, hydraulic conductivity, shrinkage characteristics, strength, water interaction (pH of pore water or leachate) and rheology/segregation characteristics for application in repository plugs and seals.

All of the low-pH concrete mixes used in the DOPAS Project used a common approach to provision of the low pH. This included the substitution of cement used in high-pH concretes with silica fume and fly ash, with the addition of filler. Aggregates were locally sourced. All of the cement mixes needed to be accounted for the properties of the specific components, such as locally-sourced cements and aggregates, and had to be tailored to the boundary conditions of the experiments (e.g., dimensions and positioning of other structures such as reinforcement and monitoring systems). 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.

Table 2-2: Concrete recipes with material quantities used in the DOPAS Project full-scale experiments. Some aspects of the concrete recipes are confidential and are not, therefore, reproduced here. Note that the mixtures are not directly comparable, and any application needs to be tailored to the local needs and parameters (more information available at Experiment summary reports D4.3; D4.5; D4.7 and D4.8. (Noiret *et al*., 2016; Svoboda *et al*., 2016; Grahm *et al*., 2015; and Holt and Koho, 2016).

Quantities:	FSS SCC	FSS Shotcrete	EPSP Shotcrete[1]	DOMPLU SCC	POPLU SCC
Cement	CEM III/A 52.5 130 kg	CEM I 52.5 190 kg	CEM II / B – M (S-LL) 42.5 N	120 kg/m^3	106 kg/m^3
Silica Fume	130 kg	190 kg	Yes (approx.. 1:1 to cement)	80 kg/m^3	89 kg/m^3
Fly Ash	-	-	-	-	85 kg/m^3
Slag	-	-	-	-	0
Water	201.1 kg	200 kg	Yes	165 kg/m^3	128 kg/m^3
Limestone or Quartz Filler	408.4 kg	-	-	369 kg/m^3 (limestone)	115 kg/m^3 (quartz)
Sand	698.7 kg	1,347 kg	Yes	1,037 kg/m^3 (natural sand 0-8 mm)	929 kg/m^3
Gravel	682.1 kg	408 kg	Yes	558 kg/m^3 (8-16 mm crushed granite)	911 kg/m^3
Superplasticiser	2.2%	3.4%	SIKA 1035CZ	6.83 kg/m^3	18.6 kg/m^3
Retardant	0.1%	0.7%	SIKA VZ1	0	0

[1] note that, in addition to the components shown for EPSP, glass fibres are also used.

2.5 WP4 Appraisal of Plugs and Seals System's Function

The work in WP4 covers evaluation and assessment of each experiment performance and the ability of plug and seal designs to meet their foreseen functions specified in the experimental design bases. The findings from WP2 and WP3 work were used to support the evaluation and assessment work in WP4. The starting point of the collection of the WP4 results takes place both prior and after the emplacement of the plug or seal experiments. For EPSP, DOMPLU and POPLU, evaluation has been in response to installation and initial pressurisation of the experiment. In these experiments, the work started with collection of the monitoring data from the installed sensor systems and with the installation of the pressurisation system for water pressurisation of the plugs. The results from the stepwise pressurisation were then collected from the instrumentation and from the water collection systems and by observations.

For the FSS experiment in the test box, the performance evaluation has been in response to monitoring during installation of the seal components since the experiment was not pressurised. A dismantling of the experiment is carried out and data from the installed sensors collected, analysed and compared with the monitoring results before the dismantling.

The experimental designs and their implementation undertaken in the DOPAS Project have been carried out as planned. By the time of the data freeze date for this report, all four of the full-scale tests had been designed, constructed and initial evaluation of short-term performance based on the test results as described in Figure 2-3 (see Section 2.4.1) had been undertaken.

The assessment and evaluation of the results included the assessment of the compliance of the experiment designs with the experiment requirements. The experiment requirements have a set of differences from the reference design as addressed in WP2. Further assessment was made on the technical feasibility of the construction of the design. The main objective of both the FSS and the EPSP experiments was to achieve confidence in the capability to build such plugs and seals. This included the assessment of the instrumentation and the assessment of the implementation of the components and the outcomes of the construction of all of the experiments.

In addition to the assessment of the technical feasibility, the development work and the design solutions were assessed. More detailed assessment targets are explained in 2.4.2-2.4.6 and in Sections 2.5.1-2.5.5 covering the individual experiment results in more detail.

The analysis of results was focused in addition to the overall technical feasibility on the feasibility evaluation of the materials, test methods and design. In the evaluation, as acceptance criteria, the primary functions assigned to the plugs i.e. their capability for hydraulic limitation and load bearing are used. The results contribute to developing more detailed design targets for those design requirements that have not yet been fixed like e.g. the limits for DOMPLU's and POPLU's allowable water leakages.

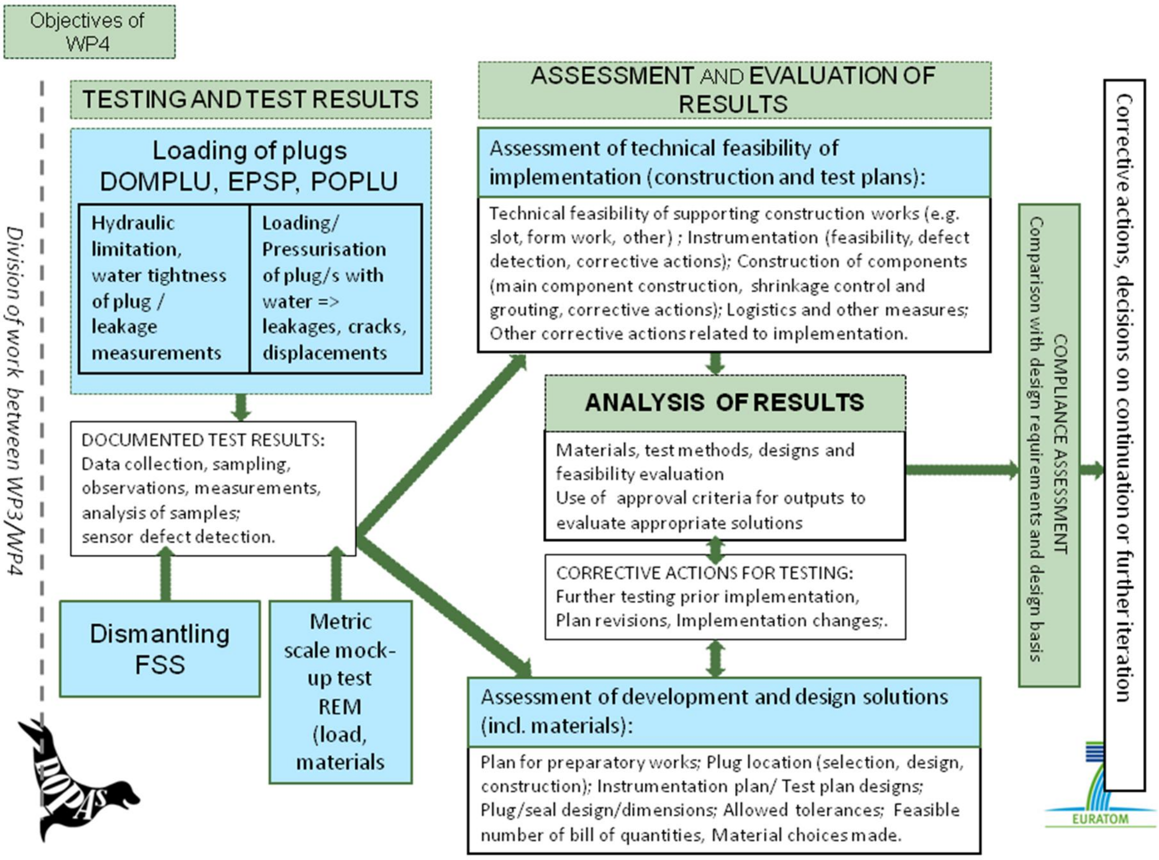

Figure 2-4 Structure of work in WP4 prior integration of outcomes and conclusions resulting from Expert Elicitation (Palmu, 2016a).

In all cases, the evaluation of the experimental results with respect to the functions and design specifications has demonstrated that the results are consistent with the experiment design basis.

The functional compliance evaluation conducted for each experiment reflected the observations by the set data freeze dates. Additional analysis of the compliance is still on-going and it is expected that experiment dismantling and long-term assessment calculations will also be used to assess the compliance of the designs to the foreseen functions including safety functions.

As a result of the German ELSA Project Phase 2 work methods and material tests for the different long-term and short term sealing elements have been carried out and analysed based on the continuous iterative evaluation of the outcomes from these laboratory scale tests, the experimental settings for work methods and material tests have been changes for improved results and the tests are on-going. The long-term performance analysis and modelling is included in the work of WP5 and in the future phase 3 of the German ELSA Project after DOPAS Project.

All of the plug/seal design experiments have had to respond to challenges during the conduct of the experimental work, and this illustrates the need for flexibility during the planning for full-scale tests and demonstration work. Summaries of assessing the compliance and performance of the outcomes for each experiment are provided in Sections 2.5.1 to 2.5.5.

Further details can be found in the WP4 summary report D4.4 (DOPAS, 2016b). Learnings with regards to the WP4 outcomes, including compliance of the experiments with key design specifications are provided in Section 2.5.6.

2.5.1 FSS Experiment

The FSS experiment is focused on the construction feasibility of the seal. Therefore, the materials were not saturated or otherwise pressurised to check the swelling pressure and hydraulic conductivity. Complementary experiments were undertaken in parallel with FSS to address these issues (like REM Test see Conil et.al., 2015).

Performance of the monitoring equipment during construction works and bentonite emplacement was good. The monitoring system installed inside the plugs was able to reliably monitor the curing temperature and shrinkage of the two types of concrete. The curing temperature and shrinkage in the SCC wall was less than what was specified (i.e., they were compliant with requirements). However, requirements were not met for the shotcrete, owing to the influence of a hardening additive, which was incorporated in the concrete mix at the time of spraying. The time domain reflectometer (TDR) device installed inside the test box provided qualitative information on the density and homogeneity of the bentonite backfilling of the crown space. As anticipated, residual voids and segregation of the bentonite admixture occurred. These effects were more significant in the upper third of the core, where mechanical interference between the backfilling machine boom and the core supporting wall prevented a thorough transfer of bentonite material into the recesses. Improved techniques for filling the upper parts of the core can be readily implemented by modifying the boom or using shotclay.

The FSS experiment has demonstrated that it is feasible to industrially build a horizontal seal system in the Callovo-Oxfordian Argillite host rock considered for the French Cigéo repository. This includes verification of practical aspects such as logistics and arranging of concurrent activities. Health and safety issues for workers have been identified and mitigation solutions proposed for the future real case (time needed to build a seal underground is also better estimated at around three months). This is of interest when planning the future Cigéo closure operations.

2.5.2 EPSP Experiment

The EPSP experiment is the first time that the Czech programme has undertaken a full-scale test of part of the repository multi-barrier system, in which the test has included an integrated programme of design (including materials testing and numerical modelling), site selection and construction, installation of multiple components including a detailed monitoring system, and performance monitoring and evaluation in response to pressurisation of the system. Data on the performance of the EPSP were available up to a data freeze date of 31 March 2016. By that date, the plug had been pressurised using air and water with an injection pressure of up to 1 MPa, and bentonite slurry with an injection pressure of up to 3 MPa. The glass-fibre-reinforced low-pH shotcrete plugs have performed well, although the plugs-rock contact zone had to be regrouted owing to leakages being detected during early water injection tests. Some flushing of bentonite has occurred, although this is thought to have originated from contamination of the filter during installation of the EPSP experiment components. The bentonite has started to show the first signs of swelling.

Performance of the monitoring equipment during construction works and bentonite emplacement was good. The monitoring system has been able to reliably monitor the curing temperature and shrinkage of the concrete plugs. The monitoring system has had an impact on the installation of the experiment components, for example it has affected the spraying of the concrete walls, and concrete behind cables may be of lower strength.

Monitoring of the performance of the EPSP experiment is on-going. Early results from the monitoring indicate that the plug performance is consistent with the design basis. The EPSP experiment has provided extensive opportunities for experience and expertise development within the Czech programme, and this experience and expertise will be utilised in the next stages of repository design and implementation of the geological disposal programme.

2.5.3 DOMPLU Experiment

Data on the performance of the DOMPLU experiment were available up to a data freeze date of 30 September 2014. At this date, the water pressure in the filter had been at approximately 4 MPa since 17 February 2014.

Installation of the concrete dome was controlled using a cooling system. The cooling system worked well, keeping temperatures in the dome below 20°C during cooling to avoid cracking and was also used to pre-stress the concrete prior to contact grouting. Although full release of the concrete dome was planned for, strain measurements indicated that there was only partial release of the concrete from the rock as a result of shrinkage and pre-stressing.

Monitoring of relative humidity, total pressure, pore pressure and displacement have demonstrated performance consistent with design specifications. The performance is also consistent with modelling predictions providing confidence in the modelling and its application for detailed design of repository plugs. Monitoring also included measurement of the main leakage past the plug, which was collected in a weir and weighted with an on-line scale to calculate the flow.

During the build-up of pressure in the filter, water-bearing fractures opened in the rock and water pathways were created in the concrete dome via the main cable bundle, both of which resulted in significant experiment-related leakages (and which were monitored using manual recording methods). However, owing to the swelling of the bentonite seal, water leakages have decreased through time. After eight months of subjecting the dome plug to a water pressure of 4 MPa, the leakage across the plug was about 0.043 litres/minute (2.6 litres/hour). This is well below the desired level of leakage past the plug of less than 0.1 litres/minute. The measurements also indicate that the leakage rate may continue to follow a decreasing trend.

In general, the monitoring systems have performed well, and have been used to evaluate the performance of the experiment with respect to design specifications. Almost all of the installed sensors in the concrete dome have worked successfully and captured the behaviour from a few hours after casting up to the point of contact grouting the concrete dome, which occurred about 3 months after casting. However, after this, several of the sensors failed, mainly as a result of the increasing water pressure, since none of these concrete-related sensors were designed to withstand the water pressure and contact with water was not anticipated. The sensors installed in the bentonite sections were all known in advance to be subjected to high water pressures and therefore these were all designed to withstand a water pressure of at least 10 MPa. However, a few of the sensors in the bentonite sections have also failed during the full-scale test.

The DOMPLU experiment has demonstrated that it is feasible to build the dome plug system. This includes verification of practical aspects such as logistics and arranging of parallel activities. It was also shown that it is possible to use an unreinforced concrete dome plug.

2.5.4 POPLU Experiment

During construction and concrete delivery for the POPLU experiment, quality control testing was done to evaluate the fresh properties of the mixture prior to pumping. The hardened concrete properties for long-term performance were also evaluated, and the concrete temperature was monitored following pouring. All of the concrete properties complied with the design specifications.

Pressurisation of the POPLU experiment commenced in January 2016. Monitoring data included an initial pressurisation phase when the experiment was pressurised up to 1.4 MPa over a one month period until the end of February 2016. By this time, no displacement, strains or temperature changes in the plug sensors in response to the pressurisation were detected. Based on these results, the concrete plug was not performing satisfactorily., . During the initial pressurisation phase, leakages were observed, although, following each increase of pressure, the water leakages decreased indicating that the bentonite strips started performing as expected. Nonetheless, based on the preliminary pressurisation and monitoring results, a decision was made to re-grout the plug-rock interface to reduce the observed leakage amounts below the target criterion of the pressurisation plan i.e. 0.1 litres/minute (6 litres/hour) prior the next pressurisation phase.

Further a shorter duration complementary higher pressure test up to 4.1 MPa was undertaken in April 2016. During this test no major temperature or strain changes were observed. However, a displacement resulting from the wedging effect was recorded as it had been predicted. The subsequent water leakage was excessive. However, it also assisted in pointing out how the corrective re-grouting could be optimised for the interface critical locations. Water movement through the POPLU plug was observed by using relative humidity measurements. No significant increase in water pressures measured in the surrounding boreholes, or additional visual leakage was detection in the near-field monitoring locations as a result of the test.

The plug monitoring system was successfully used in evaluating the material and structural performance of the plug at all stages of construction and during the early stages of pressurisation. Over 100 sensors were installed according to the test plan and their majority had sufficient water-protective shielding. The sensors were used to evaluate mechanical load transfer, concrete stresses, and location of water during pressurisation and temperature development. Comparative samples from the method tests of concrete were used for evaluation of water tightness (hydraulic conductivity), shrinkage, compressive and tensile strength, and leachate pH.

There were significant positive achievements from the overall POPLU experiment. Valuable insight was gained regarding the interdisciplinary nature of work required for successful tunnel plugging. The fields of expertise have ranged from rock mechanics, through structural and hydraulic design, monitoring technologies, data management, quality control practices, construction, and safety practices.

2.5.5 ELSA Project and work undertaken in DOPAS Project

During the experimental work related to the German ELSA Project, improvements to specific sealing elements for the current shaft sealing concept (Figure 1-12) have been developed. Evidence has been provided that the long-term sealing element originally consisting of pure crushed salt can be improved by using a mixture of crushed salt and fine granular clay. The reason is that it is rather difficult to achieve a sufficient initial porosity of the pure crushed salt sealing element during installation. Compaction of the material can be improved with method development and a lower initial porosity can be achieved when a mixture of crushed salt and clay is used instead. Laboratory and mock-up experiments suggest that a sufficient initial *in situ* compaction of the mixture (porosity of about 10%) is possible which ensures a sufficiently low permeability.

In case of fluid movement into the sealing element, the clay admixture starts to swell, causing the fine pores in the crushed salt to become closed. This means that this sealing element is able to realise the sealing function much earlier than originally planned (Glaubach *et al*., 2016).

The gravel column originally intended to act as an abutment for the overlaying bentonite sealing element and as a fluid storage or fluid buffer to delay the fluid pressure load on the sealing elements, can be improved by adding low viscous bitumen in the lower part of the column. By adding bitumen, a small part of the gravel column can act as a sealing element as well. In contrast to the bentonite sealing element, which needs a huge amount of time to saturate and thus to develop its full sealing abilities, a bitumen filled gravel element fulfils its sealing task straight after installation. A bitumen-filled gravel column can be used as an additional sealing element extending the options for establishing the required sealing system (Glaubach *et al*., 2016).

The low permeability of bitumen as a sole sealing element has also been demonstrated during the *in situ* tests. The bitumen element has been pressurised just after cooling and the permeability was extremely low. A combination of both kinds of elements, bitumen and clay based elements, serve on both ends, on the short-term as well as on long-term tasks (Glaubach *et al*., 2016).

The flow time for water/brine through the whole shaft sealing system will be small enough to allow the crushed salt backfill in the adjacent drift to be compacted down to a permeability which is close to the undisturbed salt host rock.

From the small scale in-situ tests and materials research projects performed so far for the modular shaft sealing system, it can be stated that the sealing abilities and the permeabilities of the individual sealing elements provide the required basis for their application in large scale shaft sealing module demonstrations in the phase 3 of the ELSA Project.

2.5.6 Key Outcomes of WP4

The design basis work undertaken in WP2 has provided a basis for the method used to evaluate the performance of the experiments and the content of the requirements evaluated. Performance evaluation has focused on the overall functions of the plugs and seals, and their design specifications. The design basis for each experiment includes many tens of design specifications, and it is deemed outside the scope to systematically evaluate the performance of the experiments against each design specification. Therefore, in addition to evaluation of performance against safety functions, performance has been evaluated against a set of "key design specifications". These comprise a set of design specifications that capture the most significant aspects of the performance of a plug/seal from the judgement of the experiment leader, and which relate to the design work and monitoring.

There are some differences in the features and processes considered in the performance evaluation and key design specifications evaluated for each experiment, which reflects the different host rocks, conceptual designs and priorities of different programmes. However, properties common to many of the experiment performance evaluation and design specifications can be recognised. These are: the pH of concrete leachate, the curing temperature of concrete/shotcrete, density of bentonite and hydraulic performance of the system (e.g. hydraulic conductivity and/or flow).

Examples of the compliance assessment and evaluation of the four properties above for the full-scale experiments are provided in Table 2-3. The assessment includes consideration of the requirement or design specification justification, compliance approach, compliance assessment and feedback to the design basis.

Table 2-3: Key design specifications tested through measurement of the results of the four full-scale experiments or during materials development as part of the experiment, and their compliance assessment, including feedback to the design basis presented in DOPAS 2016c and in Noiret *et al*., 2016; Svoboda *et al*., 2016; Grahm *et al*., 2015; and Holt and Koho, 2016).

Property	Full-scale Experiment	Design Specification	Justification	Compliance Approach	Compliance Assessment	Feedback to the Design Basis
pH of concrete leachate	**FSS**	The pH of the concrete shall not exceed a value of 11, and shall ideally lie between 10.5 and 11 at 28 days.	At pH < 11, the impact of cement leachate on bentonite and argillite performance is acceptable.	Three different mixes were tested in the laboratory.	For the SCC, the three mixes gave a pH between 11.8 and 12.2 after 28 days and a pH of 10.1 to 10.3 after 90 days. For the shotcrete, the three mixes gave a pH between 11.3 and 12.3 after 28 days. A couple of the mixes gave a pH of <11 after 90 days.	Design basis needs to be changed to reflect the pH of the concrete leachate after 90 days, as the leachate chemistry is still evolving at 28 days. Note that the “28 days” is not critical – it comes from standard practices of the concrete industry.
pH of concrete leachate	**EPSP**	The pH of the concrete leachate shall be less than 11.7.	Saturation of high-pH concrete with groundwater produces a hyperalkaline pore fluid with a pH in the range 11–13.5. These pore fluids have the potential to react chemically with bentonite, which may affect its physical and chemical properties.	Measurement of leachate pH during laboratory testing of proposed concrete mixes.	Compliance with the pH requirement was met through testing of the selected concrete mix pH values.	This requirement specifies a higher pH than typically adopted for low-pH concrete (11.7 compared to <11 as adopted in other DOPAS Project experiments). Therefore, the suitability of this requirement, and the shotcrete mix developed to meet it, need review during the on-going programme.

Property	Full-scale Experiment	Design Specification	Justification	Compliance Approach	Compliance Assessment	Feedback to the Design Basis
pH of concrete leachate	**DOMPLU**	Low-pH concrete that generates a leachate with a pH ≤11 shall be used.	Saturation of high-pH concrete with groundwater produces a hyperalkaline pore fluid with a pH in the range 11–13.5. These pore fluids have the potential to react chemically with bentonite, which may affect its physical and chemical properties.	Statement in the construction report providing evidence that B200 recipe has been used. Evidence that the leachate from this concrete will be of low pH is provided in Vogt *et al.* (2009).	Compliance with the requirement for the concrete to generate a leachate with a pH≤11 is met through the use of the B200 concrete mix, which is discussed in Vogt et al. (2009).	During the elaboration of the design basis during the DOPAS Project, it has been recognised that the requirement should specify which aspects of the plug this requirement relates to (e.g., just to the concrete dome or to all cementitious materials).
pH of concrete leachate	**POPLU**	The cementitious materials that are used in plugs shall have a calcium to silica mass ratio less than 1:1.	Ensuring a low pH for concrete pore water can be achieved by replacing Portlandite with low Ca:Si CSH phases, e.g. by increasing the quantity of additives such as pulverised fly ash, blast furnace slag or silica fume. Therefore, in Posiva's programme, meeting the requirement on the pH of concrete leachate is expressed in terms of a requirement on the calcium to silica mass ratio.	Quality control sampling of the concrete mix.	Compliance with this requirement has been met by adopting a ternary concrete mix containing silica fume and fly ash. In addition, as this requirement responds to the expectation for the pH of the concrete leachate to be <11, testing of the mix at 28 days and 91 days in simulated Olkiluoto groundwater confirmed that the pH of the concrete leachate was <11.	It is still an option to consider specifying a pH for concrete leachate rather than a calcium to silica ratio.

Property	Full-scale Experiment	Design Specification	Justification	Compliance Approach	Compliance Assessment	Feedback to the Design Basis
Curing temperature	**FSS**	The maximum curing temperature of the concrete and shotcrete of containment walls shall not exceed 50ºC.	Ettringite can form in concrete at temperatures above 70°C and lead to expansion and cracking, and a consequent loss of strength in the concrete. The maximum curing temperature is set to avoid the possibility of this process occurring, and takes into account the ambient temperature of the Cigéo repository (i.e., ~20ºC).	Measurement of peak curing temperature in the SCC and shotcrete containment walls.	For the SCC concrete, the maximum curing temperature was 48.8ºC, and, therefore, the design specification was met. For the shotcrete, the maximum curing temperature was 66.7ºC, and, therefore, the design specification was not met.	Although the temperature criterion was not met by the shotcrete, further research may identify suitable materials that could be used to develop a suitable shotcrete mix. However, based on the results of FSS, it is likely that SCC will be adopted as part of the reference design for seals.
Curing temperature	**EPSP**	The temperature of the concrete during curing shall be less than 60°C.	The temperature of the concrete is maintained below 60°C to avoid the formation of thermally induced cracks.	Monitoring of the temperature using embedded sensors.	The curing temperature of the concrete was monitored using an array of thermometers installed in both concrete plugs. The maximum temperature recorded was approximately 55°C, and is, therefore, compliant with this requirement.	See evaluation for the EPSP requirement of the pH of the concrete leachate. The shotcrete mix will be reviewed in the ongoing programme.

Property	Full-scale Experiment	Design Specification	Justification	Compliance Approach	Compliance Assessment	Feedback to the Design Basis
Curing temperature	**DOMPLU**	The temperature in the concrete dome shall not exceed 20°C during curing.	The temperature in the concrete dome is controlled by a cooling system to avoid the formation of thermally induced cracks, help the concrete dome release from the rock, and pre-stress the dome before contact grouting.	Monitoring of the temperature using embedded sensors. Compliance evaluation includes comparisons with model calculations that will support arguments supporting the use of numerical models for compliance assessment in the future.	Compliance with this requirement was demonstrated by the monitoring of the temperature in the concrete dome. The maximum temperature reached was just below 18ºC.	The experience from the DOMPLU experiment related to this requirement supports a conclusion that the cooling procedure was successful and can be specified in detail in the design basis provided for future plugs to be implemented in the repository.
Curing temperature	**POPLU**	The temperature in the concrete wedge shall not exceed 60°C in the first days after casting.	The temperature gradients established in the concrete wedge in response to hydration must not lead to the formation of thermally induced cracks or to the transformation of the cement hydration products that may induce secondary ettringite formation.	Validation of concrete hydration heat (based on concrete mix design proportions) by laboratory experiments and quantitative models, prior to wedge casting. Monitoring of the curing temperature using sensors embedded in the concrete wedge.	The peak temperature measured in the concrete wedge was approximately 42°C, confirming compliance with this requirement.	This requirement appears appropriate to maintain within the design basis.

Property	Full-scale Experiment	Design Specification	Justification	Compliance Approach	Compliance Assessment	Feedback to the Design Basis
Density of bentonite	**FSS**	The dry density of the bentonite materials used in the swelling clay core shall be 1,620 kg/m^3.	This design specification is linked to a design requirement which states "*The swelling clay materials, pure or with additives, shall ensure that an overall swelling pressure of 7 MPa is reached on the whole core, and a maximum hydraulic conductivity of 1x10^{-11} m/s throughout the core.*" An effective mechanical stress of 7 MPa is required to counter-balance the host rock natural mechanical stress. A dry density value of 1,620 kg/m^3 corresponds to a swelling pressure of 7 MPa after hydration. The density required to achieve a hydraulic conductivity of 1x10^{-11} m/s is significantly lower than the density required to achieve a swelling pressure of 7 MPa, and, therefore, the density value was predicated on the swelling pressure requirement only. Further details in White *et al*. (2014).	Compliance with the density requirement was determined through mass balance of the bentonite materials used in FSS, time domain reflectometer (TDR) penetrometer measurements and gamma-gamma logging.	The dry density of the lower part of the core (~2/3 of the core) was 1,580 kg/m^3 and the dry density of the upper part of the core (~1/3 of the core) was 1,280 kg/m^3. This gave an overall average density across the clay core of 1,480 kg/m^3. In addition, the upper part of the last recess was not filled completely resulting in a gap of around 50 cm. The original 1,620 kg/m^3 was not achieved.	Investigation into the required swelling pressure undertaken during the FSS experiment concluded that a pressure of 5 MPa would be sufficient to meet the safety functions of the seal. This revised requirement could be met with an emplaced dry density of the bentonite materials in the swelling clay core of 1,500 kg/m^3. Therefore, as a result of the work undertaken in support of FSS, there is a need to re-evaluate the swelling pressure requirement and subsequent bentonite dry density design specification currently used for seals in Andra's programme.

Property	Full-scale Experiment	Design Specification	Justification	Compliance Approach	Compliance Assessment	Feedback to the Design Basis
Density of bentonite	**EPSP**	The emplaced bentonite shall achieve a dry density of 1,400 kg/m^3.	The density is specified to achieve a swelling pressure of 2 MPa and a hydraulic conductivity of 1x10^{-12}m/s. The swelling pressure is consistent with swelling pressures assumed in existing designs (e.g. in Swedish KBS-3) and the hydraulic conductivity is a value considered to be readily achievable.	Mass balance of emplaced bentonite recorded and average density from known volume calculated. Samples taken during emplacement process.	Based on a mass balance approach, the bentonite dry density was estimated to be 1,410 kg/m^3, and is therefore compliant with this requirement.	This result provides confidence that Czech bentonite can be installed in plugs at the required density using existing technology.
Density of bentonite	**DOMPLU**	The bentonite forming the seal shall consist of blocks with an installed dry density of 1,700 kg/m^3 and water content of 17%, peripherally surrounded by pellets (of lower density).[1]	Modelling showed that a configuration of compacted blocks (with 17% water content and dry density of 1700 kg/m^3) peripherally surrounded by pellets (of lower density) would be sufficient to achieve 2 MPa swelling pressure in the seal, which is defined by SKB as a design premise.	In the DOMPLU experiment, compliance was tested through monitoring the total pressure in the bentonite seal (as well as sampling of the bentonite in the laboratory to check the bentonite density). Comparison of measured and calculated values will help to underpin the compliance approach to be applied in the repository.	The swelling pressure achieved by the bentonite seal developed slowly but quite consistent with model predictions, therefore, the installed density is assumed to be consistent with the requirement.	Consideration of this requirement has noted that it should be expressed in terms of a target with associated tolerances.

Property	Full-scale Experiment	Design Specification	Justification	Compliance Approach	Compliance Assessment	Feedback to the Design Basis
Density of bentonite	**POPLU**	N.A. No bentonite sealing layer in POPLU.				
Hydraulic requirement	**FSS**	The seals shall include a swelling core comprised of a clay-based material with a maximum overall hydraulic conductivity of 10^{-11} m/s.	Performance assessment studies have shown that seal performance can be achieved with a hydraulic conductivity of 10^{-9} m/s. 10^{-11} m/s has been specified because it is an achievable value.	Laboratory tests to determine the required bentonite density. A design specification is then provided for the design to determine an appropriate dry density.	Design basis includes a requirement for the designers to determine the dry density of the clay core material in order that the hydraulic conductivity and swelling pressure requirements are met (see entry on the bentonite density design specification in FSS above).	It was found to be difficult to achieve the required dry density (especially at large scale) that was initially specified; flexibility in the definition of requirements is required. Further work on the required density for swelling clay cores to achieve hydraulic conductivity and swelling pressures is ongoing (see entry on the bentonite density design specification in FSS above).

Property	Full-scale Experiment	Design Specification	Justification	Compliance Approach	Compliance Assessment	Feedback to the Design Basis
Hydraulic requirement	**EPSP**	There was no specific water tightness requirement on the plug structure, however hydraulic conductivity values were specified for the concrete plugs (10^{-11} m/s) and the bentonite layer (10^{-12} m/s)	For the EPSP experiment, which is focused on development of experience rather than testing of a reference design, there is no specific basis for these hydraulic conductivity requirements, apart from general experience from other disposal programmes.	For the concrete plugs: samples taken during the installation of the plug were subjected to a permeability test. For bentonite: the relationship between density and hydraulic conductivity was used (density requirement was: 1,400 kg/m^3). To calculate the density, mass balance of emplaced bentonite was recorded and average density from known volume calculated.	For concrete, compliance demonstrated through sampling of test specimens prepared in parallel with EPSP installation process. Test samples had a permeability of 7.9×10^{-11} m/s with an uncertainty margin of 2.7%. For bentonite, and based on a mass balance approach, the bentonite dry density was estimated to be 1,410 kg/m^3, and is therefore compliant with this requirement.	These results provide confidence that the concrete and Czech bentonite materials used in EPSP can be installed in plugs with the required hydraulic conductivity using existing technology.

Property	Full-scale Experiment	Design Specification	Justification	Compliance Approach	Compliance Assessment	Feedback to the Design Basis
Hydraulic requirement	**DOMPLU**	Reduce the leakage across the plug to be "as low as possible".	Extensive leakage of groundwater past the plug can result in unacceptably high erosion (mass transfer) of bentonite clay in certain deposition holes and out from the deposition tunnel. This design specification is directly linked to the safety function "Provide a barrier against water flow that may cause harmful erosion of the bentonite in buffer and backfill. Recent calculations predicted a leakage of 0.1 litres/minute. However, the DOMPLU experiment aims to achieve values lower than this.	Automatic measuring device supplying daily digital leakage data to the plant control room. Measurement based on mass of water in the measurement device. Random checks of bentonite content in the water during drainage from the filter.	By 30 September 2014, the recorded leakage rate collected in the weir (i.e. excluding experiment-related water escapes) was about 2.6 litres per hour (0.043 l/min).	This requirement appears appropriate to maintain within the design basis, although the maximum leakage rate should be defined as a specific value rather than a general objective. The bentonite seal was still not fully functional at the time of the data freeze. This proves that the contact grouting of the concrete dome was well performed and gave an effective seal in the initial stage. The experimentally-related water escapes recognized at Äspö HRL are judged to be very unlikely in Forsmark.

Property	Full-scale Experiment	Design Specification	Justification	Compliance Approach	Compliance Assessment	Feedback to the Design Basis
Hydraulic requirement	**POPLU**	Reduce the leakage across the plug to be "as low as possible".	Water shall not penetrate (from the filter layer) into the concrete or interface (grouted area), so as to maintain water tightness of the plug. Extensive leakage of groundwater past the plug can result in unacceptably high erosion (mass transfer) of bentonite clay in certain deposition holes and out from the deposition tunnel, and thus unacceptable levels of buffer bulk density. Reducing the leakage rate ensures that buffer and backfill material is confined in the deposition tunnel and deposition holes. POPLU calculations predict the leakage rate across the plug can be less than 0.1 litres per minute (6 litres per hour).	Leakage monitoring with pressurisation simulating the design life.	Based on the initial stages of monitoring of the POPLU experiment, with pressures up to 1 MPa, the detected leakage rate was over 0.1 litre/minute (6 litres/hour) at the interface. However, there was no leakage through the concrete mass itself and quality control tests showed a watertightness under 15 mm. Therefore, the concrete was accepted as being compliant with a requirement on the hydraulic conductivity of the concrete mass of <1x10-11 m/s.	The final evaluation of the performance of the POPLU experiment with respect to this requirement will be undertaken at a later date, and will consider the lessons learned regarding contact grouting.

2.6 WP5 Performance assessment of plugs and seals system

2.6.1 Introduction

WP5 of the DOPAS Project was focused on the implications of plug and seal performance on safety over the assessment period, including the development of justifications for model simplifications applied in long-term safety assessment simulations. The main objective was to improve the state-of-the-art in process modelling and its abstraction in integrated performance assessment. The work in WP5 was divided into more specific objectives that were experiment or experiment subproject specific. The work carried out under WP5 related to the specific objectives is explained under each experiment in the following Sections 2.6.2 - 2.6.6 in more detail.

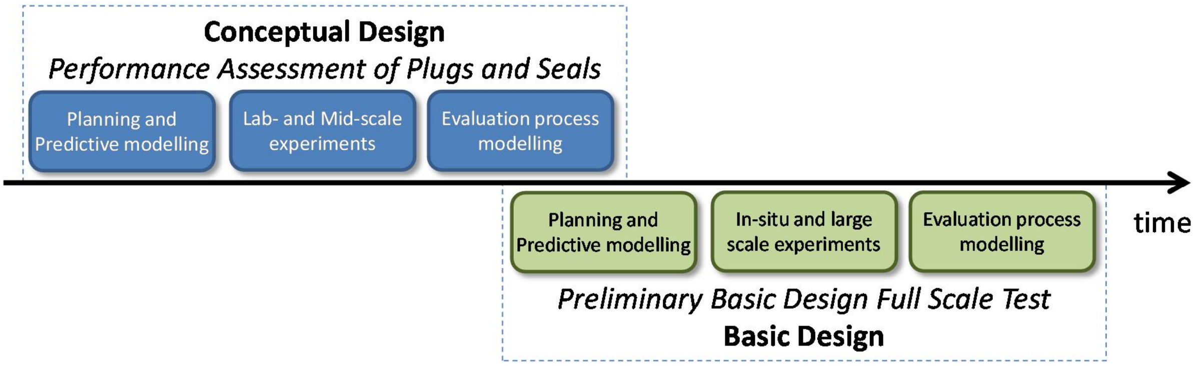

Figure 2-5 Role of process modelling in the workflow of development of the conceptual design and the basic design.

Figure 2-5 addresses the work performed within WP5. The work carried out falls into the fields of "*performance assessment of plugs and seals*", shown and "*preliminary basic design full scale test*", of the DOPAS Design Basis Workflow (see **Figure 1-14**). Both are again multi-step processes consisting of the experiments itself and the pre- and post-work including planning and prediction and evaluation by process modelling.

The modelling activities performed in WP5 can be classified and distinguished into the following four categories:

1. Modelling in support of experimental design and design optimisation. This type of modelling has to be based on reliable tools and a robust test set-up to be able to predict the temporal evolution of the experiment and allow for the optimisation thereof. Typical modelling tools and modelling strategies are simple (forward) scoping calculations, sensitivity analyses and scenario assessments, aimed at assessing the experimental procedures for a representative range of initial and boundary conditions.
2. Model development and model validation. This type of modelling includes the development of phenomenological or process-level models, often by comparison with experimental results or by code comparison. The model development needs a clear

and traceable verification and validation strategy in the framework of prediction-evaluation benchmarks.

3. Model-based experiment analyses with verified codes and validated models for model calibration or to analyse the conceptual and parametric uncertainties.
4. Modelling in support of performance assessment aims at assessing the expected temporal evolution of the reference (sub-) system on an abstracted or integrated level. Typically this type of modelling includes deterministic simulations, but also stochastic simulations for sensitivity analyses and scenario assessment.

All types of processes were modelled including thermal (T), mechanical (M), hydraulic (H) and chemical (C) processes. However, coupling of those processes was addressed only to a very minor degree in WP5.

Table 2-4 shows which processes have been taken into consideration in the modelling of the different experiments. The processes regarded comprise the following hydraulic and geomechanical evolution of the seals and sealing materials:

Hydraulic state evolution of the seal

- Flow rates of fluid through the seal with time;
- Temporal evolution saturation state of the sealing pore space;
- Temporal evolution of the pore pressure of fluids in the seal.

Mechanical state evolution of the seal

- Temporal evolution of the mechanical stress and load of the seal.

Hydraulic and mechanical coupled evolution of the seal

- Temporal evolution of seal permeability;
- Temporal evolution of the sealing porosity;
- Temporal evolution of the total pressure in the seal;

Chemical evolution of the sealing and the sealing material

- Mineral phase changes in sealing material.

Table 2-4 Information on the thermal (T), hydraulic (H), mechanical (M) and chemical (C) processes modelled in DOPAS.

	T	H	M	C
DOMPLU[1]	x	x	x	
POPLU		x	x	
EPSP		x		
FSS		x		
ELSA	x	x	x	x

[1] Work was not performed as part of the DOPAS project

Different computer codes were used to perform the modelling work reported in DOPAS. With two exceptions of integrated level codes, all other are process level codes.

In addition to the work that falls into the DOPAS Design Basis Workflow and relates the experiment specific or experimental and laboratory test activities, the WP5 included two additional pieces of more generic work.

The first reported work is a review of the safety case work based on public safety case reporting that from the different waste management organisations during the last decade. The work is reported from the perspective of a less advanced programme and was carried by the request of RWM and presents their view (Chapter 4 in D5.10, DOPAS, 2016d).

The second reported work is addressing options to link demonstrator activities with performance assessment by the use of performance indicators. This work has been carried out by NRG (Chapter 11 in D5.10, DOPAS, 2016d). It has been experienced also in the review work of the DOPAS summary deliverable's elicitation and also earlier in this report that within the time available the project, it is challenging to address and produce inputs for the long-term performance assessment (covering hundreds of thousand years) from this type of a project. Within the WP5, the integrated modelling and the improvement made e.g. to the LOPOS code are another development area addressing (long-term) performance assessment.

The expected performance lifetime of the different plugs and seals are significantly different depending on their intended function. The categorisation of the timeframes (Section 1.5.7) is used in the following with the purpose of assisting the reader to put the work carried out in WP5 into its relevant context. Only the integrated modelling as part of the “ELSA” addresses the very long-term performance (i.e. performance on the scale of tens of thousands of years), although the period over which performance is required for other plugs and seals, e.g. deposition tunnel plugs as considered in the DOMPLU and POPLU experiments is much shorter (i.e. of the order of centuries).

The nature of the different modelling approaches carried out is unique for each piece of work and cannot be compared to each other directly. Each of the work has a different function for to the related experiment or in the related national program and therefore has to be regarded as independent.

2.6.2 FSS Experiment

The aim of the modelling work in DOPAS can be concluded in general as being clearly related to the behaviour of the individual experiments, but not to predict the long-term behaviour of the full plug in the repository system. The modelling related to the FSS experiment does not address the behaviour of the full-scale sealing system, but the complementary metric-scale REM experiment which investigates the saturation of the bentonite. The timescale regarded in this experiment and the modelling is some decades of years.

Numerical modelling of the REM experiment results from the size of the FSS experiment that is a phenomenological test where the saturation/pressurisation of the experiment could not be envisaged to be tested as the saturation of the experiment materials would take hundreds or thousands of years. Also it would generate high mechanical stress on the drift model structure (concrete liner) owing to bentonite swelling). Therefore, a series of experiments are being implemented in addition to the FSS construction demonstration in order to test the phenomenological aspects and the seal hydro-mechanical behaviour under real operating conditions.

One such experiment, the REM saturation experiment, is investigating the saturation of the bentonite admixture used in FSS and is being used to analyse the pellets/powder mixture behaviour during saturation. In the REM experiment, a cylindrical pressure vessel of 1 m internal diameter and an inside height of 1 m. Based on preliminary two-phase flow calculations without mechanical coupling, the saturation of the bentonite is expected to take approximately 30 years.

Within WP5 modelling of the REM experiment was also undertaken. These simulations are based on simple Hydraulic models, with no mechanical coupling. This assumption was made following the results of some small scale experimental tests showing that the powder/pellets mixture water uptake was not significantly different than the one measured with powder only. Under this assumption, and using other small scale experimental results, one was able to determine two-phase flow parameters for the bentonite mixture. Using than Darcy flow approximation model, the resaturation time was estimated around 30 years. Based on return of experience on previous comparison between experimental data and simulation results, this estimated time can be seen as a minimum value.

2.6.3 EPSP Experiment

The modelling related to the EPSP plug does not address the behaviour of the full-scale seal itself. Modelling includes the investigation of the bentonite during resaturation in a complementary laboratory experiment. The time-scale of the modelling is some years.

Numerical modelling of a laboratory-scale physical model of bentonite saturation was carried out for the EPSP plug materials by ÚJV (D5.10 Chapter 10, DOPAS, 2016d). The simulation of unsaturated swelling materials is complex and the underground EPSP laboratory experiment will not be dismantled during the course of the DOPAS Project, a two physical model tests using a Physical Hydraulic Model (PHM) were conducted by ÚJV at the laboratory scale on the candidate EPSP materials to support the design of EPSP.

The objectives of the two PHM tests were to investigate the hydraulic and mechanical processes during saturation of bentonite and to derive data for the subsequent calibration of numerical models of the saturation of the bentonite material saturation. One PHM test was conducted with bentonite powder and the other with bentonite pellets, in which the samples were gradually saturated with synthetic granitic water under pressure.

The data were used to develop water retention for the bentonite. The two water retention curves obtained through the two tests were comparable and were applied in numerical modelling of the plug performance.

The modelling results suggested that saturation of bentonite pellets in the laboratory model would be three-times quicker than the saturation of bentonite powder, although interpretation of the results needs to take into account that the initial saturation of the pellets is somewhat higher than that of the bentonite powder.

In order to scope the range of impacts on the effective dose rate from bentonite erosion, ÚJV undertook a series of safety assessment calculations. The purpose was to demonstrate the requirement for plugs and seals to confine bentonite material and maintain its ability to limit radionuclide migration in the event of disposal canister failure. Four variant states of the bentonite layer were considered.

2.6.4 DOMPLU Experiment

The DOMPLU-related THM modelling was done prior DOPAS and it was thus not included into the WP5 work. The monitoring results from DOMPLU within DOPAS WP4 gave feedback to the model validation and design iterations (see Section 2.5.3).

2.6.5 POPLU Experiment

The modelling related to the POPLU plug includes water tightness and mechanical stability of the plug related to the plug performance during the experiment. The POPLU experiment is the only experiment where modelling of the behaviour of the full plug system has been performed in WP5. This timescale regarded in the modelling is the intended lifetime of the experiment.

Predictive process modelling for POPLU using computer simulations was undertaken to assess the water tightness and mechanical integrity of the design of the POPLU experiment. The results were used to finalise the experiment design, including the design of the instrumentation and monitoring system.

The modelling of water tightness considered three design options for the plug components:

- The concrete plug and no seal material (Case A).
- The concrete plug and a seal section made of the current Posiva reference backfill material: Friedland clay blocks, Cebogel pellets and Minelco granules (Case B).
- The concrete plug and a seal section made of MX-80 bentonite blocks and MX-80 bentonite pellets with a permeable concrete beam placed between the seal and the plug (Case C).

Further process understanding was gained by also modelling

- Case B with the addition of a permeable concrete beam placed between the seal section and the plug.
- Case C without the permeable concrete beam placed between the seal and the plug.

The modelling results demonstrated that adding a seal section to the POPLU experiment design would reduce flows by greater than an order of magnitude. However, numerical modelling of the plug hydraulic performance concluded that the massive concrete structure, together with contact grouting of the concrete-rock interface and the introduction of bentonite tapes around the concrete would be sufficiently watertight during pressurisation. Building the experiment without a bentonite sealing layer would allow evaluation of the reliability of the concrete wedge specifically.

Mechanical modelling of the POPLU experiment focused on the prediction of rock mass displacements and impact on *in situ* rock stress as a result of pressurisation up to 10 MPa. Three cases were run, which represented different assumptions regarding the heterogeneity of the rock mass as represented by the lithological model.

Water pressure in the cavity is transferred into the rock mass through the longer wedge surfaces of the concrete part of the plug. The more heterogeneous the rock mass (in terms of lithology and fractures), the more uneven the stress field in the vicinity of the drift. In addition, changes in lithology and presence of fractures in the rock mass at the downstream side of the plug in comparison to the pressurised upstream cavity, induce higher displacements to the immediate vicinity of the load transferring surfaces.

The modelling demonstrated that no material failures were expected even in the case that undetected rock features were present at the most critical locations. On-going monitoring of pressure in response to water injection will allow the mechanisms of the transfer of the mechanical load through the plug to the rock mass to be evaluated at a later stage in the experiment.

2.6.6 ELSA Project related work

The modelling related to the ELSA experiment includes the mechanical and chemical performance of the reference shaft materials. There has been an integrated modelling of the full system and lifetime of the ELSA sealing system, but that of course lacks a detailed description of the actual long-term development on the process-level, but is only an abstracted one. The timescale regarded in the process modelling is the timescale of the individual experiments.

In order to better underpin the design of sealing elements in the conceptual design of the German shaft seal three sets of predictions of laboratory experiments were undertaken as described below.

Process level modelling of compaction processes affecting granular materials was carried out for the long-term and short term sealing elements with crushed salt and with salt - bentonite mixture. The work on analysing the performance of compaction of the seals focused on the emplacement of the proposed sealing element made of crushed salt contained in the conceptual design for a shaft seal in a salt formation in the German repository programme (Figure 1-12).

Numerical model calculations were undertaken with two objectives:

- To increase the understanding of the crushed salt compaction process.
- To support development of a modelling tool that can be used to predict the compaction behaviour of crushed granular material to be applied as sealing material.

A particle model was developed that can be used to generate different grain size or grain distributions and grain shape, and which is able to simulate different compaction processes. The modelling demonstrated that the best compaction could be achieved with:

- Particles with a size ratio between 20 and 10 and a normal size distribution.
- Particles with a uniformly plate-like, round particle shape.
- Compaction using impulse compaction methods.

The modelling was performed not only to identify suitable grain size distributions but also to get information about compaction procedures which lead to a suitable in-situ compactibility and thus a suitable initial porosity after installation. For this purpose, a particle model was developed that can be used to generate different grain size or grain distributions and which is able to simulate different compaction processes. At first, round particles with different grain sizes were studied. In order to approach the best distribution curve possible, the first simulation runs were carried out with samples that consisted of particles with two different sizes. The best compaction could be achieved using particles with a size ratio between 20 and 10. Using a size ratio of 15, various size distribution curves were generated. The best compaction could be achieved using a normal size distribution.

In a second step the model has been further developed to simulate two different types of compaction processes, compaction by a vibrating plate and impulse compaction. To simulate a vibrating plate a horizontal plate was put on top of the granular material which is able to move in horizontal directions with different frequencies. The modelling results show that impulse compaction is much more efficient. Using the vibrating plate model a mean porosity reduction of about 10% could be achieved depending on material composition and vibrating frequency. The impulse compaction models deliver a mean porosity reduction of about 23%.

The results of the modelling work performed during DOPAS will be used to improve the corresponding modelling capabilities with regard to specific constitutive laws for describing sealing material compaction. The results of the laboratory and in-situ investigations are a fundamental basis for the constitutive material laws which can be used within the calculational proofs for this specific purpose.

Modelling of clay seal materials (THM-Ton) were carried out for three types of clay materials:

- compacted MX80 bentonite;
- compacted MX80-sand mixed in the ratio 70:30;
- compacted Callovo-Oxfordian Argillite clay (COX)-MX80 mixture in the ratio 60:40.

In order to enhance the predictive capability of numerical models for the long-term performance of the sealing systems in a repository, the existing constitutive models describing the hydro-mechanical behaviour of the sealing materials were verified and improved. New constitutive equations were formulated and the related parameters fitted to the laboratory observations. Based on the experimental results, the key parameters were determined for each sealing material. They were applied for numerical simulations of various laboratory experiments using the THM code CODE_BRIGHT.

First of all, adequate hydro-mechanical material models were established for the studied sealing materials, i.e. the compacted bentonite, bentonite-sand and claystone-bentonite mixtures. Model parameters were determined from the test data, including the porosity, permeability, water retention curve, the nonlinear elastic modulus, and others. Based on these parameters, the development of water saturation and swelling pressure in the seal materials was calculated. The modelling provides a satisfactory agreement with the measured data. However, some uncertainty in the models and the parameters remains and has to be minimized through further investigations.

Mechanical modelling of concrete-based sealing materials (LASA) investigated the deformation behaviour of salt concrete by laboratory testing and numerical modelling. In the laboratory different types of tests were carried out: Triaxial compression tests, uniaxial and triaxial creep tests. The tests were simulated using CODE_BRIGHT and the calculation results were compared to the laboratory results. The simulation of the triaxial tests aimed at the investigation of material changes between the second and third stress level in the uniaxial tests. The results were useful because the onset of dilatancy could be pinpointed.

In all the simulations, the onset of dilatancy occurred before the load limit was reached. The perceptions of the uniaxial tests in combination with the results of the triaxial tests showed that the material behaviour of salt concrete at an axial stress up to 10 MPa is different from the material behaviour at 20 MPa. Strains and strain rates clearly increase at higher stresses. The simulations showed that an adaptation to laboratory results was only possible if two different sets of parameters were used at the lower stress level (phase 1) and the higher stress level (phase 2). The main problem of simulating the deformation behaviour of salt concrete is the description of the viscoplastic (transient creep) material behaviour. Elastic deformations and stationary creep can be adapted by the available material properties. For a better description of transient material behaviour a constitutive model should be adapted or developed.

It has been shown, that Alkan's model fits very well with laboratory data. However the major drawbacks are: (1) that the maximum measured permeability (ultimate connectivity) has to be inserted individually for each sample and (2) that the onset of gas flow has to be defined for each sample individually. In the present study, it was not possible to define a percolation threshold or ultimate conductivity for a specific state of confining stress due to the limited amount of measurements. As a consequence of the heterogeneity of salt concrete, it remains questionable, if a specific percolation threshold can be defined at all.

The constitutive models used here allowed only mathematical adaptation. Salt concrete consists of the cement matrix and the grains of salt concrete. This structure and its changes could not really be considered yet. If the structure of salt concrete could be considered in detail, the description of the deformation behaviour at different stress levels would become easier and clearer (Czaikowski et al. 2016). Further investigations and developments in this direction are necessary.

Chemical modelling of concrete-based sealing materials (LAVA) studied chemical corrosion mechanisms in salt concrete by comparing calculation results and results of batch-experiments. In general calculations correspond in development of concentrations with laboratory results. Indeed calculations show development of concentrations versus mass of reacted concrete while batch-experiments investigate development of solution composition versus time. Hence a comparison could only be given up to solid-solution-ratio of 0.3 and calculation does not consider development of solution composition versus time. Results from cascade-experiments need to be awaited for a better comparison between calculation and laboratory results. On basis of cascade-experiments the chemical reaction path between concrete and solution until equilibrium between powdered concrete and solution is reached can be determined similar to executed calculations.

Further aspect to be considered is the adaption of thermodynamic database to calculations with saline solutions. In doing this a better agreement of modelling results with laboratory data probably could be achieved.

Further development of the simulation of brine inflow through shaft seals by safety assessment modelling was carried out as part of the improvement of the integrated safety assessment code named Loop Structures in Repositories (LOPOS). LOPOS has been developed by GRS to simulate the one-dimensional, single-phase transport processes in a repository in salt (Hirsekorn, 1999). The code is used to simulate the evolution of a repository, including calculation of the inflow of brine from the overburden, through the repository to the emplaced waste, the mobilisation of radionuclides from the waste matrix, and migration of the radionuclides through the repository up to the shaft top (biosphere).

In the LOPOS code, the performance of the EDZ and the sealing material is integrated into a single time dependent parameter, known as the resistance of the seal. The influence on a sealing element of EDZ closure (resulting from creep) and groundwater-concrete interaction were evaluated using an illustrative calculation, a simulation for the ELSA shaft seal concept and illustrative probabilistic calculations. In the illustrative calculation, the hydraulic resistance of the sealing is initially dominated by the comparatively low resistance of the EDZ. The resistance increases during the first 300 to 400 years as a result of self-sealing in response to rock creep. After about 500 years, the hydraulic resistance of the EDZ exceeds those of the sealing core, which dominates the resistance of the sealing thereafter. The hydraulic resistance of the sealing concrete core is nearly constant for nearly one thousand years. After one thousand years, the resistance is slowly decreasing due to interaction with groundwater, but does not change more than a factor of two until about ten thousand years. After about 13,000 years, the hydraulic resistance decreases rapidly and reaches a minimum value after about 15,300 years. The models developed for abstraction of the EDU behaviour and cement corrosion well describe experimental and process level findings. The new model was successfully tested and applied. Additional processes that might be considered in the future are cracks in the sealing material, which allow for an advancing non-homogeneous corrosion of the sealing material along these pathways.

2.6.7 Key outcomes from WP5

The DOPAS project and Work package 5 contribute significantly to the further development of the safety cases for radioactive waste repositories by bringing forward the plug and sealing concepts in three main host rock types considered in Europe: crystalline rock, clay rock and salt rock.

The role of the Work package 5 in this contribution is shown in Figure 2-6 (Fig 12-2 in D5.10, DOPAS, 2016d) and results from predictive and evaluation process modelling of laboratory (blue boxes) as well as in-situ and large-scale experiments (green boxes). The different aspects of the achievements are (white boxes):

- **Gain in process understanding and improvement of models for safety assessment by evaluation process modelling of laboratory experiments:** Process modelling performed of laboratory experiments (ELSA Project related work) in Work package 5 (GRS, Chapter 8 in D5.10, DOPAS, 2016d and UJV, Chapter 10 in D5.10, DOPAS, 2016d) was able to predict and interpret the results from laboratory experiments enhancing the confidence in the suitability of the used models to describe the observed processes. The process models were party converted to abstract models that could be included in integrated safety assessment models to achieve a better process representation in future total system performance assessments. Future comparison of the performed predictive modelling on mid-scale experiments (FSS related work, Chapter 6, DOPAS, 2016d) with experimental results will contribute in the confidence of the validity of the up-scaling of process modelling results from small scale to metric scale.
- **Advancement of the sealing concept:** The process modelling of laboratory and mid-scale in-situ experiments (GRS, Chapter 8 in D5.10, DOPAS, 2016d and DBETEC, Chapter 7 in D5.10, DOPAS, 2016d) contributed update of the sealing concept and the choice of sealing materials. The predictive process modelling of the in-situ experiment (Posiva, Chapter 5 in D5.10, DOPAS, 2016d) directly supported and influenced the layout and construction of the experiment.
- **Confidence in concept and models:** Future comparison of the predictive modelling with experimental results will contribute in the confidence of the validity of the up-scaling of process modelling results from small scale to large scale.
- **Proof of constructability:** All aspects given before jointly contribute to the confidence in the fact that the plugging and sealing systems will develop as planned and will be able to meet their designed function in the overall repository concept.

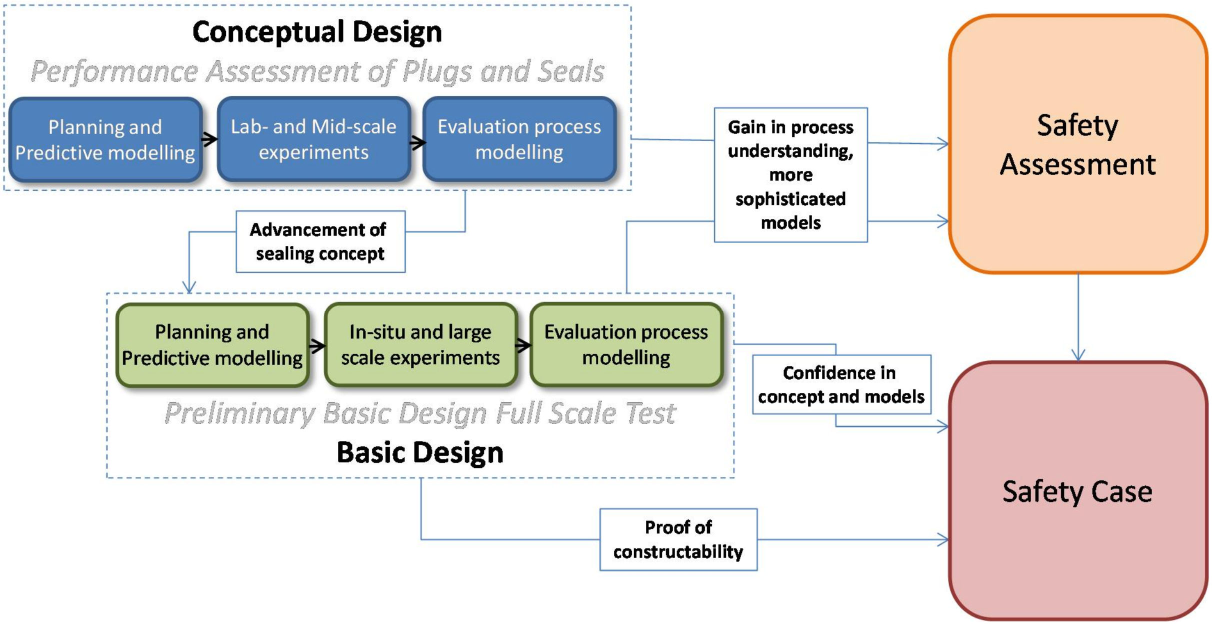

Figure 2-6 Contribution of Work package 5 to safety assessment and the development of the safety case

Finally it can be concluded that the process modelling work performed in WP5 of DOPAS has significantly contributed to the preparation and execution of the experiments and has helped to interpret the obtained results of some of the experiments.

Since many of the experiments are not finished at the date of reporting more updated process modelling is expected in the future to investigate the experimental results and to confirm predictive modelling. This also is true for the full analyses of the in-situ large scale experimental data for integrated performance assessment, which will mostly be feasible in following programme stage.

2.7 WP6 Integrating analysis including cross-review of each other's work

The Work Package 6 of the Project had an integrating and quality assurance tasks in the DOPAS Project. In addition, the work package included competence exchange in the form of planned staff exchange between the consortium member organisations' personnel and on-going experiments in another consortium Member State.

This final summary report of the DOPAS Project is also a task carried out as part of the work aiming to integrate the technical and scientific results of the Project for the use of wider audiences. This report is aimed to act as a guiding document for the future user by highlighting the main lessons learned and outcomes and directing the reader to the more detailed public sources of information, experience and knowledge accumulated during the Project.

In addition to the final summary report D6.4, the other main task of the WP6 was to carry out an external review of the final work package deliverable D2.4 (DOPAS, 2016a), D3.30 (DOPAS, 2016b), D4.4 (DOPAS, 2016c) and D5.10 (DOPAS, 2016d), which summarise the work of the individual RTD and Demonstration work packages in DOPAS. The external experts helped in pinpointing the lessons learned and further uses of the DOPAS results, in identifying controversies, omissions or errors in the individual deliverable drafts submitted for the expert elicitation and also the elicitation process helped in identifying eventual gaps in the work reported between the individual work packages.

2.7.1 Expert elicitation in DOPAS Project

The expert elicitation (EE) carried out in the DOPAS Project was based on the methodology developed for Posiva's Safety Case expert elicitation by Ms. Kristiina Hukki from VTT (Hukki, 2008). The view taken in the elicitation is that the elicitation and validation process is regarded as a collaborative and cross-disciplinary whole and it has a systemic character and follows a formal process aiming to support collaboration of the experts during the process.

In general, structured performance, transparency and traceability are goals for an elicitation and validation process from the quality assurance point of view. The process was originally designed to be used in the quality assurance of Posiva's Safety Case TURVA- 2012. This process was adapted with the help of a pilot elicitation for the use of the DOPAS Project quality assurance and the process was continuously developed during the elicitation work.

The Expert Elicitation (EE) was carried out first as a pilot action for the POPLU test plan in Autumn 2013. The pilot elicitation demonstrated that the process could be applied for a technical target of the elicitation. It also highlighted the need to have the comprehensive report draft available for the elicitation experts. This requirement is based on the objective of having a relative fast elicitation and review process of the deliverables with a lead time of around three months for the process.

The main elicitations were carried out for the DOPAS Work packages 2, 3, 5 and 4 in this order. The Work packages 2 and 5 were in their nature RTD work packages and the WP3 and WP4 were DEM work packages in the original work plan.

The elicitation process includes (Hukki, 2008) the steps described in Table 2-5.

Table 2-5: Expert Elicitation (EE) process steps and their application in DOPAS.

Expert Elicitation Process Steps and their application in DOPAS		
Step number	Elicitation process step according to Hukki 2008.	Elicitation process steps as adopted in DOPAS Expert Elicitation
1	Selection of issue (generally something not easily agreed, but requiring judgment and consensus)	The target for elicitation was the DOPAS Project Work Package summary reports and this selection was made in the Project proposal. During the Project, it was decided in the consortium to do separate elicitations for each of the four summary reports D2.4, D4.4, D3.30 and D5.10 (in this order).
2	Selection of forum	The selection of the forum was defined by the decision that the individual summary reports were elicited separately. The forum consisted of 4-6 experts, the facilitator and as an observer the work package leader or/and the main editor of the summary report in question. It was also planned that the elicitations would take place

Expert Elicitation Process Steps and their application in DOPAS		
Step number	Elicitation process step according to Hukki 2008.	Elicitation process steps as adopted in DOPAS Expert Elicitation
		either in Finland or at the location of the organisation responsible for the work package in question.
3	Selection of domain experts (probabilistic SA)	The selection of the experts took place by long-listing and short-listing suitable technical domain experts and experts with performance/safety assessment (PA/SA) expertise for the individual work packages by the consortium and by the Project officer from the EC. This long-list was screened and at the same time it was recommended that one of the experts would participate as the main expert in all of the four elicitations as the other experts varied based on the content and expertise needed for each work package EE. The final contracting of experts for the individual elicitations started by the facilitator after the timetables for the WP summary reports and their availability for the EE were available from the work package leaders.
4	Selection of shared conceptual frameworks (description production)	The DOPAS EE did not include training for probabilistic safety assessment and therefore both the domain experts and the PA/SA experts all participated in the same process. The shared conceptual frameworks were already partly included in both the WP2 and WP5 RTD work packages, but the rest of these descriptions needed to be produced by the facilitator prior the elicitation start.
5	Preparatory work of safety analysts	The preparatory work of the safety analysts was not included into the DOPAS EE as no probabilistic SA training was needed in this elicitation. In addition to the description production, the facilitator adopted the EE forms that had been produced for Posiva's EE for each WP elicitation separately. After the WP2 elicitation, the forms were also reviewed and commented by the main elicitation expert.
6	Training of domain experts	The training of the domain and PA/SA experts took place simultaneously in a kick-off meeting. The kick-off gave each expert a share framework about what was expected from their independent review work and it also set the timing for the production of their independent

Expert Elicitation Process Steps and their application in DOPAS		
Step number	Elicitation process step according to Hukki 2008.	Elicitation process steps as adopted in DOPAS Expert Elicitation
		work and for the consensus meeting.
7	Instruction of domain experts	The kick-off meeting presented both the elicitation process and a summary of the work package report under elicitation. The experts were able to ask questions about the WP work and about the process and the common dates were set. The main materials and the supporting background materials were given to the experts. A pdf-version of the summary report in question had been sent via e-mail few days earlier to the experts with the intention to give them a chance for more focussed questions about the work and the report at hand.
8	Independent work of domain experts	The experts were given time from 2.5 weeks to 4 weeks to respond to the elicitation form questions and to make their conclusions about the WP summary reports. The inputs were then compiled by the facilitator and the consensus meeting content structured based on the replies.
9	Iterations (consensus meeting)	The experts participated the consensus meeting and gave first their general impression of the work done. This was followed by going through and discussing the items listed by the facilitator from the replies of the experts and common views were recorded after the discussion by the facilitator. The descriptions either produced by the work packages or by the facilitator were discussed and modified accordingly.
10	Treatment of possible controversies (consensus meeting)	Very few controversial views came up in the experts' review. The general views of the experts were very well in alignment. Eventual misunderstandings were clarified in the meeting itself.
11	Validation of expert judgments for later use	The validation of the expert judgments itself did not take place. However, the consensus meeting minutes were approved by all experts who participated the consensus meeting and any mistakes in the minutes were commented by the experts. Also the expert inputs on the elicitation forms are stored as raw data for any future use, but the individual replies are treated as the project's internal information. In addition to the expert elicitation, these

Expert Elicitation Process Steps and their application in DOPAS		
Step number	Elicitation process step according to Hukki 2008.	Elicitation process steps as adopted in DOPAS Expert Elicitation
		reports will further undergo the consortium and in some cases organisational internal review process, too.
12	Final documentation of the process (facilitator)	The approved consensus memorandums produced by the facilitator will be checked by the Project coordinator and they will be published as public deliverables of the Project.

This process was modified for the DOPAS elicitations so that some of the steps were combined and some of them were left out from the process as described in Table 2-5.

The WP2 elicitation was carried out in Autumn 2015, the WP3 elicitation started in April 2016 and the consensus memorandum was approved by middle of July 2016 by the experts, the WP5 and WP4 elicitations were started the second half of May 2016 and the approvals for the consensus memorandums were received by the end of July 2016 .

The experts provided a large amount of comments related to the draft reports, which were then incorporated into the relevant work package summary reported when the comments required for revision of the reports. Editing comments are not included in these figures. The amount of comments for the draft reports are included in the following Table 2-6 with the purpose of giving an idea of the amount of inputs produced by the process. The comments include overlapping comments, too, with few exceptions.

Table 2-6: Summary of expert elicitation review outcomes in numbers.

Deliverable draft no	Total number of comments	Comments requiring revision of the report	Consensus memorandum
Pilot elicitation	25*)	22	D6.1.1
D2.4	80*)	35	D6.3
D3.30	103	59	D6.3.1
D4.4	431	184	D6.3.2
D5.10	203	151	D6.3.3

*) different comments

The first conclusion to the most of the reports subjected to elicitation was that the reports were comprehensive enough. However, they could be improved especially taking into account a potential reader not having the full expertise on the topic in question. Other users for the summary reports were developers of the work following DOPAS and manager requiring a quick overview of the work. For knowledge preservation the number of photographs used to describe the work stages was found valuable.

The feedback from the experts on the process and their suggestions for improvement and clarification of the report content suggests that this quality assurance process worked within the context of the DOPAS Project. It could have been useful also for this DOPAS final summary report D6.4, but could not be implemented due to the project's duration and timetable. The preparation of the descriptions for the elicitations itself also contributed to the integration of the DOPAS Project work.

The experts provided feedback on the elicitation process itself and their main feedback related to:

- The timing of the elicitation.
- The potential to integrate the elicitations into one elicitation and have it in two stages: at the planning stage of the work and at the end of the Project work.
- The structure and length of the questionnaires and their potentially redundant questions.

The feedback related to the elicitation itself is described in more detail in the consensus memorandums (listed in the Appendix C: List of DOPAS deliverables). The planning of the elicitation process is reported in the Deliverable D6.1 of WP6 (Palmu, 2016b).

2.7.2 Programme on Exchange of Expert Staff

The part of competence building for the DOPAS consortium organisations themselves included a planned expert staff exchange programme. The target group for the staff exchange was personnel of the partner organisations that were not directly working in the DOPAS Project, but who would benefit from the knowledge, skills and competence gained from the DOPAS Project work. A planning template was produced for the three staff exchanges that took place to FSS experiment (hosted by Andra), to the EPSP experiment (hosted by CTU and SÚRAO) and to POPLU experiment (hosted by Posiva). The exchanges were relatively short 3-4 days and they focussed on specific implementation aspects of the experiment. The exchange included in addition to the personnel visiting the experiment site, review comments and exchange of lessons learned also from the participants to the host organisations. Nine staff members participated in the exchanges.

Table 2-7: Programme on exchange of expert staff by numbers and location.

Experiment and host	Number of exchange staff	Organisation of exchange staff	Country of origin[6]
FSS (Andra)	3	GSL, Posiva	GB, FI
EPSP (CTU, SURAO)	2	Andra, Posiva	FR, FI
POPLU	4	CTU, GSL, SKB	CZ, GB, SE

Each group produced a report from their staff exchange that is also included as a DOPAS deliverable (Appendix C) into the DOPAS documentation. These reports themselves were quite extensive including evaluation of what had been learned and found of interest on the site. At least in Posiva and GSL, the participants to the staff exchange gave presentation about their visits to their colleagues upon their return from the exchange. Some of the

[6] coding according to ISO 3166

learning contributed immediately to internal development work related to machinery and work condition improvements.

2.8 WP7 Analysis on achievements and conclusions for dissemination activities and impact of the DOPAS project

2.8.1 Objectives

The objectives for WP7 were:

- Produce a comprehensive dissemination plan, implement it and carry out an active follow-up of the activities undertaken. As a part of the implementation of this dissemination plan a project description is prepared early in the beginning of the project for the "Euratom FP7 Research & Training Projects" project compendium;
- To set up a training planning group and to organise one plugs and seals training workshop that is open also for participants outside the consortium. The training workshop plan and the training process content are produced as a deliverable of the project and published on the IGD-TP/DOPAS public website.
- To organise in cooperation and produce input for the IGD-TP's full-fledged international seminar or conference in early 2016 focussing on plugs and seals and the lessons learned around the full scale demonstrations from 2012 to 2015. For the seminar/conference a call for papers will be issued and the call and the conference papers will be published on the DOPAS website in pdf
- On the four experiment sites either at the entry of the underground facilities or adjacent to the experiments underground (depending on safety requirements set by each underground facility) posters describing the experiment with the acknowledgements of the EC financial contribution and logos of the EC/FP7 are set up for information purposes to visitors and experts at the sites.
- To publish and present the DOPAS project's public results by producing scientific/technical papers and conference presentations. For this purpose also regular newsletters of the project's progress are published in pdf-format at 9 months intervals and two 2-page documents summarising the scientific and technical achievements of the DOPAS project will be produced for wider audiences with the assistance of a professional writer or journalist.

2.8.2 Dissemination and exploitation of DOPAS Project

The work started by defining the dissemination strategy, target groups and methods for reaching the groups. Dissemination of the DOPAS Project results was planned to be in alignment with the Vision 2025 (IGD-TP, 2009) and it meets the IGD-TP SRA requirements (IGD-TP, 2011 Chapter 4.1.4).

There were four different group of stakeholders (general public, WMOs, TSO's and regulators, and higher education people not working in area) identified and the dissemination activities were planned so that all of the groups were reached

The dissemination and exploitation plan DOPAS Deliverable D7.1 (Hansen and Palmu, 2013) was published in the beginning of the DOPAS Project aiming to describe the dissemination strategy, philosophy and methods including the target groups. The planned dissemination activities were discussed and agreed by the DOPAS Project General Assembly yearly and the dissemination activities were conducted according to the plan, which was updated yearly and compiled to represent both the national needs for Beneficiaries and to reach the DOPAS target groups sufficient way. Altogether 92 dissemination activities divided to the different categories were published during the DOPAS Project. The main part of the dissemination activities have been published through DOPAS web site and the scientific and oral presentations in many different conferences and seminar, reaching the target groups. Other dissemination activities are related to the publicity of DOPAS Project and its content and therefore DOPAS Experiments have been topics or presented in different public materials produced by organisations implementing the experiments (like company journals, web interviews, annual reports, calendars, video films, miniature model, posters for visitors). As a part of the implementation of the dissemination plan a project description was prepared early in the beginning of the project for the European Commission and it was published in "Euratom FP7 Research & Training Projects" project compendium in June 2014.

2.8.3 DOPAS Training Workshop 2015

The dissemination of the DOPAS experiences included an activity to set up a training workshop for participants outside the project consortium. The initial ideas for the DOPAS training workshop were produced in collaboration with Posiva Oy and the Czech Technical University's (CTU) Centre of Experimental Geotechnics in June 2013, when the location and the time for the training was were agreed.

The training workshop followed the experiential learning (e.g. Kolb, 1984) process integrating both practical and theoretical learning activities for the participants leading into further learning. The learning outcomes for the training workshop were described applying the ECVET approach dividing them into Knowledge, Skills and Competence that the participants were expected to acquire from the Training Workshop. A recommendation for recognising academic credits equalling 4 ECTS for graduate or post-graduate level studies was issued by CTU's and Posiva's representative for the participants who had completed the full DOPAS Training Workshop.

The detailed content planning for the training workshop started in May 2015 with the eight consortium members acting as trainers. Four planning meetings were held using remote connections (teleconferencing and a video link) and two weeks prior the meeting a face-to-face material review meeting was held in Helsinki, Finland. The planning consortium consisted of Posiva, SKB, Andra, CTU, SURAO, RWM and GRS complemented with ÚJV Řež staff and with training materials from Nagra adding the ninth member to the planning group.

The duration of the training workshop was fixed to five days. The week in September 2015 that was scheduled for the training provided unhindered access for the trainees to the Josef URC and underground laboratory. The other training locations were at the faculty of Civil Engineering at the CTU in Prague and at the ÚJV Řež, a.s. in the Czech Republic. In addition to the planning group members, the practical implementation of the training workshop was carried out with the help of additional tutors and lecturers from the Czech Republic.

One of the main planning decisions made was to emphasize two themes in the training. First, the aim was to give the participants an orientation to reflect on the purpose of the plugs and seals and the time that is applicable to the plugs and seals and for their needed isolation and containment function. These vary significantly among the various plugs and seals depending on the repository safety concept and on the host rock environment. Second, the training order was planned in such a way that each of the learning outcomes was presented first by introducing one experiment in detail. This was then followed by shorter introductions related to the other experiments and with an exercise or activity requiring the participants to apply what they had just learned. The approach aimed to provide the participants themselves an opportunity to start to identify and contrast the differences between the choices made for the five different DOPAS experiments and to understand the underlying reasons for the differences. One of the feedbacks from the participants confirmed the usefulness of this approach in creating increased interest in the participant to gain more knowledge about the national programme and in being able to assist in the programme by using the learning outcomes.

The training workshop was advertised on different venues and using contact lists of the planning group in the waste management community and universities and relevant websites in addition to the DOPAS website were used. These websites included e.g. the IGD-TP (www.igdtp.eu) and the ENEN association (www.enen-assoc.org) sites. The number of participants to the training workshop was limited to 12 persons. The training workshop was not oversubscribed, but some last minute cancellations enabled the participation of few more participants who had been alerted to this opportunity only after the registration closing.

The participants came from Czech Republic (3 persons), Finland, Germany (2 persons), Great Britain, Hungary (3 persons), Poland, and Sweden. Four of the participants were active students in the German and Czech universities, at the same time they were working at various organizations. Seven of the participants came from consulting or engineering organizations, two came from waste management organizations and the rest from an authority and research organizations and universities. All of the participants had a scientific or technical background, with most of them with a background in geotechnical engineering or geology.

The training materials were distributed to the participants via a protected internet site for downloading prior the start of the workshop. The materials consisted of about 40 different presentations, of five major exercises and of other supporting materials, presentations of the tutor organizations and of the documentary movie "Into eternity" by director M. Madsen shown at the courtesy of the movie’s producer Magic Hour Films.

The participants’ activities and interaction were observed during the whole week as part of the assessment of their learning. The trainees worked very well together as a group and assisted each other in the exercises. All wanted to perform their tasks very well and if they felt that they had not reached the target they had set, they felt a bit disappointed. Each completed exercise was followed by both the peer assessment of the other group’s outcomes compared with the group’s own results and complemented with the tutor/s’ feedback.

In the beginning of the workshop the participants set their own expectations and goals for the training and concluded that most of their objectives were achieved at the end. In addition to this group assessment, the participants also gave their individual evaluation of the workshop on an evaluation form. The outcomes of the evaluation varied on a scale from 1 (low) to 5 (high), with the average scores varying from 4.3 to 4.8 on nine different evaluated items. Replies were received from all 12 participants. The tutors present made a similar evaluation as a group during the last training day and came to the same conclusion as the participants.

The workshop was successfully implemented according to plans and well received from both the participants and the tutors. The planning process also assisted in structuring the connections of the DOPAS work for the tutors engaged in the process and this contributed also directly to the planning of the expert elicitation of the DOPAS work package deliverables.

The training workshop plan and the training process content are produced as a deliverable of the project (DOPAS Deliverable D7.2, Palmu & Vašíček 2016). The material produced is open access unless otherwise mentioned in the materials for non-commercial use of any interested stakeholders.

2.8.4 DOPAS 2016 Seminar

The DOPAS 2016 seminar planning was initiated in February 2015, and the Conference topics were decided by the DOPAS 2016 seminar planning group. The seminar planning group did represent the different type of organisations participating in DOPAS project with representatives from IGD-TP and European Commission.

The first call for abstracts was published and the DOPAS 2016 website opened around a year before the seminar. The advertisement of DOPAS 2016 seminar was initiated via IGD-TP web site and DOPAS website during the summer 2015 and was continued on the internet. Additional seminar advertisement took place in the end of the 2015 and the scope was experts working with plugs and seals and related stakeholders worldwide. The advertisement did continue at the time of publishing the DOPAS 2016 programme.

The deadline for submitting the abstracts were extended from the end of November until the 18th December and altogether 47 abstracts or proposal for presentations/poster was received. Based on the received abstracts the seminar sessions were modified to inform about DOPAS outcome starting from very general level and going into the detailed aspects on different areas for designing and implementing the plugs and seals and the DOPAS 2016 programme was published in the February 2016. The information from individual experiments was integrated into the presentations which summaries the achievements and experiences.

The extended abstracts were submitted to the seminar in the end of March 2016 and the received abstracts are published as part of the DOPAS 2016 seminar proceedings as DOPAS Deliverable D7.3 (DOPAS 2016e)

The DOPAS 2016 Seminar took place in Turku, Finland 25th and 26th May, with a site visit to Olkiluoto on 27th May. Over 110 participants representing WMO's, TSO's, regulators, university persons, consultants and material specialists related to design, development, production or sales from around 50 organisations and 16 countries worldwide attended the Seminar. The DOPAS 2016 programme was divided into six sessions:

- Session 1 gave an introduction to the role of full scale demonstrations and their role in the development of disposal concepts.
- Session 2 integrated the outcomes from the DOPAS project including development of the design basis for plugs and seals, lessons learnt from construction of plug and seal demonstrators and performance assessment of plugs and seals.
- Session 3 presented plugs and seals experiences from past or for other purposes like borehole sealing, and underground hazardous waste disposal facilities. The idea was to see the role of plugs and seals in a broader context and also get an understanding of how plugs and seals are treated in safety cases.
- Session 4 was concentrated more detailed on the plug and seal designs, materials used in plugs and implementation of demonstrators. The audience also heard case examples on how the plug locations were chosen, how to design concrete, bentonite and other materials to be used in plugs, how to emplace and install plugs and seals, using different DOPAS related or other experiments as case studies.

- Session 5 highlighted the role of plugs in safety and performance assessments, even the long term safety related issues were handled in almost all DOPAS 2016 presentations. Monitoring of plugs and seals and case studies related to the DOPAS Project was given in this session.
- Session 6 had aspects on training and dissemination and regulatory supervision of plugs and seals. In addition the lessons learnt were discussed during a panel where DOPAS Experiment leaders were roasted by questions, which the audience had submitted to the message wall, earlier during the seminar.

During the Olkiluoto site visit the visitors did receive an introduction to the selecting a suitable plug location in crystalline host rock and how POPLU plug was designed, constructed and monitored. The visitors did visit in the VLJ-repository with similar host rock as for Finnish spent nuclear fuel repository.

2.8.5 Publication of DOPAS foreground

DOPAS Deliverables mainly contains the project outcome related to the DOPAS foreground as stated in DOPAS Project plan (DOPAS Deliverable D1.2). DOPAS Project published over 78 reports or other Deliverables. During the course of DOPAS Project some Deliverables were combined to compile information related to each other and in some areas the results were divided into the separate Deliverables with different schedule or other appropriate reason to publish it in parts. The deliverable categories are divided into the reports, others and demonstrators. Reports are the scientific and other written documents, which describe the outcome of the work packages. Most of them are public and are published at DOPAS public website, but few which present interim information or project internal materials are restricted only for consortium members, but even restricted deliverables have been summarised in Work package and Experiment summary reports (DOPAS, 2016a; DOPAS, 2016b; DOPAS, 2016c; DOPAS, 2016d, Noiret *et al*., 2016; Svoboda *et al*., 2016; Grahm *et al*., 2015; Holt and Koho, 2016; Jantschik and Moog, 2016; Czaikowski and Wieczorek, 2016; and Zhang, 2016). Some deliverables (e.g., plans, posters, meeting materials and test results) are materials and are classified as “others”. To the demonstrators category belongs the DOPAS full-scale experiments. Two short video films were produced of the experiments, and these have been published on the DOPAS website or on YouTube, aiming to show the work phases in descriptive and informative manner.

2.8.6 Key outcomes from DOPAS Dissemination and Exploitation

The main outcome was to create and publish planned deliverables and organisation of DOPAS training workshop in September 2015 and DOPAS 2016 seminar in May 2016, and actively disseminate the progress and achievements of DOPAS Project work and Experiments for different target groups. The dissemination activities were planned and implemented according to the plan and the extent was greater than anticipated. Altogether, there were 92 dissemination activities and the DOPAS Project was highly visible among IGD-TP frames and in different seminars and conferences going beyond waste management area (e.g. concrete research and monitoring research). The DOPAS Project is referred in materials published by Ministries responsible for licensing the waste management programmes in some of the participating countries.

2.9 Summary of the state-of-the-art, lessons learned and way forward for plugging and sealing based on DOPAS

2.9.1 State-of-the-art from the DOPAS Project

Full-scale testing of future repository components has a significant role of developing the future procedures for repository design, licensing, commissioning and operation. Plugs and seals are part of an integrated EBS and provide safety in concert with the surrounding host rock and other components of the multi-barrier system.

Plugs and seals in certain repository concepts are part of the deposition tunnel backfill and their expected service life is intended assist the backfill to reach saturation and to stay within the design target after the plug has served its function. In other concepts, the seals have direct safety functions and their service life needs to cover longer periods, i.e. until host rock creep has re-established *in situ* hydraulic conductivity or for the whole assessment period for long-term safety. Due to these reasons the safety functions for plugs and seal vary and therefore many different designs for them are needed depending on the host rock conditions, on the role of the plug and seal in questions, on their dimensions and the planned lifetime of the plug or seal and their components (especially the materials).

Within the DOPAS Project, various plug and seal designs for different repository concepts have been tested at full-scale taking into account the above mentioned variations in their functions and their future repository environment. Since the participating WMOs and Member States are in different phases of development with regard to their disposal concepts, the full-scale experiments and supporting materials research projects carried out have been implemented to meet the maturity of the participating waste management programmes. For the programmes closer to licensing, the work carried out has contributed to advances in the basic design of the plugs and seals. For the programmes planning to start their repository in decades from now, the DOPAS Project has advanced their conceptual designs and provided input to the formulation of preliminary design requirements for their plugs and seal. The DOPAS Design Basis Development Workflow developed in WP2 (DOPAS, 2016a) integrated in an unprecedented way the experiences of the consortium into an iterative and step-wise approach that produces a requirements-compliant design. The workflow has much value as a generic guideline for any design work in the various development stages and it can be used as a yardstick for assessing the future development steps (see also section 2.9.2).

In addition, the experiments, and the design and implementation solutions discussed and reasoned collaboratively within the consortium and in the work package meetings have provided a forum for mutual learning irrespective of the state of the repository development. This interaction has provided complementary exchanges and it has given each partner and experiment comprehensive knowledge on the different areas of plug and seal development needs from different viewpoints. Any full scale experiment has limitations both due to its test function with additional components that are not required in the real repository and also due to the changing conditions due to the natural host rock environment and conditions (including the differences in the local thermal, mechanical, hydraulic and chemical properties). Therefore, in repeating the experiences or the experiments from the DOPAS Project, these limitations need to be addressed and an adaptation to the case in question is required. Still the learning and knowledge accumulated and widely disseminated also outside the consortium during the four-year-long project can be used for further development of other EBS components as well as for plugs and seals. This collected knowledge of the DOPAS Project can be used for development of mechanical and hydraulic plugs in crystalline, in clay and in salt host rock environments. The DOPAS Project experiments have provided to date experimental options for a wide variety of composite plug and seal sizes in variable groundwater and loading conditions: the dimensions of plugs and seals varying from 100 m^3 to 1200 m^3; the host rock groundwater chemistry varying from fresh surface water into the saline groundwater and hydrostatic pressure varying from 0 MPa up to 4.2 MPa.

For illustrative purposes, an example of how the DOPAS Project has contributed to Posiva's programme in Finland, a description of the state-of-the-art is given in Figure 2-7 in the context of the whole repository development programme stages.

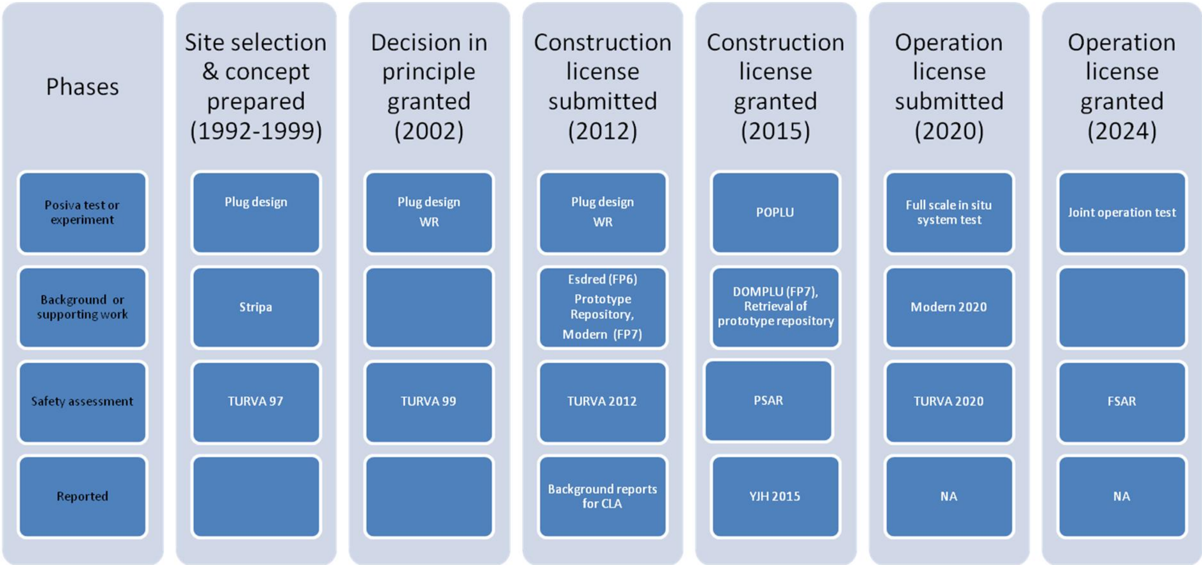

Figure 2-7 An example of Posiva's deposition tunnel plug experiment POPLU as one part on the stepwise implementation of repository. Posiva received a construction licence for the spent fuel repository in November 2015. The facility is to be constructed and the operation to be started within the next 10 years. The concept optimisation continues for industrial scale production operations during this period.

2.9.2 Assessment of the Technology Readiness Level of the Plugs and Seals

The work carried out in DOPAS project has contributed to the development of the plugs and seals enabling the experiment owners to finalise their current development stage (conceptual or basic design in the D2.4 workflow) and to move to the next stage of design development.

The Figure 2-8 demonstrates where in the context of the workflow the experiments are at the end of the project.

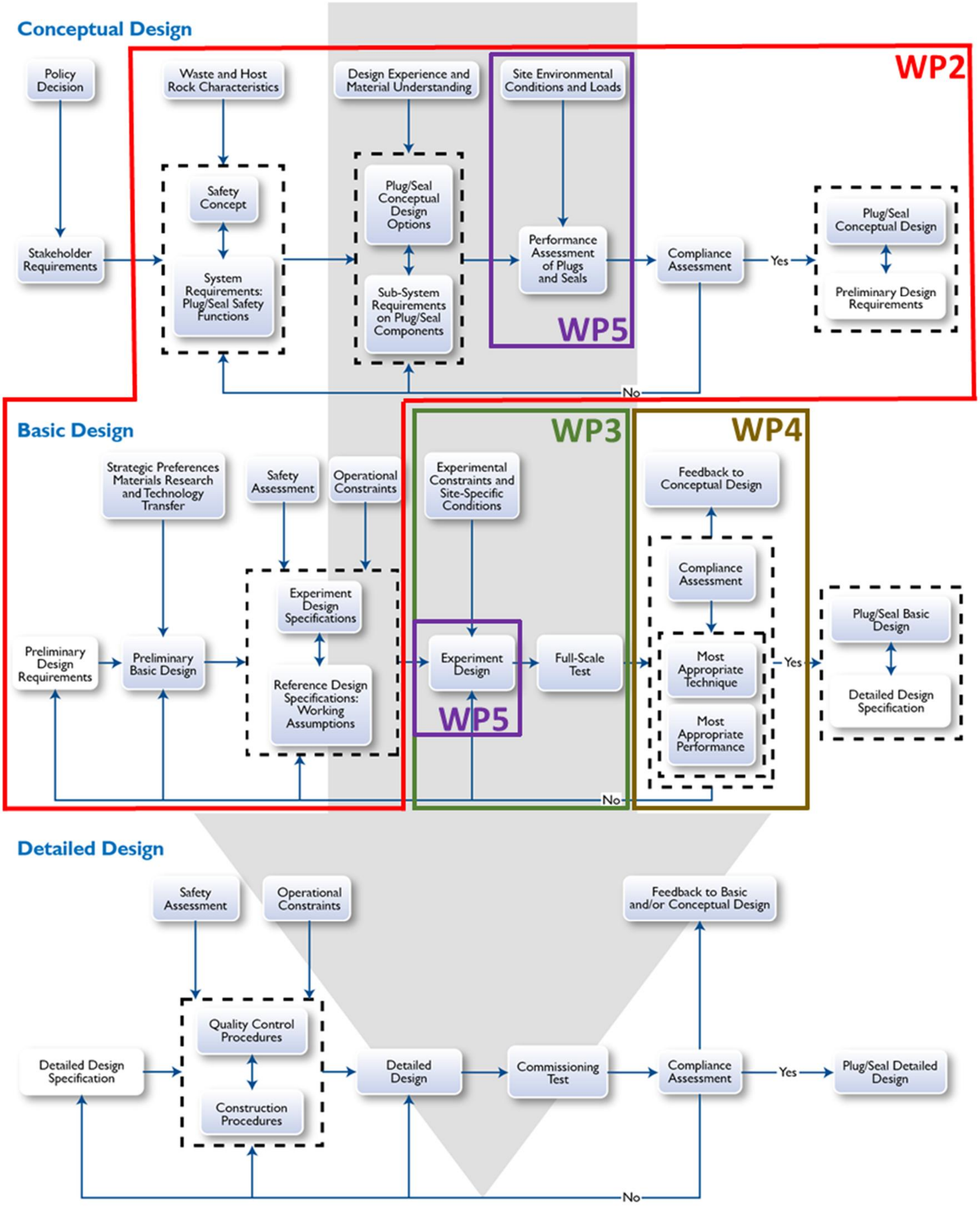

Figure 2-8 State-of-the-art of plug and seal system design basis

The DOPAS experiments have advanced the TRL of the plugs and seals. An example TRL assessment has been undertaken for the POPLU and DOMPLU experiments and is included in the POPLU summary report (Holt and Koho, 2016).

2.9.3 Summary of Lessons Learned

The work done in DOPAS Project has produced lessons learned, which are summarised below for technical Work packages (Table 2-8) and are reported more thoroughly in WP2-WP5 summary reports (DOPAS 2016a, DOPAS 2016b, DOPAS 2016c and DOPAS 2016d). The Work package learning are somewhat overlapping. Some of the findings feed information to all work packages and the division is therefore approximate. One main learning are is the information and understanding related to the practical implementation of safety culture and of quality assurance e.g. under regulatory oversight is improved by implementing the tests while these needs are not so well known by the subcontractors or companies who have not yet been working in the nuclear sector.

Table 2-8 Summary of the main technical lessons learned during the DOPAS Project.

From WP2	**Lessons about the definition of requirements and design basis of the plugs and seals to be demonstrated**
	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. It is an iterative process.
	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.
	The design basis incorporates both requirements and the conditions under which the requirements must be met.
	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).
	WMOs apply systems engineering approaches and the structure of the requirements are described in the form of hierarchies.
	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. However updates and modifications to requirements may be needed as the development progresses.
	A design basis process created to be used by organisations planning for full scale experiments

	Clear conceptual design is useful to have when planning a full scale experiment
	New requirements may be created based on the tests and work and safety functions may change
	An iteration is needed - preliminary design requirements based on conceptual design, their assessment based on experiment results, might be cause the need of reformulations
	Development of a structured approach to requirements hierarchies that is applicable to all waste management programmes.
	Development of a structured approach to development of designs in parallel with development of the design basis (concurrent design); the approach has been captured in the DOPAS Design Basis Workflow.
From WP3	**Lesson learned about design and technical construction feasibility of the plugs and seals**
	Good practices in successful experiment planning and how to mitigate or prevent the posssible risks.
	Procedure for selection of proper site for demonstrators have been developed and tested in real conditions
	Design of concrete components of plugs and seals and their tests in different scale have showed that a range of low-pH concrete mixes can be considered for different type of plugs and seals.
	Design of bentonite systems of plugs and seals and their tests in different scale have showed that overall emplaced dry density of the system meets the specifications.
	Methods for construction and installation of plugs and seals were practiced and lessons learned to be derived for repository use achieved and practical aspects of supervising the work by client and safety authority was trained.
	Logistics related bottlenecks were observed to be develop further and procurement related items were exercised during the implementation and practices can be improved for full scale operation in future.
	It is necessity to have procedure to approve new materials to be used in future repository. The standards cannot be applied.
	The design specifications should be developed so that a range, which can be reached in real repository conditions are reached.
	The full scale experiments can be constructed and the work procedures have been developed. The bottlenecks have been identified and the development needs identified.
	There is need to test the different scales of materials: laboratory scale, metric scale and full scale and also the iteration and modification need to be prepared
	Safety culture issues and understanding have been increased in all organisations participating to the implementation of full scale experiments

	Occupational safety and quality assurance needs to be involved already at the time of planning experiments, it is also important to have the designers and contractors to discuss with each other when imitating the work
	If the site conditions or other requirements cannot be met it is good to have contingency plans for making emplacement actions.
WP4	**Lessons learned about the appraisal of plug and seals system's function**
	Development and application of techniques for siting repository plugs and seals by testing two different methods wire sawing (DOMPLU) and drilling, wedging and grinding (POPLU).
	Application and assessment of techniques for construction of plug/seal slots to high specifications.
	Successful demonstration of the application of low permeability bentonite seals in the FSS, EPSP and DOMPLU experiments.
	Demonstration of the application of 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.
	Further development of contact grouting materials and approaches, application of bentonite strips, and use of highly-mobile bitumen to seal the plug/seal-rock interface in anhydrites.
	Demonstration that tight plugs can be constructed combining bentonite layers providing tightness and concrete serving mechanical strength
	Demonstration of the application of filters, delimiters and formwork to aid the installation of plugs and seals.
	Calibration of sensors in realistic conditions (long cables, free water, pressure) is a necessity
	High water pressures can be detrimental for sensors and cables and therefore redundancy and good protection are needed and was tested at DOPAS
	The requirements and design specifications can be met and methods how to validate the methods and verify the design are introduced.
WP5	**Lessons learned about the performance assessment of plugs and seals system**
	DOPAS projects has compiled the used computer codes available to the research community and the results presented in DOPAS can be exploited by other organisations outside of DOPAS by serving as test case library for model comparison or by adopting the models to their own boundary conditions together with source of information on the internet
	Future comparison of the predictive modelling with experimental results will contribute in the confidence of the validity of the up-scaling of process modelling results from small scale to large scale. This validation might support organisations to plan their tests and their scales.
	The full scale experiments did produce valuable information to the building of

	scenarios and counteracted to define the scales, frames, the initial data and the specification for sensitivity analysis

2.9.4 Way forward base on the DOPAS Project's state-of-the art

The TRL DOPAS Project has allowed consideration of the remaining issues associated with plug/seal design and the next steps in industrialisation of plug/seal installation. Key recommendations for further work that have been identified in the DOPAS Project include:

- Wider use of the structured design basis development methods developed in the DOPAS Project, including application of the DOPAS Design Basis Workflow, both in terms of the adoption of systems engineering approaches by more WMOs and use of the DOPAS Project approaches for other elements of the multi-barrier system.
- It is recognised that development of comprehensive design bases in formalised hierarchies containing all of the links between the requirements is a highly-intensive process. Therefore, processes must be developed by WMOs to make requirements management and effective and efficient process.
- Use of the results from the DOPAS Project to revise reference designs for plugs and seals, and to consider the compliance of the revised designs with the design basis.
- Further clarification on the requirements on the rock adjacent to plugs and seals to support the siting of the structures.
- Consideration of the application of plug/seal slot excavation techniques to the site-specific conditions to be found in repository sites.
- Evaluation of the requirements on bentonite homogeneity and greater understanding of homogenisation processes for bentonite seals used as part of plug/seal design.
- For SCC, optimisation of delivery routines and logistical issues needs to be considered as part of the industrialisation of plugging and sealing.
- For shotcrete, improved mixes and delivery methods (e.g. reducing rebound to ensure a more homogeneous product) are required before application in repositories.
- Development of plans for monitoring of plugs and seals that are based on relevant and measurable parameters, and are linked to the needs of the safety case.
- Undertaking work to industrialise the process of plug/seal implementation, including development and documentation of construction processes and quality control programmes.

2.10 Conclusions

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 2011) to be able to reach the Vision 2025.

The DOPAS Project contributes to the industrial scale of geological disposal facility operations with its full-scale technical feasibility demonstrations and related experiments. The outcomes of the work reported under DOPAS focuses on the early stages of the plugs and seals after their emplacement. The monitoring of the full-scale and laboratory experiments will also contribute to the understanding of the long-term performance of the sealing components.

The DOPAS Project was carried out in seven Work Packages of which two (WP6, WP7) address cross-cutting activities common to the whole Project i.e. the integrating analysis of results and dissemination of public results for European value added. The work related to the experiments, are divided for Research and technological development activities (RTD) in WP2 and WP5 and for Demonstration activities (DEM) in WP3 and WP4. WP1 includes project management and coordination and ensures the coordination and interaction between the work packages.

The DOPAS experiments represented different stages of development. Three of the experiments Full scale seal (FSS) by Andra, Dome shaped deposition tunnel plug (DOMPLU) by SKB and Posiva's wedge shaped deposition tunnel plug (POPLU) were full-scale experimental designs in the basic design stage of the plugs and seals. The Czech Experimental pressure and sealing plug (EPSP) experiment design and the German shaft sealing experiment ELSA related material tests and work method developments were part of the conceptual design of plugs and seals for the Czech and German programmes and they will contribute to the preliminary design requirements of a future reference design. Experiments did require work related to the optimisation of plug design and calculations to reason the design specifications, selection and preparation and production of suitable test location, selection and characterisation of materials to be used in plug small scale testing of field procedures, instrumentation and monitoring and assessment of plug performance in addition to the emplacement activities.

DOPAS project addressed the following areas and describes the lessons learned based on the implementation of DOPAS Experiments.

- Design basis processes: How are requirements on plugs and seals structured, and how can compliance with requirements be demonstrated? Can the learning from development of design bases for plugs and seals be applied to other repository elements?
- Conceptual designs of plugs and seals: What conceptual designs exist for plugs and seals and what are their roles within the overall safety concept?
- Plug and seal materials, and detailed design: The DOPAS Project addressed further development of plugs and seals materials, and the detailed design of the full-scale demonstration experiments.
- Siting and excavation of plug/seal locations: How are the locations of plugs and seals selected? Further development of methods for the excavation of plug and seal locations. What operational safety issues are posed by the excavation of plug and seal locations and how can one overcome these?
- Installation of plugs and seals: Further developments in the technology for emplacing plug and seal materials. What are the operational safety and logistical issues posed by the installation of plugs and seals?

- Monitoring of plugs and seals: Does suitable technology for monitoring the performance of plugs and seals exist. What are the issues and time span with monitoring of plugs and seals?
- Performance of plugs and seals: How do plugs and seals perform with respect to detailed requirements on their performance?
- Compliance of plug and seal designs with their functions: To what extent can the current designs of plugs and seals be considered to meet their overall and safety functions?

Cross-cutting themes are:

- Project management during plug and seal construction and full-scale testing: What learning has the DOPAS Project provided with respect to the management of plug and seal implementation, conducting of full-scale tests and repository operations?
- Dissemination about and integration of learning on plugs and seals: Have the dissemination activities in the DOPAS Project been successful, and can the approaches adopted in the DOPAS Project be applied elsewhere?
- Technical readiness level of plugs and seals and remaining issues: What further development including testing of plugs and seals is required before designs are ready for implementation in operating repositories?

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. The experience of the DOPAS Project has allowed the development of a structured process, the DOPAS Design Basis Workflow that captures this iterative development of the design basis in parallel with the iterative development of the design (Figure 1-14). The Workflow demonstrates the activities and the evolving status of the design basis and design during three stages of development: conceptual, basic, and detailed design. The Workflow on a generic level is applicable to any elements of the repository design

Design and construction of the experiments have contributed to the technical readiness level of plug and seal installation in repositories in the near future. The completion of the experiment design and construction represents a successful collaboration between WMOs, research institutes and consultants.

The implemented experiments and their results are evaluated and assessed including the consideration of the requirement or design specification justification, compliance approach, compliance assessment and feedback to the design basis.

The DOPAS project and Work package 5 contribute significantly to the further development of the safety cases for radioactive waste repositories by bringing forward the plug and sealing concepts in three main host rock types considered in Europe: crystalline rock, clay rock and salt rock. The main achievements were to gain in process understanding and improvement of models for safety assessment and advancement of the sealing concept and getting confidence in concept and models and proof of constructability.

Integrating analysis including cross-review of each other's work had an integrating and quality assurance tasks in the DOPAS Project. In addition, the work package included competence exchange in the form of planned staff exchange between the consortium member organisations' personnel and on-going experiments in another consortium Member State.

The main dissemination and exploitation of the DOPAS Project were to publish the planned deliverables and organisation of DOPAS training workshop in September 2015 and DOPAS 2016 seminar in May 2016, and actively disseminate the progress and achievements of DOPAS Project work and Experiments for different target groups.

This report presents in the end of the report the summary of the state-of-the-art, lessons learned and way forward for plugging and sealing based on DOPAS

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Appendix A. Overall research programme phases of the WMO's participating in the DOPAS Project and the role of plugs and seals in those programmes.

DOPAS WMO	R&D phases & Schedule	Scope	The role of plugs and seals
Andra	Dossier 2005	R&D programme for clay host rock	
	Dossier 2009	R&D programme including comments by safety authority	Rationale to test the plugs and seals
	DAC 2018	Licensing file for Cigéo repository	Justification of the industrial feasibility
	Cigéo- project (2025-2034)	Pilot phase	Underground seals will be demonstrated (in ramp and in horizontal drift)
BMWi	2015-2018	BMWi research programme for final disposal	ELSA phase II including LAVA and LASA as part of barrier studies
	2016	Site selection criteria and procedure	
	2023	Site selection for underground exploration	
	~2031-2050	Licensing procedure and repository construction	
Nagra	2010-2024	Site selection and general licensing	Gathering information based on ongoing experiments (GAST[7], FE[8], REM[9])
	2023-2050	Underground geological investigations (UGI)	
	2045-2049	Nuclear construction licensing	
	2049-2060	Repository construction	

[7] *GAST: Gas-Permeable Seal Test in Grimsel by Nagra is a large scale experimental test to study the low- and intermediate level waste repository early evolution.*

[8] *FE:* Full Scale Emplacement Experiment (FE) in Mont Terri by Nagra as part of Lucoex project.

[3] *REM: Resaturation experiment, part of DOPAS Andra work in the WP5 of the DOPAS Project as a complement to FSS Experiment.*

Appendix A. Overall research programme phases of the WMO's participating in the DOPAS Project and the role of plugs and seals in those programmes.

	2056-2060	Nuclear operation licensing	
Posiva	TKS 2009		Follow up of international cooperation
	YJH 2012	SF repository construction licence application submitted	Decision to start the component related tests (e.g., POPLU)
	YJH 2015	R&D programme for concept development and optimisation and preparing for operation	Decision about plug type (2016)
	2020	SF repository operation licence application to be submitted	Based on results from full scale in-situ system test
RWM	2015 – until site specific	Science and Technology Plan (generic stage)	Requirements gathering. Proof of concept/ develop generic design options.
	2017 - until site specific	Launch of siting process in the UK	Develop generic design options.
	TBC	Develop site specific designs	Confidence that plugs/seals can be implemented to fulfil safety functions.
	~2040	First waste emplacement of low heat generating wastes e.g. ILW	Detailed design of vault/access ways plugs/seals
	~2075	First waste emplacement of high heat generating wastes e.g. HLW	Detailed design of deposition tunnel plugs
SKB	FUD 2010	Three year R&D programme (including construction licence application)	System design of plugs
	FUD 2013	Three year R&D programme	Detailed design of plugs
	FUD 2016	Three year R&D programme	
SÚRAO	2010-2015	The search phase for site	International cooperation
	2015-2025	The investigation phase	
	2025-2050	The detailed investigation phase with an	Detail plug design demonstration in underground facility

		underground laboratory	
	2050-2065	Construction of both the underground and surface repository facilities and commissioning	

Appendix B: Previous Full-scale Demonstration Tests of Plugs and Seals

The DOPAS Project was the first European collaborative project focused specifically on full-scale demonstration of plugs and seals. Prior to the DOPAS Project, work related to plugs and seals had either been undertaken by smaller groups working on specific RD&D projects or as part of wider projects focusing a range of technological issues. Some of the most relevant international collaborations on plugs and seals prior to the DOPAS Project, and which have informed the activities within the Project, are summarised in Table B.1.

Table B.1: Summary of previous full-scale demonstration tests of plugs and seals.

Project / Experiment, Date and Main Reference	Description of the Plug or Seal Tested in the Project / Experiment	Project / Experiment Outcomes
Stripa Shaft and Tunnel Sealing Tests, Sweden 1983-1988 Gray (1993)	These experiments were both based on a design consisting of a central sand-filled pressure cell sandwiched between highly-compacted bentonite gaskets and concrete bulkheads. The objectives were to determine the effectiveness of swelling clay seals in limiting water flow at interfaces between concrete bulkheads and backfilled excavations. The long tapered seal designs used in the experiments were similar to the typical design of seals used in hydropower plants in Sweden.	Leakage of water in the rock past the plug was observed and it was concluded that an improved design with a recess into the rock, deeper than the excavation damaged zone (EDZ), was required.

Appendix B: Previous Full-scale Demonstration Tests of Plugs and Seals

Project / Experiment, Date and Main Reference	Description of the Plug or Seal Tested in the Project / Experiment	Project / Experiment Outcomes
Construction of Háje Gas Storage Facility, Czech Republic, 1992-1998, Cigler et al. (1999)	The Háje underground gas storage facility, located in the Czech Republic, consists of a network of interconnected 3.5-m diameter tunnels at a depth of 950 m below the surface. Four concrete plugs separate the gas storage spaces from the uranium production zone (a pair of plugs in each gallery). Each concrete plug is 10 m long. The plugs were constructed using wet-process sprayed steel-fibre-reinforced-concrete (SFRC) with a high fibre content (90 kg/m3), and incorporate extensive grouting of the host rock. The plug construction and testing techniques were verified underground on trial plugs.	The spray technique was successfully applied in the gas storage facility and was also used in the Experimental Pressure and Sealing Plug (EPSP) experiment during the DOPAS Project.
Äspö Backfill and Plug Test, Sweden 1996-2004 Gunnarsson et al. (2001)	The objectives of this test were to develop techniques for building tunnel plugs, to test their function, and to develop and test backfilling materials for tunnels excavated by blasting at the Äspö HRL. In order to reduce water leakage and because the maximum length of the plugs was constrained by the available clearance space, experimental set-up, and configuration, a dome-shaped plug design with a v-shaped abutment was used. The dome was constructed of ordinary reinforced concrete, and different backfill materials including crushed rock and bentonite. A specific feature of the plug design was an O-ring of bentonite, in the inner part of the recess, surrounding the concrete dome.	The O-ring did not perform as intended, and the leakage of water was found to be quite high (0.75 litres/minute at a hydraulic head of 530 kPa).

Appendix B: Previous Full-scale Demonstration Tests of Plugs and Seals

Project / Experiment, Date and Main Reference	Description of the Plug or Seal Tested in the Project / Experiment	Project / Experiment Outcomes
Äspö Prototype Repository 1995-on-going Svemar (2016) , including retrieval	The Äspö Prototype Repository consists of a deposition tunnel and six deposition holes in two sections. A concrete plug was constructed at the end of each section. The first section was constructed in 2001 and the second section in 2003. All materials and dimensions were based on the KBS-3V method. Electric heaters were used to provide the thermal output of the disposal canisters. Unlike previous experiments, both concrete plugs in the Prototype Repository were cast with SCC with steel reinforcement. The backfill consisted of a mixture of crushed rock and bentonite.	It was observed that the outer bulkhead portion of the Prototype Repository was allowing less than 7% of the potential influx of water to exit through the plug.
RESEAL Project Shaft Seal Experiment, Belgium 1996-2007 Van Geet et al. (2009)	The shaft seal experiment was installed within an experimental shaft located in the HADES underground research facility. The bottom part of the shaft was filled with grout and the concrete liner was removed at the location of the seal. The sealed section was about 2.2 m in diameter and about 2.2 m in height and consisted of a mixture of 50% of powder and 50% of highly compacted pellets of FoCa clay. The seal was kept in place by a top concrete lid with a thickness of approximately 1 m.	The RESEAL shaft seal experiment demonstrated the feasibility to design and construct a bentonite shaft seal. It also showed that the period needed to get full saturation of the seal can be longer than expected. For the test configuration, artificial hydration appeared to have only a limited influence on the period required for saturation owing to possible leakages. The diameter of the test (~2.2 m) was relatively small compared to the access shafts necessary for an actual geological disposal site, so additional upscaling work would be required to transfer the results to a repository.

Appendix B: Previous Full-scale Demonstration Tests of Plugs and Seals

Project / Experiment, Date and Main Reference	Description of the Plug or Seal Tested in the Project / Experiment	Project / Experiment Outcomes
Shaft-sealing Experiment, Salzdetfurth, Germany, 1998-2002 Müller-Hoeppe (2010)	A large-scale shaft sealing experiment carried out with regard to the underground disposal of chemotoxic waste. This joint project aimed at planning, constructing, and testing of a long-term stable sealing system. The investigations were accompanied by laboratory experiments and numerical modelling.	The experiment was considered to be a successful demonstration of the sealing elements to be used in real shafts, and the results were applied during the sealing of three shafts in a salt mine. Although the results were not intended to be used for radioactive waste disposal, a lot of expertise was gained that is currently being applied in the German radioactive waste disposal programme.
Tunnel Sealing Experiment, Whiteshell underground research laboratory (URL), Canada 1998-2004 Martino et al. (2007)	The objectives of the experiment were 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. The design of the seal consisted of two bulkheads, one composed of low-pH, low-heat, and high-performance concrete and the other of highly-compacted bentonite with sand filler in between.	During the experiment, the tunnel was filled gradually with water resulting in a pressure maximum of 4 MPa on the concrete plug. At a pressure of 0.3 MPa, the seepage of water was measured at 1.6 l/min. This was extrapolated to 20 l/min at a pressure of 4 MPa and was deemed unacceptable. As a result, the pressure was reduced and grouting was performed at the interface between the concrete plug and the rock. This led to a reduction of the seepage rate by three orders of magnitude. At ambient temperatures and 4 MPa hydraulic pressures, the seepage through the concrete plug and bentonite seal were measured at approximately 0.01 l/min and 0.001 l/min, respectively.

Appendix B: Previous Full-scale Demonstration Tests of Plugs and Seals

Project / Experiment, Date and Main Reference	Description of the Plug or Seal Tested in the Project / Experiment	Project / Experiment Outcomes
ESDRED Low-pH Shotcrete Plugs, Äspö (Sweden) and Grimsel (Switzerland) 2004-on-going Alonso et al. (2008)	The main objective of the ESDRED Project was to demonstrate, at an industrial scale, the technical feasibility of activities related to the construction, operation and closure of a geological repository for HLW and spent fuel. Module 4 of ESDRED consisted of developing and demonstrating emplacement feasibility of specific low-pH cements for application to sealing plugs using shotcrete techniques. A short plug (1 m) and a long plug (4 m) were constructed and tested at the Äspö HRL in Sweden and the Grimsel Test Site in Switzerland, respectively.	The viability of low-pH concrete recipes and seal/plug construction methods and equipment were demonstrated at an industrial scale, and the results showed that in competent rock formations such as granite shotcrete plugs can be built without recesses excavated in the rock. It also showed that this method is much faster than cast-in-place concrete, that the emplacement method can be easily automated, and that it is almost possible to construct the plugs on a continuous basis due to the low heat release of the low-pH shotcrete during hardening. However, the required curing time for achieving necessary strength must be considered and the hydraulic performance of the shotcrete plug was not tested at full saturation pressure during the Project.

Appendix B: Previous Full-scale Demonstration Tests of Plugs and Seals

Project / Experiment, Date and Main Reference	Description of the Plug or Seal Tested in the Project / Experiment	Project / Experiment Outcomes
KBS-3H Full-scale Plug Experiment, Äspö, Sweden 2009-2010 SKB (2012)	As part of studies related to the KBS-3H method for horizontal emplacement of disposal canisters, a full-scale plug experiment was undertaken. The KBS-3H method envisages disposal of a prefabricated supercontainer consisting of a disposal canister, bentonite buffer and a titanium handling shell in horizontal drifts about 300 m long. There are two types of plugs used in the horizontal drift: a compartment plug in the middle of the drift (i.e. at ~ 150 m) separating two sections of the drift, and a drift plug at the entrance of the drift next to the main tunnel. The full-scale experiment concerned the compartment plug, which consists of three components: a fastening ring which is cast into a rock notch by concrete, a collar which is attached and welded to the fastening ring, and a cap which is welded to the collar. This plug was tested in a 15-m-long drift at the 220-m level of the Äspö HRL. The three components of the plug were made of steel.	The installation was carried out successfully and the experiment showed that the criterion of water tightness with a leakage rate of 0.1 litres/minute can be fulfilled. However, this experiment was done at the 220-m level and further testing would need to be undertaken at the actual repository depth if KBS-3H were adopted for implementation.
Enhanced Sealing Project (ESP), Whiteshell URL, Canada 2009-on-going Priyanto et al. (2016)	Two shaft plugs, spanning a water-bearing fracture, were installed at a depth of approximately 275 m as part of closure of the URL. The first plug was installed in a drill and blast excavated access shaft and the second in a raise-bore ventilation shaft. These composite plugs consist of a 3-m-long compacted bentonite-sand component sandwiched between two 3-m-long concrete segments.	Monitoring of the ESP is an ongoing activity as of 2016. The main shaft seal is very gradually taking on water and approaching saturation. The moisture sensors installed in the clay near the rock-clay and concrete-clay interfaces showed rapid saturation while the core of the main shaft seal has shown more gradual wetting, as water moves slowly through the saturated perimeter clay.

Appendix B: Previous Full-scale Demonstration Tests of Plugs and Seals

Project / Experiment, Date and Main Reference	Description of the Plug or Seal Tested in the Project / Experiment	Project / Experiment Outcomes
Full-scale Emplacement (FE) Experiment at the Mont Terri URL, Switzerland 2009-ongoing Müller et al. (2015)	The FE Experiment is a full-scale heater test in a clay-rich formation (Opalinus Clay). It simulates the construction, waste emplacement, and backfilling and early-stage evolution of a spent fuel / HLW repository tunnel as realistically as possible. The entire experiment implementation and the post-emplacement thermal, hydro, mechanical and chemical (THMC) evolution is monitored using several hundred sensors. These are distributed in the host rock in the near- and far-field, the tunnel lining, the EBS and on the heaters.	A monolithic concrete plug was constructed in the Experiment. The heaters have been operating for 18 months and results are currently being evaluated.
Gas-Permeable Seal Test (GAST) in the Grimsel Test Site, Switzerland 2010-on-going Spillman et al. (2016)	The large-scale GAST is being undertaken by Nagra to demonstrate the effective functioning of a sand-bentonite mixture for gas permeable tunnel seals and to obtain upscaled water and gas permeabilities. The system was designed to realistically simulate the pressures expected in a repository seal at ~500 m depth. The central part of the test is a sand/bentonite element (8 m long, 3 m diameter) with a total volume of ~46 m3. Granular bentonite surrounds this element to protect the instrumentation system and prevent water and gas by-passes along the interface to the host rock.	The emplacement, compaction and QA measurements for the sand-bentonite mixture were successful. Saturation of the experiment was interrupted owing to an unexpected leakage event occurring and remediation works were necessary. By mid-2016, saturation had resumed and the system was ready for planned high-pressure injections.

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Project / Experiment, Date and Main Reference	Description of the Plug or Seal Tested in the Project / Experiment	Project / Experiment Outcomes
In Situ Shaft Sealing Element Tests, Morseleben, Germany 2013-2015 Stielow et al., (2016)	In Morseleben, shafts will be sealed with a combination of various sealing elements consisting of gravel, asphalt and/or bitumen and clay. To show that these sealing elements can be constructed with the quality assumed in the safety assessments, several tests have been carried out. In 2013, BfS tested the pouring of asphalt in gravel layers in a large-scale test at the surface. In 2015, an in situ test as an experimental set-up comparable to the future sealing elements was performed.	The test was evaluated by measurement of pressures and by calculating the remaining pore volume between the gravel grains and bitumen based on the masses of the materials used and the measured volume of the excavation. To assess the influence of hot bitumen on the rock mass, temperature measurements were carried out. The results indicated that the vertical sealing elements can be built as assumed.